Urban Carbon and Energy Analysis:

Calculation of energy flows and emissions from residential housing clusters and assessment of sustainable energy options

by

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Abstract

In the UK, the domestic sector accounts for around 30% of fuel-use and energy related carbon emissions, and therefore has the potential to deliver significant reductions in carbon dioxide emissions. The purpose of this work is to form and examine various heat and electricity supply scenarios at the street-level and identify which of these scenarios offer the most potential to reduce consumption of resources and carbon dioxide emissions. The path to realisation of a reduction in carbon emissions from the domestic sector incorporates three consecutive steps: (1) saving energy, (2) use of renewables and (3) use energy as efficiently as possible, including fossil fuels. In reality, there is a strong interaction between all three steps and often they take place simultaneously. The first two steps tend to minimise the use of fossil fuels, but not to eliminate them. In this work it is recognised that in mature urban regions fossil fuels cannot be readily displaced completely, but can be used in a more efficient way.

This research considers what can be achieved by applying at or near to market technologies at the street level microgrid scale, such as Combined Heat and Power (CHP). The renewable energy technologies considered were photovoltaics (PV) for electricity generation, solar thermal for domestic hot water heating and ground source heat pumps (GSHP) for space heating. For the development of the models, the transient simulation package TRNSYS was used and a residential area in Southampton that represents a typical UK area, was chosen as a case study.

The notion of combining a number of houses to form a local microgrid proved to be beneficial for all the technologies examined in this research. It was shown that renewable energy microtechnologies can improve their carbon performance up to 10% when operating as a microgrid, whilst estimated benefits were even greater for CHP systems. Parallel operation strategies were also investigated and it was shown that they have the potential to deliver further savings from microgrid schemes. Microgrids, although their high capital costs, were estimated to have better financial performance compared with the single house level for many of the cases examined. Increased generation and lower heating demand were the key outcomes due to the impact of change in climate.
Contents

Contents

List of Figures

List of Tables

List of Abbreviations

Form of declaration

Acknowledgments

1 Introduction

1.1 Background

1.2 Objectives

1.3 Research approach

1.4 Thesis outline

2 Literature Review

2.1 Energy performance of domestic buildings in the UK
CONTENTS

2.2 Building regulations - Policies ............................................. 11
   2.2.1 Part L regulations .................................................... 11
   2.2.2 Code for Sustainable Homes (CSH) ............................... 14
   2.2.3 Low Carbon Buildings Programme (LCBP) ....................... 17
   2.2.4 UK Feed-in Tariffs (FITs) .......................................... 17
2.3 Distributed Generation (DG) - Microgrids .............................. 18
   2.3.1 Current status of DG and future penetration .................... 23
2.4 Microgeneration - Low and Zero Carbon (LZC) technologies in the built environment ............................................... 27
   2.4.1 Photovoltaics (PV) .................................................... 29
       2.4.1.1 About photovoltaics ........................................... 29
       2.4.1.2 Photovoltaics in the built environment .................... 31
   2.4.2 Ground Source Heat Pumps (GSHP) ................................. 34
   2.4.3 Solar water heating .................................................. 37
       2.4.3.1 Solar Water Heating in UK .................................. 37
       2.4.3.2 Domestic solar water heating ................................. 38
   2.4.4 Combined Heat and Power (CHP) .................................... 42
       2.4.4.1 Stirling engine CHP ........................................... 46
       2.4.4.2 Fuel cell CHP .................................................. 47
       2.4.4.3 Micro-CHP - ($\mu$CHP) .................................... 49
2.5 Energy modelling .......................................................... 52
2.6 Relevant projects .......................................................... 54
## CONTENTS

2.6.1 Building simulation tools developed and projects ........................................ 54
2.6.2 LZC technologies at the building sector ..................................................... 56
2.6.3 Microgrid projects ......................................................................................... 60
2.6.4 Energy efficiency measures projects .............................................................. 62
2.6.5 Load profile - User behaviour projects ......................................................... 63
2.6.6 Domestic energy and carbon emission reduction projects and models developed ................................................................. 66

2.7 How this study addresses gaps in understanding ............................................. 69

### 3 Project Methodology

3.1 Introduction ........................................................................................................ 70
3.2 Basic steps of research methodology .................................................................. 70
3.3 Modelling Methodology .................................................................................... 72
  3.3.1 Concept of the model .................................................................................... 72
  3.3.2 Modelling approach .................................................................................... 73
3.4 Weather files - Climate change scenarios ......................................................... 76
3.5 Problem complexity .......................................................................................... 79
3.6 Data collection .................................................................................................. 82
  3.6.1 Aerial photos .............................................................................................. 82
  3.6.2 On-line libraries and surveys ...................................................................... 83
  3.6.3 Official government documents ................................................................... 84
  3.6.4 Survey - Questionnaires ............................................................................. 84
  3.6.5 Infrared thermography ................................................................................ 85
3.7 Case study ........................................................................................................ 87
4 Model Development

4.1 Introduction .................................................. 93

4.2 About TRNSYS ............................................... 94
   4.2.1 TRNSYS Simulation Studio .............................. 94
   4.2.2 TRNBUILD .................................................. 95

4.3 Building models in TRNBUILD ............................... 96
   4.3.1 Thermal zone and Heat Flows .......................... 96
   4.3.2 Type 56 models ............................................ 97

4.4 TRNSYS models for heating load prediction in simulation studio ........ 99
   4.4.1 Domestic hot water data ................................ 101
   4.4.2 Occupancy profile ....................................... 106
   4.4.3 Heating profile ........................................... 108
   4.4.4 Ventilation - Infiltration .............................. 110
   4.4.5 Internal gains ............................................ 111
   4.4.6 TRNSYS basic components used for the heating load prediction
          models ..................................................... 112

4.5 Electricity data and development of VBA
       program ...................................................... 115

4.6 TRNSYS models for solar thermal domestic hot water .................. 122
   4.6.1 Active solar thermal domestic hot water for the single house .. 125
   4.6.2 Active solar thermal domestic hot water for the cluster ....... 127

4.7 TRNSYS model for photovoltaics ................................ 129
<table>
<thead>
<tr>
<th>Section</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.7.1</td>
<td>Electricity data synchronisation</td>
<td>132</td>
</tr>
<tr>
<td>4.7.2</td>
<td>Single house PV model</td>
<td>135</td>
</tr>
<tr>
<td>4.7.3</td>
<td>Microgrid PV model</td>
<td>135</td>
</tr>
<tr>
<td>4.8</td>
<td>Ground Source Heat Pump (GSHP) model development</td>
<td>136</td>
</tr>
<tr>
<td>4.8.1</td>
<td>Water to brine heat pump (Type 668)</td>
<td>136</td>
</tr>
<tr>
<td>4.8.2</td>
<td>Ground source heat exchanger sub-routines</td>
<td>140</td>
</tr>
<tr>
<td>4.8.2.1</td>
<td>Ground temperature routine (Type 501)</td>
<td>140</td>
</tr>
<tr>
<td>4.8.2.2</td>
<td>Buried horizontal pipes (Type 556)</td>
<td>141</td>
</tr>
<tr>
<td>4.8.2.3</td>
<td>Vertical U-tubes (Type 557)</td>
<td>142</td>
</tr>
<tr>
<td>4.8.3</td>
<td>Ground source heat pump model for the single house</td>
<td>143</td>
</tr>
<tr>
<td>4.8.4</td>
<td>Ground source heat pump model for the cluster</td>
<td>144</td>
</tr>
<tr>
<td>4.9</td>
<td>Combined Heat and Power (CHP) model development</td>
<td>146</td>
</tr>
<tr>
<td>4.9.1</td>
<td>Combined heat and power model for the single house</td>
<td>148</td>
</tr>
<tr>
<td>4.9.2</td>
<td>Combined heat and power model for the microgrid</td>
<td>150</td>
</tr>
</tbody>
</table>

5  Sensitivity Analysis  

<table>
<thead>
<tr>
<th>Section</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.1</td>
<td>Space heating demand model</td>
<td>155</td>
</tr>
<tr>
<td>5.2</td>
<td>Domestic hot water (DHW) sub-routine and solar thermal model</td>
<td>157</td>
</tr>
<tr>
<td>5.3</td>
<td>Photovoltaic model</td>
<td>159</td>
</tr>
<tr>
<td>5.4</td>
<td>Ground source heat pump model</td>
<td>160</td>
</tr>
<tr>
<td>5.5</td>
<td>Combined heat and power (CHP) models</td>
<td>161</td>
</tr>
</tbody>
</table>
6 Results

6.1 Space heating demand prediction ........................................ 163
6.2 Domestic hot water demand prediction .................................. 173
6.3 Active solar thermal system for DHW results ............................. 174
6.4 Photovoltaics results ...................................................... 179
6.5 Ground Source Heat Pump (GSHP) results ................................. 185
6.6 Combined Heat and Power (CHP) schemes results ......................... 193

7 Discussion - Future work

7.1 Key findings ............................................................... 200
  7.1.1 Space heating demand findings ....................................... 200
  7.1.2 Solar thermal schemes findings ...................................... 201
  7.1.3 PV schemes findings ................................................ 203
  7.1.4 GSHP scheme findings ............................................... 205
  7.1.5 CHP schemes findings ............................................... 207

7.2 Discussion - Implications to UK energy policy ........................... 210

7.3 Implications-Future work ................................................ 215

8 Conclusions ....................................................................... 217

References ............................................................................ 222

A Questionnaire for the area of Marchwood .................................... 236

B Source Code for Type 159, Type 162 and Type 156 ......................... 240
C  TRNSYS basic components used for the heating load prediction models  260

D  VBA program for electricity data analysis  264


F  List of Publications  277
List of Figures

1.1 Main energy flows within an average residential region in the UK for 2008: energy consumption, energy conversion and emissions . . . . . . 4

2.1 Energy consumption and carbon emissions in the UK by end use for 2008 and 2007 respectively . . . . . . . . . . . . . . . . . . . . . . . . 7

2.2 Energy consumption for domestic sector from 1990 to 2006 . . . . . 8

2.3 Domestic energy consumption by fuel for 2008 and by end-use for 2007 9

2.4 SAP Rating for the Domestic Sector in UK, from 1970 to 2007 . . . . 10

2.5 Domestic heat loss from walls, roofs, floors, doors and windows . . . 11

2.6 Ownership of cavity wall insulation and loft insulation for domestic sector 12

2.7 Distribution network: Conventional and With distributed generation . 22

2.8 Distribution network with microgrids . . . . . . . . . . . . . . . . . 22

2.9 Principle of a housing cluster CHP system to provide better thermal load matching . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 23

2.10 Total capacity of DG connected to the UK distribution network . . . 24

2.11 Examples of PV installations in building sector, roof-mounted bolt on and roof integrated . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 31

2.12 Projected generated energy costs for domestic PV according to Energy Saving Trust . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 34
2.13 Shallow geothermal systems; horizontal, borehole vertical, groundwater well (open system) .............................................. 36
2.14 UK Solar Radiation Resource on a 30° incline ....................... 38
2.15 Solar Collectors: flat-plate and evacuated tube .......................... 39
2.16 Illustration of a typical thermosiphon system ............................ 41
2.17 CHP versus Separate Heat and Power production (SHP) .............. 44
2.18 A Stirling engine CHP system ............................................ 46
2.19 Hydrogen fuel cell principle .............................................. 48

3.1 Basic steps to be followed for the completion of this research program . 71
3.2 Three consecutive steps of Trias Energetica .............................. 73
3.3 Main stages of the modelling approach being taken in this research .... 75
3.4 Flowchart of the modelling approach followed in this research ......... 77
3.5 Complexity of the problem based on the number of possible options .. 80
3.6 Complexity of the problem based on the number of possible options after allocating heating and electricity demand profiles to an occupancy profile ................................................................. 81
3.7 An aerial photo of Marchwood, near Southampton, the residential area chosen for the case study .............................................. 83
3.8 An infrared image of a 3 bedroom house, Marchwood, December 2007 . 87
3.9 Location of Marchwood relative to Southampton ........................ 88
3.10 Map and aerial photo of the area in Marchwood, chosen as the case study 89

4.1 Plan of the first floor of two semi-detached houses with all the thermal zones ................................................................. 98
<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.2</td>
<td>Flowchart of the Type 159 component for synchronising the domestic hot water dataset with the occupancy profiles.</td>
</tr>
<tr>
<td>4.3</td>
<td>An example of the synchronisation routine over a 24 hours period for a working couple profile: (Up) Before synchronisation, (Down) After synchronisation.</td>
</tr>
<tr>
<td>4.4</td>
<td>Heating demand for a residential cluster in Marchwood for all possible occupancy configurations.</td>
</tr>
<tr>
<td>4.5</td>
<td>Cold water temperature profile for Southampton 2000 weather file and 1.5m pipes depth.</td>
</tr>
<tr>
<td>4.6</td>
<td>Schematic of how the various components in a simulation are related.</td>
</tr>
<tr>
<td>4.7</td>
<td>TRNSYS Simulation Studio Screen for the prediction of the heat demand of a dwelling.</td>
</tr>
<tr>
<td>4.8</td>
<td>Plot of hourly average consumption per month for house 1.</td>
</tr>
<tr>
<td>4.9</td>
<td>Hourly and daily average consumption over a year for summer, autumn/spring and winter.</td>
</tr>
<tr>
<td>4.10</td>
<td>Hourly consumption profiles for 3 days in September.</td>
</tr>
<tr>
<td>4.11</td>
<td>Flowchart of the algorithm used to forecast values for missing or negative data points from the electricity consumption datasets.</td>
</tr>
<tr>
<td>4.12</td>
<td>An example of a dataset with continuous missing data, before and after applying the forecasting technique.</td>
</tr>
<tr>
<td>4.13</td>
<td>Hourly averages over a year of the three electrical load profiles.</td>
</tr>
<tr>
<td>4.14</td>
<td>Combined pre-heat and storage of a typical domestic system.</td>
</tr>
<tr>
<td>4.15</td>
<td>Single house solar thermal domestic hot water model in TRNSYS.</td>
</tr>
<tr>
<td>4.16</td>
<td>Flow diagram for a solar thermal domestic hot water system.</td>
</tr>
<tr>
<td>4.17</td>
<td>Separate pre-heat and storage.</td>
</tr>
</tbody>
</table>
4.18 Microgrid solar thermal domestic hot water model with flat plate collectors in TRNSYS ......................................................... 129
4.19 PV model in TRNSYS ............................................................. 130
4.20 Flowchart of algorithm developed for synchronising electricity data with occupancy profile ................................................. 134
4.21 Studied configurations of PV model for the single house .............. 135
4.22 Configurations of PV model for the microgrid .............................. 136
4.23 Performance curves of the Veismann Vitocal 300 BW106 and BW232 ................................................................. 138
4.24 Ambient (24h mean) and ground temperatures for Southampton, 2000 142
4.25 Nodes for finite difference model of buried horizontal pipes ............. 143
4.26 TRNSYS ground source heat pump model for the single house ........ 144
4.27 Configurations of GSHP model for the single house ...................... 144
4.28 TRNSYS ground source heat pump model with vertical boreholes for the 10 houses cluster ................................................... 145
4.29 Configurations of GSHP model for the 10 houses cluster ................ 146
4.30 Flowchart of the modelling approach for the single unit micro-CHP model149
4.31 Flowchart of greedy algorithm for the scheduling of the three CHP devices152
4.32 Schematic of the 4 different heating options considered for CHP schemes154
5.1 Change in the annual space heating demand due to change in the average house U-value .................................................... 156
5.2 Sensitivity analysis for models that predict space heating demand ........ 156
5.3 Sensitivity analysis for model that predicts the DHW energy consumption158
5.4 Sensitivity analysis for the solar thermal model .............................. 158
5.5 Sensitivity analysis for the PV model ........................................... 159
5.6 Sensitivity analysis for the PV model due to change in the total installed capacity ................................................................. 160
5.7 Sensitivity analysis for the GSHP model ........................................ 161
5.8 Impact of CHP’s minimum operation cycle ..................................... 162
6.1 Estimated space heating demand for houses in Southampton for the present day (2000) ................................................................. 164
6.2 Estimated space heating demand for houses in Southampton for 2020s . 165
6.3 Estimated space heating demand for houses in Southampton for 2050s . 166
6.4 Estimated space heating demand for houses in Southampton for 2080s . 167
6.5 Estimated CO$_2$ emissions associated with space heating from various houses in Southampton, 2000 .................................................. 168
6.6 Comparison of the results obtained from TRNSYS and the data collected from the questionnaire survey for the “Marchwood cluster” .... 169
6.7 % increase in the space heating demand due to the conservatory ....... 171
6.8 Annual space heating demand per building fabric for various houses in Southampton, 2000 ............................................................... 172
6.9 Fossil fuel savings achieved from solar thermal for the 10 houses cluster and the microgrid, for the flat plate (FP) collectors and the evacuated tube (ET) collectors in kWh per year compared with a BaU scenario of a condensing gas boiler ....................................................... 176
6.10 Estimated operating expense savings in £/year for solar thermal systems at the single house and at the microgrid level ....................... 178
6.11 Estimated savings in £/year and corresponding payback periods (assuming 0% interest rate) for solar thermal systems at the single house and at the microgrid level, assuming a feed-in tariff of 12p/kWh generated 179
6.12 Electricity demand, import and export for the single house and the 10 houses cluster in Southampton, 2000 .......................... 181

6.13 CO$_2$ emissions from electricity with and without PV, at the single house level for three occupancy profiles at Southampton, 2000 .......................... 182

6.14 OPEX savings in £/year and corresponding payback periods (assuming 0% interest rate) for PV at the single house level, in Southampton, 2000 .......................... 183

6.15 OPEX savings in £/year and corresponding payback periods (assuming 0%) for PV for 10 houses, in Southampton, 2000 .......................... 184

6.16 Heat pump power and auxiliary power in one year for one detached house built in the 1980’s in Southampton, 2000 .......................... 185

6.17 CO$_2$ emissions from a detached house with a GSHP, with the 1980’s building fabric, in Southampton, 2000 .......................... 187

6.18 Savings in £/year achieved from a GSHP system and corresponding payback periods, assuming a parity reward scheme for a detached house with the 1980’s building fabric in Southampton, 2000 .......................... 188

6.19 Heat pump power consumption and auxiliary heating required from a 10 houses cluster and the microgrid, in Southampton, 2000 .......................... 189

6.20 CO$_2$ performance of the two microgrid GSHP schemes versus a 10 houses cluster with individual GSHPs in Southampton, 2000 .......................... 190

6.21 Savings in £/year and corresponding payback periods for GSHP schemes for 10 houses in Southampton, 2000, when not linked and when they form a microgrid (horizontal and vertical systems). A FIT of 3.475p/kWh generated is assumed. .......................... 192

6.22 Climate change impact on annual savings and payback periods for three GSHP schemes operating at 35°C for a cluster of 10 detached houses in Southampton .......................... 192
6.23 Annual CO$_2$ emissions for BaU scenario and CHP schemes for clusters located in Southampton at the present day ........................................ 194

6.24 Carbon performance of the CHP schemes studied compared with the BaU scenario ................................................................. 195

6.25 Electricity export for all CHP schemes for the cluster in Southampton for the present day assuming three building fabrics ........................................ 196

6.26 Electricity import for all CHP schemes for the cluster in Southampton for the present day assuming three building fabrics ........................................ 197

6.27 Annual savings from CHP schemes over the BaU scenario for the cluster in Southampton at the present day ........................................ 198

7.1 Cost of each kWh$_{th}$ generated from a solar thermal system, during a 15 year period, for a 10 house cluster in Marchwood, 2000 ................. 202

7.2 Cost of each kg of CO$_2$ saved from a solar thermal system, during a 15 year period, for a 10 house cluster in Marchwood, 2000 ................. 202

7.3 Cost to the household of each kWh$_{el}$ generated from various PV schemes, during a 15 year period assuming a 0% interest rate, for a 10 house cluster in Marchwood, 2000. The impact of a 5% interest rate on the economics (IR 5%) is also shown ........................................ 204

7.4 Cost to the household of each kg of CO$_2$ saved from various PV schemes, during a 15 year period assuming a 0% interest rate, for a 10 house cluster in Marchwood, 2000. The impact of a 5% interest rate on the economics (IR 5%) is also shown ........................................ 205

7.5 Cost of each kWh$_{th}$ generated from various GSHP schemes (at 35°C), during a 15 year period assuming a 0% interest rate, for a 10 house cluster in Marchwood, 2000. The impact of a 5% interest rate on the economics (IR 5%) is also shown ........................................ 206
7.6 Cost of each kg of CO$_2$ saved from various GSHP schemes (at 35°C), during a 15 year period assuming a 0% interest rate, for a 10 house cluster in Marchwood, 2000. The impact of a 5% interest rate on the economics (IR 5%) is also shown. .................................................. 206

7.7 Cost of each kWh$\text{el}$ generated from various CHP schemes, during a 15 year period assuming a 0% interest rate, for a 10 house cluster in Marchwood, 2000. The impact of a 5% interest rate on the economics (IR 5%) is also shown. .................................................. 209

7.8 Cost of each kg of CO$_2$ saved from various CHP schemes, during a 15 year period assuming a 0% interest rate, for a 10 house cluster in Marchwood, 2000. The impact of a 5% interest rate on the economics (IR 5%) is also shown. .................................................. 209

7.9 Ranking of various microgeneration technologies according to the cost of each kg CO$_2$ saved, during a 15 year period assuming 0% interest rate, for a 10 house cluster in Marchwood, 2000. No capital subsidies or FITs have been applied. .............................. 211

7.10 Ranking of various microgeneration technologies according to the cost of each kg CO$_2$ saved, during a 15 year period assuming 5% annual interest rate, for a 10 house cluster in Marchwood, 2000. No capital subsidies or FITs have been applied. ......................... 211

7.11 Ranking of various microgeneration technologies according to the cost per kWh generated, during a 15 year period assuming 0% interest rate, for a 10 house cluster in Marchwood, 2000. No capital subsidies or FITs have been applied. .............................. 212

7.12 Ranking of various microgeneration technologies according to the cost per kWh generated, during a 15 year period assuming 5% annual interest rate, for a 10 house cluster in Marchwood, 2000. No capital subsidies or FITs have been applied. .............................. 212

7.13 'Zero carbon home' definition as it currently is and as it may be in the future ................................................................. 213
C.1 Cold water temperature profile for Southampton 2000 weather file and
1.5m pipes depth .......................................................... 263
List of Tables

2.1

Elemental Method: U-values (W/m2 K) for construction elements

2.2

Minimum boiler SEDBUK to enable adoption of the U-values in the

. . .

13

elemental method and reference boiler SEDBUK for use in the Target
U-value Method . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . .

13

2.3

Levels of Code for Sustainable Homes (CSH) . . . . . . . . . . . . . . .

16

2.4

Generation tariffs for first year of FITs (2010-2011) as proposed from
DECC . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . .

19

2.5

Most important types of Low and Zero Carbon (LZC) technologies

. .

27

2.6

Number of installations of microgeneration technologies in the UK . . .

28

2.7

Main characteristics, advantages and disadvantages of various types of
PV cells . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . .

30

2.8

Installed photovoltaic capacities by 2008 in MWp in European Union .

35

2.9

Summary of all CHP technologies . . . . . . . . . . . . . . . . . . . . .

45

3.1

CIBSE TRY data set and UKCIP02 projections for Southampton, UK
in 2000, 2020s, 2050s and 2080s . . . . . . . . . . . . . . . . . . . . . .

78

3.2

Characteristics of Marchwood cluster . . . . . . . . . . . . . . . . . . .

90

3.3

UK housing stock by age (post 1965 only) and dwelling type . . . . . .

90

xvii


3.4 Characteristics of the Marchwood building stock (surveyed area) compared with the UK average .......................... 92

4.1 U-Values (W/m²K) used for buildings with bad fabric, 2002 regulations and 2006 regulations ........................................... 100

4.2 U-Values (W/m²K) and g-values (%/100) for windows and conservatory (including frame) ............................................... 100

4.3 Coefficient of hot water total load according to the number of occupants 103

4.4 Description of parameters for defining occupancy profile as used in TRNSYS models ......................................................... 107

4.5 Occupancy profiles considered in TRNSYS models .......................................................... 107

4.6 Description of parameters for defining heating profile as used in TRNSYS models ....................................................... 110

4.7 Heating profiles considered in TRNSYS models .......................................................... 111

4.8 Values used for internal gains due to lighting, cooking and use of other electrical appliances ........................................ 112

4.9 Monthly electricity demand for each occupancy profile as used in this work ......................................................... 123

4.10 Technical characteristics of Winkler VariSol A flat plate collector ....... 124

4.11 Technical characteristics of Sieger Solar Sunstar HP65-30 evacuated tube collector ......................................................... 124

4.12 Parameters and inputs for type 94a, representing a multicrystalline PV module .................................................. 131

4.13 Technical characteristics of the Veismann Vitocal 300 BW106 and BW232 ............................................................. 137

4.14 Soil diffusivity values for a variation of soil types ......................................................... 140
4.15 Weather data used for the calculation of the ground temperature in Southampton, UK, according to a UKCIP02 medium-high emissions scenario ................................................................. 141

4.16 Technical characteristics of CHP units used in the CHP schemes ........ 148

6.1 Space heating demand in kWh/m²/year for the three building types, with and without conservatory, and the three occupancy profiles for the present day .......... 170

6.2 Domestic hot water demand for 3 occupancy profiles and 4 climate data in kW per annum ................................................................. 173

6.3 CO₂ emissions from domestic hot water for 3 occupancy profiles and 4 climate data in kg/year ................................................................. 174

6.4 Auxiliary heating to solar thermal system for the three occupancy profiles 175

6.5 Auxiliary heating demand to solar thermal system for domestic hot water (columns 2-4) compared with the total annual heating demand for DHW of a 10 houses cluster in Marchwood (1st column) ............. 175

6.6 CO₂ emissions in tonnes/annum from the solar thermal system compared with the BaU scenario at the single house level ...................... 177

6.7 CO₂ emissions in tonnes/annum from the solar thermal system compared with the BaU scenario for a cluster of 10 houses in Southampton 177

6.8 Annual electricity generation from PV in kWh/annum for the single house and the 10 houses cluster ...................................................... 179

6.9 Feed-in tariff (FIT) scenarios used for the economical analysis of the PVs 182

6.10 Delivery temperatures from the GSHP for various heating distribution systems ................................................................. 185

6.11 Capital and maintenance costs for the BaU scenario and the GSHP systems ................................................................. 190
6.12 Capital and maintenance costs for the BaU scenario and the three CHP schemes .............................................. 196

C.1 Technical characteristics of the tank used for the domestic hot water ........................................... 263
## List of Abbreviations

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Full Form</th>
</tr>
</thead>
<tbody>
<tr>
<td>ASCII</td>
<td>American Standard Code for Information Interchange</td>
</tr>
<tr>
<td>BaU</td>
<td>Business as Usual</td>
</tr>
<tr>
<td>BERR</td>
<td>Department for Business, Enterprise and Regulatory Reform</td>
</tr>
<tr>
<td>BHE</td>
<td>Borehole Heat Exchangers</td>
</tr>
<tr>
<td>BIPV</td>
<td>Building Integrated Photovoltaics</td>
</tr>
<tr>
<td>BRE</td>
<td>Building Research Establishment</td>
</tr>
<tr>
<td>CAPEX</td>
<td>Capital Expenditure</td>
</tr>
<tr>
<td>CCGT</td>
<td>Combined Cycle Gas Turbine</td>
</tr>
<tr>
<td>CFD</td>
<td>Computational Fluid Dynamics</td>
</tr>
<tr>
<td>CHP</td>
<td>Combined Heat and Power</td>
</tr>
<tr>
<td>CIBSE</td>
<td>Chartered Institution of Building Services Engineers</td>
</tr>
<tr>
<td>CLG</td>
<td>Department for Communities and Local Government</td>
</tr>
<tr>
<td>COP</td>
<td>Coefficient of Performance</td>
</tr>
<tr>
<td>CSH</td>
<td>Code for Sustainable Homes</td>
</tr>
<tr>
<td>DBIS</td>
<td>Department for Business, Innovation and Skills</td>
</tr>
<tr>
<td>DECC</td>
<td>Department of Energy and Climate Change</td>
</tr>
<tr>
<td>Abbreviation</td>
<td>Full Form</td>
</tr>
<tr>
<td>--------------</td>
<td>-----------</td>
</tr>
<tr>
<td>DG</td>
<td>Distributed Generation</td>
</tr>
<tr>
<td>DHW</td>
<td>Domestic Hot Water</td>
</tr>
<tr>
<td>DOE</td>
<td>Department of Environment</td>
</tr>
<tr>
<td>DTI</td>
<td>Department of Trade and Industry</td>
</tr>
<tr>
<td>EEE</td>
<td>Energy Export Equivalence</td>
</tr>
<tr>
<td>EPBD</td>
<td>Energy Performance Certificates</td>
</tr>
<tr>
<td>EST</td>
<td>Energy Saving Trust</td>
</tr>
<tr>
<td>FITs</td>
<td>Feed-In Tariffs</td>
</tr>
<tr>
<td>FORTRAN</td>
<td>The IBM Mathematical Formula Translating System</td>
</tr>
<tr>
<td>GSHP</td>
<td>Ground Source Heat Pump</td>
</tr>
<tr>
<td>IAMs</td>
<td>Incidence Angle Modifiers</td>
</tr>
<tr>
<td>IEA</td>
<td>International Energy Agency</td>
</tr>
<tr>
<td>IPCC</td>
<td>Intergovernmental Panel on Climate Change</td>
</tr>
<tr>
<td>LCBP</td>
<td>Low Carbon Buildings Programme</td>
</tr>
<tr>
<td>NGET</td>
<td>National Grid Electricity Transmission</td>
</tr>
<tr>
<td>NREL</td>
<td>U.S. National Renewable Energy Laboratory</td>
</tr>
<tr>
<td>ODPM</td>
<td>Office of the Deputy Prime Minister</td>
</tr>
<tr>
<td>OFGEM</td>
<td>Office of the Gas and Electricity Markets</td>
</tr>
<tr>
<td>ONS</td>
<td>Office for National Statistics</td>
</tr>
<tr>
<td>OPEX</td>
<td>Operational Expenditure</td>
</tr>
</tbody>
</table>
LIST OF ABBREVIATIONS

PV/T  Photovoltaic and Thermosyphonic system
PV    Photovoltaic
RET   Renewable Energy Technologies
RHI   Renewable Heat Incentive
RO    Renewables Obligation
SAP   Standard Assessment Procedure
SEDBUK Seasonal Efficiency of Domestic Boilers in the UK
SSE   Scottish and Southern Energy
TER   Target CO2 Emission Rate
TESS  Thermal Energy System Specialists
TMY2  Typical Meteorological Year
TRY   Test Reference Year
TUS   Time Use Survey
UKCIP02 UK Climate Impacts Programme 2002
VBA   Visual Basic for Applications
Form of declaration

I, Anastasios Papafragkou, declare that the thesis entitled *Urban Carbon and Energy Analysis: Calculation of energy flows and emissions from an urban region and implementation of sustainable energy solutions*, and the work presented in the thesis are both my own, and have been generated by me as the result of my own original research.

I confirm that:

- This work was done wholly while in candidature for a research degree at this University.

- Where any part of this thesis has previously been submitted for a degree or any other qualification at this university or any other institution, this has been clearly stated.

- Where I have consulted the published work of others, this is always clearly attributed.

- Where I have quoted from the work of others, the source is always given. With the exception of such quotations, this thesis is entirely my own work.

- I have acknowledged all main sources of help.

- Where the thesis is based on work done by myself jointly with others, I have made clear exactly what was done by others and what I have contributed myself.

- Part of this work has been published as Papafragkou et al. 2009.

Signed:...........................................................................................................................................

Date:...............................................................................................................................................
Acknowledgments

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First of all, my supervisor Patrick B. James whose continued supervision and advice was valuable for producing this final document. I thank him for the numerous conversations we had, for his open mind and willingness to listen and for his continuous support. Patrick has been a great supervisor and I feel lucky I worked with him.

My other supervisor, AbuBakr Bahaj for his original ideas on the project and above all for giving me the chance to be involved on this research field.

Mark Jentsch, for his advice and particularly for developing the tool for generating the weather data that has been used in this research.

My housemates, Orestis Tzanetis, Polyvios Polyviou, Jack Giles and Mark Leybourne. Except great housemates they were, and still are, great friends. They were always supportive and understanding and I am happy I shared a part of my life with them.

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Last, I would like to thank my family, my mother and my sister, who were always there for me ready to help in their own special way!
Chapter 1

Introduction

1.1 Background

Since the early 19th century, consumption of biomass and fossil fuels (oil, gas, and coal) has played a crucial role in economic growth. Grübler assigns the first main transition of the energy system during that period, as the transition from wood to coal in the industrialising countries, initiated by the steam engine. The second transition was related to the proliferation of electricity, resulting in a diversification of both, energy end-use technologies and energy supply sources (Gruebler et al., 1995).

Early on, however, it became apparent that fossil fuel consumption had harmful environmental effects, contaminating the air, water, and land. More recently, the major concern has focused on greenhouse gas emissions which are considered as the main reason for global warming. It is widely believed that climate change is being driven by excessive release of greenhouse gases (GHGs), mainly CO₂, which come from the burning of fossil fuels. Whilst some environmental impacts of burning fossil fuels were known from an early stage, the world community has not responded to carbon emissions until recently; first by adopting the United Nations Framework Convention on Climate Change in 1992 and subsequently by ratifying the Kyoto Protocol in February 2005. In the UK, other measures have been implemented, such as the Renewables Obligation (RO). The UK’s Renewables Obligation, which came into force in 2002, places a legal obligation on all electricity suppliers to source an increasing proportion
of their power from renewable sources. This percentage rises from 7.9% for 2006 to 15.4% in 2015/16. Companies which fail to achieve their percentage have to pay a “buy-out” price for any shortfall, which was \( \sim £37 \) per MWh for 2007. These payments are then re-distributed among those suppliers who successfully achieved their targets (BERR, 2008b; OFGEM, 2009).

The residential sector accounts for a large proportion of fuel-use and energy related carbon emissions, and therefore has the potential to deliver significant reductions in the total CO\(_2\) emissions. Most actions and services that are performed in a building need energy. The five most important energy related functions are space heating, water heating, lighting, cooling and ventilation. The built environment accounts for about 30% of the total national primary energy consumption, divided almost equally between the residential and commercial sectors. This percentage is valid for most developed countries and it makes the built environment an important sector in national energy policy and planning for every country (DESA, 1999).

At the moment, the major sources of the energy used in the built environment are fossil fuels, contributing to considerable environmental problems. At the same time this sector is quite diverse; there is a very large variation in the forms and types of houses and other buildings. The diversity of the built environment makes it impossible to find one single sustainable solution that can be widely applied. In essence there is no “magic bullet”. The complexity of the sustainability problem in the built environment is therefore high and dependent on local factors which are explained later on (Sections 3.3 and 3.5).

The scope of this work is to determine the potential of various microgeneration technologies to deliver heat and/or electricity in a residential setting and to investigate the implications if a street-level microgrid scheme is established.

1.2 Objectives

The overarching aim of this research is to assess the potential contribution of various energy efficient measures and renewable energy technologies (RET) in the urban resi-
dential sector. Building stock condition, user profile and climate change are regarded as important factors that their impact on energy efficient measures and renewable energy technologies should be determined. In addition, the impact of the scale of the application (from a single house to the street-level) on the measures adopted will need to be explored.

More specifically the objectives of this research, for a UK context, may be stated as follows:

- To critically appraise microgeneration technologies in terms of their carbon and financial performance across a range of domestic building types and occupancy profiles.

- To understand the economic and carbon implications of grouping a number of houses together to form a local microgrid at the street-level. Such microgrids could include heat only networks, electricity only networks and heat and electricity combined networks.

- To examine various gas and electricity profiles, typical of various user types (retired couple, family, working couple), and their impact on the level of emissions that energy efficient measures, renewable energy technologies, microgrids and climate change may have.

- To project the future performance of various microgeneration technologies based on changes in climate.

- To investigate alternative CHP schemes (such as master/slave CHP configuration) and examine if these schemes have the potential to deliver further carbon savings.

### 1.3 Research approach

In this work, models to assess residential energy consumption were developed. Using a “commuter village” on the outskirts of Southampton, a small port city on the South
coast of the UK, as a case study, a simulation model was developed and the major factors affecting housing stock energy consumption were evaluated.

Figure 1.1: Main energy flows within an average residential region in the UK for 2008: energy consumption, energy conversion and emissions data source: (DECC, 2009b)

Individual household and “street-level” energy flows were modelled. For the purposes of this research the “street-level” is defined as a group of 10 houses within a street. The term “energy flows” stands for the energy consumption from the buildings and their occupants within the area, the amount of energy that may be produced from the buildings within the area and the total emissions released to the environment as a result of energy consumption. For the latter, the term “energy footprint” is more often used. Various scenarios, including renewable energy technologies, are examined in order to propose sustainable solutions within acceptable investment cost limits.

1.4 Thesis outline

This thesis consists of seven chapters, as follows: (1) Introduction to the research area, (2) literature review, (3) project methodology, (4) model development, (5) results, (6) discussion and further work and (7) conclusions. More analytically the chapters are as follows:

Chapter 1. A general background to the project, giving the reader an overview of the research areas. Then the justification of the project follows, by showing the high contribution of the residential sector to CO₂ emissions. The main objectives are mapped out and the key steps of the methodology of this research are presented.
Chapter 2. A literature review regarding the current and also the potential energy performance of the building sector. The various energy performance regulations according to the year in which the buildings were built are detailed in order to classify buildings according to their 'potential baseline’ energy performance. Since the project deals with the residential sector, special reference is made to microgeneration, which concerns small scale technologies suitable for the domestic sector. Then a review of the most important Low and Zero Carbon Technologies (LZC) that may be implemented in the built environment is given, since many of these technologies are considered later on in this thesis or may be considered in the future. The various technologies are ranked according to various parameters, such as efficiency, cost, payback period, etc. Finally, a classification of the models found in literature for regional planning is given and this research is classified accordingly. This chapter shows that the building sector has good potential to reduce its carbon emissions and can so contribute to a significant reduction in overall emissions.

Chapter 3. Analyses the methodology to be followed throughout this project. Firstly, the most basic steps of this research are given, while the remainder of the chapter focuses on two of these steps; (1) the modelling methodologies used and (2) the data collection. The basic concept on which the thermal model of a dwelling is based is presented and then it is explained how this concept is applied in terms of a modelling approach. The data collection stage follows where the main sources and the types of data used are classified.

Chapter 4. This chapter deals with the development of the models for the calculation of the carbon footprint. First some general information is given about the simulation software (TRNSYS) that is used for the modelling. Important definitions are explained, such as the “thermal zone” and “energy flows”. Then it is explained how the actual models were developed. The problem incorporates a large number of parameters, therefore only the fundamental ones are mentioned. A basic model is regarded as one where if the values of parameters are changed, then different modelling scenarios occur. For the TRNSYS Simulation Studio, where the complete model is compiled, the components which are common to
all the variations developed are listed and their role is explained. The various scenarios examined are the result of a number of profiles considered for parameters such as the occupancy or the heating which are summarised in tables and the result of the deployment of renewable energy technologies. Finally, a VBA (Visual Basic for Applications) program developed for calculating the carbon footprint from the electricity data is presented.

Chapter 5. A sensitivity analysis is performed in order to investigate the robustness of the developed models.

Chapter 6. This chapter presents the results from all the developed models. The carbon footprint for three main building types has been calculated for four weather data sets, that represent the present day and three future time slices; 2020s, 2050s and 2080s. The impact of the building type, the building fabric and projected climate change in the UK according to the UKCIP02 medium-high emissions scenario are assessed. The results from solar thermal water heating, photovoltaics, ground source heat pumps and the various CHP schemes are also presented and their performance in terms of carbon savings and economics is evaluated. Results are given for the single house and for a cluster of 10 houses when they are not linked and when they form a street-level microgrid in terms of heat and electricity. In each case, results are compared with the “Business as Usual” (BaU) scenario, which is a condensing boiler (90% efficiency ≡ 0.211kgCO$_2$/kWh$_{th}$) and electricity from the national grid (0.43kgCO$_2$/kWh$_{el}$).

Chapter 7. The models developed in this thesis are evaluated and the main findings discussed. The various microgeneration technologies considered are ranked in respect of their financial performance per kg of CO$_2$ saved compared to the BaU case and also per kWh generated. Areas of future work, that have the potential to deliver further financial and carbon savings, are highlighted. The introduction of time-of-use pricing, the use of a variable value for the carbon intensity of the UK’s generation mix and the parallel operation of multiple microgeneration units are recognised as aspects for further investigation.

Chapter 8. The most important conclusions of this research are drawn together.
Chapter 2

Literature Review

2.1 Energy performance of domestic buildings in the UK

In the UK, activities are underway to quantify the existing building stock targeting improvements that will result in a reduction of the energy consumption and hence the carbon footprint of buildings. Such efforts are undertaken in response to national emission targets and current EU directives (DTI, 2003). The UK residential sector accounts for a large proportion of the national energy consumption and its related carbon emissions.

Figure 2.1: Energy consumption (left) and Carbon emissions (right) in the UK by end use for 2008 and 2007 respectively (DECC, 2009b)
As shown in Figure 2.1, in 2008 the domestic sector contributed towards 27.5% of final energy consumption by final user, while transport accounted for 35.5%, industry for 18.5% and others (mainly services and agriculture) for 12.5% (total of 164.9 millions of tonnes of oil equivalent per annum in 2008) (DECC, 2009b).

Figure 2.2 illustrates the energy consumption per dwelling in the UK from the year 1990 until 2006, while the mean air temperatures for winter months are given in the graph, to relate the impact of the mean air temperature to energy demand. Energy consumption of the domestic sector is dominated by heating, therefore a higher mean air temperature during the winter months results in reduced energy consumption. From 1990 to 2006, energy consumption per dwelling has increased by 14% and the domestic stock has increased by 13% (DUKES, 2008).

Therefore, addressing energy consumption profiles in the domestic sector offers significant potential for energy reduction through energy efficiency and better use of fuel resources. The domestic sector is characterised by high natural gas usage. According to the UK Government’s Department for Energy and Climate Change (DECC) natural gas accounted for 68% of the total energy consumed by the domestic sector in year 2008, whilst electricity only accounted for 22% (Figure 2.3a). The major consumer of energy in the domestic sector is space heating (56%) for the year of 2007 followed by
domestic hot water (26%) (Figure 2.3b) (DECC, 2009c).

A typical UK 3 bedroom house, built in the 1930’s, consumes ∼20,000 kWh of energy for space heating and domestic hot water per year. However a significant proportion of this energy is effectively ‘wasted’ due to poor levels of insulation, low air tightness and heating systems with low efficiency (Watson et al., 2006). The English house condition survey undertaken by the Office of the Deputy Prime Minister (ODPM) in 2004 revealed that the most common criterion on which homes are classified as non decent is thermal comfort, corresponding to 4.6 million dwellings or 21% of all homes (ODPM, 2005). The level of a building’s heat loss is in general directly related to its age. The older a building is, the less strict were the building regulations during its construction. This is significant as one of the main characteristics of the UK housing stock is its old age; 40% of the housing stock was built before 1945, 46% between 1945 and 1984, and only 14% after 1984 (DTI, 2002).

The UK Government has adopted a methodology for calculating the energy performance of dwellings, which is called Standard Assessment Procedure (SAP). The calculation of the procedure is based on the energy balance of the house, by taking into account various factors that contribute to the energy efficiency of the house. It is independent of factors related to the individual characteristics of the dwelling, such as the floor area, or characteristics that are not dependent on the house, such as the geographical location. In this way houses of different size in every part of the UK may be compared. The Standard Assessment Procedure was first published by the
Department of Environment (DOE) and BRE in 1993 and various revisions followed. The first consolidated edition is considered the one published in 1998 (SAP 1998) and two further revisions have been released (SAP 2001 and SAP 2005). Figure 2.4 shows the average SAP rating for the domestic sector building stock portfolio in the UK from year 1970 to 2004. The SAP ratings for this figure were calculated using the SAP 2005 and the numbers refer to the entire building stock, taking into account all existing buildings. The average SAP rating for the year 2007 was 49.8 with a rise $\sim 10\%$ from 2000 to 2007 (DECC, 2009c).

Figure 2.4: SAP rating for the domestic sector building portfolio in UK, from 1970 to 2007 (DECC, 2009c)

SAP in general measures the fuel efficiency of the heating systems and the thermal efficiency of the building fabric. Therefore, the better the building fabric is, the better the SAP rating is. An effective way of improving the energy performance of buildings is insulation, reducing the heat losses from walls, lofts, floors, etc. Figure 2.5 shows the distribution of total heat loss from a dwelling as identified in the review of sustainability of existing buildings, from the Department for Communities and Local Government (DCLG, 2006b). The largest level of heat is loss is through the walls and the loft, which accounts for the 60% of the total heat losses; therefore, cavity wall insulation and loft insulation can improve dramatically the SAP rating of a dwelling.
2.2 Building regulations - Policies

The DTI (now BIS) estimates that around 30% of the houses that will be standing in 2050 are yet to be built. So whilst improving the existing housing stock is very important, it is clear priority to ensure that new houses are built to the highest cost-effective energy efficient standards (DTI, 2006b). This is achieved through the building regulations set by the Government and the European Union.

2.2.1 Part L regulations

CHAPTER 2. Literature Review

Figure 2.6: Ownership of cavity wall insulation (left) and loft insulation (right) for domestic sector (DECC, 2009c)


According to the elemental method of the previous editions, the requirement is met if the construction elements achieve specific U-value thermal performance. These values
are given in Table 2.1. Regarding the heating efficiency, reasonable provision would be demonstrated by using a boiler with SEDBUK (Seasonal Efficiency of Domestic Boilers in the UK) not less than the appropriate entry in Table 2.2 (ODPM, 2002).

<table>
<thead>
<tr>
<th>Exposed Element</th>
<th>U-value (W/m²K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pitched roof with insulation between rafters</td>
<td>0.2</td>
</tr>
<tr>
<td>Pitched roof with integral insulation</td>
<td>0.25</td>
</tr>
<tr>
<td>Pitched roof with insulation between joists</td>
<td>0.16</td>
</tr>
<tr>
<td>Flat roof</td>
<td>0.25</td>
</tr>
<tr>
<td>Walls, including basement walls</td>
<td>0.35</td>
</tr>
<tr>
<td>Floors, including ground floors and basement floors</td>
<td>0.25</td>
</tr>
<tr>
<td>Windows, doors and rooflights (area weighted average), glazing in metal frames</td>
<td>2.2</td>
</tr>
<tr>
<td>Windows, doors and rooflights (area weighted average), glazing in wood or PVC frames</td>
<td>2.0</td>
</tr>
</tbody>
</table>

Table 2.1: Elemental Method: U-values (W/m²K) for construction elements

<table>
<thead>
<tr>
<th>Central Heating System Fuel</th>
<th>SEDBUK %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mains natural gas</td>
<td>78</td>
</tr>
<tr>
<td>LPG</td>
<td>80</td>
</tr>
<tr>
<td>Oil</td>
<td>85</td>
</tr>
</tbody>
</table>

Table 2.2: Minimum boiler SEDBUK to enable adoption of the U-values in the elemental method and reference boiler SEDBUK for use in the Target U-value Method

TER is the method proposed in the latest 2006 edition of Part L for calculating the energy performance of buildings. It is expressed in terms of the mass of CO₂, in units of kg per m² of floor area per year emitted as a result of the provision of heating, hot water, ventilation and internal fixed lighting for a standardised household (ODPM, 2006). The TER is determined using the following formula:

\[
TER = \left( C_H \times Fuel\ Factor + C_L \right) \times \left( 1 - Improvement\ Factor \right) \tag{2.1}
\]

where:

- \( C_H \) = CO₂ emissions arising from the provision of heating and hot water
- \( Fuel\ Factor \) = A constant according to the fuel used (from 1 to 1.47) taken from
CHAPTER 2. Literature Review

tables

\[ C_L = CO_2 \text{ emissions arising from the use of internal fixed lighting} \]

*Improvement Factor* = A constant according to the revision of the regulations. For the 2006 revision of Part L is 0.2, i.e. 20% (ODPM, 2006).

The current Parts L1a and L1b which address new dwellings and existing dwellings respectively can be anticipated to have a significant impact on the future domestic building stock’s energy performance. According to the energy review published by the DTI in July 2006, the changes introduced in 2002, 2005 (covering new boilers and windows) and April 2006 have collectively delivered a 40% improvement in the energy efficiency standards of new houses (DTI, 2006b). A new built 3 bedroom house, built according to the part L 2002 regulations, would be expected to consume around 6,000 kWh per annum space heating, which is less than one third of the energy required by an old house built in 1930’s (Watson et al., 2006).

### 2.2.2 Code for Sustainable Homes (CSH)

The Department for Communities and Local Government (CLG) has set a far reaching target that by 2016 all new build housing should be “zero carbon” in operation meeting level 6 of CLG’s Code for Sustainable Homes (CSH). This target is to be achieved through the building regulations, and more specifically by gradually tightening the Part L regulations according to the energy performance levels defined in the CSH. The Code for Sustainable Homes has been developed to enable a step change in sustainable building practice for new homes. It is intended as a single national standard to guide industry in the design and construction of sustainable homes. It is a means of driving continuous improvement, greater innovation and exemplary achievement in sustainable home building. The Code complements the system of Energy Performance Certificates which was introduced in June 2007 under the Energy Performance of Buildings Directive (EPBD). The EPBD requires that all new homes (and in due course other homes, when they are sold or leased) have an Energy Performance Certificate providing key information about the energy efficiency/carbon performance of the home. Energy assessment under the code uses the same calculation methodology, therefore avoiding the need for duplication. In the short-term, code compliance
is voluntary but home builders are encouraged to follow code principles because the Government is considering making assessment under code standards mandatory in the future.

The code measures the sustainability of a home against design categories, rating the ‘whole home’ as a complete package. The measured categories are:

- energy/CO$_2$
- water
- materials
- surface water run-off
- waste
- pollution
- health and well-being
- management
- ecology

The Code uses a sustainability rating system indicated by stars (*), to communicate the overall sustainability performance of a home. A home can achieve a sustainability rating from one (*) to six (******) stars depending on the extent to which it has achieved code standards. The code is quite flexible, though important categories such as energy/CO$_2$ have minimum standards that need to be met at every level. Table 2.3 shows the minimum standards and number of points required in order to achieve each level of the Code. The fifth level of the Code refers to home which has zero emissions in relation to building regulations issues (i.e. zero emissions from heating, hot water, ventilation and lighting), while the sixth level of the Code refers to a completely zero carbon home from all energy use in the home (DCLG, 2006a).

Code for Sustainable Homes has many potential benefits, notably environmental, which are:

- Reduced greenhouse gas emissions. With minimum standards for energy efficiency and water consumption for every level of the code there will be a reduction in greenhouse gas emissions.

- Better adaptation to climate change. With minimum standards for water efficiency at each level of the code, and other measures in the code, including better management of surface water run-off, our future housing stock will be better adapted to cope with the projected impacts of climate change.
CHAPTER 2. Literature Review

Minimum Standards

<table>
<thead>
<tr>
<th>Code Level</th>
<th>Standard (Percentage better than Part L 2006)</th>
<th>Points Awarded</th>
<th>Standard (litres per person per day)</th>
<th>Points Awarded</th>
<th>Other Points Required</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 (*)</td>
<td>10</td>
<td>1.2</td>
<td>120</td>
<td>1.5</td>
<td>33.3</td>
</tr>
<tr>
<td>2 (**)</td>
<td>18</td>
<td>3.5</td>
<td>120</td>
<td>1.5</td>
<td>43.0</td>
</tr>
<tr>
<td>3 (***)</td>
<td>25</td>
<td>5.8</td>
<td>105</td>
<td>4.5</td>
<td>46.7</td>
</tr>
<tr>
<td>4 (****)</td>
<td>44</td>
<td>9.4</td>
<td>105</td>
<td>4.5</td>
<td>54.1</td>
</tr>
<tr>
<td>5 (***** )</td>
<td>100</td>
<td>16.4</td>
<td>80</td>
<td>7.5</td>
<td>60.1</td>
</tr>
<tr>
<td>6 (******)</td>
<td>Zero carbon home</td>
<td>17.6</td>
<td>80</td>
<td>7.5</td>
<td>64.9</td>
</tr>
</tbody>
</table>

Table 2.3: Levels of Code for Sustainable Homes (CSH) (DCLG, 2006b)

- Reduced overall impact on the environment. Inclusion of measures which, for example, promote the use of less polluting materials, and encourage household recycling, will ensure that our future housing stock has overall fewer negative impacts, on the environment.

Other sectors that will benefit from the code are:

- Home builders. The code can be used by home builders to demonstrate the sustainability performance of their homes and to differentiate their homes from their competitors. In addition, the code brings more regulatory certainty, acting as a guide to support effective business and investment planning. The code itself is quite flexible, hence it does not act as an extra regulatory burden for the builders, but it allows them to innovate and find energy efficient and cost-effective solutions.

- Social housing providers. Buildings which are built under the code will certainly have lower running costs (lower bills) for the consumers, allowing the providers to demonstrate the improved sustainability of their buildings. In the case of renewable energy technologies this assumes that operational and maintenance costs will be covered mainly by the providers.

- Consumers. Reduced running costs are the principal benefit for the consumers. Another important benefit is their improved well-being since they will be living
in pleasant and healthy homes. Other benefits may be regarded as the reduced
carbon footprint of the people living in such homes and the assistance (in terms
of valuable information about the property) that the code will provide to the
buyers before they buy a new home (DCLG, 2006a).

2.2.3 Low Carbon Buildings Programme (LCBP)

LCBP (Low Carbon Building Programme, 2006) was a Government programme that
aimed to ease the uptake of microgeneration technologies in the domestic sector or
larger scale distributed generation installations for communities, businesses and public
buildings by offering grants towards the installation cost. The programme was run by
the Department of Energy and Climate Change (formerly BERR) and it was first
launched on 1st of April 2006. In May 2010, under the new consenate, the closure of
the programme was announced. A week later an alternative government incentive was
announced, the Feed-in-Tariffs.

In four years, the LCBP programme has provided approximately 20,000 grants for the
capital and installation costs of Microgeneration equipment of which, to date 11,000
have been for thermal technology (33% by value, 58% by number of installations).
Department of Energy and Climate Change estimate that these will produce carbon
savings of 300,000 tonnes of CO$_2$ over the lifetime of the system (DECC, 2010).

2.2.4 UK Feed-in Tariffs (FITs)

The Renewables Obligation (RO) is designed to encourage investment on renewable
electricity generation from UK electricity suppliers. It places an obligation on UK
electricity suppliers to generate an increasing proportion of their electricity from re-
newables. Eligible renewables generators receive 1 Renewable Obligation Certificate
(ROC) for each megawatt hour (MWh) of renewables electricity generated. The Re-
newables Obligation, the Renewables Obligation Scotland and the Northern Ireland
Renewables Obligation are designed to incentivise renewable generation into the elec-
tricity generation market, but they mainly target companies in large-scale projects.
In order to also support and incentivise small low-carbon generators, the Department of Energy and Climate Change (DECC) proposed a new system of Feed-in Tariffs (FITs) that aims to make low carbon generation more cost effective to communities and householders (DECC, 2009a). The key FIT design aspect is that they consist of two tariffs:

- **Generation tariff**: A fixed payment from the electricity supplier to the consumer for every kWh generated. The technologies supported from 2010 and the relevant generation tariffs as suggested from DECC are presented in Table 2.4.

- **Export tariff**: A guaranteed minimum price payment to the generator for each kWh exported to the wider grid. This payment is additional to the generation tariff. Its range is considered to be between the minimum price paid for unplanned exports to the electricity system and the retail price. A guaranteed export price of 3p/kWh has been assumed from DECC.

### 2.3 Distributed Generation (DG) - Microgrids

Distributed Generation (DG) is a term referring to the wide range of electricity generation technologies that do not rely on the high-voltage electricity transmission network, and heat technologies that are not connected to the gas grid (DTI, 2006a). Other terms used for distributed generation are embedded generation and decentralised generation. According to the definition given by the DTI, distributed generation includes:

- **Distributed electricity generation**: This category of generation refers to smaller-scale, low carbon sources of power by directly connecting them to the distribution grid. Types of distribution electricity generation include:
  
  - Plants connected to a distribution network rather than the transmission network;
  
  - Small scale plants that supply electricity to a building, industrial site or community, potentially selling any surplus of energy back through the distribution network (microgrids); and
<table>
<thead>
<tr>
<th>Technology</th>
<th>Scale</th>
<th>Initial tariff (p/kWh) (Tariffs will be inflated annually)</th>
<th>Tariff lifetime (years)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Anaerobic digestion</td>
<td>≤500kW</td>
<td>11.5</td>
<td>20</td>
</tr>
<tr>
<td>Anaerobic digestion</td>
<td>&gt;500kW</td>
<td>9.0</td>
<td>20</td>
</tr>
<tr>
<td>Hydro</td>
<td>&lt;15kW</td>
<td>19.9</td>
<td>20</td>
</tr>
<tr>
<td>Hydro</td>
<td>15kW-100kW</td>
<td>17.8</td>
<td>20</td>
</tr>
<tr>
<td>Hydro</td>
<td>100kW-2MW</td>
<td>11.0</td>
<td>20</td>
</tr>
<tr>
<td>Hydro</td>
<td>2-5MW</td>
<td>4.5</td>
<td>20</td>
</tr>
<tr>
<td>Micro-CHP pilot</td>
<td>≤2 kW</td>
<td>10.0</td>
<td>10</td>
</tr>
<tr>
<td>PV</td>
<td>&lt;4kW (new build)</td>
<td>36.1</td>
<td>25</td>
</tr>
<tr>
<td>PV</td>
<td>&lt;4kW (retrofit)</td>
<td>41.3</td>
<td>25</td>
</tr>
<tr>
<td>PV</td>
<td>4-10kW</td>
<td>36.1</td>
<td>25</td>
</tr>
<tr>
<td>PV</td>
<td>10-100kW</td>
<td>31.4</td>
<td>25</td>
</tr>
<tr>
<td>PV</td>
<td>100kW-5MW</td>
<td>29.3</td>
<td>25</td>
</tr>
<tr>
<td>PV</td>
<td>Stand alone system</td>
<td>29.3</td>
<td>25</td>
</tr>
<tr>
<td>Wind</td>
<td>&lt;1.5kW</td>
<td>34.5</td>
<td>20</td>
</tr>
<tr>
<td>Wind</td>
<td>1.5-15kW</td>
<td>26.7</td>
<td>20</td>
</tr>
<tr>
<td>Wind</td>
<td>15-100kW</td>
<td>24.1</td>
<td>20</td>
</tr>
<tr>
<td>Wind</td>
<td>100-500kW</td>
<td>18.8</td>
<td>20</td>
</tr>
<tr>
<td>Wind</td>
<td>500kW-1.5MW</td>
<td>9.4</td>
<td>20</td>
</tr>
<tr>
<td>Wind</td>
<td>1.5-5MW</td>
<td>4.5</td>
<td>20</td>
</tr>
<tr>
<td>Existing microgenerators transferred from RO</td>
<td>9.0</td>
<td>to 2027</td>
<td></td>
</tr>
</tbody>
</table>

Table 2.4: Generation tariffs for first year of FITs (2010-2011) as proposed from DECC (DECC, 2009a)
CHAPTER 2. Literature Review

- “Microgeneration”, which are small installations, such as photovoltaic panels or wind turbines, that supply one building or small community, again with the potential to sell back to the grid any surplus. In this case a microgrid may be also formed.

- Combined Heat and Power (CHP). Plants that generate heat and power that may be used locally. Types of CHP plants include:
  - Large CHP plants, where the heat is used locally but a significant amount of the electricity output feeds into higher voltage distribution network;
  - Building- or community-level CHP plants (microgrids);
  - “Micro-CHP” plants that are used mainly in domestic sector by replacing the domestic boilers and producing both heat and electricity for the home.

- Non-gas heat sources. This category includes sources such as biomass, solar thermal heaters, geothermal energy or heat pumps, which generate heat that is used locally, either from one single building or from a community through a small network (DTI, 2006a).

Since this research is focused on the domestic sector, the large scale plants were not examined and all the models developed were based on small scale plants and micro-generation.

As seen above, microgrids are an important example of distributed generation. A microgrid is a small-scale power supply network that is designed to provide power for a small community. The small community may be a typical housing estate, an isolated rural community, a mixed suburban environment, an academic or public community such as a university or school, a commercial area, an industrial site, a trading estate, or a municipal region (Abu-Sharkh et al., 2006). Typically, the term microgrid is defined in terms of electricity generation (Camblong et al., 2009; Jiayi et al., 2008; Costa et al., 2008; Ventakataramanan and Mahesh, 2002; Marnay et al., 2001; Abu-Sharkh et al., 2006) and only a few works expand the term to include heat generation (Markvart, 2006; Hawkes and Leach, 2008).
Distributed generation presents a number of benefits, some of which can deliver a significant reduction in costs and CO₂ emissions:

- **Increased energy efficiency of the system due to the close proximity of the generation to the user.** DG has the potential to minimise the losses of electricity resulting from its transportation to the customer. According to OFGEM for the year 2006/2007 around 6.5% of all generated electricity was lost as it was transported to consumers; 1.5% in transmission and 5% in distribution, while these numbers have not changed significantly from 2002/2003. These losses have an environmental cost as well as financial cost (Abu-Sharkh et al., 2006; OFGEM, 2007). The reduction of losses is even greater for the case of microgrids, where the distribution network is even smaller, while losses are minimised for the case of microgeneration where a domestic microgeneration technology replaces a supply that previously came from remote transmission-connected generation (DTI, 2007a). In any case a certain level of losses cannot be avoided, since the main grid needs to be active and transportation losses will always take place.

- **The technologies of distributed generation in general are lower carbon than the centralised alternative;** either technologies are renewables (solar, wind) or they offer greater efficiencies even though they burn fossil fuels, such as CHP schemes.

- **Security of supply, since the provision of electricity by a much wider range of producers reduces the importance of any one generator and potentially makes the system more robust to equipment failure and other temporary outages (DTI, 2007a).**

- **Improved flexibility of the energy system, since a decentralised energy system is able to respond more readily to technological changes.**

- **Enhanced reliability and resilience due to reduced transmission power flows and the ability of the system to secure local demand even at times of system stress.**

- **Increased number of energy suppliers, which raises the competition amongst them.** A larger number of energy participants in the market is to the customer’s benefit, since they have more choice and there is the potential for better service and reduced prices due to competition (DTI, 2006a).
Figures 2.7 illustrates the conventional distribution network and the distribution network with distributed generation respectively, and figure 2.8 illustrates a microgrid scheme, which is an example of distributed generation. Thin black lines indicate flow from the network to the consumer, while thicker red lines indicate flow to, and from, the network.

Microgrids, as a form of DG, offer the same benefits as DG whilst in most of the cases these benefits are even greater, such as the increased efficiency, improved flexibility and the use of renewables. Further benefits that microgrids present are:

- Better matching between generation and consumption. For the thermal output
They have the potential to tackle fuel poverty, particularly for those houses not connected to the gas grid network (DTI, 2006c). Many of these technologies involve substantial set-up costs but then lower ongoing fuel bills. This facilitates the involvement of public authorities in the installation of equipment, leaving families more able to meet their ongoing bills (DTI, 2007a).

• Microgrids may also help in an indirect way. They help users to develop increased awareness of environmental issues and energy technologies, due to the fact that the energy generation takes place on site. In this way, the users improve their energy consumption behaviour, leading to extra carbon savings (Bahaj and James, 2007).

2.3.1 Current status of DG and future penetration

At present, distributed energy accounts for only a small proportion of the UK’s total energy supply. Renewable electricity and Combined Heat and Power plants connected...
to the distribution grid nearly represent 10% of the total electricity generation, whilst off-grid heat generation (heat generation that does not depend on either the gas grid or on electricity) represents less than 10% of the total heat market. Figure 2.10 shows the distribution energy technologies connected to the distribution networks in the UK in 2006 (DTI, 2006b).

![Figure 2.10: Total capacity of DG connected to the UK distribution network (DTI, 2006b)](image)

This figure includes only the electricity generation capacity and any heat produced from the CHP plants is not considered. As seen on the figure the electricity generation capacity connected to the distribution networks mainly comes from gas dependent electricity technologies (excluding CHP) and then CHP. The vast majority of the UK’s CHP plant is located on industrial sites and very little of it provides electricity for residential buildings. CHP represents around 7% of UK electricity, two thirds of which connects to the distribution networks and the rest to the transmission network. The remainder of the electricity connected to the distribution networks comes mainly from microgeneration technologies, but still a negligible amount of electricity is generated in this way (DTI, 2006b).

Given the benefits of DG it is important to explain why penetration of DG is not very high in the UK. The Department of Trade and Industry (DTI), now BIS, identifies three key barriers that affect DG and result in low penetration. These barriers are:

**Market value for carbon.** In general, despite the significance of DG for reducing
CHAPTER 2. Literature Review

carbon emissions, the market does not fully reward such actions. DG technologies have the potential to offer significant carbon savings and this is recognised through mechanisms such as the Renewables Obligation, but at the same time they have high capital costs. A greater financial reward for the carbon savings from DG technologies would improve their level of penetration.

Regulatory burdens. DG technologies try to take a share on a system which was primarily designed for centralised generation. Some aspects of the current system present barriers to DG technologies. The first of the barriers comes from the system operator, National Grid (NGET). All licensed operators and suppliers must be registered with the National Grid, and comply with onerous requirements. At the same time market arrangements are similar for the large energy supply companies as for a local authority wanting to operate a low carbon energy scheme, at a fraction of the size. Other regulatory burdens are the difficulties in obtaining planning permission for DG technologies and the issue of export reward. Getting a permission at the moment is a costly and time consuming procedure, while the rewards for exporting excess electricity to the wider network are small and in many cases non-existent. All of these problems become disproportionately larger the smaller the distributed generator.

Informational barriers. The most common barrier of DG is the lack of information on the options available. One reason is that different commercial firms and trade associations support their own products, therefore a potential customer has to undertake individual research on the available options. The only relevant information provider at the moment at the residential scale, is the Energy Saving Trust (EST), which covers in general the energy efficiency area. There are no organisations that cover exclusively and comprehensively technologies such as microgeneration or CHP (DTI, 2007a).

In order to overcome the barriers that DG faces, and boost DG technologies in the near future the DTI addressed the sectors in which actions need to be taken:

- More flexible market and licensing arrangements. Currently distributed generators don’t bring the large quantities of electricity onto the system that large
power stations have to offer and this results in low prices for the electricity they produce. Distributed generators aim to generate power for local communities and they are not in a position to bid for supply blocks in advance like large power stations do. At the same time, in many cases there is big difference between the import and export prices, which is crucial for determining the economic viability of DG schemes.

- Better information and certification. Many DG technologies are relatively new to the market and there are many areas of uncertainty about the use of these technologies, such as technical performance, expected lifetime, etc. Some advice and information is available for householders, local authorities and developers to implement DG solutions but the information in many cases is patchy or located in a variety of places. According to DTI more than half of respondents to the DG consultation “Call for evidence” in 2006 complained about the lack of information available on DG (DTI, 2006a). DTI suggests that more clear and coherent information is required on the following areas:

  - information about various technologies and how they work,
  - guidance on the potential benefits of microgeneration
  - information for local authorities and developers regarding specific technologies, costs and options to help them achieve their emission targets (DTI, 2007a).

In this research, a local heat and/or power network is investigated, operating for a cluster of residential buildings at the street level. The domestic cluster essentially forms a local microgrid, where exchanges of heat and/or power take place within the cluster and any excess of generated power is exported to the wider national grid.
2.4 Microgeneration - Low and Zero Carbon (LZC) technologies in the built environment

Low and zero carbon technologies (LZCs), such as photovoltaics (PV) or combined heat and power (CHP), provide space and water heating and electricity through renewable energy technologies or through better fuel efficiency technologies than the conventional ones. LZC technologies are retrofitted to or are integral to the building or community. Table 2.5 summarises the most important on-site energy generation technologies and classifies them according to the carbon emissions they produce in operation (low carbon or zero net carbon) and according to the type of energy they produce (heat, electricity or both) (Boardman et al., 2005).

<table>
<thead>
<tr>
<th>Carbon 'In operation'</th>
<th>Heat Only</th>
<th>Heat and Electricity</th>
<th>Electricity Only</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low Carbon</td>
<td>Ground Source Heat Pumps (GSHP)</td>
<td>Stirling Engine CHP</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Fuel Cell CHP</td>
<td></td>
</tr>
<tr>
<td>Zero Carbon</td>
<td>Solar Collectors</td>
<td>Waste or Biomass CHP</td>
<td>Photovoltaics</td>
</tr>
<tr>
<td></td>
<td>Biomass</td>
<td></td>
<td>Wind Turbines</td>
</tr>
<tr>
<td></td>
<td>Geothermal - Aquifers</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 2.5: Most important types of Low and Zero Carbon (LZC) technologies

This project focuses on the domestic sector and the implementation of small scale technologies that provide low or zero carbon energy to a home or a small cluster of homes. These technologies are described with the term microgeneration. Microgeneration, as defined in the Energy Act 2004, is the small-scale production of heat and/or electricity from a low carbon source plant, the capacity of which does not exceed 50 kilowatts for electricity production and 45 kilowatts for thermal production. The sources of energy and technologies included in this definition are:

(a) biomass
(b) biofuels
(c) fuel cells
CHAPTER 2. Literature Review

<table>
<thead>
<tr>
<th>Technology</th>
<th>No. Installations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Micro-wind</td>
<td>650</td>
</tr>
<tr>
<td>Micro-hydro</td>
<td>90</td>
</tr>
<tr>
<td>Ground source heat pumps</td>
<td>546</td>
</tr>
<tr>
<td>Biomass boilers (pellets)</td>
<td>150</td>
</tr>
<tr>
<td>Solar water heating</td>
<td>78,470</td>
</tr>
<tr>
<td>Solar PV</td>
<td>1,301</td>
</tr>
<tr>
<td>Micro-CHP</td>
<td>990</td>
</tr>
<tr>
<td>Fuel Cells</td>
<td>5</td>
</tr>
<tr>
<td><strong>TOTAL</strong></td>
<td><strong>82,202</strong></td>
</tr>
</tbody>
</table>

Table 2.6: Number of installations of microgeneration technologies in the UK (DTI, 2006c)

(d) photovoltaics

(e) water (including waves and tides)

(f) wind

(g) solar power

(h) geothermal sources

(i) combined heat and power systems

(j) other sources of energy and technologies for the generation of electricity or the production of heat, the use of which would, in the opinion of the Secretary of State, cut emissions of greenhouse gases in Great Britain (UK Parliament Public General Acts, 2004).

Deployment of all these technologies in the UK is at a very low level, with the installed base being dominated by solar water heating. Less than 0.5% of the electricity produced in UK comes from microgeneration. Combined Heat and Power plants (predominantly large scale industrial units >10MW) provide about 7% of UK electricity (DTI, 2006b). Table 2.6 gives the number of installations of each technology as recorded by the DTI until March of 2006. The majority of solar water heating installations were installed before 2000 (DTI, 2006c).

In this research the following technologies are considered: PV, GSHP, Solar thermal and CHP (fossil fuel and biomass). Micro-wind is not investigated, as recent literature
shows that this technology is not well suited for the domestic sector and only a small number of sites are suitable to install this technology (James et al., 2010). Load factors are predicted to be generally less than 4%. Location is the main limiting factor, reducing significantly the successful household small-scale wind installations potential (EST, 2009a). According to EST, approximately 455,650 sites in the UK are estimated to be suitable for small-scale wind turbines (up to 6kWp), with a wind resource of at least 5m/s and adequate land area and/or building profiles. This figure equates to only 1.9% of the UK households. James et al. (2010) estimated that 105,000 buildings in England and Wales and 93,000 in Scotland (far smaller building stock but better wind resource) would meet a threshold average wind speed of 5m/s.

2.4.1 Photovoltaics (PV)

2.4.1.1 About photovoltaics

Photovoltaics (PV), also called solar cells, convert sunlight directly into electricity. There are a number of PV cells technologies, including polycrystalline silicon, monocrystalline silicon and various thin-film materials which are summarised in Table 2.7 (BERR, 2008c).

For all but the smallest applications, a number of connected solar cells will be required to generate the required supply of electricity. The cells will therefore be fixed in a sealed unit, called a photovoltaic panel or module. In turn, a group of these panels may be referred to as a photovoltaic array. The capacities of each installation range from small, kilowatt-sized solar arrays for use in domestic households, to larger arrays, which function as separate solar power plants feeding power directly into the electricity grid (BERR, 2008c).

Solar PV cells can be used in both stand-alone and grid-connected systems. Off-grid applications have, historically, represented the main PV market, though in most cases they require storage capacity, e.g. a battery, which raises the cost of the system. The advantage of off-grid applications is that they may be an alternative to extension of the grid or compete with options like small-scale diesel generators. On the other hand
### Chapter 2: Literature Review

#### Monocrystalline Silicon Cells
- **Efficiency**: Higher efficiency than the other types (around 18%)
- **Issues to consider**:
  - High costs due to complicated manufacturing process
  - High durability
  - Proven lifetime
  - Increased costs
  - Uniform colour (blue or black)

#### Multicrystalline (Polycrystalline) Silicon Cells
- **Efficiency**: Slightly lower efficiency than monocrystalline, around 13%-15%
- **Issues to consider**:
  - Lower price than monocrystalline
  - Proven lifetime
  - Lower efficiency than monocrystalline
  - A random pattern of crystal borders

#### Amorphous Silicon (Thin film)
- **Efficiency**: Variety of colors
- **Issues to consider**:
  - Wide range of substrates (rigid or flexible)
  - Low costs
  - Low efficiency
  - Stability issues

#### CdTe (Cadmium Telluride)
- **Efficiency**: Efficiency from 6% to 10%
- **Issues to consider**:
  - Easy to deposit
  - Suitable for large-scale production
  - Stability issues

#### CIGS (Copper Indium Gallium Selenide)
- **Issues to consider**:
  - Easy to deposit
  - Higher costs compared to other thin films
  - Stability issues

#### Organic / Polymer
- **Issues to consider**:
  - Mechanical flexibility
  - Disposability
  - Low efficiency
  - Stability issues

<table>
<thead>
<tr>
<th>Type</th>
<th>Efficiency</th>
<th>Issues to consider</th>
</tr>
</thead>
<tbody>
<tr>
<td>Monocrystalline Silicon Cells</td>
<td>Higher efficiency than the other types (around 18%)</td>
<td>+ High costs due to complicated manufacturing process&lt;br&gt; + High durability&lt;br&gt; + Proven lifetime&lt;br&gt; - Increased costs&lt;br&gt; ◦ Uniform colour (blue or black)</td>
</tr>
<tr>
<td>Multicrystalline (Polycrystalline) Silicon Cells</td>
<td>Slightly lower efficiency than monocrystalline, around 13%-15%</td>
<td>+ Lower price than monocrystalline&lt;br&gt; + Proven lifetime&lt;br&gt; - Lower efficiency than monocrystalline&lt;br&gt; ◦ A random pattern of crystal borders</td>
</tr>
<tr>
<td>Amorphous Silicon (Thin film)</td>
<td>Variety of colors</td>
<td>+ Variety of colors&lt;br&gt; + Wide range of substrates (rigid or flexible)&lt;br&gt; + Low costs&lt;br&gt; - Low efficiency&lt;br&gt; - Stability issues</td>
</tr>
<tr>
<td>CdTe (Cadmium Telluride)</td>
<td>Efficiency from 6% to 10%</td>
<td>+ Easy to deposit&lt;br&gt; + Suitable for large-scale production&lt;br&gt; - Stability issues</td>
</tr>
<tr>
<td>CIGS (Copper Indium Gallium Selenide)</td>
<td></td>
<td>+ Easy to deposit&lt;br&gt; - Higher costs compared to other thin films&lt;br&gt; - Stability issues</td>
</tr>
<tr>
<td>Organic / Polymer</td>
<td></td>
<td>+ Mechanical flexibility&lt;br&gt; + Disposability&lt;br&gt; - Low efficiency&lt;br&gt; - Stability issues</td>
</tr>
</tbody>
</table>

Table 2.7: Main characteristics, advantages and disadvantages of various types of PV cells
grid-connected systems do not require separate storage capacity, if the grid can handle the power variations (Hoogwijk, 2004). The built environment and the large scale centralised generation in countries such as Spain and Germany now represents the major PV market (Solarbuzz, 2008).

2.4.1.2 Photovoltaics in the built environment

Photovoltaic panels used in building sector are fitted on a building’s roof or walls, and usually feed electricity directly into the building. With the latest PV technology, cells can also be integrated into the roof tiles themselves (BERR, 2008c). There are two ways of applying PV panels on buildings; integrated or “mounted”. Integrated technologies include: roof tiles, PV cladding and PV shading systems. “ Mounted” are PV panels ‘bolted’ on top of flat or pitched roofs. At present and for the next decade it is expected that the dominant market will be roof top systems, since their cost is considerably lower (30%-50%) than building integrated PV (BIPV) (Hoogwijk, 2004). Figure 2.11 shows examples of installations of both methods.

Before the installation of a PV array on a building there are some planning considerations that need to be taken into account:
Orientation. In order to maximise the efficiency of a PV system, access to direct sunlight for the longest possible time is required. Mobile arrays can track the sun at all times, however almost all PV arrays on buildings will be fixed, so they need to be orientated so as to make the best use of available sunlight at different times of the day and year. For Europe, this means that the PV array should face roughly South. The only significant exceptions to that rule are where solar panels are overshadowed at a specific time of a day or where the main load for electricity is required at a specific time of a day. Hence if the main power requirement is in the morning, then the PV array will be orientated in the south-east. Another important factor included in the orientation is the inclination at which the panels are placed. In general, optimum yield is achieved at 10 degrees less than the latitude. For this reason installation of PV on pitched roofs is usually an ideal place on the building (Cradick, 1999).

Overshadow. Overshadowing is an important factor that has a major impact on the efficiency of a photovoltaic panel. Overshadowing may occur due to adjacent buildings or trees and these sites will have less potential. Therefore, it should be ensured that photovoltaic panels are installed on a building so that they have continuous access to direct sunlight, when they are installed but also in the future. Regarding sunlight and the related legal framework, it should be noted that it is a complicated issue. There are relevant laws in the UK that define the “rights of light” but these apply to daylight and were drafted decades before the PV effect was discovered (Cradick, 1999).

Aesthetics. The incorporation of PV technology into buildings is a challenge for architects and planners, since PV may have a major impact on the aesthetics of a building. PV technology should be incorporated in way that does not have a negative visual impact either to the building, or to the surroundings. The options for fitting PV technology today are many (on roofs, on walls, on windows, integrated or not), and there is some choice available in terms of materials and colours. Normally PV cells colours vary from blue to dark-grey (monocrystalline cells), from blue to blue-grey (polycrystalline cells) or from dark brown to black (amorphous silicon). PV cells in a greater range of colours have been developed as
well, but their efficiency is much lower at the moment (Cradick, 1999). In general integrated PV panels minimise the visual impact, but usually their installation needs to be considered during the design phase of the building. In the final report of DTI, “UK Photovoltaic Domestic Field Trial”, a survey regarding the visual impact of the PV was performed for 27 domestic sites. According to the results the appearance of the PV systems was believed to enhance the appearance of the property according to half (52%, 14) of the project leaders, and the majority of the remainder (41%, 11) said it made no difference. Two project leaders (7%) said the appearance of the house was less pleasing with PV, but added that it had not been raised as an issue by the occupier (Munzinger et al., 2006).

A typical current residential installation of 12 m$^2$ could generate around 1600 kWh per annum with a peak of around 1.9 kW$_p$, though larger and more efficient installations are possible. The main limiting factor for larger installations is the available roof space, with the right orientation and minimum shading. The efficiency of an application depends on many factors, such as orientation, shading, solar irradiance and the PV material. The typical sized household PV system of (1.9 kW$_p$) is estimated to save 0.6-0.85 tonnes of carbon dioxide annually. The cost for a bolt on system is approximately £4,500/kW$_p$ and monocrystalline or polycrystalline PV modules usually come with a 25 year manufacturers warranty (STA, 2008a).

In general, the cost of PV electricity appears to be high and according to Energy Saving Trust (EST) cost effectiveness is not predicted to occur until 2030. However, a technology breakthrough could reduce capital costs and bring this forward towards 2020. EST estimates that if cost issues were overcome, by 2050 this technology could supply almost 4% of UK electricity demands, and reduce domestic sector CO$_2$ emissions by up to 3% (EST, 2005b). Figure 2.12 illustrates projected generated energy costs for a domestic 2.5kW capacity PV installation, as presented in the “Potential for Microgeneration” report from EST. Break even is projected for the median scenario circa in 2030-2040, with energy export equivalence (EEE) support. Without energy export equivalence support break even is not reached for the median scenario, since PV-generated electricity costs stabilise at a higher value than the non-EEE level.

The European Union photovoltaic market reached the limits of the sector’s procure-
ment capacity for the first time in 2005. Photovoltaic industrialists would have been able to produce many more modules if it had not been for the shortage of silicon, the principal raw material of solar cells at that time. In 2005, the European photovoltaic market finally reached 644 MW in terms of annual cell production, bringing the cumulative total of installed European capacity to 1792 MW. This capacity consists essentially of grid-connected applications (solar roofs and facades and photovoltaic power plants) with 94.4% of installed capacity. Germany continued to be the leading photovoltaic market in the world in 2005, far ahead of Japan and the USA. Table 2.8 shows the top ten countries in European Union according to the installed photovoltaic capacities in MW (EUROPA, 2010). In 2007, the worldwide production of solar cells was \( \sim 1,300 \text{ MW} \) with the market growing at about 30% year on year (Solarbuzz, 2008).

### 2.4.2 Ground Source Heat Pumps (GSHP)

The most typical application of direct geothermal heat use is the Ground Source Heat Pump (GSHP). Ground Source Heat Pumps (GSHP), or Geothermal Heat Pumps, are systems combining a heat pump with a system to exchange heat with the ground. Heat pumps are able to force the heat flow in the opposite direction to which it would naturally flow. GSHP systems can be subdivided into those with a ground heat
<table>
<thead>
<tr>
<th>2005 Cumulative installed capacity (MW$_p$)</th>
</tr>
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<tbody>
<tr>
<td>Spain</td>
</tr>
<tr>
<td>Germany</td>
</tr>
<tr>
<td>Italy</td>
</tr>
<tr>
<td>Czech Rep.</td>
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<td>Portugal</td>
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<td>Belgium</td>
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<td>France</td>
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<tr>
<td>Greece</td>
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<tr>
<td>United Kingdom</td>
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<tr>
<td>Austria</td>
</tr>
</tbody>
</table>

Table 2.8: Installed PV capacities by 2008 in European Union (MW$_p$) (EUROPA, 2008a)

exchanger (closed loop systems), or those fed by ground water from a well (open loop systems). The means to harness the ground as a shallow heat source comprise:

- groundwater wells (“open” systems),
- borehole heat exchangers (BHE),
- horizontal heat exchanger pipes (incl. compact systems with trenches, spirals etc.)
- “geostructures” (foundation piles equipped with heat exchangers) (Sanner et al., 2003).

Heat pumps can transform low temperature heat from the subsoil, underground water or rock sources to a higher level that can be useful for low-temperature heating. Figure 2.13 illustrates the three most common types of ground source heat pump systems. In summer, when the ground is cooler than ambient air, shallow geothermal systems circulate the heat carrier fluid between building and ground, hence by-passing the heat pump. In effect the heat of the building is transported to the ground to be stored for extraction in winter (“free cooling”). The same shallow geothermal system therefore, performs both heating and cooling services. Reversible heat pumps in small air conditioners are mostly used for cooling only and are therefore not considered as renewable heat from ambient sources (IEA, 2007).
A geothermal heat pump needs electricity to drive it. The coefficient of performance (COP) is the ratio of heat output to energy input. A conventional ground-coupled system has a COP of 3 to 4, although, depending on the system configuration, a COP of up to 7 can be attained, for example by minimising the temperature lift and applying to an underfloor low temperature radiant heating system. Heat pumps that extract heat from air or surface water are less effective due to the more variable temperature of the source (IEA, 2007). A typical BHE system has a COP 3-4, which is 30%-50% better than the COP of air-to-air heat pumps, which use the atmosphere as a heat source/sink (Sanner et al., 2003).

Existing geothermal heat pumps are better suited for operation with low temperature heating systems, which limits their application mainly to new buildings, and they are not designed to meet the high supply temperature demands of older wet heating systems already installed in many existing buildings. At the same time, the low upper temperature of 50°C-55°C, limits heat pumps applications to low temperature heating systems, such as fan-coils, low temperature radiators or floor heating, which usually use water from 35°C to 45°C. Traditional wet heating systems with fossil fuel boilers and standard radiators are high temperature heating systems and they circulate hot water at 80°C to 90°C. Therefore, the installation of a heat pump would not be suitable, unless the whole heating system was replaced, increasing significantly the cost of retrofit GSHP (Sanner et al., 2003).

Ground-source heat pumps were first introduced in the early 1980s, when electricity was cheaper. After a long period of stability they are now becoming more popular, with an increasing number of heat pumps installed throughout the UK in homes, commercial
buildings and swimming pools. This is because of their energy-efficient status and gas prices recent volatility in domestic sector. There are currently around 250 ground-source heat pumps installed in the UK every year. According to BERR, since 1992 around 3,000 heat pumps have been installed in detached homes, predominantly off the gas network (BERR, 2008a).

Ground source heat pumps technologies can be commercial when compared to electric or liquid petroleum gas (LPG) heating, but they are not competitive with natural gas or oil fired heating. According to the “Potential for Microgeneration” report, published by the Energy Saving Trust, break even with electrical heating is expected before 2010. A comparison with oil or LPG and gas heating was not considered in the report. In the UK, only a small proportion of the housing market uses electric heating (∼8%), and the number of houses that are suitable for GSHP technologies would be even smaller due to other limiting factors, such as lack of or non-existence space (e.g. flat) for the ground heat exchanger (EST, 2005b; DECC, 2009c).

2.4.3 Solar water heating

2.4.3.1 Solar Water Heating in UK

The solar resource in the UK is far greater than most people imagine. The annual irradiation on the horizontal plane in the south of the UK is as much as 60% of the value at the equator. The optimum elevation for solar radiation is ∼10° less than the latitude. This makes roofs in the UK ideal sites for PV. Figure 2.14 shows the total average solar radiation falling on one square metre surface inclined at 30 degrees to the horizontal, measured in kilowatt hours per annum (STA, 2008b).

Solar water heating is an active solar heating system that uses collectors, usually on the roof of a building, to capture and store the sun’s heat via water storage systems. The collectors provide heat to a fluid, water or a non-toxic anti-freeze, that circulates to a storage tank. The heat is primarily used for heating water in domestic dwellings, industrial facilities and commercial buildings. This includes the growing market for solar swimming pool heaters (BERR, 2008c).
The UK is currently ranked 11th by country in Europe in terms of cumulated capacity of thermal solar collectors installed, with 201,160 m$^2$, equivalent to 141 MWh, up until the year 2005, while Germany represents nearly half of the EU solar thermal market with 7,109,000 m$^2$ installed, equivalent to 4,976 MWh (EUROPA, 2008b).

### 2.4.3.2 Domestic solar water heating

A solar water heating system for domestic hot water comprises three main components: solar thermal panels; hot water cylinder; and a wet plumbing system.

**Solar Thermal Panels.** These are fitted to the roof to capture the irradiance of the sun’s rays, convert this to heat and transfer this to heat to a fluid. They are the most important component of the system, since the type of solar panels used limits the overall efficiency of the system. There are two types of solar panels or solar collectors:

- Flat plate collectors (Figure 2.15a). Flat-plate collectors are the most common solar collector for solar water-heating systems in homes and solar space heating. A typical flat-plate collector is an insulated metal box with a glass or plastic
cover (the glazing) and a dark-colored absorber plate. These collectors heat fluid at temperatures less than 82°C. They have an efficiency of around 30 per cent and have lower capital costs than evacuated tube collectors.

- Evacuated tube collectors (Figure 2.15b). Evacuated-tube collectors can achieve extremely high temperatures (77°C to 177°C), making them more appropriate for cooling applications and commercial and industrial applications. However, evacuated-tube collectors are more expensive than flat-plate collectors, with unit area costs about twice that of flat-plate collectors. The collectors are usually made of parallel rows of transparent glass tubes. Each tube contains a glass outer tube and metal absorber tube attached to a fin. The fin is covered with a coating that absorbs the solar energy and also inhibits radiative heat loss. Air is removed, or evacuated, from the space between the two glass tubes to form a vacuum, which eliminates conductive and convective heat loss. Evacuated tube systems occupy a smaller area and have an efficiency of approximately 40 per cent.

![Flat-Plate Collector](image1)

![Evacuated-Tube Collector](image2)

Figure 2.15: Solar Collectors: (a) Flat-Plate, (b) Evacuated Tube (EERE, 2008a)

**Hot Water Cylinder.** The hot water cylinder stores the water that is heated during the day, so it can be supplied to the user at any time.

**Plumbing System.** The plumbing system includes all the piping or other equipment such as pumps, that is used to circulate the hot water around the system (EERE, 2008a; EST, 2008).
There are various solar water systems and they can be split into two main categories, according to whether they use additional components such as pumps (active systems), or not (passive systems).

**Active systems**

Active solar water heaters rely on electric pumps, and controllers to circulate water, or other heat-transfer fluids through the collectors. There are the two types of active solar water-heating systems:

- **Direct systems.** These systems use a pump to circulate pressurized potable water from the water storage tank through one or more collectors and back into the tank. These systems are appropriate in areas that do not freeze for long periods and do not have hard or acidic water.

- **Indirect systems.** In this system, a heat exchanger heats a fluid that circulates in tubes through the water storage tank, transferring the heat from the fluid to the potable water. The two most common indirect systems are:
  - **Antifreeze.** The heat transfer fluid is usually a glycol-water mixture with the glycol concentration appropriate for the expected minimum temperature.
  - **Drainback systems.** In these systems, the water in the collector loop drains into a reservoir tank when the pumps stop. This makes drainback systems a good choice in colder climates, where the temperature drops to freezing and the water may freeze in the pipes and cause damage to the system. Drainback systems must be carefully installed to ensure that the piping always slopes downward, so that the water will completely drain from the piping.
Passive systems

Passive solar water heaters rely on gravity and the tendency for water to naturally circulate as it is heated. They contain no electrical components, and are therefore more reliable, easier to maintain, and possibly have a longer lifetime than active systems. The two most popular types of passive systems are:

- Thermosiphons. In these systems the tank is placed above the solar collectors. Water is heated in the collector and because of conduction rises up to the tank, while the heavier cold water goes down to the solar collector. As water in the solar collector heats, it becomes lighter and rises naturally into the tank above, while the cooler water flows down the pipes to the bottom of the collector, enhancing the circulation. The storage tank may be either on the roof or in the attic, but in either case the storage tank must be placed higher than the solar collectors. Figure 2.16 shows a typical thermosiphon system.

- Integral-collector storage systems. These systems consist of one or more storage tanks placed in an insulated box with a glazed side facing the sun. Cold water flows progressively through the collector where it is heated by the sun. Hot water is drawn from the top, which is the hottest, and replacement water flows into the bottom. These systems are simple because pumps and controllers are not required. On demand, cold water from the house flows into the collector and hot water from the collector flows to a standard hot water auxiliary tank within the house. Such systems are appropriate for areas where temperatures rarely
go below freezing. They are also good in households with significant daytime and evening hot-water needs; but they do not work well in households with predominantly morning draws because they lose most of the collected energy overnight (EERE, 2008b).

In the UK, mainly active systems are installed. The costs vary due to a range of factors such as size of collector, type of roof, existing hot water system and geographic location. A typical installation in the UK has a panel of 3 m\(^2\) to 4 m\(^2\) for flat plate collectors and 2 m\(^2\) for evacuated tube collectors while the tank varies from 150 to 200L. The cost of installing a solar hot water system ranges from approximately £2000-£3000 for a flat plate collectors system, to £3500-£5000 for an evacuated tube system (EST, 2008). Solar hot water systems generally come with a 10-year warranty and require very little maintenance. Solar water heating in the UK can provide almost all the hot water needs of a dwelling during the summer months and about 50 per cent of the total annual demand (EST, 2008). This equates to a reduction in carbon emissions of 370-750 kg per year, for a dwelling with 3,500 kWh of annual demand, depending on the fuel displaced.

Solar water heating currently is by far the largest microgeneration industry in the UK, installing about 2,000 units annually, and solar water heating represents 44% of the total microgeneration market by installation numbers. At present, it is not a cost effective technology, and break-even point is not predicted when replacing gas or oil boiler water heating, due to high capital costs combined with low oil and gas prices. The technology is most effective when replacing electric heating systems. The Energy Saving Trust proposes that significant grant funding, of the order of 50% of capital costs, would need to be maintained long term to support the market. In that case financial break even point is predicted with electrical water heating around 2015 - 2020 (EST, 2005b).

2.4.4 Combined Heat and Power (CHP)

Combined Heat and Power (CHP), also known as co-generation, is the sequential or simultaneous generation of multiple forms of useful energy (usually electrical and ther-
mal) in a single, integrated system. The main characteristic of CHP systems is that they capture the heat which is produced as a byproduct during electricity generation. The term useful energy describes the maximum amount of work that can be thermodynamically exploited from a system. The usefulness of the heat, defined as process steam, hot water or hot air, is dependent on the actual heat quality requirements in the system being served by the co-generation plant. The temperature mainly defines the quality of the heat. Low heat temperature requirements will increase the amount of usable heat from the co-generation system. Heat can be used for various types of heating purposes in industrial processes, residential heating and also for cooling processes (COGEN3, 2003).

The simultaneous production of heat and power has several advantages over electric-only and heat-only systems; these include:

- The simultaneous production of two energy forms in CHP systems leads to increased fuel efficiency and reduction in CO\textsubscript{2} emissions.
- CHP units can be located close to the point of energy consumption. Hence, transmission and distribution losses that would occur in the national grid, are avoided.
- CHP technology is quite versatile and can be implemented in every sector (industrial, domestic, commercial) and can be matched with existing technologies, such as chillers.
- Because of its versatility in terms of location and coupling with other technologies, CHP is appropriate for the utilisation of local fuel sources, such as biomass (EPA, 2002).

Figure 2.17 illustrates the CHP efficiency in comparison to separate heat and power generation. As shown, for the production of 30 units of electricity and 45 units of heat different amounts of energy are required in each case. For BaU commercial separate generation 111 units of energy are required and the overall efficiency is \( n = \frac{30+45}{111} = 67\% \). Co-generation requires only 100 units of energy for the same production, and the overall efficiency of the system is \( n = \frac{30+45}{100} = 75\% \). In this calculation a Combined
Cycle Gas Turbine (CCGT) power plant is assumed with 60% efficiency and 10% transmission and distribution losses.

CHP systems consist of a number of individual components. The principal elements are the prime mover (heat engine), the generator, the heat recovery component and the electrical interconnection system. The heat engine is the most important component since it drives the overall system. There are various CHP systems and many of these are commonly used today, some are in the early stages of commercialisation, and others are expected to be available in a few years. Table 2.9 summarises all the CHP technologies, and for each one the most important advantages and disadvantages and the typically available capacity range.

Generally, CHP plants must operate for prolonged periods to avoid inefficient start-up cycles where the device will operate at a very low electrical output, thus compromising its carbon intensity. Consistent operation without interruption for many hours per day also increases the lifetime of CHP units (mainly internal combustion engines), since the start-up of each running cycle is the most stressful activity and the point at which the engine suffers the most wear (Carbon Trust, 2007).

Out all the technologies summarised on table 2.9 only two are appropriate for small scale CHP and hence for domestic use. These are the Stirling engine CHP and fuel cell CHP.
### CHP system

<table>
<thead>
<tr>
<th>CHP system</th>
<th>Advantages</th>
<th>Disadvantages</th>
<th>Available sizes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gas turbine</td>
<td>High reliability. Low emissions. High grade heat available. No cooling required.</td>
<td>Require high pressure gas or in-house gas compressor. Poor efficiency at low loading. Output falls as ambient temperature rises.</td>
<td>500 kW to 40 MW</td>
</tr>
<tr>
<td>Microturbine</td>
<td>Small number of moving parts. Compact size and light weight. Low emissions. No cooling required.</td>
<td>High costs. Relatively low mechanical efficiency. Limited to lower temperature co-generation applications.</td>
<td>30 kW to 350 kW</td>
</tr>
<tr>
<td>Spark Ignition (SI) reciprocating engine</td>
<td>High power efficiency with part-load operational flexibility. Fast start-up. Relatively low investment cost.</td>
<td>High maintenance costs. Limited to lower temperature co-generation applications.</td>
<td>20 kW to 5 MW</td>
</tr>
<tr>
<td>Diesel / Compression Ignition (CI) reciprocating engine</td>
<td>Can be used in island mode and have good load following capability. Can be overhauled on site with normal operators. Operate on low-pressure gas.</td>
<td>Relatively high air emissions. Must be cooled even if recovered heat is not used. High levels of low frequency noise.</td>
<td>High Speed (20 Hz) 1 kW to 4 MW Low Speed (1-4.58 RPM) 2 MW to 65 MW</td>
</tr>
<tr>
<td>Steam turbine (Rankin process)</td>
<td>High overall efficiency. Any type of fuel may be used. Ability to meet more than one site heat grade requirement. Long working life and high reliability. Power to heat ratio can be varied.</td>
<td>Slow start up. Low power to heat ratio.</td>
<td>50 kW to 250 kW</td>
</tr>
<tr>
<td>Stirling Engine</td>
<td>High overall efficiency. Any type of fuel may be used. Low emissions and low noise. Good performance at partial load. Power to heat ratio can be varied. No extra thermal-boiler necessary.</td>
<td>High costs. Not fully developed technology. No statistical data for reliability. Low capacities. Low electrical efficiency.</td>
<td>10 kW to 30 kW</td>
</tr>
<tr>
<td>Fuel Cells</td>
<td>Low emissions and low noise. High efficiency over load range (up to 85%).</td>
<td>High costs. Low durability and power density.</td>
<td>200 kW to 250 kW</td>
</tr>
<tr>
<td>$\mu$CHP Fuel Cells</td>
<td>Modular design. Electrical output is computer grade power. Flexibility in capacity.</td>
<td>Fuels requiring processing unless pure hydrogen is used. Limited commercial availability.</td>
<td>100 W to 2 kW per cell</td>
</tr>
</tbody>
</table>

Table 2.9: Summary of all CHP technologies (EPA, 2002; EDUCOGEN, 2001b,a)
2.4.4.1 Stirling engine CHP

A Stirling engine is an externally heated system with a closed gas cycle, where heat is supplied and removed at a constant temperature. The external source that supplies the engine with heat typically is burning gas, and this makes a working fluid, e.g. helium, expand and cause one of the two pistons to move inside a cylinder. This is known as the working piston. A second piston, known as a displacer, then transfers the gas to a cool zone where it is re-compressed by the working piston. The displacer then transfers the compressed gas or air to the hot region and the cycle continues. This process is similar to the theoretically high efficient Carnot cycle. The system has fewer moving parts than conventional engines, and no valves, tappets, fuel injectors or spark ignition systems. It is therefore quieter than normal engines, a feature also resulting from the continuous, rather than pulsed, combustion of the fuel. It is a high efficiency system, appropriate for small scale power and co-generation applications. Since it is an externally heated system, the energy source can be almost any fuel, with the appropriate combustion system. Hence, it can be coupled with biomass technologies, for a more sustainable system. Stirling engines have even been demonstrated for concentrating solar power. Stirling engines are capable of electrical efficiencies of 25% to 30% in the 10kW to 30kW range (EDUCOGEN, 2001b; COGEN3, 2003).

At the moment this technology is not cost effective, however commercial introduction of Stirling engine CHPs is expected by 2010 (WhisperGen, 2008; Baxi-SenerTec, 2006).
This technology is likely to be successful in larger dwellings with higher than average heat loads. After this technology achieves cost effectiveness, it could take another 10-15 years before a significant proportion of domestic energy is generated this way. EST estimates that the potential for Stirling engine CHP is high and that over 8 million homes could be supplied by Stirling CHP by 2050, supplying 40% of domestic heating requirements and 6% of UK electricity supplies (EST, 2005b).

2.4.4.2 Fuel cell CHP

Fuel cell systems produce electricity, heat and water during an electrochemical process. Hydrogen and oxygen react in an electrolytic cell, without combustion, hence the level of emissions at the fuel cell stage of the process is very low. A fuel cell operates as follows: hydrogen reacts with oxygen in the presence of an electrolyte and produces water, while at the same time an electrochemical potential is developed, which causes the flow of an electric current in the external circuit (load). The following electrochemical reactions take place on the two electrodes:

Anode: \[ H_2 \rightarrow 2H^+ + 2e^- \]

Cathode: \[ 2H^+ + \frac{1}{2}O_2 + 2e^- \rightarrow H_2O \]

Thus the total reaction is: \[ H_2 + \frac{1}{2}O_2 \rightarrow H_2O + Q \]

At the anode, ions and free electrons are produced. Ions move towards the cathode through the electrolyte. Electrons move towards the cathode through the external circuit, which includes the load (external resistance). The reaction is exothermic and the released heat can be used in thermal processes. The only significant source of emissions is the fuel processing subsystem, as it converts fuel to hydrogen and to a number of by-products such as CO, CO$_2$, NO$_x$ and SO$_x$, depending on the fuel used to extract hydrogen. Therefore, fuel cells should not be regarded as an emissions free technology, unless the fuel to generate the hydrogen was provided via a sustainable method. The fuel cell principle is illustrated in Figure 2.19. In general there are high temperature and low temperature fuel cells. High temperature fuel cells have higher efficiencies and are appropriate to be coupled with gas turbines or steam turbines,
resulting in a high electrical efficiency systems (up to 70%) (EPA, 2002; COGEN3, 2003; EDUCOGEN, 2001a).

Fuel cell systems are constructed from individual cells that generate 100 W to 2 kW per cell. This enables systems to be extremely flexible in capacity. Their overall efficiency varies between 65 - 85%. In practice, several losses in the various components of a fuel cell system, which consists of the fuel reformer, the cell stack, the inverter and the auxiliary equipment, result in efficiencies much lower than in theory. Their typical power to heat ratio varies from 1 to 2, which is much higher than any other type of CHP plants.

Fuel cells offer a combination of performance and environmental advantages for on-site co-generation:

- They operate at high efficiency even at low load, hence they are suitable for small applications such as micro-CHP (μCHP).
- They have fewer moving parts and are not susceptible to wear-and-tear arising from the need to convert explosive combustion into mechanical energy.
- The latter provides reliable operation combined with minimum interruptions for service, reducing maintenance costs and interrupted supply.
- Very low noise level makes them suitable for domestic use.
- Modular construction makes it easy to build units with the desired power output and match the needs of any application.
• Siting flexibility allows by-product heat to be used, increasing energy efficiency (EDUCO-GEN, 2001a,b; EPA, 2002).

• High electrical to thermal ratio makes this technology appropriate for applications with moderate thermal load.

Fuel cell CHP is suited better for small dwellings with below the average heating demand or for bigger dwellings but with high standards for building fabric. Other future measures that will help to reduce the domestic heating requirements will also increase the market for this technology. At the moment it is not a cost effective technology, but commercialisation is expected around 2013, while costs will continue to fall (DECC, 2009a). The high power to heat ratio means that in many cases a significant amount of electricity will have to be exported, hence this technology is dependent economically on a more equitable value for exported electricity equivalence. The FITs recently announced from the UK Government in the “Consultation on renewable electricity financial incentives” (DECC, 2009a) in conjunction to the “Renewable heat incentives”, published in February 2010, are expected to benefit this technology more than any other, whilst further work is being undertaken by DECC in order to suggest an appropriate tariff for technologies such as fuel cell micro-CHP. According to Energy Saving Trust (EST), a 3kWe fuel cell, without a value for the exported electricity, could produce 1.6% of UK’s annual electricity demand, whilst with EEE, this percentage could rise to 18%. Energy Saving Trust has estimated that by 2050 small fuel cells could supply 9% of UK electricity requirements (EST, 2005b).

2.4.4.3 Micro-CHP - (µCHP)

Micro-CHP devices are typically run as heating appliances, providing space heating and warm water for domestic purposes, though they are also applicable for other applications such as small hotels, commercial buildings, etc. The size of a micro-CHP unit varies according to the application, hence the micro-generation category can differentiate between domestic co-generation and non-domestic co-generation. The first sub-category being 3 kW_e or below is effectively designed to suit the needs of a
household whereas the second is typically from 3 kW_e up to 10 kW_e and can be used in bigger dwellings (apartment blocks, small hotels) or small facilities (swimming-pools).

The technology is based on three engine types, which are:

- internal combustion engines, which are already available on the market. Europe had 8,000 installations in 2003, of which 6,000 were installed in Germany.

- external combustion engines, which typically are Stirling engines, organic Rankine cycle engines or steam engines. The first commercial sales of Stirling engines in the UK occurred in June 2003.

- fuel cells, which still are in development and demonstration stages, though there are some models in the market. The first fuel-cell CHP system in the UK was installed on behalf of Woking Borough Council at the Woking Park leisure complex in December 2001 and it was launched in June 2003 (COGEN, 2003, 2005).

The main target market for micro-CHP is the domestic mass market as a replacement for conventional gas boilers in domestic dwellings, where the unit will operate in a "heat-led" mode.

Currently in the UK there are four units available in the market, and these are:

1. **WhisperGen.** This unit produces 1 kW_e of electricity and 7 kW_th of heat. The prime mover of the unit is a Stirling engine and it is designed for micro use (one dwelling). It is manufactured by Whisper Tech and it was being sold as part of a market trial, until 2008. The unit is expected to become commercial in 2010, with a capital cost of approximately £2600 and it is estimated to achieve on average a £150 of annual savings when installed in appropriate dwellings compared with a conventional boiler (COGEN, 2005; WhisperGen, 2008).

2. **SenerTec DACHS.** This unit produces 5.5 kW_e of electricity and 12.5 kW_th of heat and it is built around an internal combustion engine. It is usually installed in commercial buildings and in general buildings with higher demand than a single dwelling. It is manufactured by SenerTec, a subsidiary of Baxi, and the capital
cost of the unit, including installation, is approximately £12,000 (COGEN, 2005; Baxi-SenerTec, 2006).

3. **Ecopower.** This unit may produce 4.7 kW\textsubscript{e} and 12.5 kW\textsubscript{th} and its prime mover is also an internal combustion engine. Due to its size it is installed to similar locations to the DACHS. The manufacturing company is Power Plus Technologies, a subsidiary of Vaillant (COGEN, 2005).

4. **EC Power.** This is a fully automatic system with heat storage, real time load following, automatic peak-shaving and optional integrated heat-pump system control. It has a natural gas-fueled engine unit that generates 3-12 kW\textsubscript{e} of power and 17-32 kW\textsubscript{th} of heat. Due to its bigger capacity it is installed in apartments blocks, commercial buildings, office buildings, etc (COGEN, 2005).

Micro-CHP systems have the potential to reduce significantly the carbon footprint of a single dwelling even when compared to a normal system of a condensing boiler and network electricity. It is estimated that a 1 kW\textsubscript{e} system can achieve CO\textsubscript{2} savings of between 9% for Stirling engine systems and 16% for fuel cell systems. The scale of saving is approximately equivalent to that of changing from gas-fired central-heating boilers (estimated efficiency of 78%) to a condensing boiler (n=90%). Naturally, the carbon and the cost savings are dependent on the prime mover capacity, the electrical efficiency and the adopted control logic. Current-generation Stirling engine systems are expected to have limited use during mild and warm weather (i.e. for 40–50% of the year) due to their low prime mover efficiency. Greater annual savings would emerge from improving the electrical efficiency of the prime mover and optimising the control regime (Peacock and Newborough, 2005). Thermal storage can further improve the thermal performance of such systems. FITs for electricity generated from micro-CHP have not yet been published from the UK Government but they are expected to benefit such systems alongside other heat policies, most notably the the Renewable Heat Incentive (RHI) (DECC, 2009a).
2.5 Energy modelling

Energy models are simplified representations of a real energy system. Energy models may be designed to meet different objectives, or may have different structure or may be based on different assumptions, but often they share some characteristics, such as the tool used (statistical, simulation, etc.), the sector for which they are designed (domestic, commercial or a mix of the two), the purpose of the model (optimisation, forecasting, better matching and others).

Jebaraj and Iniyan (2006) in an attempt to understand and review the various emerging issues related to energy modelling, reviewed approximately 250 studies and they suggested the following classification:

- Energy planning models,
- energy supply-demand models,
- forecasting models,
- optimisation models,
- energy models based on Neural Networks and
- emission reduction models.

Different classifications are possible since energy models often bear characteristics of more than one of the categories mentioned above. For instance the performance of a renewable energy technology can be regarded as a forecasting model, but a model representing the parallel operation of multiple units may be a forecasting/optimisation model.

A more general classification was suggested by Hiremath et al. (2007), who mainly focused on regional energy planning models. The main difference of decentralised energy planning to other energy planning models, is that except the energy requirements of the region decentralised energy planning models also consider the available resources within the region (e.g. a site with geothermal energy/Iceland). Their classification was
based on the common characteristics that some models share, such as the mathematical approach, the time horizon and the size of the modelled area. The classification that Hiremath et al. (2007) suggested is:

- Optimisation models,
- decentralised energy models,
- energy and environmental planning models,
- energy supply/demand driven models and
- resource energy planning models.

The work presented here can be classified as an energy supply/demand forecasting model. The energy demand of a single dwelling and a cluster of dwellings is predicted under various scenarios and the associated carbon emissions are estimated. Various microgeneration technologies are considered and their performance is also forecasted under various scenarios of different demand profiles and different climates.

For modelling the residential sector energy consumption, Swan and Ugursal (2009) identify two distinct approaches: top-down and bottom-up. Top-down approach treats the residential sector as an energy sink. The energy consumption of the housing stock is the result of a regression analysis of historic aggregated energy data. Variables such as economic indicators, energy prices and climate data, are used. The bottom-up approach is an extrapolation method of a representative set of individual houses to regional and national levels. There are two bottom-up methodologies: statistical methods that rely on historical information, and engineering methods that account for the energy consumption of end-uses based on thermodynamic and heat transfer relationships. Generally, Swan and Ugursal (2009) regard bottom-up approaches as more detailed, but at the same time more complex, than the top-down approaches. For this research a bottom-up approach has been chosen. The energy demand of various residential clusters is predicted based on the energy demand of single dwellings, representative of the modelled region.
2.6 Relevant projects

The literature relevant to this research can be broken down to the following categories:

- Building simulation
- Low and zero carbon (LZC) technologies for individual buildings or small communities
- Microgrids
- Energy efficiency measures (insulation measures, improved glazing, high efficiency heating systems, etc.) and refurbishment of the building stock
- User behaviour, occupancy profile and the potential of reducing carbon emissions through improved awareness
- Domestic energy and carbon emissions reduction

The following sections (2.6.1 to 2.6.6) are an overview of relevant projects on decentralised energy planning and domestic carbon footprint. The approaches and the relevant applications are given, along with key results and conclusions where necessary.

2.6.1 Building simulation tools developed and projects

Over the years, large and complex energy simulation computer programs for buildings have evolved. Many of these programs are open source code programs, making them more suitable to research purposes, whilst proprietary programs are traditionally used by planners, developers and consultants.

DOE-2, developed by Lawrence Berkeley National Laboratory (LBNL), is a building energy analysis program that can predict the energy use and cost for various types of buildings. DOE-2 consists of five parts, one program for translating the input and four simulation subprograms which are executed in sequence. BLAST is another building simulation program, developed in the US the same period as DOE-2. The two programs are similar, but BLAST uses a heat balance approach. Both programs, though
open source, are difficult to modify and they require experience working within the code. Since the development of both programs was supported from the US government, in 1996 it was decided to merge the two programs and the development of a new program named EnergyPlus began (Crawley et al., 2001). EnergyPlus is a simulation engine, with no interface, that consists of three basic components: a simulation manager, a heat and mass balance simulation module and a building systems simulation module. The simulation manager handles communication between the heat balance module and various HVAC modules. Since the program does not include modules for technologies such as photovoltaics, solar thermal, ground source heat pumps etc., it provides the possibility to be linked with other programs such as TRNSYS and receive input from these modules (Crawley et al., 2001).

ESP-r is a European, integrated, open source, building simulation tool for the simulation of the thermal, visual and acoustic performance of buildings and the assessment of the energy use and gaseous emissions associated with the environmental control systems and constructional materials. ESP-r has been the subject of sustained development since 1974. It comprises a central Project Manager (PM) that allows communication between support databases, a simulator, various performance assessment tools and a variety of third party applications for CAD, which are arranged around the PM. ESP-r is based on a finite volume, conservation approach; the problem which is specified in terms of geometry, operation, construction quality, etc., is transformed into a set of conservation equations (energy, mass, momentum, etc.). The tool also incorporates various component networks, representing HVAC systems, distributed fluid flow and electrical power circuits (Clarke et al., 1998; ESRU, 2009).

TRNSYS is another tool, designed to simulate the transient performance of energy systems. Its development started during the 1970s at the University of Wisconsin-Madison Solar Energy Lab. TRNSYS is not designed to model only buildings, but whole energy networks. TRNSYS applications include low energy buildings and HVAC systems, renewable energy systems, cogeneration and fuel cells and others (TRNSYS, 2005). TRNSYS is described in detail in following chapters, since it is the main tool used in this research.

Various studies have been performed using the simulation programs described above,
whilst other researchers have developed their own tools to simulate the energy behaviour of a building. Gonzalez and Zamarreno (2005) suggested a method, based on a special kind of artificial neural network for predicting the short-term electric load of buildings or whole regions and countries. Their algorithm used as inputs the forecasted values of temperature, the current electric load and the hour and the day. Caldera and Filippi (2008) used a statistical approach to estimate the energy demand for space heating demand of residential buildings. In their study they analysed data from 50 residential buildings in order to find correlations between the energy demand and the building’s main geometric and thermophysical properties. Karatasou et al. (2006) used a combination of the two approaches mentioned above. They used a statistical procedure to design feed forward neural networks for modeling energy use and predicting hourly electric load profiles. Their analysis also focused on the significance of the various inputs used in their model. They concluded that real building data presents different characteristics and therefore, a number of input sets should be used to feed the algorithm.

2.6.2 LZC technologies at the building sector

The literature is quite wide when it comes to LZC technologies applied to the residential sector. The potential for these technologies to contribute to CO$_2$ reductions is acknowledged by the UK Government, though there are barriers that have to be overcome. Financial backing, to support and stimulate the market, is regarded as a key measure, whilst the current level of funding for these technologies is unlikely to stimulate the market and lower the capital costs for these technologies in the near future Allen et al. (2008).

Underwood et al. (2007) investigated the potential contribution to electricity supply to a remote community, considered as a housing cluster, based on photovoltaic “slate” roof coverings and micro-windturbines by applying a simulation model to a remote area in the United Kingdom. Results indicated the importance of exporting the excess of generated electricity in order to make the scheme economically viable. The cost effectiveness of a photovoltaic system and a domestic solar thermal water heating system were evaluated from Fuentes et al. (1996) by monitoring for nine months the

56
Oxford Solar House. Both technologies performed at levels very close to manufacturer’s claims, but in terms of financial return they proved to be poor. In order to improve the economical viability of a PV system Kalogirou and Tripanagnostopoulos (2006) considered a hybrid PV/T system for domestic hot water and electricity generation. The system performed better for high levels of energy, but even for areas with high available solar radiation the payback period was greater than the system’s lifetime, indicating the need for state subsidies for the promotion of such systems.

Solar thermal, although is a mature technology, is used in a small percentage of European buildings. The literature mainly focuses on the potential for solar thermal technologies and the economics. Voivontas and Tsiligridis (1998) explored the potential for solar domestic hot water heating in Greece, using Geographic Information System (GIS) technology, in order to provide spatial insight on their results and make them more informative to policy makers. In a later work, Tsilingiridis and Martinopoulos (2009) assessed the contribution of domestic solar hot water systems to the reduction of conventional energy and greenhouse gases and other air pollutant emissions in Greece, from its early years in mid ’70s to the present day. They concluded that solar thermal can play an important role in the energy and the environmental policy of the country, but regulatory measures have to be combined with economic measures to achieve higher installation rates. The European Solar Thermal Technology Platform stated that costs of solar thermal systems are expected to reduce by more than 50% by 2030 (Bokhoven et al., 2006). Solar thermal systems have also been used at a district level for central heating systems. In Sweden, Annemberg project comprises 50 residential units and 2,400 m² solar collectors, to supply heating for low temperature heating systems. Lundh and Dalenback (2008) reported the initial results from the Annemberg project, one of the largest solar heating plants in Europe, and concluded that besides the problems occurred, the overall system performance was as expected.

Another LZC technology that is growing fast in the building sector, are ground source heat pumps (GSHP). In the UK, use of GSHP systems has grown from only one installation in 1994 to currently over 1 MWth of geothermal energy delivered to residential and commercial premises. The performance of ground source heat pumps in domestic scenarios has been estimated through the use of simulations, theory or empirical mea-
measurements. Hepbasli and Akdemir (2004) presented an energy and exergy analysis of a vertical GSHP system, to evaluate a system applied in a 65m² room. Their analysis aimed to provide designers with a better, quantitative handle, of the system’s inefficiencies and how each component affects the overall performance. Nam et al. (2008) focused on the ground heat exchanger of the system and developed a numerical model to predict the heat-exchange rates from/into the ground. Fischer and Rees (2005) used the building energy simulation program EnergyPlus to model the performance of a water-to-water ground source heat pump. Their model consisted of simplified representations of heat exchanger and expansion device components, with a more detailed compressor model. They concluded that the advantage of such models is that they do not require very detailed component data or measurements and that they can tackle a wider range of operating conditions.

Jenkins et al. (2009) developed a model based on manufacturers and empirical data in order to predict the carbon performance of a domestic application in the UK. Their results showed that a GSHP matching 60% of the peak thermal demand and an electrical auxiliary heating meeting the remainder, are suitable for providing a system that can meet the majority of the annual thermal requirement (≈95%). The performance of another domestic application in the UK was reported by Doherty et al. (2004), who discussed the experimental results from an 8 kW reversible ground source heat pump system that was successfully installed and tested at the Eco-House, University of Nottingham. They concluded that the design coefficient of performance of the heat pump can be achieved through proper installation and careful consideration of the operation of the system as a whole.

Peacock and Newborough (2005) investigated the impact of micro-CHP systems based on Stirling engine and fuel cells, on domestic sector CO₂ emissions. They estimated that the level of saving is approximately equivalent to that of changing from gas-fired central heating boilers (78% efficiency) to a condensing boiler (90% efficiency), with fuel cell based systems performing better due to less production of heat surplus during mild and warm weather. However in their work, for the investigated dwelling, the Stirling engine micro-CHP was predicted to result in increase in annual CO₂ emissions when compared with a non-CHP case, highlighting the importance of adopting
an appropriate control logic in order to avoid production of heat surplus. A more recent study by Peacock and Newborough (2008) showed that a micro-CHP may result in an emissions increase if implemented after a set of heat-saving measures, demonstrating the strong relationship of micro-CHP systems between heat-saving measures, which translates to a strong relationship between carbon savings and heat demand load. Therefore, CO$_2$ emission savings attributable to micro-CHP systems depend on a number of behavioural (user), technical (dwelling), external (network) and policy (reward schemes) factors.

Similar were the findings of a micro-CHP field trial performed by Carbon Trust (2007) for over a period of four years. The trial demonstrated that the carbon and cost savings from micro-CHP, are generally better for houses where they can operate for long and consistent heating periods. Annual heating demand was found to be the main criterion for assessing potential carbon savings from micro-CHP systems in domestic applications. Large houses with poor building fabric were estimated to have the potential to deliver carbon savings in the range of 5% to 10% relative to a typical A-rated condensing boiler. Smaller and newer houses with low heating demand were found to be less likely to deliver carbon savings and in some cases results suggested that the use of a micro-CHP system may lead to an increase in emissions relative to a condensing boiler.

Another option for domestic applications that has received a certain degree of recent attention in the UK are micro-wind turbines. As Peacock et al. (2008) highlight though, there is a serious issue concerning the ability to reliable estimate their energy yields, mainly due to lack of robust methods for estimating urban wind speeds and due to the lack of an independent test method to produce turbine power curves. Acknowledging the same problem Bahaj et al. (2007), developed a modelling tool for studying energy yields and payback periods for micro-wind turbines. Their analysis has shown that wind resource itself is the key parameter in ensuring the success of the technology and payback within the lifetime of the device occurs only if the turbine is placed in windy locations. Their results demonstrated that wind shear and shadow effects in urban areas can reduce the annual yielding by up to 50%, making proliferation of this technology among UK urban areas highly unlikely.
A field trial performed by Energy Saving Trust from 2007 to 2009 (EST, 2009a) showed that local topography and site characteristics have considerable impact on the available wind resource. Building mounted turbines located in urban and suburban locations were found to have inadequate wind speeds and were not cost effective. Remote rural locations, usually individual dwellings near the coast or on exposed land with undisturbed wind resources, were observed to have load factors of up to 5%, still half to 10% assumed in many rule of thumb calculations. The best sites for pole mounted turbines also performed poorly in urban or suburban areas (EST, 2009a). Generally, literature shows that micro-wind is the least appropriate microgeneration technology for urban areas, characterised by poor performance, and therefore is not considered in this research (James et al., 2010).

2.6.3 Microgrid projects

Development of microgrid concepts is in progress in many countries and various research groups study the numerous technical, economical and commercial challenges of this concept.

The 'EU More Microgrids' project is a European international effort that focuses on the increase of penetration of microgeneration in electrical networks through the exploitation and the extension of microgrids. The consortium consists of 22 partners from 11 EU countries. Research mainly focuses on technical aspects of microgrids, such as the development of alternative network designs and control strategies and the impact on the wider grid (macrogrid) (Hatzigiourgiou et al., 2007).

In the U.S, the Consortium for Electric Reliability Technology Solutions (CERTS) microgrid concept aims to explore implications for power system reliability of emerging technological, economic, regulatory and environmental influences. It presents an alternative microgrid design that ensures high levels of reliability and flexibility, by seamlessly separating from the normal utility service during a disruption. The CERTS microgrid concept is designed for sites with peak demand $\sim<2\text{MW}_{el}$ (Lasseter et al., 2002).
Japan is one of the leaders in microgrid demonstration projects, with three pilot field tests, running under the Regional Power Grid with Renewable Energy Resources Project from the New Energy and Industrial Technology Development Organization (NEDO). These field tests assess the integration of new energy sources, such as wind turbines and fuel cells, into a local distribution network and focus on the microgrid’s control system. Micrgrids have peak demand from 710 kW to 2400 kW and incorporate power storage in battery banks. All three systems operate for multiple commercial buildings and loads are supplied with private power lines that are isolated from the utility power system. The microgrid is connected at only one point to the utility grid (Funabashi and Yokoyama, 2006).

In the UK, Supergen Highly Distributed Power Systems (HDPS) is a consortium of UK Universities (University of Strathclyde, Imperial College, Loughborough University, University of Bath, University of Cardiff and University of Oxford) and industrial partners who are addressing the engineering challenges associated with a systems approach to the design, operation and control of future power systems, including microgrid schemes. Their work can be divided into three categories: 1. Conceptual design and simulation, 2. Operation and appraisal of HDPS, 3. Integration and interfaces.

Other projects include the “MICROGRIDS” project, where Pudjianto et al. (2005) investigated various economic, regulatory and commercial issues faced by the development of microgrids. They proposed a closed loop price signal approach to control the operation of the microgrid, where the microgenerators are feeding the system operator with the electricity prices they are willing to pay. Such operations give the autonomy to the microgenerators to determine the level of energy they are going to produce at a given price. Marnay et al. (2008) also investigated various economic and regulatory issues of microgrid implementation, taking examples from Europe, the U.S and Japan. They highlight the potential economic benefits created by microgrids, but they conclude that significant changes in the regulatory framework (e.g. interconnection issues) are required in order to turn these potential economic benefits into commercial income.
2.6.4 Energy efficiency measures projects

The improvement in the energy performance of existing dwellings is crucial towards achieving the reduction in greenhouse gas emissions in the framework of the Kyoto protocol. In their large scale analysis, based on the Belgian building stock, Hens et al. (2001) conclude that increasing the energy efficiency on new buildings is not sufficient. The housing policy adopted by governments needs to be reviewed in order to save energy through retrofit of the present housing stock as well. Verbeeck and Hens (2005) extended the work by discussing economically feasible ways and means to choose between energy efficiency measures, such as improved insulation, better glazing, installation measures and renewable energy systems. Though some of the measures proved to be far beyond the economic optimum, they proposed a hierarchy of energy-saving measures, sorted according their effectiveness and their durability. The proposed hierarchy is: 1. roof insulation, 2. floor insulation, 3. thermally better performing glazing, 4. more energy efficient heating system, and 5. renewable energy systems.

A different aspect was investigated by Gaterell and McEvoy (2005) who investigated the impact of external costs associated with the generation and consumption of energy on the cost effectiveness of energy efficiency measures applied to existing dwellings. They concluded that despite the inevitable variation in the projection of energy prices and climate impacts there is little change in the ranking of the energy efficiency measures, going forward in time. Therefore, any measures implemented today are likely to be effective in the future.

The majority of the work performed in this area is based on simulation models, therefore all the related results are estimations of carbon reductions as result of measures implemented. Hong et al. (2006) examined the differences that appear between modelled and monitored values from English dwellings before and after refurbishment and they tried to explain the reasons why the simulation models deviate from the real values. They observed that wall insulation appeared to reduce space heating fuel consumption by 10-17%, though it was predicted to deliver savings up to 49%. Such differences were mainly justified by technical reasons, such as incomplete insulations, or by user’s behaviour, such as increased thermal comfort. These results suggest that
energy efficiency measures implemented to existing dwellings will not deliver as high a reduction in energy consumption as often models predict.

2.6.5 Load profile - User behaviour projects

Energy use in buildings is closely linked to the behaviour of their occupants. The occupants take actions to change the indoors environmental conditions directly (heating, natural ventilation, lighting, etc.) and actions are taken for other purposes, but have an impact on the environmental conditions, e.g. gains from cooking. In this respect, user behaviour may be defined as the actions users take and have an impact on the indoor environmental conditions, but also as the presence of occupants in the building.

The majority of the publications focus on the implementation of energy efficiency measures and renewable energy technologies, whilst they simply mention the importance of end-user behaviour to the energy load of a dwelling. Quite often the potential carbon savings from the domestic sector are overestimated because the impact of consumer’s behaviour is neglected in technical studies. As Hoes et al. (2009) suggest, the impact of users behaviour on a building’s energy balance will be even greater in the future. More passive buildings, with lower energy demand, will be built due to the demand for more sustainable buildings and therefore, the weight of users behaviour on the building’s energy demand will increase.

A method for generating realistic occupancy data for UK households, based upon the UK 2000 TUS (Time Use Survey) data set (Dobbs et al., 2003), was developed by Richardson et al. (2008). In their work, statistical occupancy time-series data was generated by a Markov-chain technique and could be used as an input to any domestic energy model. A similar approach was used by Page et al. (2008) who developed a generalised stochastic model for the simulation of occupant presence to be used as an input for future occupant behaviour models within building simulations. The model considered occupant presence as a inhomogeneous time-discrete Markov chain to predict the state of presence of each occupant of a zone, for each zone of any number of buildings, instead of using a set of predefined scenarios.
Depending on the type of the model, many energy simulations for buildings either generate energy consumption profiles or they use them as inputs. In both cases, these consumption profiles comprehend and typify the user behaviour. Various studies have been published over recent years, which generate load profiles that reflect realistic user behaviour or investigate the correlation between the load profiles and the user behaviour.

Most of the studies performed are not based on aggregated data, but on census survey data. Yao and Steemers (2006) proposed a simple method for formulating load profiles for UK domestic buildings. The method can produce daily load profiles of appliances, domestic hot water and space heating for an individual house and it is based on national census data and surveys in order to form and examine various representative scenarios. This data regards the number of occupants and the occupancy patterns, the energy consumption of domestic appliances and the energy consumption of domestic hot water.

Yohanis et al. (2008) studied 27 representative dwellings in Northern Ireland and investigated how occupancy and dwelling characteristics affect domestic electricity consumption. The study showed that the electricity consumption per person decreased as the number of occupants increased, whilst a strong correlation was found between average annual electricity consumption and floor area. The daily profiles proved to vary according to the age and the average income of the occupants, therefore when designing a detailed model, these are factors that should be taken into account.

Jardine (2008), synthesised high resolution domestic electricity profiles, utilising an occupancy model which can serve as a proxy for both non-baseload electricity demand and heat demand. The occupancy model developed used a sample of measured electricity load profiles (of 30 min resolution) from 100 dwellings for one week in each of the seasons of winter, spring and summer. The 1 min resolution generated profiles showed higher peak loads than the conventional 30 min resolution profiles, making them more suitable for modelling microgeneration technologies. However, another important aspect that was not investigated in Jardine’s work, is how user’s behaviour and consumption profiles are influenced by the adoption of renewable energy technologies.

A study through questionnaires and interviews, performed from Keirstead (2007),
recorded changes in the energy use that were encouraged by the adoption of PV systems in dwellings. Specifically, a 6% saving in the overall amount of electricity used and load-shifting to times of peak PV generation was observed. At the same time, monitoring devices that informed the occupants regarding the generation and consumption, proved to increase energy awareness and boost the observed changes. In this work it was not specified if these changes in consumption behaviour are lasting, but Bahaj and James (2007) observed that increased awareness decreases within some months. Bahaj and James (2007) recorded the load profiles of 9 social houses with photovoltaics and though at the first place significant reductions in electrical consumption were recorded, within a year the consumption within some houses returned to the previous levels.

User behaviour is not only formed by comfort criteria or environmental awareness, but also by economical factors. Energy use in a household is strongly related to the household’s average income and to energy prices (Anker-Nilssen, 2003; Sardianou, 2007; Mills and Schleich, 2009). Further, environmental concerns and willingness to pay for environmental benefits increase with income (Fransson and Garling, 1999). Anker-Nilssen (2003) noticed that developments or political initiatives that influence the costs of energy use have greater effects on low-income households, even though their energy use reflects basic necessities and represents a minor part of the total household consumption. He also concluded that for high-income households, consumption becomes an act of pleasure beyond satisfying basic needs. At the same time, some scientists argue that an increase in energy efficiency sector will lead to reduced prices; this increase will also lead to extra energy demand from the sector which will outweigh the conservation effect (Haas et al., 1998). Economists commonly term this effect as as the “rebound-effect”.

Haas et al. (1998) indicated that there is no linear relationship between energy demand for space heating and the thermal quality of a building, and therefore service demand depends on the efficiency of providing the service “warm room”. On the other hand, they showed that there is a linear relationship between energy demand for space heating and indoor temperature. These results provide evidence of a “rebound-effect”. Brännlund et al. (2007) examined how exogenous technological progress, in terms of an increase in energy efficiency, affects consumption choice and thereby associated emis-
sions, from the domestic sector in Sweden. They concluded that the “rebound-effect” can be that considerable, that an increase in energy efficiency may not necessarily lead to lower energy consumption. On the contrary, they regarded as more likely a “growth effect” scenario, according to which emissions are expected to increase.

2.6.6 Domestic energy and carbon emission reduction projects and models developed

In recent years there has been a growing interest in reducing the energy consumption and the associated greenhouse gas emissions from the domestic sector. This section presents studies and different approaches for modelling the residential sector and its energy performance.

The approach chosen in this research is a bottom-up engineering model. One of the main strengths of such approaches is their ability to model new technologies solely based on their traits. Bottom-up methods, statistical and engineering, are well documented and many models have been suggested from researchers (Swan and Ugursal, 2009).

Shorrock et al. (2005) looked into various scenarios for achieving a 60% reduction in carbon emissions from the UK domestic sector by 2050. This work was performed under the auspices of the Building Research Establishment (BRE) and was supported by the Department for the Environment, Food and Rural Affairs (DEFRA). The project consisted of three parts: part one considered various energy efficiency measures and for each one assessed the potential carbon savings and cost-effectiveness; part two focused on energy efficiency policies and their effectiveness; part three considered various scenarios in order to estimate the future carbon emissions from the housing stock and examined how the UK might approach a 60% reduction in carbon emissions by 2050. Future projections were based on a set of scenarios formed by the authors. The first scenario was used as a reference, the next one focused on energy efficiency measures, one focused on policies and the next two adopted further use of renewables. They concluded that a radical change in the heating system mix could result in savings that
outweigh the costs by about 2012, indicating that, each of the scenarios would be cost effective for society as a whole.

Johnston et al.’s (2005) work is strongly related to the work undertaken by Shorrock et al. (2005), since it also looked into various scenarios for achieving CO$_2$ emissions reductions by 60% from the UK housing stock by the year 2050, though it mainly focused on the technical feasibility for realising this target. The model designed was a selectively disaggregated physically based bottom-up energy and CO$_2$ emission model, which covered both energy demand and energy supply side, through a set of scenarios. The model consists of two components: a data module and an energy and CO$_2$ calculation module which is a modified version of the Building Research Establishment’s domestic energy model used in the work mentioned previously, undertaken by Shorrock et al. (2005). The basic characteristic of the model was the adoption of “notional” dwelling types. The term “notional” dwelling refers to a broad range of dwellings, independent of size, form, tenure or age of the building, and the only distinction made was between pre- and post-1996 dwellings. The work concluded that it is technically possible, though demanding, using currently available technology (only heat pumps were considered), to achieve the desired CO$_2$ reductions, by increasing significantly the rate at which fabric and end use efficiency measures are currently being implemented into the UK housing stock. The work focused only on carbon reductions and no cost analysis was performed.

The UK domestic carbon model (UKDCM) is another bottom-up housing stock model, initially developed for the the “40% House” (Boardman et al., 2005) and subsequently updated for the Building Market Transformation project. The UKDCM tracks changes to the housing stock, such as refurbishments, demolitions, new construction, installation of new technology, changing internal temperature, in the context of a changing population, changing household size, and future variability in the UK climate. The UKDCM is essentially a numerical model of energy flows, that uses an elemental U-value approach to calculate the heat demand, whilst demand for lights, appliances, etc., is calculated based on various behavioural approaches. UKDCM uses a disaggregated approach that gives around 20,000 dwelling configurations by 2050 with an appropriate weighting factor and then investigates three scenarios for the domestic
carbon emissions and energy demand till 2050 (Boardman et al., 2005; Boardman, 2007).

Another model developed to test the hypothesis on achieving 60% CO$_2$ reduction from the domestic sector, is the DECarb model developed by Natarajan and Levermore (2007). DECarb is a housing stock model based on two classes of data: future climate data and current UK housing stock data. It explores various scenarios, including the deployment of microgeneration, but only for heat pumps and micro-CHP. Emissions due to electricity consumption are estimated as in the 40% project.

Clarke et al. (2008) chose an archetypes approach and focused on a set of house designs to create distinct thermodynamic classes to represent the spectrum of houses in Scotland. 3,240 classes were developed based on the following energy determinants of energy demand: insulation level (6), capacity level (2), capacity position (3), air permeability (3), window size (3), exposure (5) and wall-to-floor ratio (2). Each class was modelled using the building simulation program ESP-r to determine the thermal energy demand of the dwelling. DHW loads, lighting and appliance energy use, were then applied to estimate the total energy consumption of each dwelling. The results were encapsulated within a Web based tool for comparative analysis and assessment of upgrading strategies upon the stock.

Swan et al. (2008) developed a national energy and greenhouse gas emissions model of the Canadian housing stock, using a database of 17,000 houses. The database utilised data from various housing surveys and other databases, and defined in detail the geometry and thermal envelope of each house. The ESP-r building simulation program was used to predict the energy consumption of each house. Future scenarios, such as upgrading the building stock or adopting renewable energy technologies were not investigated.

The model developed by Saidur et al. (2007) utilised an energy and exergy analysis which was applied to the residential sector of Malaysia. It determined the energy and exergy flows of the Malaysian residential sector for a period of 8 years, based on estimates of appliance ownership, appliance power rating and utilisation time.
2.7 How this study addresses gaps in understanding

The models described in literature analyse the building stock in order to estimate the energy demand and the associated emissions under various scenarios (technology uptake, energy efficiency, building retrofit, etc). For the majority of these models, projections are scaled to the entire building stock of a country, e.g. UK, and the same models cannot perform at a specific local level, i.e. district, projections. Many of the scenarios modelled in most of the studies described focus on various parameters, such as the building fabric quality and the building stock mix (existing/new), population and household size, electric appliances ownership, etc., but the deployment of microgeneration technologies is limited or in some cases it is not considered at all. Options, such as district heating or the formation of microgrids, are scenarios investigated separately in other studies as described earlier.

This research aims to estimate the carbon savings that can be achieved from microgeneration technologies when operating at the small residential cluster level. The models developed in this research are not representative of the entire UK building stock, as the clustering approach is not suitable for all the residential areas in the UK due to the geographical layout of certain areas (low density).

The new knowledge presented in this research is described as follows:

1. To the author’s knowledge there appears not to be any work on the street-level scale, either for heat only, electricity only or heat and electricity combined systems. The issue that this work addresses therefore, is what is the potential impact of inter-connecting houses at the street-level in the UK. Similar concepts have been found in literature but at a significantly larger scale of hundreds of houses (e.g. microgrids and district heating schemes).

2. This research investigates what will be the impact of near future (2020s and 2050s) predicted changes in climate on the options considered.

3. The parallel operation of multiple micro-CHP units is considered and the problem of scheduling the units in order to maximise the system’s efficiency is addressed.
Chapter 3

Project Methodology

3.1 Introduction

This chapter deals with the methodology and the structure of this thesis. The basic steps of the research methodology are outlined and presented in order to help the reader understand the approach taken. Based on the objectives stated earlier, the modelling approach is split into four stages: 1. Single dwelling thermal and electrical demand, 2. Clustering 10 dwellings, 3. Energy efficiency and LZC technologies, 4. Sensitivity analysis and 5. Economics. These stages may also be regarded as five key milestones of this project. The data collection stage is subsequently described and all the sources and methods used for collecting the required data are detailed.

3.2 Basic steps of research methodology

The methodology of this research consists of a number steps which are determined through the presentation of the objectives. These steps have been put in logical order, but this does not necessarily mean that were performed independently. Therefore, the model development started before the completion of the data collection, whilst some validation of the model was performed at the same time, based on the first results.
Figure 3.1: Basic steps to be followed for the completion of this research program
CHAPTER 3. Project Methodology

3.3 Modelling Methodology

3.3.1 Concept of the model

The structure of the model is based on the principle 'Trias Energetica' (Triangle of energetics) that was first proposed in the Netherlands for saving energy in buildings. According to “Trias Energetica” the path to realisation of a reduction of the use of fossil fuels and a maximal share of renewables in the built environment can be subdivided in three consecutive steps, which are:

**Saving energy.** This step suggests that energy efficient methods, materials, appliances and systems that can save energy should be implemented in buildings. Examples of these are thermal insulation, improved glazing and heat recovery from ventilation.

**Renewable energy sources.** The second step suggests the use of renewable energy sources instead of fossil fuels in order to satisfy the resulting energy demand as much as possible. Examples are the use of solar energy, small wind energy, biomass, ground source heat pumps (GSHPs), etc.

**Efficient use of fossil fuels.** The last step suggests producing and using fossil fuel energy with the most efficient techniques that are available. If local renewable energy sources are not sufficient to supply the complete energy demand, the third step is necessary: use the traditional fossil fuels as efficiently as possible. For instance implementing high efficiency condensing boilers or combined heat and power units. This step incorporates the user’s behaviour, which is critical to efficient use of energy (ECN, 2008).

The three steps are illustrated in Figure 3.2, where it is shown that the first two steps tend to increase their share in the triangle, in order to minimise the area that the third step (efficient use of fossil fuel energy) occupies.

In practice, it is sometimes difficult to assign a method or a measure to exactly one of the 'Trias Energetica’ steps. An illustrative example is the use of passive solar
energy. Here, solar energy contributes to the heating of the building in a passive way; hence energy is saved from the central heating system. It is obvious that it is difficult to draw a line between energy saving and the use of solar energy. This difficulty indicates the strong interconnection that exists between energy saving measures and renewable energy measures. In this project buildings, are seen as one large system for the implementation of renewable energy technologies and energy efficiency measures.

### 3.3.2 Modelling approach

As stated previously, the main objective of this research is the estimation of the carbon footprint of a cluster of houses in a street level as a result of various scenarios. The complexity of the problem in terms of modelling is quite high and mainly lies in the different scenarios that may be assumed and the fact that the problem refers to an area (at the street-level). The high diversity of the problem results in a large number of parameters that have to be taken into account. For this reason the modelling process has been split to 5 main stages; these are:

**Stage 1.** Single dwelling thermal and electrical demand. The heating and electrical demand for various single dwellings are predicted. In addition to the 'present day’, future predictions have also been undertaken using climate data for three future time slices; 2020s, 2050s and 2080s. At this stage
no energy efficiency measures or LZC technologies are considered and the operational carbon footprint of each dwelling is calculated.

Stage 2. LZC technologies operating for the single house are considered in this stage and the operational carbon footprint of each dwelling is re-calculated.

Stage 3. Clustering 10 dwellings. Various 10 dwelling domestic clusters, at the street level, are formed initiating from various single dwellings. Essentially, the microgeneration technologies considered in Stage 2 are operating as a common facility for the residential cluster. The energy consumption of each cluster is calculated and compared with the energy consumption from 10 non-linked houses.

Stage 4. Sensitivity analysis. A sensitivity analysis is performed and the robustness of the models developed is investigated.

Stage 5. Economics. An economical analysis is performed in order to estimate the cost of the energy and the carbon saved for each one of the microgeneration technologies considered. The microtechnologies are ranked accordingly.

The first three stages which describe the main approach taken in this research, are presented in Figure 3.3.

For the first three stages various simulation models have been developed. These can be split into 2 categories:

**Building models** that predict the thermal demand of various types of single dwellings or a number of dwellings.

**Microgeneration models** that forecast the energy performance of the technologies considered.

Simulations were undertaken for a number of configurations in order to depict differences related to various energy demand profiles, various building types and different regions. The factors considered for the variations of the models are:
Figure 3.3: Main stages of the modelling approach being taken in this research
CHAPTER 3. Project Methodology

- mix of building types within the examined area,
- building construction quality,
- occupancy profiles,
- heating demand,
- electricity demand and
- climate.

These configurations in conjunction with the renewable technologies considered, are referred as “scenarios” in this research.

Figure 3.4 illustrates a flowchart of the modelling approach followed in this research.

3.4 Weather files - Climate change scenarios

One important aspect of this project is to consider the predicted climate by assessing its impact on the domestic carbon footprint and on the technologies considered. The energy performance of building fabrics, energy efficiency measures and renewables is strongly related to climate data. Therefore climate change has to be taken into account when assessing the future performance of buildings and technologies. The Intergovernmental Panel on Climate Change (IPCC) states that it is ‘very likely’ that cold nights, cold days and frost will become less frequent over most land areas (IPCC, 2007). This will clearly lead to lower heating demands for domestic heating in temperate climates such as the UK.

The performance of a business as usual (BaU) condensing boiler and electricity from the utility grid, versus a set of energy efficient or renewable technologies under predicted future climates was estimated using ‘morphed’ weather files. These weather files are based on the 2002 UK climate impacts programme (UKCIP02) series of monthly estimates of climate change across the UK at a 50 km grid square resolution. The future UK climate is predicted across three decadal timeslices, the 2020s, 2050s and
Figure 3.4: Flowchart of the modelling approach followed in this research
### Table 3.1: CIBSE TRY data set and UKCIP02 projections for Southampton, UK in 2000, 2020s, 2050s and 2080s

<table>
<thead>
<tr>
<th>Parameter</th>
<th>2000s</th>
<th>2020s</th>
<th>2050s</th>
<th>2080s</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average ambient temperature (°C)</td>
<td>11.0</td>
<td>11.8</td>
<td>13.1</td>
<td>14.7</td>
</tr>
<tr>
<td>Minimum ambient temperature (°C)</td>
<td>-5.7</td>
<td>-4.8</td>
<td>-3.7</td>
<td>-2.3</td>
</tr>
<tr>
<td>Maximum ambient temperature (°C)</td>
<td>30.2</td>
<td>31.7</td>
<td>33.4</td>
<td>35.8</td>
</tr>
<tr>
<td>Average relative humidity (%)</td>
<td>78.0</td>
<td>79.0</td>
<td>76.0</td>
<td>73.0</td>
</tr>
<tr>
<td>Average wind velocity (m/s)</td>
<td>2.77</td>
<td>2.78</td>
<td>2.80</td>
<td>2.82</td>
</tr>
<tr>
<td>Total radiation on horizontal (kWh/m²/year)</td>
<td>958</td>
<td>983</td>
<td>1012</td>
<td>1052</td>
</tr>
<tr>
<td>Total beam radiation on horizontal (kWh/m²/year)</td>
<td>373</td>
<td>383</td>
<td>394</td>
<td>409</td>
</tr>
<tr>
<td>Total sky diffuse on horizontal (kWh/m²/year)</td>
<td>586</td>
<td>601</td>
<td>618</td>
<td>643</td>
</tr>
</tbody>
</table>

2080s. This study adopts only one emissions scenario, the medium–high emissions scenario, as this is considered as BaU projection (Jentsch, 2009). The Microsoft Excel conversion tool *CCWeatherGen* developed at Southampton University (CCWeatherGen, 2008), was used to generate climate change adapted weather files. This tool takes the monthly UKCIP02 projections and applies them to hourly weather data by adopting the morphing approach outlined by Belcher et al. (2005).

Unmorphed Chartered Institution of Building Services Engineers (CIBSE) test reference year (TRY) weather files were used as the baseline present-day weather file. TRY weather files represent ‘average years’ and are typically used for the design of heating and mechanical cooling systems in buildings. Since this work addresses winter heating loads, the TRY format is the appropriate type. TRY weather files generated from CIBSE were converted into climate change Typical Meteorological Year (TMY2) format files, which were developed by the U.S. National Renewable Energy Laboratory (NREL) in the beginning of the 1990s (Marion and Urban, 1995) and are compatible with the simulation program TRNSYS used in this work.

For all the models developed, weather data for Southampton, UK was used. Four TMY2 files were generated, for the 2000s (today), 2020s, 2050s and 2080s, at a one hour timestep for an entire year. The main characteristics of the weather files for Southampton, UK are given in Table 3.1.
3.5 Problem complexity

From the modelling approach it becomes apparent that the problem has high complexity. For each scenario there is a large number of the possible configurations that may be examined. In Figure 3.5 the different options that form the possible configurations and scenarios of the problem are illustrated.

The total options of the example problem illustrated in this graph are the number of possible routes on the graph; in this case 7,776 pathways. This means that 7,776 different results may be obtained or in other words 7,776 variations of the problem may be examined. Naturally, some of these options are not expected to give significantly different results, therefore it is very important to map out those parameters that are expected to have a substantial impact on the results and examine them thoroughly. In terms of computational complexity the problem is classified as polynomial and in any case polynomial procedures are considered feasible, however computational time may be high.

The middle part of the schematic Figure 3.5 may be simplified in order to reduce the possible number of routes on the graph. Occupancy is strongly related to the heating and electricity demand. Hence, each heating and electricity demand profile was allocated to an occupancy profile, based on the following criteria:

- The space heating demand profiles were modelled as a function of the time that occupants spend in the house. If the occupants of a dwelling do not spend a long time at home, the heating demand is expected to be lower compared with a similar dwelling where occupants stay at home for the most of the day. For example the low heating demand of the working couple will always be less than that of the 'family' or 'retired' in a low heating mode.

- It was assumed that the “retired” are not constraining usage of heating in terms of duration or temperature set-point for financial reasons.

- The domestic hot water demand profiles were modelled as a function of the total number of occupants. These considerations were taken in to account when
Figure 3.5: Complexity of the problem based on the number of possible options
Figure 3.6: Complexity of the problem based on the number of possible options after allocating heating and electricity demand profiles to an occupancy profile.
developing the models for predicting the heating demand of each dwelling and therefore, heating demand profiles were based on the occupancy profiles.

- Electricity demand profiles were generated by raw data, monitored from an eco-home development, at New Lane, Havant, UK. The datasets chosen to be used were taken from houses with essentially the same occupancy profiles as the ones used in this research.

By allocating each heating and electricity demand profile to an occupancy profile, the schematic illustrated in Figure 3.5 can be simplified to the schematic illustrated in Figure 3.6, with only 864 possible routes.

3.6 Data collection

Data collection can essentially be divided into three categories:

- Data regarding buildings and their energy efficiency.
- Data regarding the characteristics of the region (street) which is modelled.
- Occupancy profiles data.
- Data regarding the proposed technologies to be installed.

The following sections describe the main data collection methods used.

3.6.1 Aerial photos

Aerial photos were used in order to select a case study area and data for that area. Simply by observation aerial photos provided information about the following:

- Type of the area (rural, sub-rural, urban)
- Layout and density of the area
CHAPTER 3. Project Methodology

- Type of buildings
- Special characteristics of buildings (e.g. conservatory)

Aerial photos were the first source of data in order to obtain some general characteristics of the examined area. It proved a fast and efficient approach that helped in selecting an area for a case study. Aerial photos from programs such as “Google Earth” (Google, 2007) and “Windows Local” (Windows Live, 2008) were used. Figure 3.7 illustrates the area that was chosen as the case study for this project. This area is Marchwood, a commuter village 7 miles from the port of Southampton, on the south coast of the UK.

![Aerial photo of Marchwood](image)

Figure 3.7: An aerial photo of Marchwood, near Southampton, the residential area chosen for the case study (Google, 2007)

3.6.2 On-line libraries and surveys

Here more detailed information regarding the characteristics of the buildings and the mix of the building stock were determined. For example, what wall type is typical for a semi-detached house built in the 1970s, what kind of insulation is expected for a detached house built in the 1980s or what percentage of the houses of a specific area have cavity wall and loft insulation, etc. Also demographic and occupancy data for the case-study region was obtained. The main source used was the neighbourhood
statistics available on line from the Office for National Statistics (ONS) which is a UK government department (Neighbourhood Statistics, 2008).

3.6.3 Official government documents

These are official publications from government departments, such as the Department for Business, Enterprise and Regulatory Reform (BERR), current BIS. These publications are Energy White Papers, Energy Reviews or regulations regarding the building construction characteristics. The publications from the Office of the Deputy Prime Minister (ODPM), reclassified to the Department for Communities and Local Government are a key data source. These documents describe the building regulations according to the period that a building was built. They define the design and construction characteristics for new or refurbished dwellings and they give analytical tables with u-values, infiltration rates, etc. In this research these documents are referred to as Part L of the building regulations, related to the conservation of energy and power in new and existing buildings (ODPM, 2002, 2006).

3.6.4 Survey - Questionnaires

After selecting the area for the case study a questionnaire was designed and was sent to all the dwellings of the case study area. The aim of the questionnaires was to collect more detailed data at the household level. Specifically the questionnaires provided information of the following:

- Building extensions
- Fabric improvements
- Dwelling size
- Type of heating system
- Annual energy consumption
- Number of occupants
A successful questionnaire survey is essentially determined by the level of response. For this reason the questionnaire designed here, was kept short and simple. Almost all the questions could be answered just by ticking a box, while no technical terms were used. Its length was limited to a double sided A4 paper. The full questionnaire is given in Appendix A.

The level of response was high at approximately 30%. However, particular questions had lower level of response showing that many of the occupants are not aware of certain characteristics of their dwelling. These questions were the total floor space of the dwelling and questions regarding the building’s type(s) of insulation, with the cavity wall insulation having the lowest level of response, followed by the loft insulation.

### 3.6.5 Infrared thermography

Infrared thermography can be regarded as another form of building survey, which complements the questionnaire survey approach. Questionnaires provided inadequate about the building fabric and therefore an alternative method had to be used. Infrared thermography was used to collect more detailed information on the building fabric of the surveyed dwellings and also as a quality assurance to verify the answers given in the questionnaires.

IR images of all the buildings in the area chosen for the case study were taken with a thermographic camera (InfraTec variocam 1.3MP). The camera has the ability to capture accurate temperature measurements through a fully radiometric image which may be analysed with an appropriate software (thermal resolution 0.05°C). This image can be described as the instantaneous “thermal footprint” of a building and can be used to assess the level of thermal losses from the building.

For optimum results, the infrared thermography survey was performed in a cold winter night, due to the following reasons:
• Allow enough time for solar gain effects to dissipate

• Low ambient temperate

• Low levels of parasitic light

• Occupants are more likely to be at home

• Central heating is more likely to be on.

The program IRBIS Plus (InfraTec, 2007) was used to process the pictures. By setting the appropriate upper and lower limits for the temperature range on the thermographic image and with the use of isotherm curves, it was possible to spot warm and cold areas on the building fabric and determine their temperature difference. Cold areas indicate areas that no significant heat losses occur, while warm areas indicate the opposite. Temperature variations therefore, were used as an indirect method to draw conclusions regarding the building fabric characteristics, such as the existence of loft insulation or cavity wall insulation. Figure 3.8 illustrates an example of a thermal image of a house as it appears in the thermal processing software. From the picture it is easy to identify the areas where significant heat losses occur (colours towards the red range). The red stripe observed on the right wall is the pipework connecting the boiler with the hot water tank. The image indicates that the pipe running through the wall is not properly insulated and therefore, the area around the pipe appears to be warmer than the rest of the wall.

Infrared thermography proved to be a very efficient method for collecting data about the building fabric of the buildings at the case study area. In some cases the answers that the occupants provided with the questionnaires did not agree with the results collected from the infrared thermography. The most typical example was the existence or not of a cavity wall insulation. This confirms the fact, also evident with the questionnaires directly, that in many cases the occupants of a dwelling are not aware of some construction characteristics, such as the existence of insulation. Therefore, in case of building surveys, information provided by the occupants should be treated with caution and a certain level of unreliability should be taken into account.
3.7 Case study

The area of Marchwood was chosen as a case study in order to examine and evaluate the performance of the models developed in this work in real-life context. This area was chosen for the following reasons:

1. Marchwood consists of a series of developments from 1965 to the present day, making the area quite representative for the UK building stock and suitable to apply the models assuming different building stock qualities.

2. Smaller areas with high homogeneity in the quality of the building stock were observed in Marchwood, therefore each domestic cluster would also be homogeneous. At the street level the houses are more likely to have been constructed by the same developer and therefore are expected to have the same age, to be of the same type and to share the same fabric quality. Barratt for example, one of the biggest housing developers in the UK, have delivered developments ranging in size from 33 houses up to several thousand (Barratt, 2010).

3. The house density and the layout are ideal for applying the concept of domestic clusters at a street-level. The area consists of many culs-de-sac (no through routes) with a small number of houses (from 5 to 15).
4. There is available space to consider a range of technologies that require land space (ground source heat pumps) or roof space (photovoltaics), making the assessment appropriate to many UK suburban developments.

Marchwood is a commuter village near the city of Southampton, Hampshire, UK. It is located approximately 7 miles by road south-west of the city center, between Totton and Hythe on the western shore of Southampton water, next to the New Forest (Figure 3.9). The population of the village in the census of 2001 was 5,586. Due to its easy access to New Forest and Southampton it is a developing village and though mainly a domestic area, Marchwood has a large military port and from 2007 a new refuse incinerator power plant has been in operation. A 800 MW CCGT power plant has also been built recently and brought on line in early 2010 (Marchwood Power, 2010). The village has two schools, an infant school and a junior school and there are several shops in the village centre. There are over 80 acres of public open space and plenty of green areas (www.marchwoodparishcouncil.org.uk/, 2008).

The area of Marchwood was chosen after observation from aerial photos. From the aerial photos, the size of the area and the number of houses could easily be estimated. Also, smaller areas with high homogeneity in the quality of the building stock could be identified. Thereafter, a questionnaire was designed and sent to all the houses of the case study area.
Figure 3.10: Map and aerial photo of the area in Marchwood, chosen as the case study (Windows Live, 2008)
A representative cluster of 10 houses was formed based on the questionnaire survey, IR thermography, aerial photos and building fabric datasets. This cluster is used as the case study throughout this work and is referred to as a “Marchwood cluster”. Each cluster consists of 10 houses, a representative number of houses usually found in a cul-de-sac. The main characteristics of the Marchwood cluster are given in Table 3.2.

The residential cluster in Marchwood consists of typical UK households, built after 1965, and is a mix of terraced, semi-detached and detached houses. Table 3.3 shows the percentage per building type of the UK residential stock built in the period 1965-1980 (first column) and the post 1980 period (second column). The last column shows the percentage of the total UK residential stock that corresponds to each building type for the post 1965 period. As such, the cluster in Marchwood represents ~33% of the total UK residential stock, in terms of building characteristics only (type and age).

Table 3.4 summarises some of the characteristics of the residential cluster in Marchwood and its occupants, and how these compare with the UK average. The Marchwood
cluster appears to be similar to the UK average domestic stock built after 1965 in terms of size and occupancy profile. Building fabric characteristics, such as loft and cavity wall insulation and glazing, are improved in Marchwood compared with the post 1965 UK average. This may be attributed to differences in the disposable income of the residents in Marchwood and a UK average resident. It should also be noticed that all houses in Marchwood cluster were found to have a natural gas fired boiler. Naturally, this is not the case for the entire UK, since a number of remote properties may not be connected to the natural gas network. Such remote properties are not included in this research, since they would not be appropriate for a “clustering approach”.
## CHAPTER 3. Project Methodology

### Marchwood cluster UK average (post 1965 only)

<table>
<thead>
<tr>
<th>House area</th>
<th>Marchwood cluster</th>
<th>UK average (post 1965 only)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Detached</td>
<td>140 m²</td>
<td>146 m²</td>
</tr>
<tr>
<td>Semi-detached</td>
<td>101 m²</td>
<td>93 m²</td>
</tr>
<tr>
<td>Terraced</td>
<td>89 m²</td>
<td>82 m²</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Average number of occupants per household</th>
<th>Marchwood cluster</th>
<th>UK average (post 1965 only)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2.5</td>
<td>2.4</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Average hours worked</th>
<th>Marchwood cluster</th>
<th>UK average (post 1965 only)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Men</td>
<td>42.6</td>
<td>42.2</td>
</tr>
<tr>
<td>Women</td>
<td>29.6</td>
<td>31.4</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Central heating</th>
<th>Marchwood cluster</th>
<th>UK average (post 1965 only)</th>
</tr>
</thead>
<tbody>
<tr>
<td>100% NG fired boiler</td>
<td></td>
<td>86% NG fired boiler</td>
</tr>
<tr>
<td>8.5% Electrical</td>
<td></td>
<td>5.5% Others</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Boiler Type</th>
<th>Marchwood cluster</th>
<th>UK average (post 1965 only)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Standard or back boiler</td>
<td>61%</td>
<td>55%</td>
</tr>
<tr>
<td>Combi</td>
<td>29%</td>
<td>32%</td>
</tr>
<tr>
<td>Condensing</td>
<td>10%</td>
<td>13%</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Loft insulation (when loft present)</th>
<th>Marchwood cluster</th>
<th>UK average (post 1965 only)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>100%</td>
<td>92%</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Cavity wall insulation</th>
<th>Marchwood cluster</th>
<th>UK average (post 1965 only)</th>
</tr>
</thead>
<tbody>
<tr>
<td>cavity insulated</td>
<td>60%</td>
<td>47%</td>
</tr>
<tr>
<td>cavity uninsulated</td>
<td>40%</td>
<td>53%</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Double glazing</th>
<th>Marchwood cluster</th>
<th>UK average (post 1965 only)</th>
</tr>
</thead>
<tbody>
<tr>
<td>None</td>
<td>5%</td>
<td>11%</td>
</tr>
<tr>
<td>&lt;50%</td>
<td>3%</td>
<td>7%</td>
</tr>
<tr>
<td>&gt;50%</td>
<td>3%</td>
<td>15%</td>
</tr>
<tr>
<td>all</td>
<td>89%</td>
<td>67%</td>
</tr>
</tbody>
</table>

Table 3.4: Characteristics of the Marchwood building stock (surveyed area) compared with the UK average (Communities and Local Government, 2009)
Chapter 4

Model Development

4.1 Introduction

This chapter deals with the development of the models for the calculation of the carbon footprint of a house or an area. The developed models may be split into three different categories: (1) the building models (Type 56) that simulate the characteristics of one or more buildings, (2) the TRNSYS models that simulate the complete energy network of one house or a cluster of houses, including energy efficiency and renewable energy technologies and (3) the VBA model which is developed for processing the electricity data and for analysing all the results from TRNSYS. The most basic characteristics and definitions are given here for TRNSYS Simulation Studio and TRNBUILD which are the two software packages used for the model development. Modelling starts with the prediction of heating and electrical demand for the single house and the cluster of 10 houses.

Heating demand is predicted with the development of Type 56 models, which are explained in detail. The definition of a thermal zone is clearly stated here and all the formulae for the different thermal flows that occur within a house are given. For the electricity demand, real data is used from a domestic PV field trial in Havant, Hampshire (Bahaj and James, 2007), which has been analysed using a custom Visual Basic for Applications (VBA) routine. The method used for analysing the data is explained and the program development is presented. Then modelling of the various
technologies considered in this project is described. For each technology, a different TRNSYS model was developed for the single house and the residential clusters.

4.2 About TRNSYS

4.2.1 TRNSYS Simulation Studio

TRNSYS is a transient simulation software package which enables the simulation of multizone buildings. It not only models the energy flows within a building but can model various energy concepts, such as simple domestic hot water systems or more complex energy networks, such as renewable energy technologies, including control strategies, climate data, etc. The simulation studio includes a library with a number of components (sub-routines) that were used in this work.

TRNSYS was chosen for the following reasons:

- It is a well documented and validated simulation program (Lomas et al., 1997; Holst, 1993).
- It is an open source program which means that the source code is available and can be changed or expanded. In this work the source code from various TRNSYS components was studied before developing new components.
- Its modular structure allows the development of new components using common programming languages, such as C++, PASCAL, FORTRAN, etc.. For this work, where required, new components were developed and compiled in FORTRAN.
- TRNSYS can be connected to other applications for pre- or post-processing data and results. For the purposes of this project, the outputs of TRNSYS were post-processed in a VBA environment.

TRNSYS essentially uses a steady-state approach based on a heat transfer function. Although dynamic modelling, such as Computational Fluid Dynamics (CFD), can
provide results with higher level of detail, the use of a steady-state simulation was selected due to following reasons:

- This study focuses on the prediction of the annual heating demand of various houses and not on the detailed heat flow at a local position in the building, such as a thermal bridge or the temperature of a wall. For the latter, a dynamic approach such as CFD would be more appropriate.

- The size of the problem is more suitable for a steady-state modelling approach. A dynamic approach would increase dramatically the computational time.

- In this research a set of microgeneration technologies are modelled based on performance data given by manufacturers. This data includes efficiency curves under various conditions and other technical characteristics such as capacity, operating temperatures, consumption, etc. Manufactures do not provide information regarding the precise geometry or materials of the units, which makes a CFD approach inappropriate.

A TRNSYS project consists of a simulation model which is built in the TRNSYS Simulation Studio and a building model which is built in TRNBuild. The building model (Type 56) is the most important component in the simulation studio and is detailed in the next section (TRNSYS, 2005).

### 4.2.2 TRNBUILD

TRNBUILD is an interface program for creating the building description of a multi-zone building (Type 56). This component models the thermal behaviour of a building divided into different thermal zones. Due to its complexity it requires pre-processing with a separate program (TRNBuild) before it is used, hence its parameters are not defined directly in the TRNSYS input file. The TRNBuild program reads in and processes a file containing the building description and generates two files, the building description (*.BLD) and the ASHRAE transfer function for walls (*.TRN) files, that will be used by the Type 56 component during a TRNSYS simulation. The
file containing the building description may be generated with any text editor or with the interactive program TRNBUILD (TRNSYS, 2005).

4.3 Building models in TRNBUILD

4.3.1 Thermal zone and Heat Flows

The first term to be defined for a building file is the thermal zone. The Type 56 building model is a non-geometrical balance model with one air node per zone, representing the thermal capacity of the zone air volume and any other capacities that may be connected to the zone, such as furniture. For this reason, the node capacity and the zone volume are two different inputs. The fact that each zone represents one air node means that each thermal zone may be set with different infiltration, ventilation, heating, cooling, gains, comfort, humidity, etc. regimes. One thermal zone may be thermally independent or linked to another. Based on this feature multiple houses were simulated in the same building file, just by treating them as different independent thermal zones. TRNSYS Simulation Studio does not allow multiple building files in the same simulation, but this approach allowed the simultaneous modelling of more than one building where that was necessary.

If the thermal zone plus the air around the zone are regarded as the control volume of the system then there are three types of heat flows within the system; convection, radiative and conduction heat flows. In the usual case where the zones are linked, there are three options to consider:

1. Heat transfer from zone A to zone B through conduction. In this case it is assumed that the two zones are adjacent and the only heat transfer takes place through walls, doors, windows, etc. There is no mass (air) transfer from one zone to the other. This approach is used for zones that are attached but there are no physical openings to allow natural air circulation. A typical example of this case are the loft and the first floor of a house. These two are always modelled as different zones, as they are always adjacent but there are no physical openings to allow air-exchange between them.
2. Heat and mass transfer from zone A to zone B through convection. Here it is assumed that there is a certain airflow between two zones but the heat transfer due to conduction is zero. This approach represents two adjacent zones with an adjacent surface which is totally insulated but allows air-flow.

3. Radiative transfer. Here energy transfer occurs in the form of electromagnetic radiation due to absorption, emission and scattering processes. Typical examples are the solar gains at the external envelope of a house and the heat that objects in a thermal zone absorb, emit or reflect.

In a real building all three mechanisms of heat transfer take place at the same time. The normal scenario modelled here is a combination of these three mechanisms.

### 4.3.2 Type 56 models

Type 56 is the component in the simulation that represents a building and its characteristics. Different configurations of the Type 56 have been generated in order to model all the different building types. In total 18 different variations of Type 56 have been programmed and these are:

1. Detached house with and without conservatory (1,2)
2. Semi-detached house with and without conservatory (3,4) \( \times 3 \) building fabrics \( \Rightarrow 18 \) building models
3. Row of 5 terraced houses with and without conservatory (5,6)

For any of the six building types above there have been assumed 3 different cases:

- Building with 1980’s quality building fabric,
- Building compliant to part L 2002 regulations and
- Building compliant to part L 2006 regulations.
The 1980’s building fabric represents houses that were built from 1965 to 1980. The houses at the case study area have the same building fabric quality, which overall represents the building fabric quality of \(~33\%\) of the entire housing stock in the UK (Communities and Local Government, 2009). The other two building fabrics were chosen in order to estimate the savings that can be achieved by improving the building fabric according to the 2002 and 2006 regulations.

The first step of modelling was to determine the number of thermal zones for every building. Every room was a potential thermal zone, unless the related parameters such as infiltration, ventilation, heating, cooling, gains, humidity, thermal losses, gains, etc, had common or very similar values to an adjacent room. Under these criteria, the thermal zones that resulted for all the building files are: Kitchen, Living/Dining Room, First Floor, Loft and Conservatory. Figure 4.1 illustrates a schematic example of the ground floor of two semi-detached houses, split into thermal zones and shows how these zones relate to one another.

Figure 4.1: Plan of the first floor of two semi-detached houses with all the thermal zones

The second step was to build the zones and define the parameters and the character-
istics of each zone. The values for parameters defined as constants were given in the TRNBUILD file and parameters defined as inputs were given in TRNSYS Simulation Studio.

**Constants:** zone volume, zone capacitance, initial values: temperature and humidity.

**Inputs:** infiltration, ventilation, zone temperature control, heating power, internal heat gains from appliances, lighting and occupants.

The next step was to define the construction quality of each zone, in other words the walls, insulation levels, windows, doors, etc. The construction quality of each zone may differ, though these characteristics are usually common throughout the whole building, unless extensions or further improvements, such as conservatories, have been undertaken. For the building files developed here it was assumed that the building fabric quality is the same for the entire building, except the conservatory.

Table 4.1 summarises the u-values of the building characteristics used for all three construction quality fabrics: '1980’s fabric', 'compliant to 2002 regulations' and 'compliant to 2006 regulations' and Table 4.2 summarises the u-values (thermal conductivity) and g-values (solar gain coefficient) used for the glazed areas. The walls used were defined to match the regulations as defined in the Part L building regulations. The walls were defined in the TRNBUILD file but the glazing areas were set as inputs for flexibility reasons. This enabled the glazing type to be changed at anytime from the TRNSYS Simulation Studio, without altering the TRNBUILD file. The windows and doors area was set in the building files and it was equal to approximately 25% of the total internal floor area (ODPM, 2002, 2006), except in the case of the conservatory. Typical values observed in Marchwood were within the range 25-30%.

### 4.4 TRNSYS models for heating load prediction in simulation studio

After completion of the building files, the development of the TRNSYS models for predicting the heating demand followed. The heating load was broken down to space
### CHAPTER 4. Model Development

<table>
<thead>
<tr>
<th></th>
<th>External Wall</th>
<th>Internal Wall</th>
<th>Ground Floor</th>
<th>Upper Floor</th>
<th>Roof</th>
<th>Conservatory Frame</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>1980s fabric</strong></td>
<td>1.00</td>
<td>1.20</td>
<td>0.72</td>
<td>0.86</td>
<td>0.36</td>
<td>2.46</td>
</tr>
<tr>
<td><strong>2002 regulations</strong></td>
<td>0.32</td>
<td>0.35</td>
<td>0.30</td>
<td>0.37</td>
<td>0.22</td>
<td>2.46</td>
</tr>
<tr>
<td><strong>2006 regulations</strong></td>
<td>0.30</td>
<td>0.33</td>
<td>0.22</td>
<td>0.24</td>
<td>0.16</td>
<td>2.46</td>
</tr>
</tbody>
</table>

Table 4.1: U-Values (W/m²K) used for buildings with 1980s fabric, 2002 regulations and 2006 regulations (ODPM, 2002, 2006)

<table>
<thead>
<tr>
<th>Glazing</th>
<th>u-value</th>
<th>g-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single</td>
<td>5.68</td>
<td>0.85</td>
</tr>
<tr>
<td>Double insulation glass</td>
<td>2.83</td>
<td>0.75</td>
</tr>
<tr>
<td>(1980s fabric)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Double Argon filled</td>
<td>2.08</td>
<td>0.67</td>
</tr>
<tr>
<td>(2002 Regulations)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Double Argon filled</td>
<td>1.40</td>
<td>0.59</td>
</tr>
<tr>
<td>(2006 Regulations)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 4.2: U-Values (W/m²K) and g-values (%/100) for glazed areas (including frame) (ODPM, 2002, 2006)
heating demand and domestic hot water demand and the two loads were predicted separately. Heating demand prediction is based on the building and its characteristics, activities within the house that require energy, user behaviour and the climate. Specifically, heating demand prediction was based on the following factors:

1. Building type and construction quality (Type 56 files)
2. Weather data
3. Domestic hot water
4. Occupancy profile
5. Heating profile
6. Ventilation - Infiltration
7. Internal gains

Building (Type 56) files and weather data were external files called by TRNSYS each time a simulation was run. The remaining factors were defined in TRNSYS Simulation Studio and are described in the following sections.

4.4.1 Domestic hot water data

Realistic domestic hot water profiles based on the work of the University of Marburg for the Solar Heating and Cooling Program of the International Energy Agency (IEA) (Ulrike and Klaus, 2001) were used. The profiles are for a period of one year at time scales of 1min, 6min and 1 hour. Each profile consists of a value for the Domestic Hot Water (DHW) flowrate for every time step of the year. The basic load in each set of DHW profiles is 100 litres per person per day, but profiles were also generated for higher demands (100, 200, 400, 800 liters, etc.). In this way, it is possible to obtain a load profile for a multi-family house just by superposing the relevant profiles. The Marburg group developed the profiles based on the following assumptions:

- Four categories to describe the different type of loads are defined:
- cat A: short load (washing hands, etc.)
- cat B: medium load (dish-washer, etc.)
- cat C: bath
- cat D: shower

- A probability function was defined in order to describe the variations of the load profile during the year, the weekday and the day:

\[
prob = prob(year) \cdot prob(weekday) \cdot prob(day) \cdot prob(holiday)
\]

- A daily distribution of the DHW demand was used which is the day probability:

\[
prob_{day} = 0.14 \cdot prob_{day}(small) + 0.36 \cdot prob_{day}(medium) + 0.4 \cdot prob_{day}(shower) + 0.1 \cdot prob_{day}(bath tub)
\]

The basic assumption for the domestic hot water is that of the total demand per person per day. The basic load in each set of DHW profiles is 100 l/day per person. The approach developed by Ulrike and Klaus (2001) assumes that the domestic hot water consumption increases proportionally to the number of occupants. In reality though, the hot water demand does not depend linearly to the number of occupants. Energy Saving Trust (EST, 2009b), after surveying 120 dwellings, concluded that hot water demand reduces for larger households. They estimated a reduction of 30% for 2 occupants, 40% for 3 occupants and 45% for 4 occupants, compared with the consumption the same number of people would have if were living in single occupancy dwellings. In another report, BRE Housing Centre (BRE, 2005) suggests that there is a marginal difference to the the average consumption per person, for households of two, three or four persons.

In this research a coefficient factor in the DHW routine was added, which determines the total load of hot water according to the number of the occupants in a dwelling. Table 4.3 gives the coefficients used, which are the average of the EST and BRE findings.
CHAPTER 4. Model Development

<table>
<thead>
<tr>
<th>Number of occupants</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coefficient</td>
<td>1</td>
<td>0.85</td>
<td>0.80</td>
<td>0.75</td>
</tr>
</tbody>
</table>

Table 4.3: Coefficient of hot water total load according to the number of occupants

When using a predefined hot water consumption profile the problem of synchronising the hot water demand profiles with the occupancy profiles becomes readily apparent. The time of the day when demand occurs, has a marginal impact on the total energy consumption for conventional systems (e.g. gas fired boiler), but it is a very important parameter for microgeneration systems, such as solar thermal or combined heat and power. Therefore, the hot water demand datasets were first synchronised with the occupancy profiles.

To achieve this synchronisation a new component was programmed in TRNSYS, written in Fortran. The new component, named “DHW Synchronisation” (Type 159), essentially shifts the load to those intervals that occupants are in the house. Type 159 has two inputs: the number of occupants in the house at every time step (Occupants_In) and the demand for domestic hot water before synchronisation (DHW_In), one output: the demand for domestic hot water after synchronisation (DHW_Out) and one dummy parameter, the buffer (B). Analytically the steps of Type 159 are:

1. Start with the TRNSYS Simulation Studio
2. Read the values for occupancy (Occupants_In) and buffer level (B) before synchronisation
3. If occupancy < 1 then add the demand for DHW before synchronisation to the buffer. Set DHW demand after synchronisation equal to zero.
4. If occupancy ≥ 1 then set DHW demand after synchronisation equal to DHW demand before synchronisation plus half of the buffer’s level. Reduce buffer’s level in half.

Figure 4.2 illustrates the flowchart for Type 159.
Figure 4.2: Flowchart of the Type 159 component for synchronising the domestic hot water dataset with the occupancy profiles
Figure 4.3: An example of the synchronisation routine over a 24 hours period for a working couple profile: (Up) Before synchronisation, (Down) After synchronisation.
The buffer’s load is equally distributed over the next two hours of the day. Therefore, the component simply shifts the load and does not change the total volume of hot water that is drawn off in a day. This type is based on the assumption that when occupants return home, an immediate demand for hot water is more likely to occur, than demand later in the day. Source code for Type 159 is given in Appendix B.

Figure 4.3 illustrates an example of the synchronisation routine, over a 24 hours period for a “working couple” profile. The first graph shows the domestic hot water demand profile before synchronisation and the second graph shows how the profile is changed after the synchronisation routine has been applied. A demand of \(~ 60\) litres appears in the first graph which does not match the occupancy profile. This demand is split into 2 equal amounts which are allocated to the first 2 timesteps where occupants are in the house (second graph).

### 4.4.2 Occupancy profile

The occupancy profile is the most significant profile for the carbon footprint of a building. Other profiles, such as the demand for domestic hot water, the electricity consumption and the heating profile are directly linked to and dependent on the occupancy profile. Three occupancy profiles were modelled:

**Retired:** This occupancy profile assumes that at least one of the occupants is at home throughout the day. It represents occupants that may be retired or occupants that work from home.

**Working:** This profile assumes that the occupants are away during the day. It represents full-time working occupants and therefore, the dwelling is empty during the day (for 9h).

**Family:** It assumes a dwelling that consists of a family with working parents and children that go to school, or part-time working occupants. The dwelling is not occupied 6h per day.

Different profiles were assumed for the weekends with longer hours spent in the house. During the weekends the occupancy of a dwelling is assumed to be zero only 3h per
day on average. A separate time profile for each zone in the house was created, in order to distribute the gains from the occupants and control the artificial lighting. Therefore, during the night all the occupants are assumed to be in the bedrooms of the house, the morning hours are assumed to be in the kitchen and the living/dining room and during the day they are assumed to be out of the house if they are working. A holiday function was also included and two weeks of holiday were assumed for each household.

Table 4.4 summarises the main variables used for the occupancy profiles as these are found in the simulation studio and Table 4.5 give the actual occupancy profiles used.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Function</th>
<th>Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>In_the_house/Out_of_the_house</td>
<td>-</td>
<td>Binary</td>
</tr>
<tr>
<td>Occupants_weekdays</td>
<td>HolidayFlag, In the house, occupants, workdays</td>
<td>Integer</td>
</tr>
<tr>
<td>Occupants_weekends</td>
<td>HolidayFlag, In the house, occupants, weekends</td>
<td>Integer</td>
</tr>
<tr>
<td>Zone_occupancy</td>
<td>Hour of the day, Occupants</td>
<td>Real</td>
</tr>
<tr>
<td>Occupants</td>
<td>Input</td>
<td>Integer</td>
</tr>
</tbody>
</table>

Table 4.4: Description of parameters for defining occupancy profile as used in TRNSYS models

<table>
<thead>
<tr>
<th>Type</th>
<th>Number of occupants</th>
<th>Hours that occupancy is zero (weekdays)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Family</td>
<td>4</td>
<td>9</td>
</tr>
<tr>
<td>Working couple</td>
<td>2</td>
<td>6</td>
</tr>
<tr>
<td>Retired couple</td>
<td>2</td>
<td>0</td>
</tr>
</tbody>
</table>

Table 4.5: Occupancy profiles considered in TRNSYS models

For modelling the residential cluster, a mix of occupancy profiles was considered, since it would be unrealistic to assume that a 10 house cluster consists of dwellings with the same occupancy. The survey undertaken in Marchwood showed that the dwellings in the surveyed area can be split based on the occupancy type, as follows: 31% working, 42% retired or stay at home and 27% family. For the 10 house cluster, it was assumed
that this consists of 3 houses with working occupants, 4 houses with retired occupants and 3 houses with families.

After completion of the models for predicting the heating demand for the single dwelling, the heating demand for the residential clusters was formed by adding the single house heating demand profiles. The heating demand profiles for the Marchwood cluster were ranked, for all the possible occupancy configurations, and it was investigated where the occupancy mix considered lies within this data set. Figure 4.4 shows the results for two clusters in Marchwood, one cluster assuming that none of the houses has a conservatory and one assuming that all houses have a conservatory.

As seen on Figure 4.4 the occupancy mix chosen is very close to the mean value of the heating demand of all the possible configurations, representing an average case scenario sitting within the 95% confidence line of the average.

### 4.4.3 Heating profile

As with the occupancy profiles, heating profiles were time dependent. The control strategy chosen for the central heating was a hybrid of a pre-set timetable and a set of conditions based on indoor temperatures. A thermostat was assumed in every thermal zone and the temperature was recorded at each timestep. The heating profiles were based on the following two assumptions:

1. Heating profiles followed the occupancy profiles. During the occupancy period the air temperature set-point was set 21°C. Outside of the occupancy period the air temperature set-point was reduced to 16°C.

2. Central heating was off during the night, and an implemented set back allowed the temperature to drop down to 16°C.

Table 4.6 lists the parameters used in the simulation studio for the heating profiles and Table 4.7 summarises the actual heating profiles used for each of the three occupancies.
Figure 4.4: Heating demand for a residential cluster in Marchwood for all possible occupancy configurations
### Variable Function Type

<table>
<thead>
<tr>
<th>Variable</th>
<th>Function</th>
<th>Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heat_pwr_zone</td>
<td>Input Integer</td>
<td></td>
</tr>
<tr>
<td>HeatSetPoint</td>
<td>Input Integer</td>
<td></td>
</tr>
<tr>
<td>MinimumHeatingThreshold</td>
<td>Input Integer</td>
<td></td>
</tr>
<tr>
<td>MaximumHeatingThreshold</td>
<td>Input Integer</td>
<td></td>
</tr>
<tr>
<td>BoilerEfficiency</td>
<td>Input Integer</td>
<td></td>
</tr>
<tr>
<td>Heat_season</td>
<td>month_year, HeatSetPoint</td>
<td>String</td>
</tr>
<tr>
<td>HeatingTime</td>
<td>hour_day</td>
<td>String</td>
</tr>
<tr>
<td>Heating</td>
<td>Ambient_Temperature, Minimum HeatingThreshold, Maximum HeatingThreshold, HeatingTime, HeatingSeason</td>
<td>String</td>
</tr>
</tbody>
</table>

Table 4.6: Description of parameters for defining heating profile as used in TRNSYS models

#### 4.4.4 Ventilation - Infiltration

Ventilation and infiltration are two parameters with strong correlation. Almost all UK dwellings rely on natural air infiltration to provide ventilation, with the possible exception of some multi storey flats. In this research only natural air ventilation is considered, caused by air leakage and by opening windows and doors. According to EST (2006) an average ventilation rate for a domestic building should be between 0.5 and 1.5 air changes per hour (ach), whilst an energy efficient ventilation rate should be lower, ranging from 0.5 to 1.0 ach.

Infiltration, as a building fabric characteristic, was set in the building file. The values used were: 1.2 ach for the 1980s fabric, 0.4 ach for the fabric compliant to 2002 regulations and 0.2 ach for the fabric compliant to 2006 regulations. In England and Wales, Approved Document L1A (ODPM, 2006) specifies a maximum air permeability limit of 10 m³/(h·m³), which corresponds to approximately 0.3 to 0.4 ach for the dwellings considered here.

For controlled natural ventilation (opening windows and doors) the same profile was used for all the simulations, assuming effectively the same user behaviour. Ventilation
CHAPTER 4. Model Development

Heating profiles for weekdays (Heating is on)

<table>
<thead>
<tr>
<th>Heating mode 1</th>
<th>Heating mode 2</th>
<th>Heating mode 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>(Family)</td>
<td>(Working)</td>
<td>(Retired)</td>
</tr>
<tr>
<td>06:00 - 09:00</td>
<td>06:00 - 08:00</td>
<td>06:00 - 10:00</td>
</tr>
<tr>
<td>15:00 - 24:00</td>
<td>18:00 - 24:00</td>
<td>13:00 - 24:00</td>
</tr>
</tbody>
</table>

Heating profiles for weekends (Heating is on)

<table>
<thead>
<tr>
<th>Heating mode 1</th>
<th>Heating mode 2</th>
<th>Heating mode 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>(Family)</td>
<td>(Working)</td>
<td>(Retired)</td>
</tr>
<tr>
<td>08:00 - 15:00</td>
<td>09:00 - 12:00</td>
<td>06:00 - 10:00</td>
</tr>
<tr>
<td>18:00 - 24:00</td>
<td>15:00 - 19:00</td>
<td>13:00 - 24:00</td>
</tr>
<tr>
<td>-</td>
<td>21:00 - 24:00</td>
<td>-</td>
</tr>
</tbody>
</table>

Table 4.7: Heating profiles considered in TRNSYS models

was based on outdoor temperatures for achieving better thermal comfort. Therefore, during summer with ambient temperatures more than 18°C, the ventilation rate was increased to 10 ach and during cold days (less than 8°C), ventilation was reduced to 0.4 ach. Ventilation, unlike infiltration, was related to the occupancy profile. In periods when occupancy was zero, ventilation was reduced by 50%, assuming that occupants are more likely to close any opened windows before they leave home. During holiday periods (household away from property) ventilation was reduced to zero.

4.4.5 Internal gains

Internal gains from lighting, electrical appliances, cooking and the occupant’s presence (metabolic gains) were addressed in the building files calculated for each thermal zone separately and not for the entire dwelling. A gains profile was created which was dependent on the dwelling occupancy. Gains from lighting and metabolic gains were linked to the occupancy profile of each zone, assuming effectively that if the occupancy of a zone is 0, then gains due to lighting and metabolic gains are also 0. For all the dwellings the same level of internal gains due to lighting, cooking and use of electrical
appliances was applied in terms of W/m\(^2\). The total values for each house type are summarised and compared with the values suggested in SAP procedure (DEFRA, 2008), in Table 4.8.

<table>
<thead>
<tr>
<th></th>
<th>Input of Gains (W)</th>
<th>Values suggested in SAP (W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Terraced</td>
<td>461</td>
<td>523</td>
</tr>
<tr>
<td>Semidetached</td>
<td>521</td>
<td>580</td>
</tr>
<tr>
<td>Detached</td>
<td>716</td>
<td>760</td>
</tr>
</tbody>
</table>

Table 4.8: Values used for internal gains due to lighting, cooking and use of other electrical appliances.

SAP figures are higher because metabolic gains due to occupants presence have been included. Here, metabolic gains have been addressed separately, assuming that occupants are seated or do light work, which corresponds to 120 W of gains per occupant, during occupancy periods.

4.4.6 TRNSYS basic components used for the heating load prediction models

A TRNSYS simulation model consists of components and equations which are linked together. Some of the components used were the following:

**Weather Data:** This component (Type 109) is the input for the weather data file. It reads from external files data such as ambient temperature, relative humidity, total radiation, beam radiation, sky diffuse radiation, etc. and performs calculations such as angles of solar incidence. Weather files provide the radiation on the horizontal only. However, when radiation is required as an input for a simulation, rarely refers to the horizontal but to other surfaces, either vertical (e.g. wall, window) or sloped (e.g. roof, PV, solar thermal). For this reason new surfaces were defined within this component, in terms of orientation and slope, and the radiation was re-calculated. The use of morphed weather data for the same location enabled the projection of future system behaviour based on predicted changes in climate.
DHW Synchronisation: This was a new component created to synchronise the domestic hot water data with the occupancy profiles by shifting the demand. It is described in detail in Section 4.4.1.

Occupancy: Here a set of equations were used to input the occupancy profile of the house. A binary (In_the_House/Out_of_the_House) declared if there are any occupants in the building, two other variables were used to distinguish between work days and weekends, whilst a different occupancy was assumed for every zone according to the time of the day.

Soil Temperature (Type 501): This is a TRNSYS subroutine for modelling the ground’s vertical temperature distribution. The subroutine requires as inputs the mean ground surface temperature for the year, the amplitude of the ground surface temperature for the year, the time difference between the beginning of the calendar year and the occurrence of the minimum surface temperature, and the soil thermal diffusivity. These parameters were calculated for all the weather files used and they were provided manually as inputs to the subroutine. Ground temperature distribution was used to predict the cold water temperature from the mains. The pipes supplying with cold water were assumed to be buried at a depth of 1.5 m. The cold water temperature profile for the Southampton 2000 weather file is illustrated in Figure 4.5.

![Figure 4.5: Cold water temperature profile for Southampton 2000 weather file and 1.5m pipes depth](image-url)
All the components are given in more detail in Appendix C.

Figure 4.6 shows a schematic of how the components used are related and gives the main inputs and outputs of the model, whilst Figure 4.7 is a print-screen of a TRNSYS simulation as it looks in the simulation studio.

Figure 4.6: Schematic of how the various components in a simulation are related

Figure 4.7: TRNSYS Simulation Studio Screen for the prediction of the heat demand of a dwelling

In total 6 models have been developed in the TRNSYS Simulation Studio. The models are very similar; the only difference is that they handle different building files which have different number of thermal zones. The models are:
4.5 Electricity data and development of VBA program

The study has focused on the heating demand of a building so far and not on the electrical load. For this research project electricity consumption data was not predicted through simulations but real data was used. The data was taken from an eco-home development, at New Lane, Havant, UK. Electricity data from 9 houses with PV modules installed and connected to the grid, has been recorded at 5 min intervals since 2004 by the Sustainable Energy Research Group at the University of Southampton.

The use of primary consumption data was chosen for the following reasons:

- Primary data has greater degree of variability. It includes peaks that do not necessarily follow a pattern. Such irregularities can only be found in primary datasets, whilst output from simulations is usually inherently smoother.

- The datasets used in this research were recorded from an eco-home development, which consists of dwellings with installed photovoltaic modules. Therefore, occupants are familiar with microgeneration technologies and any change in their behaviour in terms of electricity consumption, such as reducing their demand or shifting demand to the PV generation periods, would be reflected in the datasets.

The recorded datasets include: (1) the generated electricity from the photovoltaic module, (2) the electricity exported to the grid and (3) the electricity imported from the grid, for every 5 min step. The actual electricity consumption is calculated indirectly from the formula:

\[ El.\ Consumption = El.\ Generated + El.\ Imported - El.\ Exported \] (4.1)
Over a 12 month period, the raw data consists of 108 series, 12 months for 9 houses in total, at 5 min intervals. Data was used from August 2005 until July 2006.

The data analysis followed, in order to calculate the annual consumption for each house and investigate how the demand varies according to the occupancy profile of each house. Due to the large volume of data, the analysis was not performed manually but a program with a user form interface was designed in Visual Basic for Applications (VBA). Time plots and seasonal plots were plotted for different intervals and it was examined if the data appeared any patterns. The program performed the following calculations, at the single house scale:

- **Consumption for monthly data:**
  - 5 min consumption: The consumption for every 5 min over a month.
  - Hourly consumption: The consumption for every hour over a month.
  - Daily consumption: The consumption for every calendar day over a month.
  - Monthly consumption: Total monthly consumption.

- **Averages for monthly data**
  - 5 min averages of a day over a month: The number of averages is 288, 24 hours x 12 intervals per hour.
  - Hourly averages of a day over a month: The number of averages is 24.
  - Daily averages over a month: Average consumption according to the day of the week, throughout the current month (e.g., all Mondays, all Tuesdays, etc.), hence 7 averages in total.

- **Averages for annual data**
  - Hourly average over a year: Average consumption according to the hour of the day, over a year (24 averages).
  - Daily average over a year: Average consumption according to day of the week, over a year (7 averages).
  - Total annual consumption: Total annual consumption of the house.
The same calculations were performed for the electricity generated, for the amount of electricity imported from the grid and the amount of electricity exported to the grid and the relevant graphs were generated. These calculations, though not directly required, helped in identifying anomalies within the datasets.

The electricity data was available in 5 min intervals, therefore for each day there were 288 data points. Figure 4.8 shows a time plot of the hourly averages per month for the first house of the development. For the rest of the houses the general profile of the timeplots was similar. From the plot it is clear that for the most of the months there are two peaks in the electrical consumption, one during the morning and one during the evening. These peaks reflect the overlap in the occupancy profiles of the houses, hence in mornings one peak is expected when the occupants wake up, whilst in evenings the second peak appears when occupants return back home.

Figure 4.8: Plot of hourly average consumption per month for house 1

Figure 4.9 shows the hourly and daily average consumption over a year for three seasons (summer, autumn/spring and winter) for the first house of the development. The hourly consumption profile exhibits two peaks, one around 8am and a second one around 7pm, indicating that the occupants are away during the day. The plot on the left shows the average consumption for every day of the week for the three seasons. No patterns are observed for the days of the week, however, consumption appears to be higher for the winter months and lower for the summer months. For illustration purposes only, Figure 4.10 presents the hourly consumption profile for 3
days of September monthly dataset; the day with the minimum demand, the day with the maximum demand and a day with an average demand and the hourly average for the entire month. The profiles from all three days are similar, presenting peaks of high demand around the same time of the day, indicating a consistent occupancy profile for the occupants of that house.

After calculating the electricity consumption of each one of the nine houses and generating the time plots for each month it was observed that some data points were missing or were negative. Missing consumption data can be explained due to a possible malfunction of the data logger in a house, where no data was recorded for electricity generation, import and export. Negative values for consumption were the result of
CHAPTER 4. Model Development

the formula 4.1 for those intervals that exported electricity was recorded but not the amount of electricity generated from the PV modules.

Pre-filtering of the Havant dataset is therefore required to handle such data issues. A forecasting method was developed to address missing or negative data points, based on a moving average method. After plotting the timeplots for the electricity consumption of each house, it was noticed that the datasets exhibit regular fluctuations (cyclical components) within a month, a week and a year. This would be expected, since the electricity consumption during a specific time of the day is anticipated to be similar to the consumption of any other day at that specific time. The forecasting method designed was based on the presence of the cyclical components within the datasets.

For the 5 min datasets the cyclical component was 288, corresponding to the number of intervals within a day. The forecasting method was based on the formula:

$$F_i = \frac{1}{k} \sum_{j=1}^{j=k} Y_{i-j \cdot s}$$  (4.2)

where,

- $F_i$: The forecasted value in time step i.
- $k$: The number of values used to calculate the forecasted one, which is the integer $k = \frac{i-s}{s}$.
- $s$: The cyclical component.
- $Y_{i-j \cdot s}$: The values used for the forecast.

When a negative or missing data point is identified by the algorithm then that data point is replaced by the average value of all the previous non-negative data points with the same timestamp (same time of the day). Figure 4.11 is a flowchart that describes how the formula was applied to the datasets to forecast any missing/negative data.

The forecast method designed, was very fast and efficient. It worked very well in cases where missing data were scattered within the dataset. In cases where a large part of the dataset was missing, the method had a smothering effect. Figure 4.12 shows
Figure 4.11: Flowchart of the algorithm used to forecast values for missing or negative data points from the electricity consumption datasets
such an example before and after applying the forecasting method. Generally the datasets used were not incomplete, and datasets with large missing parts, such as the one presented in Figure 4.12 were not used.

Figure 4.12: An example of a dataset with continuous missing data, before and after applying the forecasting technique

From the 10 houses that were monitored, data from 3 houses was chosen to be used for this work. The main criteria for choosing the houses to be used were:

- The occupancy profiles (number of occupants, timetable) matched the occupancies considered in this work.
- The datasets were complete or they had less missing data compared with other houses.
- When forming a cluster of 10 houses the calculated average consumption was close to the average consumption of a cluster located in Marchwood (case study area). According to Neighbourhood Statistics for 2007, the average electricity consumption per dwelling was 4,280 kWh for the area of New Forest where Marchwood is located (Neighbourhood Statistics, 2008).

For all the simulations, the hourly electrical demand for each day of the year was used for three houses; a house with high demand (family), a house with medium demand (retired couple) and a house with low demand (working couple). The hourly averages
Figure 4.13: Hourly averages over a year of the three electrical load profiles

over a year of the three electrical load profiles are presented in Figure 4.13, whilst in Table 4.9 monthly demand for the three occupancy profiles are given.

The VBA program developed is given in Appendix D.

4.6 TRNSYS models for solar thermal domestic hot water

The first renewable technology considered in this study is the active solar thermal system for domestic hot water. Solar thermal water heating is modelled in TRNSYS as a separate routine to enhance the model’s flexibility for use in future work. Two technologies were modelled, flat plate collectors and evacuated tube collectors, for the single house and a cluster of 10 houses. For both technologies the model assumes that the efficiency versus the ambient temperature to radiation curve can be modelled as the following quadratic equation (TRNSYS, 2005):

\[ n = a_0 - a_1 \frac{\Delta T}{I_T} - a_2 \frac{(\Delta T)^2}{I_T} \]  

\[ (4.3) \]

\( a_0 \): Intercept (maximum) of the collector efficiency
Table 4.9: Monthly electricity demand for each occupancy profile as used in this work

<table>
<thead>
<tr>
<th>Month</th>
<th>Family kWh/year</th>
<th>Retired couple kWh/year</th>
<th>Working couple kWh/year</th>
</tr>
</thead>
<tbody>
<tr>
<td>January</td>
<td>336</td>
<td>307</td>
<td>296</td>
</tr>
<tr>
<td>February</td>
<td>332</td>
<td>320</td>
<td>258</td>
</tr>
<tr>
<td>March</td>
<td>458</td>
<td>366</td>
<td>264</td>
</tr>
<tr>
<td>April</td>
<td>382</td>
<td>290</td>
<td>216</td>
</tr>
<tr>
<td>May</td>
<td>303</td>
<td>204</td>
<td>144</td>
</tr>
<tr>
<td>June</td>
<td>237</td>
<td>266</td>
<td>178</td>
</tr>
<tr>
<td>July</td>
<td>229</td>
<td>272</td>
<td>202</td>
</tr>
<tr>
<td>August</td>
<td>345</td>
<td>283</td>
<td>200</td>
</tr>
<tr>
<td>September</td>
<td>331</td>
<td>285</td>
<td>202</td>
</tr>
<tr>
<td>October</td>
<td>351</td>
<td>292</td>
<td>201</td>
</tr>
<tr>
<td>November</td>
<td>371</td>
<td>317</td>
<td>270</td>
</tr>
<tr>
<td>December</td>
<td>365</td>
<td>330</td>
<td>306</td>
</tr>
<tr>
<td>Total</td>
<td>4,041</td>
<td>3,532</td>
<td>2,736</td>
</tr>
</tbody>
</table>

Cluster of 10 houses (3, 3, 4) 33,659

$a_1$: Negative of the first-order coefficient in collector efficiency equation (kJ/h·m²·K)

$a_2$: Negative of the second-order coefficient in collector efficiency equation (kJ/h·m²·K)

$I_T$: Global radiation incident on the solar collector (kJ/h·m²)

$\Delta T$: Average collector fluid temperature - Ambient (air) temperature (°C)

Coefficients $a_0$, $a_1$ and $a_2$ were determined from efficiency curves given from manufacturers (Solartechnik Prufung Forschung, 2005). The global radiation and ambient temperature were provided from the weather file of each simulation.

The solar collectors, flat plate (Type 73) or evacuated tube (Type 71), are the main component of the models developed in this section.

**Flat plate collectors (Type 73).** This component models the thermal performance of a theoretical flat plate collector. Performance data for the solar collector Winkler VarioSol A (Solartechnik Prufung Forschung, 2005) was used. This collector is suitable for mounting on a sloping roof, for integration into a sloping
CHAPTER 4. Model Development

Table 4.10: Technical characteristics of Winkler VariSol A flat plate collector

Evacuated tube collectors (Type 71). This component models the thermal performance of an evacuated tube collector. From a modelling point of view the main difference between this component and the flat plate collectors lies in the treatment of incidence angle modifiers (IAMs). This component reads from an external file a list of of transverse and longitudinal IAMs for various angles that have to be provided as inputs in the model. Performance data for a typical medium range solar collector (Sieger Sola Sunstar HP65-30 (Solartechnik Prufung Forschung, 2005)) was used and the technical characteristics are given in the Table 4.11.

Table 4.11: Technical characteristics of Sieger Solar Sunstar HP65-30 evacuated tube collector

Stagnation temperature is the temperature of the fluid over which the speed of the
fluid is zero and it occurs when the solar collectors are exposed to an excess of solar heat. After the storage tank has reached the maximum temperature the collector-loop pump is switched off by the controller, whilst the temperature of the absorber rises rapidly up to a critical point for some of the system’s components.

4.6.1 Active solar thermal domestic hot water for the single house

The modelling approach followed for the single house can be considered as the business as usual scenario for this technology, where solar pre-heat storage is combined with an auxiliary heat source into a single store. A pre-heat store may be considered as the lower part of the tank, where the energy from the solar collectors is delivered through a heat exchanger. An electric immersion heater is located in the top half of the cylinder and is used as a back up to the gas boiler. The secondary water rises upwards from the lower solar input when the DHW is drawn off due to natural circulation. A thermostat controls the temperature of the secondary water and if it is below the set point then the auxiliary heating is set on. The two indirect coils in the tank are separated to ensure a sufficient dedicated pre-heat volume and maximise the thermal performance of the solar collectors (Figure 4.14).

The system modelled here was an active indirect system, that involved an electric pump to circulate the fluid between the heat exchanger and the solar panels, a thermal storage tank, the flat plate or evacuated tube collectors and a controller. The thermal
store was a 300 litre stratified liquid storage tank (Type 60d) with uniform losses (1.67 W/m²K). The set point of the thermostat was set to 60°C with a deadband of 5°C. A subroutine for the calculation of cold water’s temperature, as described in previous sections, was also included. The hot water load profiles used are those described previously, based on the profiles developed by Ulrike and Klaus (2001). The electrical consumption from the pump (10 W) and the related emissions were not taken into account since a solar assisted circulation pump was assumed. A print screen of the model as designed in TRNSYS is given in Figure 4.15.

The flow diagram of the model is quite straightforward and is illustrated in Figure 4.16. Hourly profiles in litres per hour and weather data, are inputs to the model. Based on the load profile and the number of occupants the total demand of hot water is calculated. The temperature of the cold water is also calculated at this step. Then a diverter, splits the water and diverts a volume to the tank to be heated and a volume to a tee piece that mixes the cold with the hot water. The water in the tank is heated from a heat exchanger and an electric heating element. The fluid that runs in the heat exchanger and the solar collectors is solution of water-glycol 33%. The operation
of the solar panel is controlled by a differential controller with hysteresis (Type 2b). At every timestep, the controller checks the temperature of the water at the outlet of the tank, the temperature of the fluid exiting the solar panel and the temperature of the fluid exiting the heat exchanger of the tank and sends a signal (on/off) to the pump. The solar circuit is operated when the outlet temperature of the tank is 5°C lower than the set point. The controller stops the operation of the circuit before the stagnation point (when that occurs) of the solar collectors or before the boiling point of the water in the tank is reached.

### 4.6.2 Active solar thermal domestic hot water for the cluster

A different energy network and control strategy was adopted for the cluster case. The main difference with the single house model is the deployment of a second storage tank that allows separate pre-heat and storage. This approach was chosen in order to ensure a pre-heat volume of low temperature that allows high thermal performance of the solar collectors. The pre-heat tank has two heat exchangers connected to the solar collectors and no auxiliary heaters. When DHW is drawn-off, pre-heated water moves from the top of the pre-heat tank to the base of the storage tank. There is no set point temperature for the pre-heat store, but there is one for storage tank since it must remain hot to prevent bacteria (legionella) and to ensure comfort. A thermostat is set to 60°C with a deadband of 5°C and two auxiliary heaters are assumed (Figure 4.17).

The model for the cluster incorporates a number of solar collectors that are assumed to operate simultaneously. These collectors are connected either in series or parallel,
CHAPTER 4. Model Development

Figure 4.17: Separate pre-heat and storage

according to the technology used and the cluster’s level of demand. For comparison purposes, the same installed capacity was assumed for the 10 individual houses and the cluster.

The problem that becomes readily apparent in this case is which mode the collectors should be operated, in parallel or in series. The flat plate collectors scheme is expected to perform better with more collectors connected in series in order to achieve the set point required. Evacuated tube systems can reach higher temperatures than flat plate collectors and therefore the evacuated tube scheme is expected to perform better with more collectors in parallel, in order to maximise the volume of the hot water provided by the solar system. The optimum configuration for both schemes was determined by performing a number of simulations, for all the possible configurations. The optimum configuration for the flat plate collectors model was found to be 2 parallel sets of 5 collectors in series; with one set of collectors per heat exchanger in the pre-heat tank. For the evacuated tube model, the optimum configuration was found to be 10 collectors in parallel mode; with a set of 5 collectors in parallel per heat exchanger in the pre-heat tank.

The thermal storage tank was initially assumed to be 10 times larger than the tank considered for the single house case (3,000 litres). The hot water demand from the cluster is of course smoother than the single house profile with proportionally smaller peaks. The optimum size of the thermal store for the 10 house cluster was found to be 2,500 litres. Figure 4.18 illustrates a print screen of the flat plate collectors model.
4.7 TRNSYS model for photovoltaics

The second technology considered is a photovoltaic module for electricity generation. Figure 4.19 shows a print screen of the model in TRNSYS, illustrating the flow diagram and the components used.

Type 94a models the electrical performance of a photovoltaic array. It can model mono or polycrystalline silicon photovoltaic panel simply by changing the temperature coefficients of current and voltage at the short circuit current point Isc (positive) and open circuit voltage point Voc (negative) respectively.

For the purposes of this project two technologies were modelled, for the single house and for the cluster of 10 houses forming a local microgrid; monocrystalline and polycrystalline cells. One simulation project was developed for all four options. All the simulations performed were based on the typical medium range monocrystalline STP 175S and the polycrystalline STP 200 modules manufactured by Suntech Power (2009). The inputs used for both modules are given in Table 4.12.

The inputs used for the PV models mainly depend on the technical characteristics of the PV modules considered and the weather files, apart the total installed capacity.
For determining the system’s size two criteria were used:

1. the rule of thumb, according to which typical domestic applications vary from 1.5\(kW_p\) to 2\(kW_p\) (EST, 2005a; STA, 2008a) and

2. the available roof space with the right orientation and the minimum shading.

The available roof space can vary significantly according to the roof type. The three building types considered in this research can be found with various types of roofs, including:

- Gabled. The side wall continues up to the roof edge. This type of roof potentially has the most available roof space suitable for PV.

- Hipped. It has a pyramidal form, and therefore the available roof space suitable for PV is potentially less than the previous case.
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Monocrystalline</th>
<th>Polycrystalline</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum power at STC(^a) (P_{\text{max}})</td>
<td>180 Wp</td>
<td>200 Wp</td>
</tr>
<tr>
<td>Module short-circuit current at r.c.(^b)</td>
<td>5.239 A</td>
<td>8.12 A</td>
</tr>
<tr>
<td>Module open-circuit voltage at r.c.</td>
<td>44.8 V</td>
<td>33.4 V</td>
</tr>
<tr>
<td>Module current at max power point and r.c.</td>
<td>5.0 A</td>
<td>7.63 A</td>
</tr>
<tr>
<td>Module voltage at max power point and r.c.</td>
<td>36.0 V</td>
<td>26.2 V</td>
</tr>
<tr>
<td>Temperature coefficient of Isc</td>
<td>1.935 mA/°C</td>
<td>3.654 mA/°C</td>
</tr>
<tr>
<td>Temperature coefficient of Voc</td>
<td>-0.152 V/°C</td>
<td>-0.114 V/°C</td>
</tr>
<tr>
<td>Module Temperature at NOCT</td>
<td>45 °C</td>
<td>45 °C</td>
</tr>
<tr>
<td>Dimensions</td>
<td>1580×808×35 mm</td>
<td>1482×992×35 mm</td>
</tr>
</tbody>
</table>

\(^a\)STC: Irradiance 1000W/m\(^2\), Module Temp:25°C
\(^b\)r.c. = reference conditions

Table 4.12: Parameters and inputs for type 94a, representing a multicrystalline PV module

- Double pitched. It may be either gabled or hipped, but it is pitched twice. One of the two inclinations may be not suitable, depending on the needs of the dwelling (maximise yearly output, maximise early in the day performance, maximise late in the day performance, etc.)

Assuming a house of 50m\(^2\) floor space per floor with a roof pitched at 40°, the maximum potential available roof space suitable for PV is approximately 32m\(^2\). Allowing a 10% free space around the edge of the roof to protect the modules from strong wind effects, the available space reduces to 29m\(^2\). Dormers and roof lights, which are commonly seen in UK houses, would further reduce the available roof space two-ways: either, by occupying space or by shading. For a house of the same size (50m\(^2\)), a hipped roof would reduce significantly the available space suitable for PV.

The Marchwood housing stock is characterised by a mixed roof type, which is a common case. Mixed roof types often result in much less roof space for PV systems, due to non-optimum orientation and/or shading issues. Taking into account all these factors, it was estimated that an average house in the area of Marchwood will have approximately 14-15 m\(^2\) of available roof space for installing a PV system. This space can accommodate a 1.8-2 kW\(_p\) system.

The PV system considered here is a multi-module array. A single inverter was assumed and no shading or mismatch losses were considered.

Another fundamental variable which directly affects the electrical output of the PV...
system and its efficiency, is the operating cell temperature. It is extremely sensitive to wind speed and solar irradiance (Skoplaki et al., 2008). In this PV modeling, the operating cell temperature was calculated for every time step, based on the Nominal Operating Cell Temperature (NOCT). NOCT is the operating cell temperature under the reference values; ambient temperature $20^\circ C$ and solar irradiance $800 \text{W/m}^2$. The NOCT value was set to $45^\circ C$ which is a middle of the range value, according to the predictions from various studies (Skoplaki et al., 2008), when the wind speed is $1 \text{m/s}$. This NOCT value refers to a typical sloped-roof mounted PV system.

### 4.7.1 Electricity data synchronisation

The economic performance of the PV system is strongly related to the electricity demand profiles of the single house and the microgrid. All models were evaluated under three demand profiles (Section 4.5) that correspond to the three occupancy profiles (family, working, retired). As explained previously, these demand profiles are real datasets recorded from a set of houses, therefore they do not fully match the occupancy profiles considered in this work. There were observed intervals with electrical demand higher than the baseload, when occupancy was zero. However, the data is recorded from an eco-house development with installed photovoltaic systems, making the datasets ideal for the PV model developed in this research (incorporates adaptive load shifting, energy awareness).

The problem of synchronising the electrical data with the occupancy profiles was solved by developing a new component (Type 162) in TRNSYS. Type 162 operated as a buffer for the system; it stored the level of demand for those timesteps that no occupants were in the house and distributed this load over the first two hours that occupants were back in the house. The principal characteristics of the approach chosen are:

- The total electricity consumption per year, before and after synchronisation, is exactly the same.
- Due to the short hysteresis chosen the electricity consumption profile does not change significantly before and after synchronisation.
• Distributing the load over the next two hours, resulted in a more realistic profile. Shifted amounts of electricity demand are the result of more than one timestep and therefore it would be unrealistic to allocate all the load in one timestep. The result is relatively smoother electricity consumption profiles with lower peaks.

Type 162 was written in Fortran and compiled in Compaq Visual Fortran 6. The flowchart of the algorithm is presented in Figure 4.20.

The algorithm reads four variables:

1. **Occupants In**: The number of occupants in the house. This is the occupancy profile of each house and is given as an input in the simulation studio.

2. **El In**: The electricity consumption as in the raw data from Havant. This is the consumption profile before synchronisation.

3. **B**: The level of the buffer. This is a dummy variable that stores the amount of electricity that will be equally distributed over the next two timesteps.

4. **BaseLoad**: The baseload consumption for each dwelling. Baseload consumption has been calculated for each profile and it is given as an input to the algorithm.

If no occupants are in the house then the level of electricity consumption used for the simulations (El_Out) is the baseload or less (right branch of the flowchart). The algorithm compares the level of consumption from the raw data with the baseload consumption. If the baseload is less than the consumption in the primary dataset, then the electricity consumption for that time step is the same before and after synchronisation. Otherwise, the electricity consumption is equal to the baseload. When occupancy becomes greater than 0 then the electricity consumption after synchronisation is equal to the electricity consumption before synchronisation plus half of the buffer’s total level, if any (left branch of the flowchart). A flag (binary) was used as a dummy variable to indicate if half of the buffer’s level should be utilised (Flag=0) or the entire buffer (Flag=1). Type 162 source code is given in Appendix B.
Figure 4.20: Flowchart of algorithm developed for synchronising electricity data with occupancy profile
4.7.2 Single house PV model

For the single house model an installed peak capacity of 1.8 kW$_p$ was chosen, that requires about 13 m$^2$ of array area. The installed capacity is expected to cover less than 50% of the needs of a single house. Generally, the lower the installed capacity, the less economic the installation becomes due to the non linear cost of the inverters and installation, but a limiting factor for not installing a larger system is the lack of unshaded roof space with appropriate orientation. For the single house, 24 simulations were performed in total and all the possible configurations are illustrated in Figure 4.21.

![Figure 4.21: Studied configurations of the PV model for the single house](image)

4.7.3 Microgrid PV model

For the cluster of ten houses, the total installed capacity was ten times the capacity installed for the single house, e.g. 18 kW$_p$. In this way the performance of the technology can be evaluated versus the single house case and any observed differences may be attributed solely to the formation of the microgrid. Each house within the cluster is connected to a local distribution grid which allows electricity to be transferred from one house to another. Distribution losses within the residential cluster were ignored, due to the small size of the local network.

In terms of modelling, the approach is the same as the one used for the single house. The model calculates the total electricity generation, import and export for the whole microgrid without specifying at each timestep the levels of import and export for each house separately. For the microgrid 8 simulations were performed in total and all configurations are illustrated in Figure 4.22.
4.8 Ground Source Heat Pump (GSHP) model development

As an alternative energy source for space heating, ground source heat pump systems were considered. Models for the single house and the microgrid have been developed in TRNSYS and two different options for the ground heat exchanger have been considered; horizontal pipes and vertical boreholes. Only closed loop systems were modelled as they are more common. Open loop systems require the existence of ground water in a vicinity and such a requirement would severely limit the possible applications. In order to maximise the heat pump’s thermal performance, heat storage was considered for all the cases. The storage tank is a vertical cylinder with uniform losses (1.67 W/m²K). It has an auxiliary heater that is only enabled when the demand cannot be met by the heat pump. The models developed can be split into two parts: 1. the ground source heat pump, and, 2. the ground source heat exchanger.

4.8.1 Water to brine heat pump (Type 668)

This component models a single-stage water to brine (or water to water) heat pump that can operate in heating or cooling mode and was developed by TESS (2009). For the purposes of this research cooling loads were not considered and the heat pump was only used to drive the central heating system of the house. Three types of central heating, suitable for a GSHP, were considered:

1. Low temperature underfloor heating (35°C)
CHAPTER 4. Model Development

<table>
<thead>
<tr>
<th>Vitocal 300 (single stage)</th>
<th>BW 106</th>
<th>BW 232</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rated heating output kW</td>
<td>6.4</td>
<td>32.6</td>
</tr>
<tr>
<td>Power consumption kW</td>
<td>1.40</td>
<td>7.2</td>
</tr>
<tr>
<td>Coefficient of performance (COP)</td>
<td>4.57</td>
<td>4.51</td>
</tr>
</tbody>
</table>

**Brine (Primary)**

| Min. throughput (litre) | 1600 | 7800 |
| Max inlet temperature (°C) | 25 | 25 |
| Min inlet temperature (°C) | -5 | -5 |

**Heating Water (Secondary)**

| Min. throughput (litre) | 530 | 2800 |
| Max flow temperature (°C) | 55 | 55 |

Table 4.13: Technical characteristics of the Veismann Vitocal 300 BW106 and BW232 (Viessman, 2009)

2. High temperature underfloor heating (45°C)

3. Low temperature radiators (55°C)

Type 668 operates in temperature level control and therefore it is equipped with two control signals, one for heating and one for cooling. In all the models developed in this section, the control signal for cooling was set to 0 (Off). Type 668 relies on two data files that contain cooling and heating performance data, readily available from heat pump manufacturers. These files provide capacity and power consumption of the heat pump as functions of the entering source fluid and entering load fluid temperature. A set of data curves were used from the Viessman’s (2009) technical guide for two of their Vitocal 300/350 range brine-water heat pumps; the BW232 and the BW106 model (Figure 4.23). Generally, detailed data sheets or performance curves are not made publicly available by manufacturers. Often, manufacturers give the coefficient of performance (COP) for an output temperature (typically 35°C) and a brine temperature (typically 0°C) and not the full curve for a range of temperatures. The technical characteristics of the two heat pumps modeled, are given in Table 4.13.

Based on the performance data files the model uses a set of equations that calculate the COP of the heat pump and the entering and exiting temperatures of the fluids on both streams; source and load.
Figure 4.23: Performance curves of the Veissmann Vitocal 300 BW106 (left) and BW232 (right) (Viessman, 2009)
In heating mode the heat pump’s COP is given from the equation:

\[ \text{COP} = \frac{\text{Cap}_{\text{heating}}}{\dot{P}_{\text{heating}}} \]  

(4.4)

The amount of energy absorbed from the source fluid stream is:

\[ \dot{Q}_{\text{absorbed}} = \text{Cap}_{\text{heating}} - \dot{P}_{\text{heating}} \]  

(4.5)

The outlet temperatures of the two liquid streams (source and load) can be then calculated using the equations:

\[ T_{\text{source,out}} = T_{\text{source,in}} + \frac{\dot{Q}_{\text{absorbed}}}{\dot{m}_{\text{source}}C_{p_{\text{source}}}} \]  

(4.6)

\[ T_{\text{load,out}} = T_{\text{load,in}} + \frac{\text{Cap}_{\text{heating}}}{\dot{m}_{\text{load}}C_{p_{\text{load}}}} \]  

(4.7)

where,

\( \text{Cap}_{\text{heating}} \) = Heat pump heating capacity at current conditions (kJ/hr)

\( \dot{P}_{\text{heating}} \) = Power drawn by heat pump in heating mode (kJ/hr)

\( \dot{Q}_{\text{absorbed}} \) = Energy absorbed by the heat pump in heating mode (kJ/hr)

\( \dot{m} \) = Mass flow rate of the liquid on the source side or the load side of the heat pump (kg/hr)

\( C_{p} \) = Specific heat of the liquid on the source side or the load side of the heat pump (kJ/kg.K)

\( T_{\text{out}} \) = Temperature of the liquid entering the heat pump (°C)

\( T_{\text{in}} \) = Temperature of the liquid exiting the heat pump (°C)
### Soil Type and Diffusivity (m²/day)

<table>
<thead>
<tr>
<th>Soil type</th>
<th>Diffusivity (m²/day)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sandstone-dry</td>
<td>0.074-0.28</td>
</tr>
<tr>
<td>Clay-damp</td>
<td>0.046-0.056</td>
</tr>
<tr>
<td>Clay-wet</td>
<td>0.056-0.074</td>
</tr>
<tr>
<td>Sand-damp</td>
<td>0.037-0.046</td>
</tr>
<tr>
<td>Sand-wet</td>
<td>0.065-0.084</td>
</tr>
</tbody>
</table>

Table 4.14: Soil diffusivity values for a variation of soil types (Jenkins et al., 2009)

#### 4.8.2 Ground source heat exchanger sub-routines

The main inputs for the ground heat exchanger are the properties related to the weather files and the soil properties. The weather files for Southampton, as described in Section 3.4 were used. In relation to the soil type, it was assumed that the soil is wet clay, with the following properties:

- Specific heat \( C_p = 1.05 \) kJ/kg·K
- Density \( \rho = 3200 \) kg/m³
- Thermal conductivity \( k = 8.72 \) kJ/hr-m-K

According to the formula \( \alpha = \frac{k \cdot \rho \cdot C_p}{\pi} \), the corresponding soil diffusivity \( \alpha \) is 0.062 m²/day. Typical soil diffusivity values for a variation of soil types are given in Table 4.14.

#### 4.8.2.1 Ground temperature routine (Type 501)

This subroutine models the vertical temperature distribution of the ground given the mean ground surface temperature for the year, the amplitude of the ground surface temperature for the year, the time difference between the beginning of the calendar year and the occurrence of the minimum surface temperature, and the thermal diffusivity of the soil (TESS, 2009). It uses the model developed by Kusuda (1967), according to which the ground temperature is a harmonic function of the time of the year and the depth below the surface:

\[
T = T_{\text{mean}} - T_{\text{amp}} \cdot \exp[-\text{depth} \cdot \left(\frac{\pi \alpha}{365}\right)^{0.5}] \cdot \cos\left\{\frac{2\pi}{365} \cdot \left[t_{\text{now}} - t_{\text{shift}} - \frac{\text{depth}}{2} \cdot \left(\frac{365\alpha}{\pi}\right)^{0.5}\right]\right\}
\]

(4.8)
where,

\[ T_{\text{mean}} = \text{mean surface temperature (°C)}, \]

\[ T_{\text{amp}} = \text{amplitude of surface temperature (°C)}, \]

\[ \text{depth} = \text{depth below surface (m)}, \]

\[ \alpha = \text{soil thermal diffusivity (m}^2/\text{hr}) \]

\[ = k/\rho \cdot C_p, \]

\[ t_{\text{now}} = \text{current day of the year}, \]

\[ t_{\text{shift}} = \text{day of the year that the minimum temperature occurs}. \]

Temperature data for the city of Southampton, UK was used and the relevant values are summarised in Table 4.15.

<table>
<thead>
<tr>
<th></th>
<th>2000s</th>
<th>2020s</th>
<th>2050s</th>
<th>2080s</th>
</tr>
</thead>
<tbody>
<tr>
<td>( T_{\text{mean}} ) (°C)</td>
<td>10.96</td>
<td>11.95</td>
<td>13.08</td>
<td>14.69</td>
</tr>
<tr>
<td>( T_{\text{amp}} ) (°C)</td>
<td>12.27</td>
<td>13.47</td>
<td>14.84</td>
<td>16.73</td>
</tr>
</tbody>
</table>

Table 4.15: Weather data used for the calculation of the ground temperature in Southampton, UK, according to a UKCIP02 medium-high emissions scenario

The ground temperature routine is the same one used for the calculation of the cold water temperature in the domestic hot water model. The output of this sub-routine was used as an input for the calculation of the brine temperature in the buried horizontal pipes, which is the first part of the ground source heat exchanger. Figure 4.24 illustrates the ground temperatures for various depths as calculated from the ground temperature routine using the weather file for Southampton, 2000 and the soil properties listed above.

### 4.8.2.2 Buried horizontal pipes (Type 556)

This sub-routine models a buried horizontal pipe that operates as a ground coupled heat exchanger. It is a finite difference model where the horizontal pipe is assumed to be in the center of a large cylinder of soil (Figure 4.25). The cylinder is divided into a grid of nodes, each having a thermal capacitance determined by its volume.
and specific heat. The radial and circumferential heat transfers are modelled using a thermal resistance approach. The energy flowing from the fluid in the pipe to the soil is calculated using the resistance of the fluid, the resistance of the pipe and the resistance of the backfill. The farfield (undisturbed) boundary temperatures, required by the model, are calculated from Type 501. The temperature for each node is updated by stepping through time. Type 556 runs in a different timestep to that of the main TRNSYS routine, which is always shorter or equal to the TRNSYS timestep. In the models developed here, it was set 150 times shorter than the main TRNSYS timestep to ensure precision. Increasing the timestep for Type 556 results in higher precision at the expense of computational time. However, it was observed that results did not change for shorter timestep values than main TRNSYS timestep/150.

4.8.2.3 Vertical U-tubes (Type 557)

This subroutine models a ground coupled vertical heat exchanger. It can model either a U-tube or a concentric tube ground heat exchanger. The model assumes that the boreholes are placed uniformly within a cylindrical storage volume ground and it allows up to 10 U-tubes per borehole. Within the pipes the heat is transferred
via convection and from the pipes to the storage volume the heat is transferred via conduction. The temperature in the ground is calculated from three parts: a global temperature, a local solution, and a steady-flux solution. The global problem is a heat conduction problem within the storage volume and a sufficient part of the surrounding ground. The simulated ground is divided into a 2-dimensional mesh using a radial and a vertical coordinate and the temperature of each cell is calculated with a finite difference method. As the fluid flows in the heat exchangers its temperature will vary across its flow path and it will absorb (heating mode) or reject (cooling model) energy. The local problem models the heat transfer around the individual ducts due to short-time variations. The storage region is divided into a number of subregions and the local problem is assumed to be the same around each pipe in a given subregion. The steady-flux problem gives the temperature field around a pipe for a constant injection/extraction rate. The temperature in the ground is a superposition of three parts: local, global, and steady-flux temperature.

4.8.3 Ground source heat pump model for the single house

For the single house, a water to brine heat pump of rated heating power 6.4 kW was modeled. For the sizing of heat pump it was assumed that the heat pump should meet approximately the 50% of the peak space heating demand, which is likely to meet 80-85% of the annual energy space heating requirement (EST, 2007). For the system's ground heat exchanger, horizontal buried pipes of total length 240 m for each house were used. A print screen of the TRNSYS model is given in Figure 4.26.
For this model 216 possible configurations were examined; 3 building types with or without conservatory × 3 building fabrics × 3 occupancy profiles × 4 climate data. Here only the configurations illustrated in Figure 4.27, which represent the Marchwood cluster for three different building fabrics, are presented.

Figure 4.27: Configurations of GSHP model for the single house

4.8.4 Ground source heat pump model for the cluster

For the 10 houses cluster the total installed capacity was 65.2 kW, approximately ten times the capacity considered for a single house. The largest unit available from the Veismann catalog (Viessman, 2009) has a rated heating output 32.6 kW, therefore
two of these units were considered instead. Type 668 gives the possibility to model many heat pumps at the same time, simply by choosing the number of pumps operating simultaneously. In terms of modelling, the capacity and power were provided as inputs from the data files and then were multiplied by the number of heat pumps to scale up the results, without having to specify multiple Type 668 elements. The “10 houses cluster” model with the horizontal pipes was the same as the one developed for the single house. The “10 houses cluster” model with the vertical boreholes is illustrated in Figure 4.28.

![Figure 4.28: TRNSYS ground source heat pump model with vertical boreholes for the 10 houses cluster](image)

The principal reason for considering the vertical boreholes, was that for the horizontal pipes the area required to lay the heat exchanger may not always be available. For the horizontal pipes model the total length of the buried pipe used was 2400 m. Assuming a 3 m distance between each line of pipes of 100 m length each, then a total area of 7,200 m$^2$ is required. For the same installed capacity, 25 vertical boreholes of 70 m depth each, were considered in the model. Assuming a 6 m distance between the boreholes, the surface area that the heat exchanger occupies is approximately 600 m$^2$. The model for the ground coupled heat exchanger consisted of three kinds of piping, in order to simulate the entire cycle of the brine from and back to the evaporator of the GSHP:
(a) the horizontal buried pipes that transfer the brine from the heat pump to the vertical boreholes (Type 556),

(b) the vertical boreholes (Type 557) and

(c) the horizontal buried pipes that return the brine from the vertical boreholes back to the heat pump (Type 31).

Heat exchange with the ground took place at the stages (a) and (b), whereas the horizontal pipes that return the fluid to the heat pump (c) were insulated to minimise losses.

The 8 configurations examined for this model are illustrated in Figure 4.29.

4.9 Combined Heat and Power (CHP) model development

In terms of using fuel more efficiently, the concept of a Combined Heat and Power (CHP) system is considered. CHP systems can provide potential reductions in carbon emissions by generating heat and power simultaneously at the point of use, offsetting in this way the use of centrally-generated electricity from the grid. In recent years there has been an increased interest in producing new systems for use in small commercial and domestic environments. These systems can be used at a single building level, such as a domestic environment (micro-CHP) or for larger applications, such as a commercial environment, where demand is higher (mini-CHP). It is a fundamental
requirement that CHP units are installed in an appropriate environment and operate correctly in order to deliver savings in carbon emissions. A long duration operating mode with as few as possible start-up cycles is vital for the overall efficiency, the life-time of a unit and carbon emission savings (Carbon Trust, 2007).

CHP is not available in the standard TRNSYS component library and therefore a new Fortran routine was developed and is given in the Appendix B. The new component created (Type 156) can model up to three theoretical CHP units including a heat storage tank. The CHP models are based on the following assumption:

**The generated heating energy has to match the profile of the heating demand of the single house or the cluster as closely as possible. Therefore, CHP systems operate essentially as a thermally tracked process where electricity is produced as a byproduct, determined by the heating load and the heat/electricity ratio of the selected unit.**

The reasons for adopting such an approach were:

- The CHP units are examined as an alternative to condensing gas-fired boilers.
- On the grounds of economics the installation of a CHP unit and a secondary back-up boiler would be unattractive.
- Micro-CHP systems are commonly high heat:electricity ratio systems (>3:1) and as stated in the government’s standard assessment procedure (SAP), are assumed to be heat-led, meaning that they are allowed to operate only when there is a demand for heat (DEFRA, 2008).

Since the CHP unit is driven by the heat demand, one of the main inputs is the heating demand of the single house or the cluster per simulation step. Other inputs are the cold water temperature (water from the mains) and the required hot water temperature (water to the load). The component models the CHP unit and the thermal store as one combined system, with variable tank size and thermal loss coefficient.

Another important parameter that the component takes into account, is the minimum operating cycle of the CHP unit(s). This is the minimum number of hours that the
unit has to operate once it is switched on, in order to avoid inefficient start-up cycles and ensure a prolonged lifetime for the CHP unit. The minimum run time for all the CHP schemes was set to 3 hours. According to the Carbon Trust micro-CHP field trial (DEFRA, 2008), for operating cycles longer than 2.5 hours the micro-CHP performance has asymptotic behaviour (no further improvement in efficiency), whilst the same efficiency can be assumed for the entire cycle without significant error.

For all the models developed in this work, the thermal storage tank was a cylinder of 150 litres capacity with a loss coefficient of 0.833 W/m². The technical characteristics of all the CHP units used in this section are given in Table 4.16.

<table>
<thead>
<tr>
<th></th>
<th>WhisperGen micro</th>
<th>Baxi DACHS</th>
<th>EC Power CHP XRGI</th>
<th>Mini-CHP theoretical unit*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermal output: kWₜₜ</td>
<td>7.0-12.0</td>
<td>12.5-14</td>
<td>30.0</td>
<td>51.0</td>
</tr>
<tr>
<td>Electrical output: kWₑ</td>
<td>1.0</td>
<td>5.5</td>
<td>15.0</td>
<td>21.5</td>
</tr>
<tr>
<td>Fuel input: kW</td>
<td>10.0-17.0</td>
<td>22.8</td>
<td>50.0</td>
<td>83.0</td>
</tr>
<tr>
<td>Thermal efficiency (kWₜₜ/fuel input): %</td>
<td>70</td>
<td>55</td>
<td>60</td>
<td>60</td>
</tr>
<tr>
<td>Carbon benefits ratio (CHPₜₜBaUₜₜ)</td>
<td>0.99</td>
<td>0.87</td>
<td>0.74</td>
<td>0.79</td>
</tr>
</tbody>
</table>

* Capacity of mini-CHP theoretical unit = capacity of (WhisperGen micro + Baxi DACHS + EC Power CHP XRGI)

Table 4.16: Technical characteristics of CHP units used in the CHP schemes

### 4.9.1 Combined heat and power model for the single house

For the case of a CHP at household level a WhisperGen (2008) micro-CHP unit was selected. WhisperGen is the only Stirling engine micro-CHP system available on the market, whereas DACHS from Baxi-SenerTec (2006) is based on a similar reciprocating engine. Whispergen was selected due to its lower rated output and higher thermal efficiency.

The component developed in TRNSYS studio was packaged as Type 156, and can model any theoretical CHP unit with a thermal storage tank. The flowchart of the single unit CHP model is given in Figure 4.30.
Figure 4.30: Flowchart of the modelling approach for the single unit micro-CHP model
CHAPTER 4. Model Development

For the single house the same 36 configurations as for the GSHP model are presented (Figure 4.27), which represents the case study area in Marchwood, UK.

4.9.2 Combined heat and power model for the microgrid

The formation of the microgrid presents some extra benefits for this technology. The clustering of small groups of homes provides the high heat demand trend that Stirling/internal combustion engine based systems require in order to ensure long duration operating mode with as few as possible start-up cycles. Another important advantage of the clustering approach is the smoothing of the heating load. Additionally, the formation of the microgrid results in a peak thermal output of a CHP system for a cluster to be proportionally smaller than that for a single dwelling. For the microgrid two CHP schemes were investigated:

- mini-CHP microgrid level. A single CHP device that follows the heating demand of the ten houses cluster. Electricity generation from the CHP unit is distributed across the microgrid with any excess/shortfall being balanced by the utility grid. A theoretical CHP unit is assumed for this option and its technical characteristics are given in the last column of Table 4.16.

- multi-stage mini-CHP. Three CHP units of different capacities operate in parallel to provide the same peak thermal and electrical output capacity as the single mini-CHP device considered in the previous scheme. Parallel operation strategies enable better thermal load matching than in the previous option. The three units chosen for this option are the WhisperGen micro-CHP, the Baxi DACHS mini-CHP and the EC Power’s mini CHP XRGI. All three devices operate with natural gas and are commercially available.

Multi-stage operation involves the problem of scheduling the CHP devices that operate in parallel. A non-efficient control strategy could negate potential benefits from such a scheme, therefore the scheduling problem for the three CHP devices is addressed in this work. The scheduling of the three devices is based on a heuristic, greedy construction algorithm incorporated in the Type 156.
A heuristic algorithm is a set of steps that can produce an acceptable solution to a problem. The basic advantage of such algorithms is that they are fast. The main drawback is that they find the best solution from a set of solutions that are examined (local optimum). The local optimum may also be the global optimum of the problem, if the latter is in the set of solutions examined by the algorithm. Therefore, when designing a heuristic algorithm it is important to examine those solutions that are expected to be closer to the best solution.

The most popular heuristic algorithm is the greedy construction algorithm. According to this algorithm, at each step the element that has the greatest impact on a special constructed function (greedy function) is chosen. The only criterion for this algorithm in order to chose the next element of the solution is the impact of that element on the current step of the algorithm, without examining what the impact will be on future steps. By choosing consecutive local optimums at each step, the algorithm aims to end up to a global optimum.

For the scheduling of the three CHP devices the greedy function chosen was:

\[ F_{greedy} = \min(\text{total heat generation} - \text{total heat demand}) \]

According to this function the algorithm switches on as many devices as needed to cover the total heat demand. It turns on those devices so that the excess of generated heat is the minimum possible. Once a device is switched on, it has to operate for at least the minimum run time set in the model. Figure 4.31 presents the flowchart, of the greedy construction algorithm. Source code for Type 156 is given in Appendix B. The Type 156 can also be found on the Sustainable Energy Research Group, University of Southampton web page, [http://www.energy.soton.ac.uk/](http://www.energy.soton.ac.uk/). The proforma with the source code can be downloaded and installed in the TRNSYS library.

For the two microgrid CHP schemes (with the 150 litres variable-volume tank in every dwelling) an additional shared buffer of 1500 litres was added. Thermal storage enables longer operational periods and fewer start-up cycles for the CHP devices and minimises the intervals where excess or shortfall of heating energy is observed. The network for
Figure 4.31: Flowchart of greedy algorithm for the scheduling of the three CHP devices
the heat distribution within the microgrid is assumed to be highly insulated so that the transmission losses across the microgrid are negligible.

For all the cases, the results were compared to a business as usual (BaU) scenario in order to calculate the carbon savings achieved for each heating option. For the business as usual scenario a condensing boiler (90% efficiency) was considered, whilst electricity was provided from the mains. Four heating options were investigated in total in this section. Figure 4.32 illustrates a schematic of the four options.
**Option 1:** current practice (BaU). Each house has its own dedicated gas boiler and electricity is imported from the utility grid.

**Option 2:** micro-CHP household level. Each house has its own micro-CHP unit that follows the heating demand profile. Electricity is imported/exported from the utility grid as required.

**Option 3:** mini-CHP microgrid level. A single CHP device follows the heating demand of a cluster of ten houses. Electricity generation from the CHP unit is distributed across the microgrid with any excess/shortfall being accommodated by the utility grid.

**Option 4:** multi-stage mini-CHP microgrid. Three CHP units of different capacities operate in parallel to provide the same peak thermal and electrical output capacity as the single mini-CHP device considered in option 3. Parallel operation strategies enable better thermal load matching than in option 3 and, for this study, a heuristic algorithm was developed for the parallel operation of the three-CHP units.

Figure 4.32: Schematic of the 4 different heating options considered for CHP schemes
Chapter 5

Sensitivity Analysis

In this chapter the robustness of the models previously developed is examined. The uncertainty of each model’s output is investigated by varying the most important inputs and parameters.

5.1 Space heating demand model

A number of models were developed in the TRNSYS simulation studio to predict the space heating demand. In all cases, predictions were mainly dependent on Type 56, which essentially modelled the buildings under investigation. Type 56 uses a U-value approach to model a building and a large number of inputs is required. Simulations were performed for various Type 56 files where the only difference was the total U-value of the house. Results are expressed on average U-value/m\(^2\) and are illustrated in Figure 5.1.

As seen in Figure 5.1 the annual space heating demand has a linear relationship with the total U-value of the house for the examined cases. The U-value of each component (walls, windows, roof, etc.) was changed proportionally for each house, hence the good matching. The latter though, indicates the consistency of the models developed. From the gradient of the line it was estimated that a 10% change in the house U-value corresponds to 8.1% change in the annual demand for space heating. It should also
CHAPTER 5. Sensitivity Analysis

Figure 5.1: Change in the annual space heating demand due to change in the average house U-value

be noticed that the line intercepts the y-axis at 1,267 kWh/year. This is the heating demand due to infiltration, independent of the U-value of the house.

Figure 5.2: Sensitivity analysis for models that predict space heating demand

A sensitivity analysis was also performed for the other inputs given in the simulation studio, such as as ambient temperature, heat set point, infiltration rate and internal gains. Results are presented in Figure 5.2. As would be expected, a change in the ambient temperature and the heat set point, by one degree Celsius, have approximately the same impact on the space heating demand (~10% change). This estimation can
also be verified by the rule of thumb according to which a change of 1°C in the ambient temperature or the heat set point would have approximately a 10% impact on the building’s annual demand for space heating.

### 5.2 Domestic hot water (DHW) sub-routine and solar thermal model

To predict the energy demand for domestic hot water a sub-routine was developed, where all the inputs were given in the components that modelled the storage tank and the cold water temperature. Sensitivity analysis was performed for the following parameters:

- the ambient temperature that determines the cold water temperature in the ground temperature component (±1°C),
- the depth of the cold water pipes (±0.5m),
- the tank size (±10%),
- the tank loss coefficient (±10%) and
- the set point temperature for the heat element in the tank (thermostat) (±5°C).

Figure 5.3 presents the results of the sensitivity analysis performed for those parameters. Variation in the thermostat set point, as expected, had the greatest impact. A change of 5°C in the thermostat set point resulted in ∼4% change at the annual consumption for DHW. The tank loss coefficient and the tank size followed with marginally smaller impact.

For the solar thermal model the same parameters were examined plus the impact of a 10% change in the hot water demand and a 10% change in the solar panel size. Results are presented in Figure 5.4. Change in the the demand for hot water has the greatest impact as seen on the graph. The annual consumption for solar thermal DHW varied by less than 5% when changing the solar panel size by 10%. The size of
Figure 5.3: Sensitivity analysis for the model that predicts the DHW energy consumption. The solar thermal panel has a greater direct impact on the energy generated by the solar thermal system but an indirect impact on the auxiliary heating used to meet the demand for DHW. Auxiliary heating used is also dependent on the time of the day when there is demand for hot water. Therefore, a change in the panel’s size does not necessarily have a significant impact on the auxiliary heating used from the solar thermal system.

Figure 5.4: Sensitivity analysis for the solar thermal model.
5.3 Photovoltaic model

The main input and parameters of the model developed for the PV system refer to the component that models the photovoltaic panel and the weather files. Varying the value of an input has an impact on the electricity generation, electricity export and electricity import. Whilst the impact on the electricity generation is easy to predict, it is more interesting to investigate the impact on electricity export and import. Export and import are highly dependent on the matching of the generation profile with the consumption profile. Figure 5.5 presents the sensitivity analysis performed for the PV model and Figure 5.6 illustrates the impact on the electricity generation, import and export due to a 10% change in the total installed capacity.

Figure 5.5: Sensitivity analysis for the PV model

The robustness of the component developed for the electricity synchronisation with the occupancy profiles was also investigated. Instead of distributing the amount of electricity stored in the buffer over the next 2 hours, it was investigated what the impact would be if the same amount of electricity demand was distributed over the next hour and over the next three hours after the arrival of the occupants. As seen in the Figure 5.5 the impact is marginal, ∼2%. This is because the occupancy profiles considered, assume that occupants are away during the most of the day. When occupants are back in the house, generation is at minimum level or zero, and therefore distributing the amount of electricity that has accumulated in the buffer in one, two
CHAPTER 5. Sensitivity Analysis

Figure 5.6: Sensitivity analysis for the PV model due to change in the total installed capacity or three hours, does not have a significant impact. The latter also indicates the good matching of the electricity datasets used with the occupancy profiles assumed.

A 10% change in the size of the PV system has, of course, a 10% change on electricity generation. It has a marginal impact on the electricity import and far greater impact on the electricity exported to the grid, indicating low matching of the electricity generation with the electricity consumption.

5.4 Ground source heat pump model

The sensitivity analysis for the ground source heat pump was performed in respect to the total CO$_2$ emissions emitted. By varying one of the model’s inputs, the power consumed from the heat pump, the heat output and the auxiliary heating are all modified. Therefore, instead of presenting each output separately, the impact on the total carbon emissions is presented (Figure 5.7).

The size of the thermal storage has a negligible overall impact on the 10 house cluster. This is because a change in the size of the thermal storage tank had a dual impact, depending on the dwelling. For example, an increase in the size of the thermal storage tank resulted in an increase of the carbon emissions for dwellings with low heat...
demand due to increased, proportionally, heat losses from the tank. At the same time resulted in lower carbon emissions for dwellings with high heating demand due to better utilisation of the tank. In all cases though, the impact was less than 3%.

A change in the load temperature has the greatest impact on the GSHP model. For each degree Celsius change in load temperature, the system’s carbon performance varies by \(\sim 2-3\%\).

5.5 Combined heat and power (CHP) models

For the CHP models developed in this research a theoretical approach was chosen. The CHP component designed, calculated the amount of energy generated and the amount of energy delivered, taking into account thermal losses due to thermal storage. The sensitivity analysis was performed in respect to the total CO\(_2\) emitted from the CHP schemes. The parameters examined were the size of the thermal store (\(\pm 10\%\)), the tank loss coefficient (\(\pm 10\%\)), the cold water temperature (\(\pm 1^\circ\text{C}\)) and the duration of the minimum cycle that a CHP unit has to operate (\(\pm 1\text{h}\)). Generally, the model’s sensitivity in respect to CO\(_2\) emissions proved to be very low for all the parameters examined. The amount of electricity generated, exported to and imported from the
grid varied by up to 5%, but not the total CO$_2$ emissions where the observed changes were less than 1%.

Figure 5.8 presents the impact of the duration of the minimum operation cycle considered for the CHP units, which also verifies the duration selected for the models developed.
Chapter 6

Results

6.1 Space heating demand prediction

Simulations were performed for three different building types; a detached house of total floor area 140 m$^2$, a semi-detached house of total floor area 101 m$^2$ and a terraced house of total floor area 89 m$^2$. The model for the detached house simulated one house at a time; two semi-detached houses were modelled at the same time, whilst for the terraced house, a row consisting of five houses was considered. In this way, it was possible to take into account the energy flows from one house to another where there were shared surfaces between the houses (semi-detached and terraced case). For every building type a conservatory option was also considered, since it is expected to have a significant impact on the annual heating demand of a dwelling. The annual space heating demand for the 18 building (Type 56) files and for the three occupancy profiles (family, working couple, retired couple) for the present day and the three future time slices are presented in Figures 6.1 to 6.4. The impact of the building type, the building fabric and the climate change on the space heating demand may be evaluated.

Figure 6.5 presents the same results for the present day but only in terms of CO$_2$ emissions associated with space heating, assuming a condensing boiler of 90% efficiency and a carbon intensity of 0.19 kg of CO$_2$ per kWh of natural gas supplied.
Figure 6.1: Estimated space heating demand for houses in Southampton for the present day (2000)
Figure 6.2: Estimated space heating demand for houses in Southampton for 2020s
Figure 6.3: Estimated space heating demand for houses in Southampton for 2050s
Figure 6.4: Estimated space heating demand for houses in Southampton for 2080s
Figure 6.5: Estimated CO$_2$ emissions associated with space heating from various houses in Southampton, 2000
To validate the space heating demand model, the results obtained from TRNSYS were compared with the data collected from the questionnaire survey in Marchwood. Only those TRNSYS results that correspond to the Marchwood building stock were used for the comparison. Figure 6.6 compares the space heating demand for the residential cluster in Marchwood, as predicted in TRNSYS and as was estimated by the questionnaire survey undertaken.

The space heating demand predicted in TRNSYS is 14% lower when compared with the results collected from the survey. The model in TRNSYS essentially assumes an ideal user behaviour, where energy is used in an efficient way. Ventilation rates where modelled as a function of the external ambient temperature and the occupancy in order to minimise losses. In reality though this is not true and significant amount of energy is wasted due to bad user behaviour. For example many users, in order to ventilate their house, may leave a window open for prolonged periods during a cold winter’s day or in other cases for an entire night.

From all the graphs it is clear that the building type has the greatest impact on the annual space heating demand. To enable a fairer comparison which takes into account the different floor space of the 3 building types, the results were expressed in
### Table 6.1: Space heating demand in kWh/m²/year for the three building types, with and without conservatory, and the three occupancy profiles for the present day

<table>
<thead>
<tr>
<th>Building Type</th>
<th>Detached</th>
<th>Semi-detached</th>
<th>Terraced</th>
</tr>
</thead>
<tbody>
<tr>
<td>1980s Family</td>
<td>73.5</td>
<td>96.8</td>
<td>62.8</td>
</tr>
<tr>
<td>1980s Couple</td>
<td>58.3</td>
<td>80.4</td>
<td>52.6</td>
</tr>
<tr>
<td>1980s Retired</td>
<td>87.0</td>
<td>114.1</td>
<td>75.4</td>
</tr>
<tr>
<td>2002 reg. Family</td>
<td>36.2</td>
<td>57.5</td>
<td>29.6</td>
</tr>
<tr>
<td>2002 reg. Couple</td>
<td>31.7</td>
<td>47.5</td>
<td>26.7</td>
</tr>
<tr>
<td>2002 reg. Retired</td>
<td>44.2</td>
<td>68.7</td>
<td>37.9</td>
</tr>
<tr>
<td>2006 reg. Family</td>
<td>29.8</td>
<td>45.8</td>
<td>21.9</td>
</tr>
<tr>
<td>2006 reg. Couple</td>
<td>26.7</td>
<td>38.8</td>
<td>20.4</td>
</tr>
<tr>
<td>2006 reg. Retired</td>
<td>37.1</td>
<td>55.1</td>
<td>29.2</td>
</tr>
</tbody>
</table>

In terms of kWh/m²/annum, detached houses were estimated to have 10-27% higher space heating demand compared with the semi-detached houses for the present day. This difference increased to 14-46% when detached houses were compared with terraced houses. For the three future time slices the estimated differences due to the building type were slightly higher, 1-2% higher for each time slice.

Conservatories were modelled as extensions of the living room. The thermal barrier between the house and the conservatory was assumed to be removed and therefore heating is required. The latter results in much higher space heating demand for the dwelling due to the larger floor area to be heated and due to the increased thermal losses from the building fabric. Although during sunny days the conservatory acts as a passive solar room, which reduces the need for heating, these savings did not offset the amount of energy required for heating of the conservatory.

Figure 6.7 presents the % increase in the space heating demand of a dwelling with a conservatory compared with the same dwelling without the conservatory, for the three building types and the three occupancy profiles in Southampton for the present day. The space heating demand of a house without a conservatory and the increase on the space heating demand due to the conservatory, appear as a linear relationship. As the space heating demand increases the impact of the conservatory decreases. The size of
the conservatory varied according to the building type considered, as follows: 13.5 m$^2$ for detached houses, 10.5 m$^2$ for semi-detached houses and 9 m$^2$ for terraced houses. For all the building files, under all four climate data, the correlation coefficient between the two variables (space heating demand without conservatory and space heating demand with conservatory) was estimated at -0.80, indicating the strong linear relationship. For many cases it was observed that the conservatory had less impact on the annual space heating demand for the working couple than the other two occupancy profiles. As the working couple has the lowest space heating demand from the three occupancy profiles it would be expected that the existence of the conservatory would be more pronounced in the results. This did not happen as the working couple profile assumes short periods of operation for the central heating, resulting in a less responsive model. The longer heating periods of the other two occupancy profiles resulted in higher levels of thermal losses from the conservatory, increasing consequently its impact on the annual space heating demand of the dwelling.

The impact of the building’s fabric quality is also evaluated in this section. Figure 6.8 presents the annual space heating demand per building fabric for nine houses (three...
Figure 6.8: Annual space heating demand per building fabric for various houses in Southampton, 2000.

building types and three occupancies) in Southampton, 2000. The improved energy performance of the building fabric compliant to 2006 regulations and the low performance of the 1980’s fabric are evident in all cases. For example, a family in a detached house with the 1980’s fabric quality is estimated to have an annual space heating demand of 10,287 kWh. The same family in a detached house built in 2002 is estimated to require 5,073 kWh and only 4,167 kWh if the house is built in 2006. Compared with a house built in the 1980, the 2002 building fabric results in 50% reduction in space heating demand which is equivalent to 1.1 tonnes of CO$_2$ savings and the 2006 building fabric results in 60% reduction for space heating demand, equivalent to 1.3 tonnes of CO$_2$ savings per year. For the carbon emissions estimations, a condensing boiler of 90% efficiency is assumed. For all houses without conservatories the 2002 building fabric was estimated to achieve reductions of around 45-55%, under all four climate datasets, whilst the 2006 building fabric was estimated to achieve reductions of 52-72%. When conservatory was present the reductions were estimated to be 4-12% less due to increased heat loss through the relatively high U-value of the glazing.
6.2 Domestic hot water demand prediction

The heating demand for domestic hot water depends on the number of occupants living in a house, their occupancy profile and the climate data of the area examined. The number of occupants is the most important factor that determines the level of demand for hot water. The occupancy profile determines the time of the day that there is demand for hot water and the climate data determines the cold water temperature. Hot water consumption is not directly dependent to the building type and fabric, therefore only the 3 occupancy profiles (family, working couple, retired couple) under the four climate datasets (2000, 2020s, 2050s, 2080s) are examined in this section. For the three future time slices it has been assumed that the hot water demand remains unchanged. The annual results for domestic hot water consumption are presented in Table 6.2.

<table>
<thead>
<tr>
<th>DHW demand (kWh/annum)</th>
<th>Family (4 occupants)</th>
<th>Working couple (2 occupants)</th>
<th>Retired couple (2 occupants)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Present day (2000)</td>
<td>5230</td>
<td>3002</td>
<td>3006</td>
</tr>
<tr>
<td>2020s</td>
<td>5106</td>
<td>2934</td>
<td>2937</td>
</tr>
<tr>
<td>2050s</td>
<td>4963</td>
<td>2854</td>
<td>2857</td>
</tr>
<tr>
<td>2080s</td>
<td>4756</td>
<td>2785</td>
<td>2788</td>
</tr>
</tbody>
</table>

Table 6.2: Domestic hot water demand for 3 occupancy profiles and 4 climate data in kWh per annum

The annual DHW demand for the working couple and the retired couple is almost identical since both occupancy profiles assume 2 occupants. However, another important factor is the time when the demand occurs. The reason for modelling both profiles was not just to estimate the annual average but to produce sets of data for the domestic hot water demand for each hour of the year. These datasets are subsequently used for the solar thermal model which is dependent on the weather data and therefore time dependent.

The small differences observed for the three future time slices occur due to the higher ground temperatures expected in the future, which result in higher temperatures for the cold water coming from the mains. By the 2020s energy demand associated with
DHW and the related emissions are projected to be 2.5% less than the present day. By the 2050s this difference rises to 5% and by 2080s the projected difference is 7% - 9%.

Assuming a condensing boiler of 90% efficiency, the CO$_2$ emissions related to the domestic hot water are presented in Table 6.3. If an electric system is assumed then the related emissions are more than 125% higher, depending on the carbon intensity used for the UK national grid.

<table>
<thead>
<tr>
<th>DHW CO$_2$ emissions (kg/annum)</th>
<th>Family (4 occupants)</th>
<th>Working couple (2 occupants)</th>
<th>Retired couple (2 occupants)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Present day (2000)</td>
<td>1104</td>
<td>634</td>
<td>635</td>
</tr>
<tr>
<td>2020s</td>
<td>1078</td>
<td>619</td>
<td>620</td>
</tr>
<tr>
<td>2050s</td>
<td>1048</td>
<td>603</td>
<td>603</td>
</tr>
<tr>
<td>2080s</td>
<td>1004</td>
<td>588</td>
<td>588</td>
</tr>
</tbody>
</table>

Table 6.3: CO$_2$ emissions from domestic hot water for 3 occupancy profiles and 4 climate datasets in kg/year

6.3 Active solar thermal system for DHW results

The energy consumed for domestic hot water accounts for more than 20% of the total heating demand (space heating + domestic hot water) of a dwelling. New buildings with high quality building fabric are estimated to have higher energy demand for domestic hot water than for space heating. For example, a family living in a terraced house built under the 2002 regulations is estimated to have an annual space heating demand of approximately 4,000 kWh, whilst their heating demand for domestic hot water is estimated around to 5,000 kWh. Therefore, potential savings on domestic hot water can deliver significant reductions in the total CO$_2$ emissions from the domestic sector. In some cases these savings may be more important than potential savings from the space heating demand.

The solar thermal systems modelled for the single house and the microgrid are not designed to cover the demand by 100%. The seasonal nature of the solar resource
makes sizing of a system for all year round supply inappropriate. An auxiliary system
is considered and the levels of auxiliary heating demand for the three occupancy profiles
and the four weather data sets are summarised in Table 6.4, whilst Table 6.5 presents
the heating demand for a 10 house cluster, with and without a solar thermal system.
For the microgrid case two technologies are modelled; flat plate and evacuated tube
collectors.

<table>
<thead>
<tr>
<th>Auxiliary heating for single house (kWh/annum)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Family</td>
</tr>
<tr>
<td>-------------------------------------------</td>
</tr>
<tr>
<td>2000</td>
</tr>
<tr>
<td>2020s</td>
</tr>
<tr>
<td>2050s</td>
</tr>
<tr>
<td>2080s</td>
</tr>
</tbody>
</table>

Table 6.4: Auxiliary heating to solar thermal system for the three occupancy profiles

<table>
<thead>
<tr>
<th>Auxiliary heating for 10 house cluster (kWh/annum)</th>
</tr>
</thead>
<tbody>
<tr>
<td>DHW demand</td>
</tr>
<tr>
<td>Flat plate</td>
</tr>
<tr>
<td>2000</td>
</tr>
<tr>
<td>2020s</td>
</tr>
<tr>
<td>2050s</td>
</tr>
<tr>
<td>2080s</td>
</tr>
</tbody>
</table>

Table 6.5: Auxiliary heating demand to solar thermal system for domestic hot water (columns 2-4)
compared with the total annual heating demand for DHW of a 10 houses cluster in Marchwood (1st
column)

The “10 Houses” column assumes a cluster of 10 houses that consists of 3 houses with
families, 3 houses with working couples and 4 houses with retired people (case study
cluster in Marchwood). The microgrid column assumes that the 10 houses are linked
together and they form a microgrid where the solar thermal system operates as a
common facility.

At the single house level the flat plate collector solar thermal system achieves fossil
fuel savings of 45% for the family and 52% for both the working and the retired
couple, for the present day. Solar thermal systems will benefit from anticipated higher
temperatures resulting from the climate change and the savings are slightly improved
for the future time slices (3-4% for the 2080s).
For the 10 houses cluster and the microgrid, the savings achieved are illustrated in Figure 6.9. For the 10 houses cluster, solar thermal achieved savings of approximately 50% under all four weather scenarios. Further savings were achieved when the 10 houses formed a microgrid, where the evacuated tubes system doubled the savings compared with the flat plate collector system. The savings can be contributed to the smoother demand profile of the microgrid. When the houses form a microgrid the demand for hot water is more regular and more water from the pre-heat tank is drawn off, reducing in this way long storage times and increasing the usability factor of the solar thermal system. The separate pre-heat and storage approach also ensures lower temperatures in the pre-heat tank and enhances the usability factor.

To calculate the carbon savings two types of auxiliary heaters were considered; gas and electric. Table 6.6 summarises the annual CO$_2$ emissions for both auxiliary heaters against the BaU scenario of a condensing boiler with 90% SEDBUK at the single house level, whilst Table 6.7 gives the CO$_2$ emissions for the 10 houses cluster and the microgrid.

As seen from the tables when the auxiliary heating system is assumed to be electric
Table 6.6: \( \text{CO}_2 \) emissions in tonnes/annum from the solar thermal system compared with the BaU scenario at the single house level

<table>
<thead>
<tr>
<th>Family</th>
<th>Working couple</th>
<th>Retired Couple</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>BaU</td>
<td>Aux Gas</td>
</tr>
<tr>
<td></td>
<td>Aux El</td>
<td>BaU</td>
</tr>
<tr>
<td></td>
<td>Aux Gas</td>
<td>Aux El</td>
</tr>
<tr>
<td></td>
<td>BaU</td>
<td>Aux Gas</td>
</tr>
<tr>
<td></td>
<td>Aux El</td>
<td>BaU</td>
</tr>
<tr>
<td></td>
<td>Aux Gas</td>
<td>Aux El</td>
</tr>
<tr>
<td>2000</td>
<td>1.10</td>
<td>0.61</td>
</tr>
<tr>
<td>2020s</td>
<td>1.08</td>
<td>0.59</td>
</tr>
<tr>
<td>2050s</td>
<td>1.05</td>
<td>0.56</td>
</tr>
<tr>
<td>2080s</td>
<td>1.00</td>
<td>0.52</td>
</tr>
</tbody>
</table>

Table 6.7: \( \text{CO}_2 \) emissions in tonnes/annum from the solar thermal system compared with the BaU scenario for a cluster of 10 houses in Southampton

<table>
<thead>
<tr>
<th>Family</th>
<th>Working couple</th>
<th>Retired Couple</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>BaU</td>
<td>Aux Gas</td>
</tr>
<tr>
<td></td>
<td>Aux El</td>
<td>BaU</td>
</tr>
<tr>
<td></td>
<td>Aux Gas</td>
<td>Aux El</td>
</tr>
<tr>
<td></td>
<td>BaU</td>
<td>Aux Gas</td>
</tr>
<tr>
<td></td>
<td>Aux El</td>
<td>BaU</td>
</tr>
<tr>
<td></td>
<td>Aux Gas</td>
<td>Aux El</td>
</tr>
<tr>
<td>2000</td>
<td>7.75</td>
<td>3.97</td>
</tr>
<tr>
<td>2020s</td>
<td>7.57</td>
<td>3.80</td>
</tr>
<tr>
<td>2050s</td>
<td>7.36</td>
<td>3.61</td>
</tr>
<tr>
<td>2080s</td>
<td>7.13</td>
<td>3.35</td>
</tr>
</tbody>
</table>

the carbon benefits from the solar thermal system are negated. For dwellings with increased DHW consumption the estimated carbon emissions exceed the carbon emissions of the BaU scenario. A microgrid with an evacuated tube system is the only scenario where an electric auxiliary system can still deliver carbon savings, highlighting the improved performance of the system.

An economical analysis has been performed and the payback period in years for each scenario has been calculated. For the calculations it is assumed that the gas price is 3.485 p/kWh and the electricity price is 12 p/kWh. The modelled flat plate collectors system costs £3,000 and the evacuated tube system costs £4,000. These costs include all the piping, the thermal storage tank and the installation. Another £200 per house was assumed for the microgrid case for the extra piping required and the separate pre-heat tank. All payback periods are calculated against the BaU scenario of a condensing boiler that costs £900, including installation, which is the average price of the Baxi range (Baxi, 2009). For maintenance is assumed that the solar thermal system will
cost £40/year per dwelling. Maintenance assumes an inspection at £80 every two years, whilst a yearly inspection for a condensing boiler is around £50. The annual estimated savings in the operating expenses (assuming a 0% discount rate), for the lifetime of the unit(s), are presented in Figure 6.10.

The estimated financial savings are marginal and the corresponding payback periods are generally high, exceeding the lifetime of a solar thermal unit for all cases, making the scheme uneconomic at the moment. When the solar thermal system displaces electrical systems, then the payback period is estimated approximately 13 years for a cluster of 10 houses and 14-16 years for the microgrid. It becomes apparent that the Government needs to develop a way of supporting this technology. The “Renewable Heat Incentive” (RHI) that has been announced from the DBIS (2009) is expected to apply to all the heat generated from renewables. It is suggested that the minimum reward for every kWh that a solar system is estimated to generate has to be set to a minimum of 12 pence in order to make the technology economically viable at least in the first instance for the environmentally-aware early adopters. Such a scheme is expected to reduce the payback period for this technology down to 12 years for a cluster of 10 houses and \(~14\) for a microgrid, as shown in Figure 6.11.

Generally, a solar thermal microgrid scheme proved to have longer payback periods.
Figure 6.11: Estimated savings in £/year and corresponding payback periods (assuming 0% interest rate) for solar thermal systems at the single house and at the microgrid level, assuming a feed-in tariff of 12p/kWh generated than the single installations due to the increased cost of the extra piping/insulation required.

6.4 Photovoltaics results

The annual yields as estimated for the 1.8 kW\textsubscript{p} and the 18 kW\textsubscript{p} poly-crystalline arrays, under the four weather climate data, are presented in Table 6.8. All the panels are assumed to be mounted on the roof with NOCT of 45°C.

<table>
<thead>
<tr>
<th>PV electricity generation (kWh/annum)</th>
<th>1.8 kW\textsubscript{p}</th>
<th>18 kW\textsubscript{p}</th>
</tr>
</thead>
<tbody>
<tr>
<td>2000</td>
<td>1865</td>
<td>18647</td>
</tr>
<tr>
<td>2020s</td>
<td>1898</td>
<td>18980</td>
</tr>
<tr>
<td>2050s</td>
<td>1934</td>
<td>19341</td>
</tr>
<tr>
<td>2080s</td>
<td>1985</td>
<td>19853</td>
</tr>
</tbody>
</table>

Table 6.8: Annual electricity generation in kWh/annum from PV for the single house and the 10 houses cluster

PV performance is predicted to benefit from the higher levels of irradiance in the future.
For the 2080s generation is estimated to be 6.5% higher compared to the present day. The importance of such an increase is not only the potential CO$_2$ emissions that may be saved, but the fact that higher levels of irradiance will not be offset by higher temperatures in the future, benefiting PV technologies. For the mono-crystalline array, the results are very similar and therefore the rest of this section presents only the results for the poly-crystalline array.

The total installed capacity generates about 68-72%, 50-55% and 45-50% of the total electricity demand for the low, medium and high consumption profiles respectively. For the most of the cases, the generation profile does not match the consumption profile and the generated electricity cannot be consumed locally. High levels of the generated electricity are exported to the grid whilst the dwellings remain heavily dependent on the grid. The least dependent is the retired couple, where 60% of the generated electricity is consumed locally. For the working couple that percentage is 37% and for the family is 50%. For the 10 houses cluster 50% of the generated electricity is consumed locally and the rest is exported. When the houses form a microgrid the benefits are evident in terms of import and export. Lower levels of import and export are achieved, which means that more generated electricity is utilised by the microgrid (7%-8% more electricity is met by the microgrid). This approach would enable the cluster of houses that form the microgrid to achieve a higher rating in the “Code for Sustainable Homes”, due to lower imports from the grid. Figure 6.12 presents the levels of electricity demand, import and export for the single house and the 10 houses cluster when the houses are not linked and when they form a microgrid, for Southampton, 2000.

In terms of carbon, the 10 houses cluster has the same performance when it forms a microgrid and when the houses are not linked, since it is assumed that the displaced electricity has the same carbon intensity as the electricity imported from the grid. However in practice high levels of generation occur during the day when the national grid is more dependent on fossil fuels and therefore displaced electricity is expected to have higher carbon intensity. Hence, load matching that translates to on-site consumption is encouraged and this is certainly improved for the microgrid case. Increased local consumption of the generated electricity also implies that the microgrid has less
impact on the national grid. Figure 6.13 presents the contribution of the PV system towards the CO$_2$ reductions at the single house level.

The economic viability of the photovoltaic power system is strongly dependent upon the initial investment and the utility’s payback rate. The capital cost for the 1.8 kW$_p$ is assumed to be £9,500 with a maintenance cost of £100 per year. For the 18 kW$_p$ installation the capital cost is £95,000 and the maintenance cost is £700/year. For the feed-in tariff, four scenarios are examined and the values used are summarised in Table 6.9. The first scenario is a BaU case where export is not rewarded. The second scenario is based on the price offered from Scottish and Southern Energy (SSE) for electricity associated with solar power. The third scenario (DECC) is based on the prices recently published by the Government in the “Consultation on renewable electricity and financial incentives” from the Department of Energy and Climate Change (DECC, 2009a). According to the fourth scenario (On-site scenario) the local consumption of the generated electricity is encouraged by rewarding with an extra 5 p/kWh for electricity that is consumed locally instead of the electricity that is exported to the grid. All feed-in tariff scenarios are assumed to be flat over time.

Figure 6.14 and 6.15 illustrate the estimated savings from PV for the single house and the 10 houses cluster respectively, in £ per year for the present day in Southampton,
Figure 6.13: CO$_2$ emissions from electricity at the household boundary with and without PV, for three occupancy profiles at Southampton, 2000

Table 6.9: Feed-in tariff (FIT) scenarios used for the economical analysis of the PVs

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Import</th>
<th>Export</th>
<th>Consumed locally</th>
<th>Generation</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. BaU</td>
<td>12</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>2. SSE</td>
<td>12</td>
<td>18</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>3. DECC</td>
<td>12</td>
<td>5</td>
<td>0</td>
<td>36.5 (31.0)*</td>
</tr>
<tr>
<td>4. On-site</td>
<td>12</td>
<td>0</td>
<td>5</td>
<td>36.5</td>
</tr>
</tbody>
</table>

*The value in brackets applies for installations of 4-10 kW (e.g. microgrid)
under all four scenarios described above. The corresponding payback periods for each scenario are also given in order to evaluate the outcome of each scenario. For the calculation of the payback periods, no interest rate is assumed for the PV system’s capital cost.

The BaU scenario appears to result in prohibitive payback periods more than four times the lifetime of the PV system. However, the payback period estimated for the microgrid is improved compared to the 10 houses that they are not linked, but still it is not economically viable. The buy-back price offered from Scottish and Southern Energy improves the savings significantly and reduces the payback periods but further financial assistance is required for PV technology to reach a break-even point within its expected life-time. The microgrid’s performance is improved also for this scenario compared with the 10 houses that are not linked.

The last two scenarios deliver approximately the same savings and similar corresponding payback periods. The difference of the on-site scenario is that it gives an extra incentive to generators to consume the generated electricity directly on-site. It is interesting to observe that the tariff suggested from the Department of Energy and Climate Change does not benefit microgrid schemes. Some of the wider benefits of using the
generated electricity locally are offset from the high price for the generated electricity and the even higher price of the generated electricity that is exported to the network (36.5p/kWh + 5p/kWh). At the same time, the lower tariff given for installations of 4 to 10 kW compared to sub 4kW systems, limits further the potential for microgrid schemes. Under the fourth scenario, where good load matching and direct on-site consumption are encouraged the benefits from the microgrid formation are not diminished and the payback period of the scheme is further improved. Such a policy also ensures that the generators will not export high levels of electricity to the local distribution network which in long term may increase the costs to that network.

PV systems benefit from the increased solar irradiance as a result of reduced cloud cover due to climate change; the total energy generated per year is estimated to increase by 6%-7% by the 2080s. The impact on the payback periods differs, according to the feed-in tariff scenario assumed. For all the scenarios the microgrid corresponds to shorter payback periods compared with the non microgrid case, apart from the “DECC” scenario.
6.5 Ground Source Heat Pump (GSHP) results

For the purposes of this study, GSHPs are used to provide space heating only. Domestic water heating is covered from a conventional gas boiler or solar thermal if available, whilst space cooling is not considered. The gas boiler also operates as an auxiliary heating source for those intervals that the ground source heat pump cannot meet the demand. Figure 6.16 illustrates the levels of the heat pump power and the auxiliary power consumed in one year for one detached house built in the 1980s in Southampton, 2000. The results are presented for three supply temperatures for a range of domestic heating applications, as shown on Table 6.10.

<table>
<thead>
<tr>
<th>Distribution system</th>
<th>Delivery temperature</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low temperature underfloor heating</td>
<td>35 °C</td>
</tr>
<tr>
<td>High temperature underfloor heating</td>
<td>45 °C</td>
</tr>
<tr>
<td>Low temperature radiators</td>
<td>55 °C</td>
</tr>
</tbody>
</table>

Table 6.10: Delivery temperatures from the GSHP for various heating distribution systems

The working couple, though it is the profile with the lowest heating demand, corresponded to the highest levels of auxiliary heating. The non continuous heating demand
and the extended intervals between the heating periods resulted in lower temperatures in the heat storage tank and therefore more auxiliary heating was required from the scheme to meet the demand. For the other two profiles the GSHP’s performance was improved, and for the family and the retired couple auxiliary heating accounted for 14% and 9% respectively, of the total power consumed from both the gas boiler and the GSHP. The ratio of the auxiliary heating consumption over the total power consumption was principally dependent on the occupancy profile and did not vary across the three wet system temperatures assumed.

The carbon performance of the GSHP at the single house level, compared with the BaU scenario of a condensing boiler of 90% efficiency is presented in Figure 6.17. The benefits from the GSHP were maximised when the ground source heat pump was used to drive low temperature heating systems where it achieved the highest coefficient of performance (COP). For a wet heating system at 55°C the heat pump achieved an average COP of 3.15 and CO₂ emissions were reduced by 25-29% for the three occupancy profiles relative to the BaU case. When the wet system was operated at 45°C the average COP was 3.95 and the related emissions were reduced by 38-44%, whereas for 35°C the average COP was 4.75 and the carbon emissions reduction was 48-55%. Unlike the power consumption, the carbon performance of the scheme was strongly related to the type of the heating system that the heat pump drove, making GSHP an ideal option for all levels of demand when combined with low temperature systems.

To estimate the financial savings and the corresponding payback periods it was assumed that the total cost of the GSHP is £5,600 (assuming 850 £/kW for a horizontal system (EST, 2007)) and that the maintenance will be £60/year, assuming a yearly inspection of 1 hour. Financial payback periods were calculated for two scenarios: the first scenario did not assume any subsidies and the second one was based on a parity scheme, where each kWhₘₜₜ generated from the GSHP is rewarded with a price equal to the gas price from the utility grid. Financial payback periods were calculated based on the formula:

\[ \text{Financial payback period} = \frac{\Delta\text{CAPEX}(\text{GSHP} - \text{BaU})}{\Delta\text{OPEX}(\text{GSHP} - \text{BaU})} \]
Figure 6.17: CO$_2$ emissions from a detached house with a GSHP, with the 1980’s building fabric, in Southampton, 2000

Where,

CAPEX: Capital expenditure in £.

OPEX: Operational expenditure in £/year.

When no subsidy was assumed the GSHP scheme proved to be more expensive than the the BaU scenario for systems that operate at either 55°C or 45°C. Marginal savings were achieved for systems that operate in 35°C but the shortest payback period was estimated to be over 45 years.

The results under the subsidy scenario are presented in Figure 6.18 and they show the financial savings achieved from a GSHP system and the corresponding payback periods. The estimated payback periods were substantially improved compared with the no subsidy scenario but then were still high taking into account that the expected lifetime of the compressor is 15-25 years (EST, 2007). The payback periods also depict the improved performance of the GSHP scheme for those dwellings with high and continuous demand, such as a retired couple in a detached house with conservatory.

For the microgrid, two types of ground heat exchanger were investigated; horizontal
slinky heat exchanger and vertical boreholes. In all cases, the results are presented for both heat exchanger types and are compared with a 10 house cluster where the houses are not linked together, in order to evaluate microgrid’s impact. The 10 house cluster and the microgrid are assumed to be in the case study area of Marchwood in Southampton, UK.

The microgrid proved to have a substantial impact on the scheme in terms of both, carbon and economics. Figure 6.19 presents the power consumption from the heat pumps and the levels of auxiliary heating required for a cluster of 10 houses compared with the microgrid. For the microgrid, the auxiliary heating required was reduced by $\sim 75\%$ for the horizontal ground heat exchanger and by $\sim 82\%$ for the vertical boreholes, compared with the 10 houses that are not linked, whereas the heat pump consumption remained the same. The COP was estimated to be marginally higher for the vertical boreholes, though the two heat exchangers were sized as to perform equally and therefore significant differences were not expected. The higher COP, represents the improved performance of the vertical boreholes, which reach at a maximum depth
of 70m, where the ground temperature is higher and less seasonal variation is observed.

In terms of carbon performance, the microgrid achieved lower emissions that are principally associated with a reduction in auxiliary heating requirements. Figure 6.20 summarises how the two microgrid schemes performed compared with the 10 house cluster with GSHP at the single house level. The horizontal line indicates the CO$_2$ emitted from the cluster with condensing boilers of 90% efficiency at the single house level (BaU scenario). The GSHP schemes achieved significant savings for all the schemes compared with the BaU scenario. For lower temperature heating distribution systems the savings increased and for a heating system at 35°C savings were almost double that of a system at 55°C. The formation of the microgrid saved $\sim$1 tonne of CO$_2$ (6-8% reduction) for a system with a horizontal ground collector and $\sim$1.2 to 1.5 tonnes (8-10% reduction) for a vertical boreholes system.

For each GSHP scheme the annual financial savings were estimated and the financial payback periods calculated, against the BaU scenario. Table 6.11 provides the costs for the BaU scenario and GSHP systems used for the calculations of the payback periods. Costs for the heat distribution system (underfloor heating or radiators) were not included. The maintenance costs for the GSHP systems refer to the heat pump and
the circulation pumps, since the ground collector does not need any maintenance. For the microgrid it was assumed that the costs for the ground collector and maintenance are 10% less than the costs for 10 individual houses (EST, 2007).

Figure 6.20: \( \text{CO}_2 \) performance of the two microgrid GSHP schemes versus a 10 houses cluster with individual GSHPs in Southampton, 2000

If no subsidy scheme is assumed then the GSHP were estimated to achieve financial savings in OPEX only for heating systems that operate in temperatures of 45°C and 35°C. For heating systems at 45°C the estimated financial savings were marginal, whilst for heating systems at 35°C the savings were \( \sim \)£80/year per dwelling for the 10 houses cluster and \( \sim \)£110/year per dwelling for the microgrid. When the GSHP was used to drive heating systems of 55°C then the running costs were higher by \( \sim \)£50-£90/year

<table>
<thead>
<tr>
<th></th>
<th>BaU</th>
<th>GSHP</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Condensing boiler (10 Houses)</td>
<td>10 Houses (Not linked)</td>
</tr>
<tr>
<td><strong>Capital cost</strong></td>
<td>£9,000</td>
<td>£56,000</td>
</tr>
<tr>
<td><strong>Maintenance</strong></td>
<td>£500</td>
<td>£500</td>
</tr>
</tbody>
</table>

Table 6.11: Capital and maintenance costs for the BaU scenario and the GSHP systems (EST, 2007)
per dwelling, compared to the BaU scenario. For the cases where savings were achieved the corresponding payback periods were projected to be over 50 years for the present day weather data, whereas savings were projected to decrease in the future time-slices. By the 2080s, savings in £/year were estimated to be 35-45% lower than the present day, principally due to the lower demand for space heating.

When a parity scheme was introduced and each kWh of generated heat was rewarded with the same price as the price of one kWh of natural gas from the network, then the payback periods were reduced substantially. The estimated savings and payback periods compared to the BaU scenario, for 10 single houses and 10 houses that form a microgrid are presented in Figure 6.21. All houses are assumed to be in Southampton at the present day (2000). For the microgrid case the results are given for both types of ground collectors; horizontal and vertical.

The GSHP schemes were financially competitive only when they were used with low temperature heating systems (35°C). For horizontal ground collectors, the microgrid returned better payback periods compared with the 10 individual houses. For the 10 individual houses only horizontal ground collectors were assumed and therefore the 10 houses cluster has a lower financial payback period than the microgrid with vertical boreholes, which is characterised by the increased capital cost.

Climate change results in higher ground temperatures but also in lower space heating demand. Results showed that potential financial savings from the higher ground temperatures were negated from the lower heating demand. The latter was a limiting factor for the GSHP schemes and therefore, financial payback periods (assuming the same capital costs) were estimated to increase in the future. Figure 6.22 illustrates the climate change impact on the annual savings and payback periods for three GSHP schemes for a cluster of 10 detached houses in Southampton. For all cases an underfloor heating system at 35°C was assumed.

Results showed that a parity scheme such as the one assumed here is not enough to assist GSHPs. Unless substantial support is given to this technology from the Government through the Renewable Heat Incentive, the GSHPs cannot be economical viable and competitive to conventional technologies, such as condensing boilers.
CHAPTER 6. Results

Figure 6.21: Savings in £/year and corresponding payback periods for GSHP schemes for 10 houses in Southampton, 2000, when not linked and when they form a microgrid (horizontal and vertical systems). A FIT of 3.475p/kWh generated is assumed.

Figure 6.22: Climate change impact on annual savings and payback periods for three GSHP schemes operating at 35°C for a cluster of 10 detached houses in Southampton
6.6 Combined Heat and Power (CHP) schemes results

The results from three CHP schemes are presented in this section:

- a micro-CHP unit installed at the single house (7kW_th:1kW_el),
- one mini-CHP unit that operates for a cluster of 10 houses that they form a microgrid (51kW_th:21.5kW_el) and
- three CHP units connected in parallel that operate for a cluster of 10 houses that form a microgrid (51kW_th:21.5kW_el).

All schemes are compared with the BaU scenario of a condensing boiler 90% efficiency and electricity from the mains and the results are presented for a cluster of houses in the area of Marchwood, Southampton, UK. CHP schemes were designed to meet demand for space heating and domestic hot water.

The related carbon emissions varied according to the heating option deployed. Figure 6.23 shows the carbon emissions for three fabric-dependent clusters in Southampton. The 1980s building fabric represents the cluster in the area of Marchwood in Southampton, whereas the other two show the potential savings that may be achieved by improving the cluster’s building fabric. Figure 6.24 illustrates the carbon performance of the CHP schemes (options 2, 3 and 4 detailed in Section 4.9, Figure 4.32) compared with the BaU scenario. For the BaU scenario, emissions were estimated to be 47.5 t/year for the cluster in Southampton. If the cluster were built according to the 2002 regulations the emissions would be 36.4 t/year and if it were built according to 2006 regulations the related emissions would be 33.9 t/year.

Generally, the carbon performance of each CHP scheme (micro, 1-mini and 3 CHPs in series) differed significantly, with the micro-CHP resulting in higher carbon emissions than the BaU scenario of a condensing boiler. It has also to be noticed that the lower heating demand, due to the improved building fabric quality, did not reduce the carbon performance of the CHP schemes as much as it would be expected. This is because
the lower heating demand of the dwellings with improved building fabric could be met more often from the storage tank, resulting in less start-up cycles of the CHP unit(s) and lower fuel consumption.

Micro-CHP was generally characterised by poor carbon performance and did not deliver carbon savings for any of the residential clusters examined, compared with the condensing boiler option. In general, micro-CHP schemes performed better with high heating demand profiles, but none of the housing clusters in Marchwood enabled micro-CHP to deliver carbon savings. This estimate also agrees with the results of a micro-CHP field trial undertaken by the Carbon Trust (2007). The low projected performance of the micro-CHP can be attributed to the relatively low heating demand and the non-smooth heating profile of a single dwelling.

Significant savings were achieved when the ten houses were formed into a local network and the CHP units were operated as a common facility for the microgrid. In Southampton, the annual emissions for the mini-CHP scheme were estimated to be 40.5 t for the cluster in Marchwood with the potential to reach 31.5 t if the building fabric is improved according to the 2002 regulations or 30.0 t if the building fabric is improved according to 2006 regulations. Further savings were achieved from the three
CHAPTER 6. Results

Figure 6.24: Carbon performance of the CHP schemes studied compared with the BaU scenario mini-CHP units operating in parallel, and for the cluster in Marchwood the annual carbon emissions were estimated to be 39 t or 16.5% less, over the BaU scenario.

An important aspect for the CHP analysis is the level of electricity export and import to and from the utility grid. Figure 6.25 shows electricity export as a percentage of electricity generated for the three CHP schemes for the cluster in Southampton for the present day. The export is also given assuming that the same cluster has improved building fabric, compliant to 2002 or 2006 regulations.

For the micro-CHP case, almost half of the electricity generated was consumed locally (43%), while for the other two schemes more than two thirds of generated electricity was exported to the utility grid, due to the lower thermal:electrical ratio of the mini-CHP schemes compared with the micro-CHP. For all cases, it was observed that higher levels of export corresponded to higher levels of heating demand. Figure 6.26 shows imported electricity to all the microgrid schemes for the present-day weather case as a percentage of total electricity demand. It is clear that higher levels of electricity from the utility grid were displaced from those CHP schemes with high heating demand. The “1980s” bars represent the cluster in Southampton whereas the “2002 regulations” and “2006 regulations” bars show what levels of import would be if the same cluster
had improved building fabric. It should be noticed that the 3 CHPs in parallel scheme reduced a cluster’s dependency on the national grid for all the cases.

Running costs in terms of gas and electricity were also investigated for each heating option and potential savings from the CHP schemes were identified. Initial and capital costs were obtained from various case studies and costs for the microgrid pipe network were included. Table 6.12 summarises all the capital and maintenance costs for the BaU scenario and the three CHP schemes.

<table>
<thead>
<tr>
<th></th>
<th>Capital cost: £</th>
<th>Heat network costs per cluster: £</th>
<th>Total cost per cluster: £</th>
<th>Maintenance: £/year</th>
</tr>
</thead>
<tbody>
<tr>
<td>Condensing boiler</td>
<td>900</td>
<td>0</td>
<td>9,000</td>
<td>50 (dwelling)</td>
</tr>
<tr>
<td>Whispergen micro</td>
<td>2,600</td>
<td>0</td>
<td>26,000</td>
<td>100 (dwelling)</td>
</tr>
<tr>
<td>Mini-CHP theoretical unit</td>
<td>39,000</td>
<td>6,000</td>
<td>42,000</td>
<td>2,000 (microgrid)</td>
</tr>
<tr>
<td>Whispergen micro + Baxi</td>
<td>44,600</td>
<td>6,000</td>
<td>47,600</td>
<td>2,600 (microgrid)</td>
</tr>
<tr>
<td>DACHS + EC Power XRGI</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 6.12: Capital and maintenance costs for the BaU scenario and the three CHP schemes
Figure 6.26: Electricity import for all CHP schemes for the cluster in Southampton for the present day assuming three building fabrics

Figure 6.27 gives an estimation of the annual savings compared with the BaU scenario for all the Southampton clusters for the present day, the three CHP options and two feed-in tariffs scenarios, based on the tariffs published in the “Consultation on Renewable Electricity Financial Incentives” (DECC, 2009a);

- Fossil fuel scenario. The consultation document did not include any FITs for non-renewable micro-CHP technologies. However, a “pilot” system was announced, which will support the first 30,000 domestic installations (<2kW<sub>el</sub>) with a review to start only when the 12,000th installation has occurred. It is stated that support for non-renewable CHP technologies up to 50kW<sub>el</sub> will be considered in the future. The generation tariff suggested is 10p/kWh. Here it is assumed that if a tariff is suggested for larger non-renewable units, it will be significantly lower. Therefore, for the export tariff the minimum guaranteed price of 5 p/kWh is assumed. For the generation a price of 4.5 p/kWh is assumed, which is the half of the price suggested for biomass CHP in the consultation.

- Biofuel scenario. For this scenario the prices suggested for biomass CHP (<50kW) are used. The export tariff is 5 p/kWh and the generation tariff is 9 p/kWh.
Figure 6.27: Annual savings from CHP schemes over the BaU scenario for the cluster in Southampton at the present day. Financial payback periods in years are also shown.

The fuel price used for this scenario is 2.52 p/kWh (7 £/GJ) which is the price for wood pellets for domestic use (fuel price and not delivered heat), including delivery, as suggested in the UK biomass strategy report 2007 (DTI, 2007b).

The corresponding payback periods for each scenario were also calculated. The micro-CHP option was estimated to achieve marginal savings for most of the dwellings examined here. For the biomass micro-CHP, the payback period is expected to be higher than the one estimated here, due to the higher capital cost of the unit compared with the WhisperGen unit. Therefore, further support is required for domestic micro-CHP systems to be given through the RHI otherwise this technology cannot be economically viable in the near future, unless capital costs drop dramatically. Leading micro-CHP manufacturers are believed to be targeting a marginal unit cost of around £600 relative to a condensing boiler, which is expected to half the payback periods (Carbon Trust, 2007). The costs will only drop when these units are manufactured in volume and therefore support from the Government at this early stage is crucial.

The microgrid schemes were estimated to have significantly shorter payback periods, under both scenarios. Clustering seems to enable small scale CHP to yield not only more carbon savings but also financial savings over the business as usual case.
It is clear that amongst the three CHP schemes, the 3 CHPs connected in parallel performed better, and achieved the highest carbon savings for the same cluster of houses. Savings were achieved due to the following factors:

- Better matching of generation profile to the consumption profile. As stated previously one of the crucial constraints for achieving carbon savings through a CHP scheme is a long duration operating mode with as few as possible start-up cycles for the unit. In this way, not only higher carbon savings are achieved, but also the lifetime of the unit is increased. Practically this constraint means that once the CHP is turned on, it should remain on for a minimum amount of time (cycle duration). Therefore there are certain intervals where a unit may be turned on, when there is no demand for heat. Consequently generated heat (and electricity) cannot be used locally. The advantage of the 3 CHPs in parallel is that their operation can be scheduled in order to minimise the generation during intervals that is not needed.

- Less electricity import. Amongst the three different schemes it is shown that less electricity is imported from the grid for the scheme with the 3 CHPs in parallel, though less electricity is generated in total compared to the single mini-CHP case. The improved local utilisation of the generated energy can be attributed to the scheduling of the units. The units follow the occupancy, the heating and the electrical profiles closer and therefore the excess in generated electricity is lower.

Generally, results show that high heat:electricity ratio micro-CHP operated at the single house level, is a technology worth pursuing only for a limited number of dwellings (high and continuous heating demand profile). If installed in appropriate dwellings and if a favorable FITs scheme is introduced, savings can be significant enough, not only for early adopters but also for more reluctant consumers. At the same time, carbon performance and financial return were estimated to further improve with clustering, increasing the potential number of dwellings appropriate for this technology.
Chapter 7

Discussion - Future work

7.1 Key findings

This research has investigated the carbon performance of various residential houses and clusters for a number of scenarios, including energy efficiency measures and microgeneration technologies. The key findings of each model are presented in the following sections.

7.1.1 Space heating demand findings

The heating demand demand of the single house was predicted for 3 occupancy profiles (family, working couple, retired couple), 3 building types (detached, semi-detached, terraced) and 3 building fabrics (1980s fabric, compliant to 2002 regulations, compliant to 2006 regulations) for the present day. The investigated building fabrics reflect the evolution of UK building regulations and the occupancy profiles represent typical UK households. The impact of the climate change on each heating demand was assessed for three future time-slices; 2020s, 2050s and 2080s taking the projections of UKCIP02.

As would be expected, building type proved to have a significant impact on the heating demand of a single house after normalising the results at the m² level (kWh/m²/year). Terraced houses were estimated to have the lowest demand, followed by semi-detached
and then detached. The observed differences occur due to the limited heat losses from semi-detached and terraced houses, which have less external wall area exposed to the environment.

Noteworthy are the results for the three building fabrics examined, revealing the potential carbon savings that can be achieved through simple energy efficiency measures, such as improved cavity wall insulation, loft insulation and glazing improvements. A house compliant to 2002 regulations was estimated to save 45%-55% carbon emissions from space heating compared with a house built in the 1980s. Savings were 50%-70% for a house compliant to 2006 regulations. This assumes that the comfort levels in house are the same before and after a refurbishment. A typical effect of energy saving measures, is an increase in comfort levels (higher setpoint temperatures), as energy costs have fallen. This “rebound effect” reduces the delivered carbon savings of the measures adopted.

The impact of climate change on domestic space heating demand is expected to reduce further the carbon emissions from the domestic sector. Space heating demand was projected to reduce by at least 20% by the 2050s compared with the 2000 levels due to higher ambient temperatures.

### 7.1.2 Solar thermal schemes findings

Various active solar thermal systems were investigated. They were estimated to halve the fossil fuel consumption for domestic hot water for the single dwelling with the potential to deliver slightly further savings in the future due to climate change impact that benefits the technology. The formation of a microgrid increased the carbon performance of the schemes and achieved an additional 11%-14% savings for flat plate collectors systems and about 25% for evacuated tube collectors systems in relation to the non microgrid case.

None of the systems investigated were estimated to be economically viable if not subsided. Payback periods though were significantly improved for the microgrid case. The Low Carbon Buildings Programme grant was not taken into account since it has been
Figure 7.1: Cost of each kWh<sub>th</sub> generated from a solar thermal system, during a 15 year period, for a 10 house cluster in Marchwood, 2000

Figure 7.2: Cost of each kg of CO<sub>2</sub> saved from a solar thermal system, during a 15 year period, for a 10 house cluster in Marchwood, 2000

replaced from FITs. All the required financial support is expected to come through the RHI that will be soon published from the Department of Energy and Climate Change. Based on the annual yields it was estimated that a price less than 12 p/kWh<sub>th</sub> gen-
erated, would not be sufficient to support the viability of this technology in the near future. Figure 7.1 shows the cost of each kWh\_th generated from the solar thermal systems, during a 15 year period, for the 10 house cluster for two scenarios; no subsidies and a feed-in tariff of 12 p/kWh\_th generated. Figure 7.2 shows the corresponding costs for each kg of CO\_2 saved from the solar thermal systems during the same period. Costs were calculated assuming no interest rate (coloured bars) and an annual interest rate of 5\% (white bars). The capital costs of the flat plate system and the the evacuated tube system were £3,000 and £4,000 per dwelling respectively. The gas price used for all the calculations was 3.485 p/kWh.

### 7.1.3 PV schemes findings

The available roof space, suitable for PV, was estimated to be less than 15m\textsuperscript{2} for the houses in Marchwood. This was the main criterion to determine the size of total installed capacity for the PV system, which was 1.8 kW\textsubscript{p} per dwelling. A PV system of this size contributed more than 50\% towards the reduction of carbon dioxide emissions associated with electricity consumption for the cluster of 10 houses, saving approximately 8 t of CO\_2 per year. The formation of the microgrid does not affect the carbon performance of PV systems but it affects their economics. The financial performance of the PV systems considered in this research was assessed under a number of scenarios (scenarios 1-4 as presented later on this section), where the microgrid proved to deliver shorter payback periods for the most of them. It should be noted though that the prices suggested in the “Consultation on renewable electricity financial incentives” from DECC (2009a) do not benefit microgrid schemes, whilst at the same time the high price suggested for generation decreases the impact of load matching (local consumption) on the economics. The main benefit of forming a microgrid is the improved load matching, which is currently not supported strongly enough through the suggested policies.

Figure 7.3 shows the cost of each kWh\_el generated from various PV schemes, during a 15 year period for the 10 house cluster, for four scenarios:

1. No income: No capital cost subsidies, FITs or potential savings from avoided
import were taken into account. Essentially this scenario shows the cost of the generated electricity as a function of the capital and maintenance costs only.

2. Avoided import: Savings from avoided import were included (12 p/kWh\textsubscript{el}), but no capital cost subsidies or FITs from the Government applied.

3. SSE scenario: A FIT scheme was introduced, rewarding with 18 p/kWh\textsubscript{el} exported (price offered from Scottish and Southern Energy).

4. DECC scenario: A FIT scheme of 31 p/kWh\textsubscript{el} generated and an extra 5 p/kWh\textsubscript{el} exported was assumed (prices suggested from DECC).

Figure 7.4 shows the corresponding costs to the householder/developer for each kg of CO\textsubscript{2} saved from the PV schemes during the same period, for all four scenarios. Costs were calculated assuming no interest rate (coloured bars) and an annual interest rate of 5% (white bars).

Figure 7.3: Cost to the household of each kWh\textsubscript{el} generated from various PV schemes, during a 15 year period assuming a 0% interest rate, for a 10 house cluster in Marchwood, 2000. The impact of a 5% interest rate on the economics (IR 5%) is also shown.
7.1.4 GSHP scheme findings

For space heating purposes, various GSHP schemes were investigated for the single house and the cluster of 10 houses. A GSHP’s performance was assessed for three different delivery temperatures in order to assess the GSHP’s performance for three wet heating systems. The lowest COP of the GSHP was estimated to $\sim 3.1$ and the ratio for electricity (fuel for GSHP) carbon intensity over the natural gas (fuel for condensing boiler with 90% efficiency) carbon intensity is $\sim 2.1$, and therefore all the schemes delivered carbon savings (carbon benefit ratio $3.1/2.1=1.48$). The operating temperature of the heating system was a critical factor for GSHP’s performance, and when the GSHP was operated at low temperatures ($35^\circ$C) it delivered almost the double carbon savings in comparison to high temperatures ($55^\circ$C), for the same level of delivered space heating.

The formation of the microgrid improved the carbon performance of the GSHPs by 6-8% for systems with horizontal ground collectors and by 8-10% for systems with vertical boreholes. Low operating temperatures also halved the estimated financial payback periods relative to high temperatures, but generally the parity reward scheme
Figure 7.5: Cost of each kWh generated from various GSHP schemes (at 35°C), during a 15 year period assuming a 0% interest rate, for a 10 house cluster in Marchwood, 2000. The impact of a 5% interest rate on the economics (IR 5%) is also shown.

Figure 7.6: Cost of each kg of CO$_2$ saved from various GSHP schemes (at 35°C), during a 15 year period assuming a 0% interest rate, for a 10 house cluster in Marchwood, 2000. The impact of a 5% interest rate on the economics (IR 5%) is also shown.

(generation price = import price) investigated in this research is not sufficient to support this emerging technology. It has to be noted that capital cost did not include
the heat delivery system. Climate change was observed to have a negative impact on this technology, since the reduced demand for space heating in the future limits the financial savings that can be achieved from GSHPs. Figure 7.5 shows the cost of each kWh\(_{th}\) generated from various GSHP schemes, during a 15 year period for the 10 house cluster, for two scenarios; no subsidies and a feed-in tariff of 3.475 p/kWh\(_{th}\) generated (parity scheme). The corresponding costs of the carbon saved (p/kgCO\(_2\)) during the 15 year period, assuming no interest rate (coloured bars) and an annual interest rate of 5% (white bars), are summarised in Figure 7.6.

### 7.1.5 CHP schemes findings

In terms of carbon performance the three CHP schemes investigated in this research can be ranked from the best to the worse as follows:

1. Three CHPs in parallel (1×1kW\(_{el}\)/7kW\(_{th}\), 1×5.5kW\(_{el}\)/14kW\(_{th}\), 1×15kW\(_{el}\)/30kW\(_{th}\)),
2. One master mini-CHP (1×21.5kW\(_{el}\)/51kW\(_{th}\)),
3. Micro-CHP (10×1kW\(_{el}\)/7kW\(_{th}\)).

Micro-CHP was generally characterised by poor performance, especially for those dwellings with low heating demand, highlighting the need to switch to co-generation technologies with higher electricity:heat ratios such as fuel cells. For all the housing clusters in Marchwood, micro-CHP did not achieve any carbon savings and CO\(_2\) emissions were up to 5% higher than the BaU scenario. The master mini-CHP operating as a common facility for the microgrid achieved carbon savings of up to 14% of the BaU level, whereas the 3 CHPs connected in parallel increased the savings up to 17%. The advantages of the three CHPs in parallel over the master mini-CHP were not only the improved carbon performance but also the improved load matching for electricity. For all the clusters, the higher levels of electrical local consumption and the lower levels of export were observed for the 3 CHPs connected in parallel scheme.

The financial savings followed the same ranking, placing the micro-CHP as the option with the longest financial return. When the cluster formed a local microgrid, the
schemes were projected to return the investment during their lifetime, with the 3 CHPs in parallel performing slightly better than the one master mini-CHP. It was estimated that the FITs for fossil fuel CHP will have to be similar to those suggested for biomass CHP, for this technology to become cost effective in the short term and contribute to alleviation of fuel poverty in low income households.

The advantage of heat networks is that the boiler (and its failure risk) is no longer the responsibility of the household. This makes them particularly attractive to low income households, since they buy 'heat' in the same way that they buy electricity.

The cost of each kWh_{th} generated and the cost of each kg CO_{2} saved, from various GSHP schemes during a 15 year period for the 10 house cluster, were calculated for three scenarios:

1. No capital cost subsidies or FITs were assumed.

2. Fossil fuel scenario: A FIT was introduced, rewarding generation with 4.5 p/kWh_{el} (half of the price suggested from DECC for biomass CHPs).

3. Biofuel scenario: A FIT was assumed, rewarding generation with 9 p/kWh_{el}, which is the price suggested from DECC for biomass CHPs.

For the thermal energy generated from the CHP schemes, no subsidies were assumed since the CHP units burn fossil fuels.

Figure 7.7 and figure 7.8 summarise the cost of each kWh_{el} generated and the cost of each kg CO_{2} saved respectively, from the CHP schemes for the 10 house cluster. The costs have been calculated for a 15 year period assuming no interest rate (coloured bars) and with an annual interest rate of 5% (white bars).
Figure 7.7: Cost of each kWh\textsubscript{el} generated from various CHP schemes, during a 15 year period assuming a 0% interest rate, for a 10 house cluster in Marchwood, 2000. The impact of a 5% interest rate on the economics (IR 5%) is also shown.

Figure 7.8: Cost of each kg of CO\textsubscript{2} saved from various CHP schemes, during a 15 year period assuming a 0% interest rate, for a 10 house cluster in Marchwood, 2000. The impact of a 5% interest rate on the economics (IR 5%) is also shown.
7.2 Discussion - Implications to UK energy policy

The need to deliver carbon neutral homes by 2016 can be expected to accelerate the uptake of microgeneration technologies, but one of the questions that needs to be answered is how much this will cost and which technologies have the potential to deliver the cheapest carbon savings.

Figure 7.9 ranks the financial performance in respect to carbon savings of the various technologies for the 10 house cluster, when houses are not linked and when forming a microgrid. No capital cost subsidies were assumed, the economics are therefore highly dependent on the FIT scenario adopted. A 0% interest rate was assumed for the results presented in Figure 7.9, whilst Figure 7.10 presents the results assuming a 5% annual interest rate.

Figures 7.9 and 7.10 show that the microgrid formation generally resulted in lower costs for each kg of CO$_2$ saved compared with the 10 house cluster where the houses are not linked. The improved performance of the microgrid, in terms of cost per kg of carbon saved, was more evident when an annual interest rate (5%) for the investment was assumed. The assumption of a 5% interest rate depicts a more realistic scenario, which is of significance mainly for developers, who are more likely to develop microgrid schemes in the future. The ranking order of the microgeneration technologies did not change for the microgrid case; however it is clear that the formation of the microgrid was advantageous for CHP technologies, more than any other microgeneration technology examined. Micro-CHP, that was estimated to have a poorer carbon performance compared with the BaU scenario at the individual household level, was able to deliver carbon savings only when operated in a microgrid scheme.

The cost of the carbon savings delivered is an important index for policy makers and planners to determine the cost effectiveness of various microgeneration technologies. It is more likely however, that for homeowners the cost of delivered energy will be the first criterion for installing any of the microgeneration technologies considered in this research. The cost of delivered energy also allows an assessment of the potential that each microgeneration technology has to reduce fuel poverty. Figure 7.11 ranks the financial performance in respect to energy generated of the various technologies.
CHAPTER 7. Discussion - Future work

Figure 7.9: Ranking of various microgeneration technologies according to the cost of each kg of CO\textsubscript{2} saved, during a 15 year period assuming 0% interest rate, for a 10 house cluster in Marchwood, 2000. No capital subsidies or FITs have been applied.

Figure 7.10: Ranking of various microgeneration technologies according to the cost of each kg of CO\textsubscript{2} saved, during a 15 year period assuming 5% annual interest rate, for a 10 house cluster in Marchwood, 2000. No capital subsidies or FITs have been applied.

for the 10 house cluster, when houses are not linked and when forming a microgrid, assuming no subsidies and a 0% interest rate. Figure 7.12 presents the corresponding results assuming a 5% annual interest rate.
CHAPTER 7. Discussion - Future work

Figure 7.11: Ranking of various microgeneration technologies according to the cost per kWh generated, during a 15 year period assuming 0% interest rate, for a 10 house cluster in Marchwood, 2000. No capital subsidies or FITs have been applied.

Figure 7.12: Ranking of various microgeneration technologies according to the cost per kWh generated, during a 15 year period assuming 5% annual interest rate, for a 10 house cluster in Marchwood, 2000. No capital subsidies or FITs have been applied.

A microgrid, although it has higher capital costs, was beneficial for all the technologies in terms of cost per kWh generated, with PV achieving marginal savings. CHP technologies were estimated to benefit from the microgrid more than any other technology; however none of the technologies delivered energy at lower cost than the BaU scenario. Figures 7.11 and 7.12 also show the level of support each technology requires.
to break even with the BaU scenario. For example PV at the single house is estimated to require a FIT tariff of about 55 p/kWh\textsubscript{el} generated, whilst a GSHP would require a FIT tariff of 8p/kW\textsubscript{th} generated, assuming a 5% interest rate for a period of 15 years.

This research is in line with the ’Code for Sustainable Homes’, in that it examines energy efficiency usage within the boundaries of the house. However, Department of Communities and Local Government (DCLG) recognise that there may be cases where it is not reasonable to expect zero carbon to be achieved through on site measures alone (DCLG, 2008). This means that policies should set out a set of solutions that can deal with the emissions that cannot be dealt with on the site of the development (’allowable solutions’). These ’allowable solutions’ include measures ranging, from local energy technologies that are directly connected to the development, through to carbon reductions from high-quality international carbon offsetting projects (e.g. wind farms). For the latter option, DCLG believes there should be limits on the means of delivering carbon saving options in the context of zero carbon homes, but in any case policies in the future may become less tight. For example a future definition of a ’zero carbon home’ may account for green energy imported from the national grid or distributed generation. Figure 7.13 shows a schematic of the current definition of a ’zero carbon home’, Level 6 in the ’Code for Sustainable Homes’, and a less tight future definition.

Under such a scenario, microgeneration technologies will have to compete with renewables on a larger scale. Wind could play a crucial role in the future energy supply, since it has the lowest energy generation costs in comparison to other technologies.

![Figure 7.13: 'Zero carbon home' (Level 6 in 'Code for sustainable homes') current definition and possible change in the future](image)
Renewable UK (former British Wind Energy Association) estimates that the generation cost of onshore wind energy is 7-10p/kWh, whilst the cost of offshore wind energy is 12-19p/kWh (RenewableUK, 2010). Assuming an average price of 8.5p/kWh for onshore and 15.5p/kWh for offshore wind, it is clear that the most of the microgeneration technologies considered in this research are not currently economically competitive. A comparison with Figure 7.12 shows that:

- PV combined OPEX and CAPEX should decrease by ∼7 times to become competitive to onshore wind and by ∼ 4 times to become competitive to offshore wind.

- Accordingly, micro-CHP combined OPEX and CAPEX should decrease by more than 4 times and more than 2 times to become competitive to onshore and offshore wind respectively. If operating for a street level microgrid, the CHP combined OPEX and CAPEX reduction has to be ∼3 times and ∼1.5 times to make the technology competitive to onshore and offshore wind energy respectively.

- Solar thermal will become competitive to onshore wind delivering electrical water heating, if current combined OPEX and CAPEX reduce by ∼ 4 times when operating for the single dwelling and ∼ 3 times when operating for a street level microgrid. Half of this reduction is required to make solar thermal competitive to offshore wind.

- Assuming electrical space heating, GSHP is the only microgeneration technology already competitive to offshore wind. When compared with onshore wind, the cost of GSHP generated energy is ∼35-40% higher.

Solar thermal and GSHP are compared with wind energy under the assumption that heat demand will be met by electric systems and that natural gas consumption within the boundaries of the house will not be used. This analysis also assumes a grid with very high capacity of renewables. If heating demand of houses is met by electrical systems then the ‘green’ electricity drawn out of the grid will be much higher. During peak times, this may result in a grid with high carbon intensity due to the operation of coal power stations. A potential increase of the grid’s carbon intensity could result
in higher carbon emissions from the UK overall, besides the emissions reduction from the residential sector. However, a grid with high capacity of renewables ensures that its carbon intensity will remain low at all times.

7.3 Implications-Future work

The notion of combining a group of homes in a street level microgrid incorporates a number of technical and regulatory issues that need to be considered and further investigated before this concept can be applied. Some of these issues are:

- smarter control strategies/smart metering,
- variable carbon intensity and
- scheduling of the units.

A smart meter is an electronic meter that enables time-of-use metering. Time-of-use metering means that energy consumption is recorded in short intervals, such as 30 min blocks, instead of a cumulative figure being recorded over a long period of time. It is envisaged that providing the householders with real-time information about their energy consumption, will give them better control of their consumption and increase their energy awareness. Shifting consumption from peak times to off-peak times and reducing the annual peak demand of a household, can be beneficial for both consumers and the environment. Consumers can have a financial benefit through a time-of-use pricing scheme, whilst shifting demand towards the baseload will result in reduced carbon emissions from the power plants. The latter also implies the use of a variable carbon intensity that changes over time instead of a fixed value that was used in this research. Over a 24 hour period, demand for electricity fluctuates widely and therefore the “generation mix” on the grid changes and the related emissions from the power plants alter accordingly. The introduction of a variable pricing scheme and a variable carbon intensity for energy consumption are two factors that have the potential to further reduce both financial and carbon savings estimated in this research.
“Smarter” algorithms for scheduling the units operating in parallel also have the potential to increase the overall efficiency of the energy network and achieve further carbon savings. Instead of the “greedy” algorithm developed for the parallel operation of the CHP units, a more advanced approach may be considered, such as an evolutionary algorithm. Parallel operation of multiple units may also be investigated as an option for other microgeneration technologies.

The formation of more complex microgrids with multiple microgeneration technologies that are not independent, but assist each other, is also an area for further investigation. For such complex schemes, optimisation of the local energy network through the use of smart control strategies will be a task of great significance for the microgrid.
Chapter 8

Conclusions

In this research the 'in use' carbon performance of various houses and clusters in a UK street were investigated. The heating and electrical demand were predicted and their impact on the carbon footprint of the single house and the cluster was assessed. Various energy efficiency measures and microgeneration technologies were considered and their carbon and financial performance for the single house and a multi-house microgrid were evaluated. The critical question of this research was not only to evaluate the microgeneration technologies over the BaU scenario, but also to investigate if these technologies have the potential to deliver further savings in a microgrid scheme.

The main conclusions drawn from this research are summarised as follows:

- Infrared thermography proved to be of high importance and not just a supplementary method. Infrared thermography can be used to collect data that cannot be collected with other methods or to validate already collected data.

- The projected impact of climate change in the South of UK is to reduce space heating demand ~20% by the 2050s due to higher ambient temperatures and fewer occurrences of very low ambient temperatures.

- Climate change is projected to result in higher ground temperatures, which will lead to a reduction in the heating uplift required to the setpoint. Assuming no change in DHW demand with time, this will lead to a reduction of 5% in heating DHW load by the 2050s.
• Microgrid formation proved to benefit all the microgeneration technologies investigated in this research either in terms of carbon performance, or in terms of financial return, or both.

• Solar thermal systems can reduce the fossil fuel requirement for domestic hot water heating by more than 50% with the potential for a further 10% reduction if combined in microgrid schemes. This technology though is not projected to be viable (considered here as achieving a financial payback within its lifetime at a 0% interest rate) based on current capital costs, unless it is supported with a minimum 12 p/kWh\textsubscript{th} generation tariff from the Government.

• A microgrid has no effect on PV’s carbon performance but it has the potential to improve the financial return period for this technology if the appropriate reward scheme is adopted. Essentially, the microgrid is a mechanism which supports trading within the microgrid to achieve avoided import from the wider national grid.

• DECC’s suggested FITs for photovoltaics were not estimated to benefit microgrid schemes at the street-level due to (a) the high generation tariff, which encourages generation, but does not ensure local consumption and (b) the lower tariff offered for installations <4kW\textsubscript{p}.

• GSHPs were estimated to improve their carbon performance when operating in microgrid schemes. Benefits are greater when the heat pumps operate in a low temperature system (35°C) and carbon savings achieved from a microgrid are estimated to be 10% higher compared with the 10 house cluster where the houses are not linked.

• GSHP was estimated to be the only microgeneration technology economically competitive to large scale onshore wind energy, assuming heating demand is met by electrical systems.

• CHP technologies are estimated to benefit more than any other microgeneration technology, in terms of carbon and financial savings, from operating as a microgrid scheme.
CHAPTER 8. Conclusions

• High heat:electricity ratio micro-CHP (Stirling engine) results demonstrated that this technology is not appropriate to the majority of dwellings. For the housing clusters presented in this research, micro-CHP delivered higher CO$_2$ emissions than the BaU scenario, highlighting the need to focus on micro-CHP technologies with higher electricity to heat ratio, such as fuel cells.

• Microgrid formation delivers operational carbon savings from micro-CHPs. Micro-CHP at the microgrid level has a better profile load profile (smoothed and extended duration) than micro-CHP at the single house level.

• Parallel operation strategies for multiple micro-CHP units enable better load matching and have the potential to deliver further savings (both financial and carbon).

• In terms of cost per kg of CO$_2$ saved, the microgeneration technologies considered in this work are ranked from the cheapest to the most expensive, as follows (ranking order was found to be the same for the 10 houses and the microgrid at both 0% and 5% interest rates):
  1. GSHP
  2. PV
  3. Solar thermal
  4. CHP

• The microgeneration technologies were also ranked in terms of cost per kWh generated, from the cheapest to the most expensive. The ranking was based on the ratio [Microgeneration$_{p/kWh}$/BaU$_{p/kWh}$]% in order to take into account the price difference and the usefulness of 1kWh$_{th}$ and 1kWh$_{el}$. The ranking order was found to be the same for the 10 houses and the microgrid, for 0% and 5% interest rate:
  1. CHP
  2. GSHP
  3. PV
  4. Solar thermal

• The assumption of an interest rate of 5% per year (over a 15 year period) resulted in much higher costs of carbon saved and energy generated from the microgen-
eration technologies, and negated any net income that was estimated when no interest rate is applied.

• This research calculated the level of support that each microgeneration will require to break even with the BaU scenario, in terms of cost of energy delivered.

• Future policies were investigated in terms of reduction of CAPEX and OPEX for microgeneration technologies in order for them to become economically competitive to large scale renewable energy generation (onshore and offshore wind).

This research appraised various microgeneration technologies in terms of their carbon and financial performance, at the single house level and at the microgrid level. The findings of this work can be used from policy makers and consumers in order to assess the potential of these technologies to deliver CO$_2$ savings across a range of building types and occupancy profiles. Delivering low cost carbon savings to homes, is a task highly dependent on policies and frameworks adopted by the Government, and without the appropriate support the microgeneration technologies investigated here are not predicted to be economically viable in the near future. This research illustrated an alternative approach to enhance the carbon and financial performance from various microgeneration technologies, by grouping together a number of houses and forming local, street-level microgrids.

The Code for Sustainable Homes defines a 'zero carbon home' based on the energy flows within the boundaries of the house. In this research the possibility of a less tight definition, which allows large scale renewables, and its impact on the microgeneration technologies market was investigated. It was concluded that such a scenario would require radical decrease of CAPEX and OPEX of the most of the microgeneration technologies in order to become competitive to large scale renewable energy generation.

In conclusion, street-level microgrids have a real potential to improve the carbon performance of residential clusters, but only if followed by appropriate changes to the energy market. Such changes include different structure of the FITs scheme (encourage local consumption), higher FITs for microgrid schemes and low interest rates for microgeneration technologies. In relation to the the UK’s housing stock mix, street-level microgrids appear to have a significant potential market.
Of the 27 million residential properties in the UK, approximately 30% could be applicable to a street-level microgrid approach (~8.1 million). Assuming a 10% uptake of the 8.1 million potential households for the street-level microgrid concept, then ~810,000 dwellings could be inter-connected in small clusters and deliver annual savings of 341 to 2,000 thousand tonnes CO$_2$, depending on the technology or technologies deployed. These savings correspond to ~0.25% and ~1.5% respectively of the total carbon emissions from the domestic sector in the UK based on 2008 figures.

The cost reduction potential of microgeneration technologies is expected to be realised due to market growth, learning by doing and technological developments. Certain technologies have the potential for a step change in their learning rate, e.g. ultra low cost thin film PV (‘disruptive technologies’). At the same time the likely long term increase in the value of electricity and natural gas will bring some of these technologies closer to parity with the prices offered from the grid.

A common feature between the microgeneration technologies is the high upfront capital investment. Cost effectiveness and carbon savings are both benefits that can only be seen in the long term and therefore they may not be enough to make microgeneration technologies appealing to the majority of consumers.

It should also be noted the strong relationship between the demand for microgeneration technologies and regulatory framework. A sudden growth of various technologies is often policy-driven, triggered by certain initiatives that Governments announce. A generous feed-in-tariff for a certain technology could increase demand but at the same it could result in an unsustainable and non viable FITs system. A surge in interest for PV as a result of the DECC feed-in tariffs of April 2010 is such a case. Therefore, governments should continuously adapt and expand their policies and financial incentives to assist a fast growing market.

A move towards decentralised energy, such as street-level microgrids, has the potential to have an important leverage in the microgeneration market if policies and financial incentives are specifically designed for such schemes (e.g. valuing heat). At the same time, the energy companies will move towards a service-focused rather than just a supply-focused role that exist at present, so negating problems such as high capital costs, reliability, regulation, information and end-user awareness.
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Appendix A

Questionnaire for the area of Marchwood
QUESTIONNARE : MARCHWOOD HOUSING AND ENERGY

Almost daily there is a news article warning of the effects of climate change and the urgent need to change our behaviour, recycle more and use energy more efficiently. Residential housing is very important in that it accounts for almost a third of the UK’s energy consumption. The University of Southampton’s Sustainable Energy Research Group is looking at ways to make more efficient use of our energy resources, in particular the way in which heat and electricity is supplied to homes.

The majority of the Marchwood village housing stock is typical of the UK. It consists of a series of developments from 1970 to the present day by a variety of housebuilders including Wilcon, Maclean, Clarke, Westbury and Bellwinch.

The attached questionnaire is a part of a research project into regional energy planning of domestic areas. This study is investigating the energy footprint of domestic housing at the street level and testing different energy supply scenarios and their likely impact on greenhouse gas emissions (CO₂) within the examined area. The outcome of this research (energy supply and generation at the community level) will be used to inform policy, developers and planning for new and existing housing.

The survey should take about 5 minutes to complete. Your personal details are not required for this survey but you may include them if you wish. These will be treated as confidential and will not be used for any other purpose. Please post your completed questionnaire to us by using the FREEPOST envelope provided.

After the completion of this project, feedback will be provided to all the occupants who wish to receive this information. This will include a summary of our findings and suggestions to reduce your energy consumption.

If you want to support this research further by giving us more information or if you require advice, please feel free to contact us at the address shown below.

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1. How many people live in this property? Please fill in the appropriate number in each box.
   - Adults
   - Children (younger than 16 years)

2. How many of the adults are working, retired, students or other? Please fill in the right box with the appropriate number.
   - Working
   - Retired
   - Students (older than 16 years)
   - Unemployed
   - Stay-at-home mum or dad

3. What building type best describe this property?
   - Detached
   - Semi-detached
   - Terraced
   - Flat

4. How many rooms are in this property? Please fill with the appropriate number:
   - Single Bedrooms
   - Living room
   - Double bedrooms
   - Dining room

5. Please tick the box that best describes the total glazed area of this property.
   - All double glazed
   - Mostly double glazed
   - Mostly single glazed
   - All single glazed

6. Does this property have any of the following? Please tick (✓) if yes, cross (X) if no or leave blank if you do not know.
   - Conservatory
   - Cavity wall insulation
   - Loft insulation
   - Boiler cylinder insulation
   - Conservatory
   - Cavity wall insulation
   - Loft insulation
   - Boiler cylinder insulation

7. What type of central heating is installed in this property?
   - Gas Boiler
   - Electric Heating
   - Other, please specify (e.g. wood boiler): …………………

8. During winter do you use additional electrical heaters (fan heaters, etc.), and if yes, how often?
   - Never
   - Everyday
   - Often
   - Rarely

9. On average, what is your annual gas bill? If you don’t have a gas bill, please leave blank.
   - Less than £300
   - £300 - £450
   - £450 - £600
   - £600 - £750
   - £750 - £900
   - Over £900

10. On average, what is your annual electricity bill?
    - Less than £200
    - £200 - £300
    - £300 - £400
    - £400 - £550
    - £550 - £700
    - Over £700

11. Please tick if any of these appliances are in this property or put the appropriate number if there is more than one.
    - Tumble dryer
    - Dishwasher
    - Electric Shower
    - Electric Hob-Oven
    - Additional Freezer
    - Computer

12. What is approximate the total area of this property? If you do not know, please leave blank. Total area: ………………… m² / ft²

Please turn over
What is the brand / type of your gas boiler? If possible please check your boiler before writing this information. If there is no boiler installed simply tick this box: □ No boiler

If you have any comments or any further information regarding your energy consumption, please write in the space provided. This might include more unusual items such as a powershower, large screen televisions or an unusual occupancy profile, for example work from home.

Thank you for completing this survey. Please post your completed questionnaire to us using the FREEPOST envelope provided. If you wish to receive a summary of the results of the current study please tick the box below:

□ Please send me a summary of the results of the current study

Name: ___________________________________________________________________________
Address:__________________________________________________________________________
___________________________________           Post code:________________________________
Tel. number:_________________________          Email:___________________________________

*Data Protection Act 1998
Appendix B

Source Code for Type 159, Type 162 and Type 156

SUBROUTINE TYPE159 (TIME, XIN, OUT, T, DTDT, PAR, INFO, ICNTRL, * ) !

******************************************************************************
! Object: DH Synchronisation C IISiBat Model: Type159 C
! Author: Anastasios Papafragkou C Editor: Anastasios Papafragkou
! Date: September 15, 2008 last modified: September 15, 2008
!
! *** Model Inputs
! Flowrate_In kg/hr [0;+Inf]
! Occupants_In − [0;+Inf]
! *** Model Outputs
! Flowrate_Out kg/hr [0;+Inf] C

! TRNSYS access functions (allow to access TIME etc.)
USE TrnsysConstants
USE TrnsysFunctions

! TRNSYS DECLARATIONS
IMPLICIT NONE !REQUIRES THE USER TO DEFINE ALL VARIABLES BEFORE USING THEM
DOUBLE PRECISION XIN !THE ARRAY FROM WHICH THE INPUTS TO THIS TYPE WILL BE RETRIEVED
DOUBLE PRECISION OUT !THE ARRAY WHICH WILL BE USED TO STORE THE OUTPUTS FROM THIS TYPE
DOUBLE PRECISION TIME !THE CURRENT SIMULATION TIME − YOU MAY USE THIS VARIABLE BUT DO NOT SET IT! DOUBLE PRECISION PAR !THE ARRAY FROM WHICH THE PARAMETERS FOR THIS TYPE WILL BE RETRIEVED
DOUBLE PRECISION STORED !THE STORAGE ARRAY FOR HOLDING VARIABLES FROM TIMESTEP TO TIMESTEP
DOUBLE PRECISION T ! AN ARRAY CONTAINING THE RESULTS FROM THE DIFFERENTIAL EQUATION SOLVER
DOUBLE PRECISION DTDT ! AN ARRAY CONTAINING THE DERIVATIVES TO BE PASSED TO THE DIFF. EQ. SOLVER
INTEGER*4 INFO(15) ! THE INFO ARRAY STORES AND PASSES VALUABLE INFORMATION TO AND FROM THIS TYPE
INTEGER*4 NP, NI, NOUT, ND ! VARIABLES FOR THE MAXIMUM NUMBER OF PARAMETERS, INPUTS, OUTPUTS AND DERIVATIVES
INTEGER*4 NPAR, NIN, NDER ! VARIABLES FOR THE CORRECT NUMBER OF PARAMETERS, INPUTS, OUTPUTS AND DERIVATIVES
INTEGER*4 IUNIT, ITYPE ! THE UNIT NUMBER AND TYPE NUMBER FOR THIS COMPONENT
INTEGER*4 ICNTRL ! AN ARRAY FOR HOLDING VALUES OF CONTROL FUNCTIONS WITH THE NEW SOLVER
INTEGER*4 NSTORED ! THE NUMBER OF VARIABLES THAT WILL BE PASSED INTO AND OUT OF STORAGE
CHARACTER*3 OCHECK ! AN ARRAY TO BE FILLED WITH THE CORRECT VARIABLE TYPES FOR THE OUTPUTS
CHARACTER*3 YCHECK ! AN ARRAY TO BE FILLED WITH THE CORRECT VARIABLE TYPES FOR THE INPUTS

! USER DECLARATIONS – SET THE MAXIMUM NUMBER OF PARAMETERS (NP), INPUTS (NI), OUTPUTS (NOUT), AND DERIVATIVES (ND) THAT MAY BE SUPPLIED FOR THIS TYPE
PARAMETER (NP=0, NI=2, NOUT=2, ND=0, NSTORED=0)

! REQUIRED TRNSYS DIMENSIONS
DIMENSION XIN(NI) , OUT(NOUT) , PAR(NP) , YCHECK(NI) , OCHECK(NOUT) , STORED(NSTORED) , T(ND) , DTDT(ND)
INTEGER NITEMS

! PARAMETERS
INTEGER FlagIn
! INPUTS
DOUBLE PRECISION Flowrate_In
DOUBLE PRECISION Occupants_In
! OUTPUTS
DOUBLE PRECISION Flowrate_Out
DOUBLE PRECISION Buffer

! RETRIEVE THE CURRENT VALUES OF THE INPUTS TO THIS MODEL FROM THE XIN ARRAY IN SEQUENTIAL ORDER
Flowrate_In=XIN(1)
Occupants_In=XIN(2)
IUNIT=INFO(1)
ITYPE=INFO(2)
! SET THE VERSION INFORMATION FOR TRNSYS
IF (INFO(7) .EQ. -2) THEN
INFO(12)=16
RETURN
ENDIF
! DO ALL THE VERY LAST CALL OF THE SIMULATION MANIPULATIONS HERE
IF (INFO(8) .EQ. -1) THEN
RETURN 1
ENDIF

! PERFORM ANY 'AFTER-ITERATION' MANIPULATIONS THAT ARE REQUIRED HERE
IF (INFO(13) .GT. 0) THEN
NITEMS=0
ENDIF

! DO ALL THE VERY FIRST CALL OF THE SIMULATION MANIPULATIONS HERE
IF (INFO(7) .EQ. -1) THEN
! SET SOME INFO ARRAY VARIABLES TO TELL THE TRNSYS ENGINE HOW THIS TYPE IS TO WORK
INFO(6)=NOUT
INFO(9)=1
INFO(10)=0  !STORAGE FOR VERSION 16 HAS BEEN CHANGED
! SET THE REQUIRED NUMBER OF INPUTS, PARAMETERS AND DERIVATIVES THAT THE USER SHOULD SUPPLY IN THE INPUT FILE
! IN SOME CASES, THE NUMBER OF VARIABLES MAY DEPEND ON THE VALUE OF PARAMETERS TO THIS MODEL....
NIN=NI
NPAR=NP
NDER=ND
! CALL THE TYPE CHECK SUBROUTINE TO COMPARE WHAT THIS COMPONENT REQUIRES TO WHAT IS SUPPLIED IN
! THE TRNSYS INPUT FILE
CALL TYPECK(1,INFO,NIN,NPAR,NDER)
! SET THE NUMBER OF STORAGE SPOTS NEEDED FOR THIS COMPONENT
NITEMS=0
CALL SET_STORAGE_SIZE(NITEMS,INFO)
! RETURN TO THE CALLING PROGRAM
RETURN 1
ENDIF

! DO ALL OF THE INITIAL TIMESTEP MANIPULATIONS HERE -- THERE ARE NO ITERATIONS AT THE INITIAL TIME
IF (TIME .LT. (getSimulationStartTime() + .getSimulationTimeStep()/2.0)) THEN
! SET THE UNIT NUMBER FOR FUTURE CALLS
IUNIT=INFO(1)
ITYPE=INFO(2)
!
! PERFORM ANY REQUIRED CALCULATIONS TO SET THE INITIAL VALUES OF THE OUTPUTS HERE
! Flowrate_Out
OUT(1)=0
! Buffer
OUT(2)=0
!PERFORM ANY REQUIRED CALCULATIONS TO SET THE INITIAL STORAGE VARIABLES HERE
NITEMS=0
If (Occupants_In.GT.0) THEN
  If (FlagIn.EQ.1) THEN
    Flowrate_Out = Flowrate_In + Buffer
    Buffer=0
    FlagIn=1
    GO TO 10
  END IF
  Flowrate_Out = Flowrate_In + Buffer*0.5
  Buffer = Buffer*0.5
  FlagIn=1
ELSE
  Flowrate_Out = 0
  Buffer = Flowrate_In + Buffer
  FlagIn=0
ENDIF

! SET THE OUTPUTS FROM THIS MODEL IN SEQUENTIAL ORDER AND GET OUT
! Flowrate_Out
OUT(1)= Flowrate_Out
! Buffer
OUT(2)= Buffer
! EVERYTHING IS DONE – RETURN FROM THIS SUBROUTINE AND MOVE ON
RETURN 1
END
SUBROUTINE TYPE162 (TIME, XIN, OUT, T, DTDT, PAR, INFO, ICNTRL, ) !

******************************************************************************
! Object: Electricity Synch C IISiBat Model: Type162
!
! Author: Anastasios
! Editor:
! Date: May 29, 2009 last modified: May 29, 2009
!
! Electricity_In kWh [0;+Inf]
! Occupants_In any [0;1]
! BaseLoad kWh [0;+Inf]
! *** Model Outputs
! Electricity_Out kWh [0;+Inf]
! Buffer kWh [0;+Inf]
!
! TRNSYS DECLARATIONS
IMPLICIT NONE !REQUIRES THE USER TO DEFINE ALL VARIABLES BEFORE USING THEM
DOUBLE PRECISION XIN !THE ARRAY FROM WHICH THE INPUTS TO THIS TYPE WILL BE RETRIEVED
DOUBLE PRECISION OUT !THE ARRAY WHICH WILL BE USED TO STORE THE OUTPUTS FROM THIS TYPE
DOUBLE PRECISION TIME !THE CURRENT SIMULATION TIME – YOU MAY USE THIS VARIABLE BUT DO NOT SET IT!
DOUBLE PRECISION PAR !THE ARRAY FROM WHICH THE PARAMETERS FOR THIS TYPE WILL BE RETRIEVED
DOUBLE PRECISION STORED !THE STORAGE ARRAY FOR HOLDING VARIABLES FROM TIMESTEP TO TIMESTEP
DOUBLE PRECISION T !AN ARRAY CONTAINING THE RESULTS FROM THE DIFFERENTIAL EQUATION SOLVER
DOUBLE PRECISION DTDT !AN ARRAY CONTAINING THE Derivatives TO BE PASSED TO THE DIFF. EQU. SOLVER
INTEGER*4 INFO(15) !THE INFO ARRAY STORES AND PASSES VALUABLE INFORMATION TO AND FROM THIS TYPE
INTEGER*4 NP, NI, NOUT, ND !VARIABLES FOR THE MAXIMUM NUMBER OF PARAMETERS, INPUTS, OUTPUTS AND DERIVATIVES
INTEGER*4 NPAR, NIN, NDER !VARIABLES FOR THE CORRECT NUMBER OF PARAMETERS, INPUTS, OUTPUTS AND DERIVATIVES
INTEGER*4 IUNIT, ITYPE !THE UNIT NUMBER AND TYPE NUMBER FOR THIS COMPONENT
INTEGER*4 ICNTRL !AN ARRAY FOR HOLDING VALUES OF CONTROL FUNCTIONS WITH THE NEW SOLVER
INTEGER*4 NSTORED !THE NUMBER OF VARIABLES THAT WILL BE PASSED INTO AND OUT OF STORAGE
CHARACTER*3 OCHECK !AN ARRAY TO BE FILLED WITH THE CORRECT VARIABLE TYPES FOR THE OUTPUTS
CHARACTER*3 YCHECK !AN ARRAY TO BE FILLED WITH THE CORRECT VARIABLE TYPES FOR THE INPUTS
!
! USER DECLARATIONS – SET THE MAXIMUM NUMBER OF PARAMETERS (NP), INPUTS (NI), OUTPUTS (NOUT), AND DERIVATIVES (ND) THAT MAY BE SUPPLIED FOR THIS TYPE

244
PARAMETER (NP=0,NI=3,NOUT=2,ND=0,NSTORED=0)
!
REQUIRED TRNSYS DIMENSIONS
DIMENSION XIN(NI) ,OUT(NOUT) ,PAR(NP) ,YCHECK(NI) ,OCHECK(NOUT),
1 STORED(NSTORED) ,T(ND) ,DTDT(ND)
INTEGER NITEMS
!
ADD DECLARATIONS AND DEFINITIONS FOR THE USER-VARIABLES HERE
!
PARAMETERS – OUTPUTS
DOUBLE PRECISION Electricity_Out
DOUBLE PRECISION Buffer
INTEGER FlagIn
!
INPUTS
DOUBLE PRECISION Electricity_In
DOUBLE PRECISION Occupants_In
DOUBLE PRECISION BaseLoad

! READ IN THE VALUES OF THE PARAMETERS IN SEQUENTIAL ORDER
! RETRIEVE THE CURRENT VALUES OF THE INPUTS TO THIS MODEL FROM THE XIN ARRAY IN
SEQUENTIAL ORDER
Electricity_In=XIN(1)
Occupants_In=XIN(2)
BaseLoad=XIN(3)
IUNIT=INFO(1)
ITYPE=INFO(2)

! SET THE VERSION INFORMATION FOR TRNSYS
IF (INFO(7) .EQ. −2) THEN
INFO(12)=16
RETURN 1
ENDIF

! DO ALL THE VERY LAST CALL OF THE SIMULATION MANIPULATIONS HERE
IF (INFO(8) .EQ. −1) THEN
RETURN 1
ENDIF

! PERFORM ANY ‘AFTER-ITERATION’ MANIPULATIONS THAT ARE REQUIRED HERE
IF (INFO(13) .GT. 0) THEN
NITEMS=0
! STORED(1) = . . . ( i f NITEMS > 0)
! CALL SET STORAGE_VARS(STORED,NITEMS,INFO)
RETURN 1
ENDIF

! DO ALL THE VERY FIRST CALL OF THE SIMULATION MANIPULATIONS HERE
IF (INFO(7) .EQ. −1) THEN
! SET SOME INFO ARRAY VARIABLES TO TELL THE TRNSYS ENGINE HOW THIS TYPE IS TO WORK
INFO(6)=NOUT
INFO(9)=1
INFO(10)=0 ! STORAGE FOR VERSION 16 HAS BEEN CHANGED
! IN SOME CASES, THE NUMBER OF VARIABLES MAY DEPEND ON THE VALUE OF PARAMETERS TO
THE MODEL....
NIN=NI
NPAR=NP
NDER=ND
! CALL THE TYPE CHECK SUBROUTINE TO COMPARE WHAT THIS COMPONENTQUIRES TO WHAT IS
SUPPLIED IN THE TRNSYS INPUT FILE
CALL TYPECK(1,INFO,NIN,NPAR,NDER)
! SET THE NUMBER OF STORAGE SPOTS NEEDED FOR THIS COMPONENT
NITEMS=0
RETURN 1
ENDIF
END

! DO ALL OF THE INITIAL TIMESTEP MANIPULATIONS HERE -- THERE ARE NO ITERATIONS AT THE
INITIAL TIME
IF (TIME .LT. (getSimulationStartTime() + . getSimulationTimeStep() /2.D0)) THEN
! SET THE UNIT NUMBER FOR FUTURE CALLS
IUNIT=INFO(1)
ITYPE=INFO(2)
! CHECK THE PARAMETERS FOR PROBLEMS AND RETURN FROM THE SUBROUTINE IF AN ERROR IS
FOUND
CALL TYPECK(−4,INFO,0,"BAD PARAMETER #",0)

! *** ITS AN ITERATIVE CALL TO THIS COMPONENT ***

If (Occupants_In.GT.0) THEN
  If (FlagIn.EQ.1) THEN
    Electricity_Out = Electricity_In + Buffer
    Buffer=0
    FlagIn=1
    GOTO 10
  End If
  Electricity_Out = Electricity_In + Buffer*0.5
  Buffer = Buffer*0.5
  FlagIn=1
ELSE
  If (Electricity_In.GE.BaseLoad) Then
    BaseLoad = BaseLoad
  Else
    BaseLoad = Electricity_In
  End If
  Electricity_Out = BaseLoad
  Buffer = Electricity_In - BaseLoad + Buffer
  FlagIn=0
10 END IF

246
! SET THE OUTPUTS FROM THIS MODEL IN SEQUENTIAL ORDER AND GET OUT

! Electricity_Out
OUT(1) = Electricity_Out

! Buffer
OUT(2) = Buffer
RETURN 1
END
**Chapter B. Source Code for Type 159, Type 162 and Type 156**

**Subroutine TYPE155**

```c
SUBROUTINE TYPE155 (TIME, XIN, OUT, T, DTDT, PAR, INFO, ICNTRL, *)

*****************************************************************************
!* Object: 3 CHP WITH HEAT STORAGE TANK (Variable Number), WITH MACHINE SCHEDULING, GREEDY
!* IISiBat Model: Type155
!* Author: Anastasios Papafragkou C Editor: Anastasios Papafragkou
!* Date: November 18, 2008 last modified: November 18, 2008

!* Model Parameters
!* THCHP1 kW [-Inf;+Inf]
!* ELCHP1 kW [-Inf;+Inf]
!* THCHP2 kW [-Inf;+Inf]
!* ELCHP2 kW [-Inf;+Inf]
!* THCHP3 kW [-Inf;+Inf]
!* ELCHP3 kW [-Inf;+Inf]
!* MINCYCLE [-Inf;+Inf]
!* LOSSCOEF any [-Inf;+Inf]
!* TANKR m [-Inf;+Inf]
!* TANKHEIGHT m [-Inf;+Inf]
!* QMAX kW [-Inf;+Inf]
!* NumTanks [-Inf;+Inf]

!* *** Model Inputs
!* SENSEN kW [-Inf;+Inf]
!* TCOLD [-Inf;+Inf]
!* THOT [-Inf;+Inf]

!* *** Model Outputs
!* SENSEN kW [0;+Inf]
!* LOSSES kW [-Inf;+Inf]
!* HEATDUMP kW [-Inf;+Inf]
!* CAP kW [-Inf;+Inf]
!* CHPBIN1 [-Inf;+Inf]
!* CHPBIN2 [-Inf;+Inf]
!* CHPBIN3 [-Inf;+Inf]
!* SHORTAGE kW [-Inf;+Inf]

!* TRNSYS DECLARATIONS
IMPLICIT NONE !REQUIRES THE USER TO DEFINE ALL VARIABLES BEFORE USING THEM
DOUBLE PRECISION XIN !THE ARRAY FROM WHICH THE INPUTS TO THIS TYPE WILL BE RETRIEVED
DOUBLE PRECISION OUT !THE ARRAY WHICH WILL BE USED TO STORE THE OUTPUTS FROM THIS TYPE
DOUBLE PRECISION TIME !THE CURRENT SIMULATION TIME – YOU MAY USE THIS VARIABLE BUT DO NOT SET IT!
DOUBLE PRECISION PAR !THE ARRAY FROM WHICH THE PARAMETERS FOR THIS TYPE WILL BE RETRIEVED
DOUBLE PRECISION STORED !THE STORAGE ARRAY FOR HOLDING VARIABLES FROM TIMESTEP TO TIMESTEP
DOUBLE PRECISION T !AN ARRAY CONTAINING THE RESULTS FROM THE DIFFERENTIAL EQUATION
```

248
SOLVER

DOUBLE PRECISION DDTDA

INTEGER INFO(15)

INTEGER NP, NI, NOUT, ND

INTEGER NPAR, NIN, NDER

INTEGER IUNIT, ITYPE

INTEGER ICNTRL

INTEGER NSTORED

CHARACTER OCHECK(3)

CHARACTER YCHECK(3)

PARAMETER (NP=12, NI=3, NOUT=8, ND=0, NSTORED=0)

DIMENSION XIN(NI), OUT(NOUT), PAR(NP), YCHECK(NI), OCHECK(NOUT), STORED(NSTORED), T(ND), DDTDA(ND)

INTEGER NITEMS

PARAMETER

DOUBLE PRECISION THCHP1

DOUBLE PRECISION ELCHP1

DOUBLE PRECISION THCHP2

DOUBLE PRECISION ELCHP2

DOUBLE PRECISION THCHP3

DOUBLE PRECISION ELCHP3

DOUBLE PRECISION MINCYCLE

DOUBLE PRECISION LOSSCOEF

DOUBLE PRECISION TANKR

DOUBLE PRECISION TANKHEIGHT

DOUBLE PRECISION QMAX

DOUBLE PRECISION NumTanks

INPUTS

DOUBLE PRECISION SENSEN

DOUBLE PRECISION TCOLD

DOUBLE PRECISION THOT

OUTPUTS AND INTERMEDIATES

DOUBLE PRECISION LOSSES, HEATDUMP, CAP, TGEN, SHORT, SHORTAGE, TAREA

DOUBLE PRECISION TGEN2

INTEGER CHPBIN1, CHPBIN2, CHPBIN3

INTEGER CURRENTCYCLE1, CURRENTCYCLE2, CURRENTCYCLE3

READ IN THE VALUES OF THE PARAMETERS IN SEQUENTIAL ORDER
THCHP1=PAR(1)
ELCHP1=PAR(2)
THCHP2=PAR(3)
ELCHP2=PAR(4)
THCHP3=PAR(5)
ELCHP3=PAR(6)
MINCYCLE=PAR(7)
LOSSCOEF=PAR(8)
TANKR=PAR(9)
TANKHEIGHT=PAR(10)
QMAX=PAR(11)
NumTanks=PAR(12)

!RETRIEVE THE CURRENT VALUES OF THE INPUTS TO THIS MODEL FROM THE XIN ARRAY IN
SEQUENTIAL ORDER
SENSEN=XIN(1)
TCOLD=XIN(2)
THOT=XIN(3)
IUNIT=INFO(1)
ITYPE=INFO(2)

! SET THE VERSION INFORMATION FOR TRNSYS
IF (INFO(7).EQ.-2) THEN
INFO(12)=16
RETURN 1
ENDIF

!------ DO ALL THE VERY LAST CALL OF THE SIMULATION MANIPULATIONS HERE
IF (INFO(8).EQ.-1) THEN
RETURN 1
ENDIF

! PERFORM ANY 'AFTER-ITERATION' MANIPULATIONS THAT ARE REQUIRED HERE
IF (INFO(13).GT.0) THEN
NITEMS=0
RETURN 1
ENDIF

! DO ALL THE VERY FIRST CALL OF THE SIMULATION MANIPULATIONS HERE
IF (INFO(7).EQ.-1) THEN
! SET SOME INFO ARRAY VARIABLES TO TELL THE TRNSYS ENGINE HOW THIS TYPE IS TO WORK
INFO(6)=NOUT
INFO(9)=1
INFO(10)=0 !STORAGE FOR VERSION 16 HAS BEEN CHANGED
! SET THE REQUIRED NUMBER OF INPUTS, PARAMETERS AND DERIVATIVES THAT THE USER SHOULD
! SUPPLY IN THE INPUT FILE
! IN SOME CASES, THE NUMBER OF VARIABLES MAY DEPEND ON THE VALUE OF PARAMETERS TO
! THIS MODEL . . .
NIN=NI
NPAR=NPAR

250
NDER = ND

! CALL THE TYPE CHECK SUBROUTINE TO COMPARE WHAT THIS COMPONENT REQUIRES TO WHAT IS SUPPLIED
CALL TYPECK(1, INFO, NIN, NPAR, NDER)

! SET THE NUMBER OF STORAGE SPOTS NEEDED FOR THIS COMPONENT
NITEMS = 0
RETURN 1
ENDIF

! DO ALL OF THE INITIAL TIEMSTEP MANIPULATIONS HERE – THERE ARE NO ITERATIONS AT THE INITIAL TIME
IF (TIME .LT. (getSimulationStartTime() + getSimulationTimeStep()/2.D0)) THEN

! SET THE UNIT NUMBER FOR FUTURE CALLS
IUNIT = INFO(1)
ITYPE = INFO(2)

! CHECK THE PARAMETERS FOR PROBLEMS AND RETURN FROM THE SUBROUTINE IF AN ERROR IS FOUND

! INITIAL VALUES OF THE OUTPUTS HERE
! SENSEN
OUT(1) = 0

! LOSSES
OUT(2) = 0

! HEATDUMP
OUT(3) = 0

! CAP
OUT(4) = 0

! CHPBIN1
OUT(5) = 0

! CHPBIN2
OUT(6) = 0

! CHPBIN3
OUT(7) = 0

! SHORTAGE
OUT(8) = 0

! PERFORM ANY REQUIRED CALCULATIONS TO SET THE INITIAL STORAGE VARIABLES HERE
NITEMS = 0

! PUT THE STORED ARRAY IN THE GLOBAL STORED ARRAY
! CALL SET_STORAGE_VARS(STORED, NITEMS, INFO)
! RETURN TO THE CALLING PROGRAM
RETURN 1
ENDIF

! IT'S AN ITERATIVE CALL TO THIS COMPONENT
HEATDUMP = 0
SHORTAGE = 0

IF (PAR(3) .EQ. 0) THEN
GO TO 20
ELSE
GO TO 10
END IF

10 IF (SENSEN.EQ.0) THEN

IF ((CURRENTCYCLE1.LT.MINCYCLE) .AND. (CURRENTCYCLE1.GT.0)) THEN
CHPBIN1=1.
CURRENTCYCLE1=CURRENTCYCLE1+1.
CURRENTCYCLE2=CURRENTCYCLE2
CURRENTCYCLE3=CURRENTCYCLE3
ELSE
CHPBIN1=0.
CURRENTCYCLE1=0.
CURRENTCYCLE2=CURRENTCYCLE2
CURRENTCYCLE3=CURRENTCYCLE3
ENDIF

IF ((CURRENTCYCLE2.LT.MINCYCLE) .AND. (CURRENTCYCLE2.GT.0)) THEN
CHPBIN2=1.
CURRENTCYCLE2=CURRENTCYCLE2+1.
CURRENTCYCLE1=CURRENTCYCLE1
CURRENTCYCLE3=CURRENTCYCLE3
ELSE
CHPBIN2=0.
CURRENTCYCLE2=0.
CURRENTCYCLE1=CURRENTCYCLE1
CURRENTCYCLE3=CURRENTCYCLE3
ENDIF

IF ((CURRENTCYCLE3.LT.MINCYCLE) .AND. (CURRENTCYCLE3.GT.0)) THEN
CHPBIN3=1
CURRENTCYCLE3=CURRENTCYCLE3+1.
CURRENTCYCLE1=CURRENTCYCLE1
CURRENTCYCLE2=CURRENTCYCLE2
ELSE
CHPBIN3=0.
CURRENTCYCLE3=0.
CURRENTCYCLE1=CURRENTCYCLE1
CURRENTCYCLE2=CURRENTCYCLE2
ENDIF

ELSE

IF (CAP–SENSEN.GT.0) THEN !CASE 1!

IF ((CURRENTCYCLE1.LT.MINCYCLE) .AND. (CURRENTCYCLE1.GT.0)) THEN
CHPBIN1=1.
CURRENTCYCLE1=CURRENTCYCLE1+1.
CURRENTCYCLE2=CURRENTCYCLE2

ENDIF

ENDIF

ELSE

IF (SENSEN>0)

ENDIF

ENDIF

ENDIF
CURRENTCYCLE3=CURRENTCYCLE3
ELSE
  CHPBIN1=0.
  CURRENTCYCLE1=0.
  CURRENTCYCLE2=CURRENTCYCLE2
  CURRENTCYCLE3=CURRENTCYCLE3
END IF

IF ( (CURRENTCYCLE2.LT.MINCYCLE) .AND. (CURRENTCYCLE2.GT.0) ) THEN
  CHPBIN2=1.
  CURRENTCYCLE2=CURRENTCYCLE2+1.
  CURRENTCYCLE1=CURRENTCYCLE1
  CURRENTCYCLE3=CURRENTCYCLE3
ELSE
  CHPBIN2=0.
  CURRENTCYCLE2=0.
  CURRENTCYCLE1=CURRENTCYCLE1
  CURRENTCYCLE3=CURRENTCYCLE3
END IF

IF ( (CURRENTCYCLE3.LT.MINCYCLE) .AND. (CURRENTCYCLE3.GT.0) ) THEN
  CHPBIN3=1
  CURRENTCYCLE3=CURRENTCYCLE3+1.
  CURRENTCYCLE1=CURRENTCYCLE1
  CURRENTCYCLE2=CURRENTCYCLE2
ELSE
  CHPBIN3=0.
  CURRENTCYCLE3=0.
  CURRENTCYCLE1=CURRENTCYCLE1
  CURRENTCYCLE2=CURRENTCYCLE2
END IF

!-----------------------------------------------------------------------!
ELSE !IF (CAP-SENSE.NE.0) THEN! !CASE 2 !-----------------------------------------------------------------------!

IF ( (CURRENTCYCLE1.LT.MINCYCLE) .AND. (CURRENTCYCLE1.GT.0) ) THEN
  CHPBIN1=1.
  CURRENTCYCLE1=CURRENTCYCLE1+1.
ELSE
  CHPBIN1=0.
  CURRENTCYCLE1=0.
END IF

IF ( (CURRENTCYCLE2.LT.MINCYCLE) .AND. (CURRENTCYCLE2.GT.0) ) THEN
  CHPBIN2=1.
  CURRENTCYCLE2=CURRENTCYCLE2+1.
ELSE
  CHPBIN2=0.
  CURRENTCYCLE2=0.

253
CHAPTER B. Source Code for Type 159, Type 162 and Type 156

END IF

IF ((CURRENTCYCLE3 .LT. MINCYCLE) .AND. (CURRENTCYCLE3 .GT. 0)) THEN
    CHPBIN3=1
    CURRENTCYCLE3=CURRENTCYCLE3+1.
ELSE
    CHPBIN3=0.
    CURRENTCYCLE3=0.
END IF

TGEN2=CHPBIN1*THCHP1+CHPBIN2*THCHP2+CHPBIN3*THCHP3

IF (CHPBIN1.EQ.0 .AND. CHPBIN2.EQ.0 .AND. CHPBIN3.EQ.0) THEN
    TGEN2=CHPBIN1*THCHP1+CHPBIN2*THCHP2+CHPBIN3*THCHP3
    IF (TGEN2.LT.SENSEN−CAP) THEN
        CHPBIN1=1
        CURRENTCYCLE1=CURRENTCYCLE1+1.
        TGEN2=CHPBIN1*THCHP1+CHPBIN2*THCHP2+CHPBIN3*THCHP3
        IF (TGEN2.GE.SENSEN−CAP) THEN
            GO TO 30
        ELSE
            CHPBIN1=0
            CURRENTCYCLE1=CURRENTCYCLE1−1.
            CHPBIN2=1
            CURRENTCYCLE2=CURRENTCYCLE2+1.
            TGEN2=CHPBIN1*THCHP1+CHPBIN2*THCHP2+CHPBIN3*THCHP3
            IF (TGEN2.GE.SENSEN−CAP) THEN
                GO TO 30
            ELSE
                CHPBIN1=1
                CURRENTCYCLE1=CURRENTCYCLE1+1.
                TGEN2=CHPBIN1*THCHP1+CHPBIN2*THCHP2+CHPBIN3*THCHP3
                IF (TGEN2.GE.SENSEN−CAP) THEN
                    GO TO 30
                ELSE
                    CHPBIN1=0
                    CURRENTCYCLE1=CURRENTCYCLE1−1.
                    CHPBIN2=0
                    CURRENTCYCLE2=CURRENTCYCLE2−1.
                    CHPBIN3=1
                    CURRENTCYCLE3=CURRENTCYCLE3+1.
                    TGEN2=CHPBIN1*THCHP1+CHPBIN2*THCHP2+CHPBIN3*THCHP3
                    IF (TGEN2.GE.SENSEN−CAP) THEN
                        GO TO 30
                    ELSE
                        CHPBIN1=1
                        CURRENTCYCLE1=CURRENTCYCLE1+1.
                        TGEN2=CHPBIN1*THCHP1+CHPBIN2*THCHP2+CHPBIN3*THCHP3
                        IF (TGEN2.GE.SENSEN−CAP) THEN
                            GO TO 30
                        ELSE
                            CHPBIN1=0
                            CURRENTCYCLE1=CURRENTCYCLE1−1.
                            CHPBIN2=0
                            CURRENTCYCLE2=CURRENTCYCLE2−1.
                            CHPBIN3=0
                            CURRENTCYCLE3=CURRENTCYCLE3−1.
                            TGEN2=CHPBIN1*THCHP1+CHPBIN2*THCHP2+CHPBIN3*THCHP3
                            IF (TGEN2.GE.SENSEN−CAP) THEN
                                GO TO 30
                            ELSE
                                CHPBIN1=1
                                CURRENTCYCLE1=CURRENTCYCLE1+1.
                                TGEN2=CHPBIN1*THCHP1+CHPBIN2*THCHP2+CHPBIN3*THCHP3
                                IF (TGEN2.GE.SENSEN−CAP) THEN
                                    GO TO 30
                                ELSE
                                    CHPBIN1=0
                                    CURRENTCYCLE1=CURRENTCYCLE1−1.
                                    CHPBIN2=0
                                    CURRENTCYCLE2=CURRENTCYCLE2−1.
                                    CHPBIN3=0
                                    CURRENTCYCLE3=CURRENTCYCLE3−1.
                                    TGEN2=CHPBIN1*THCHP1+CHPBIN2*THCHP2+CHPBIN3*THCHP3
                                    IF (TGEN2.GE.SENSEN−CAP) THEN
                                        GO TO 30
                                    ELSE
                                        CHPBIN1=1
                                        CURRENTCYCLE1=CURRENTCYCLE1+1.
                                        TGEN2=CHPBIN1*THCHP1+CHPBIN2*THCHP2+CHPBIN3*THCHP3
                                        IF (TGEN2.GE.SENSEN−CAP) THEN
                                            GO TO 30
                                        ELSE
                                            CHPBIN1=0
                                            CURRENTCYCLE1=CURRENTCYCLE1−1.
                                            CHPBIN2=0
                                            CURRENTCYCLE2=CURRENTCYCLE2−1.
                                            CHPBIN3=0
                                            CURRENTCYCLE3=CURRENTCYCLE3−1.
                                            TGEN2=CHPBIN1*THCHP1+CHPBIN2*THCHP2+CHPBIN3*THCHP3
                                            IF (TGEN2.GE.SENSEN−CAP) THEN
                                                GO TO 30
                                            ELSE
                                                CHPBIN1=1
                                                CURRENTCYCLE1=CURRENTCYCLE1+1.
                                                TGEN2=CHPBIN1*THCHP1+CHPBIN2*THCHP2+CHPBIN3*THCHP3
                                                IF (TGEN2.GE.SENSEN−CAP) THEN
                                                    GO TO 30
                                                ELSE
                                                    CHPBIN1=0
                                                    CURRENTCYCLE1=CURRENTCYCLE1−1.
GO TO 30
ELSE
  CHPBIN1=0
  CURRENTCYCLE1=CURRENTCYCLE1−1.
  CHPBIN2=1
  CURRENTCYCLE2=CURRENTCYCLE2+1.
END IF

TGEN2=CHPBIN1∗THCHP1+CHPBIN2∗THCHP2+CHPBIN3∗THCHP3
IF (TGEN2.GE.SENSEN−CAP) THEN
  GO TO 30
ELSE
  CHPBIN1=1
  CURRENTCYCLE1=CURRENTCYCLE1+1.
END IF

TGEN2=CHPBIN1∗THCHP1+CHPBIN2∗THCHP2+CHPBIN3∗THCHP3
END IF

IF (CHPBIN1.EQ.1 .AND. CHPBIN2.EQ.0 .AND. CHPBIN3.EQ.0) THEN !1 IS ON
  TGEN2=CHPBIN1∗THCHP1+CHPBIN2∗THCHP2+CHPBIN3∗THCHP3
  IF (TGEN2.LT.SENSEN−CAP) THEN
    CHPBIN2=1
    CURRENTCYCLE2=CURRENTCYCLE2+1.
    TGEN2=CHPBIN1∗THCHP1+CHPBIN2∗THCHP2+CHPBIN3∗THCHP3
  END IF
  ELSE
    CHPBIN2=0
    CURRENTCYCLE2=CURRENTCYCLE2−1.
    CHPBIN3=1
    CURRENTCYCLE3=CURRENTCYCLE3+1.
    TGEN2=CHPBIN1∗THCHP1+CHPBIN2∗THCHP2+CHPBIN3∗THCHP3
  IF (TGEN2.GE.SENSEN−CAP) THEN
    GO TO 30
  ELSE
    CHPBIN2=1
    CURRENTCYCLE2=CURRENTCYCLE2+1.
    TGEN2=CHPBIN1∗THCHP1+CHPBIN2∗THCHP2+CHPBIN3∗THCHP3
  END IF
END IF
END IF

!/------------------------------------------------------------------------------------------------------------------

IF (CHPBIN1.EQ.0 .AND. CHPBIN2.EQ.1 .AND. CHPBIN3.EQ.0) THEN !2 IS ON
  TGEN2=CHPBIN1∗THCHP1+CHPBIN2∗THCHP2+CHPBIN3∗THCHP3
END IF

!------------------------------------------------------------------------------------------------------------------

255
CHAPTER B. Source Code for Type 159, Type 162 and Type 156

TGEN2=CHPBIN1*THCHP1+CHPBIN2*THCHP2+CHPBIN3*THCHP3
IF (TGEN2.LT.SENSEN−CAP) THEN
  CHPBIN1=1
  CURRENTCYCLE1=CURRENTCYCLE1+1.
  TGEN2=CHPBIN1*THCHP1+CHPBIN2*THCHP2+CHPBIN3*THCHP3
ELSE
  CHPBIN1=0
  CURRENTCYCLE1=CURRENTCYCLE1−1.
  CHPBIN3=1
  CURRENTCYCLE3=CURRENTCYCLE3+1.
ENDIF
ENDIF END IF

IF (CHPBIN1.EQ.1.AND.CHPBIN2.EQ.2.AND.CHPBIN3.EQ.0) THEN !1,2 ARE ON
  IF (TGEN2.GE.SENSEN−CAP) THEN
    GO TO 30
  ELSE
    CHPBIN3=1
    CURRENTCYCLE3=CURRENTCYCLE3+1.
    TGEN2=CHPBIN1*THCHP1+CHPBIN2*THCHP2+CHPBIN3*THCHP3
  END IF
ENDIF

IF (CHPBIN1.EQ.0.AND.CHPBIN2.EQ.0.AND.CHPBIN3.EQ.1) THEN !3 IS ON
  TGEN2=CHPBIN1*THCHP1+CHPBIN2*THCHP2+CHPBIN3*THCHP3
  IF (TGEN2.LT.SENSEN−CAP) THEN
    CHPBIN1=1
    CURRENTCYCLE1=CURRENTCYCLE1+1.
    TGEN2=CHPBIN1*THCHP1+CHPBIN2*THCHP2+CHPBIN3*THCHP3
  ELSE
    CHPBIN1=0
    CURRENTCYCLE1=CURRENTCYCLE1−1.
    CHPBIN2=1
    CURRENTCYCLE2=CURRENTCYCLE2+1.
  END IF
ENDIF

256
TGEN2=CHPBIN1*THCHP1+CHPBIN2*THCHP2+CHPBIN3*THCHP3
IF (TGEN2.GE.SENSEN−CAP) THEN
  GO TO 30
ELSE
  CHPBIN1=1
  CURRENTCYCLE1=CURRENTCYCLE1+1.
TGEN2=CHPBIN1*THCHP1+CHPBIN2*THCHP2+CHPBIN3*THCHP3
END IF
END IF
END IF
END IF
CHPBIN1=0
CURRENTCYCLE1=0

END IF

ELSE  !-------------------------SENSEN:0----------------------------------
IF (CAP.GE.SENSEN) THEN
  IF (CHPBIN1.EQ.0) THEN
    CHPBIN1=0
    CURRENTCYCLE1=0
  ELSE IF ((CHPBIN1.EQ.1) .AND. (CURRENTCYCLE1.GE.MINCYCLE)) THEN
    CHPBIN1=0
    CURRENTCYCLE1=0
  ELSE IF ((CHPBIN1.EQ.1) .AND. (CURRENTCYCLE1.LT.MINCYCLE)) THEN
    CHPBIN1=1
    CURRENTCYCLE1=CURRENTCYCLE1+1
  END IF
ELSE  !------------------------SENSEN:CAP---------------------------------
  CHPBIN1=1
  CURRENTCYCLE1=CURRENTCYCLE1+1
END IF

! Calculate the heat losses for every iteration
30 TAREA=2*3.141592*TANKR*TANKHEIGHT+2*3.141592*TANKR**2
LosSes = NumTanks*TAREA*(THot-TCold)*LOSSCOEF

! Calculate Total heat generation for this iteration
TGEN=CHPBIN1*THCHP1+CHPBIN2*THCHP2+CHPBIN3*THCHP3

! Calculate the capacity of the thermal storage unit for this iteration
CAP=CAP+TGEN-SENSEN-LOSSES

IF (SENSEN.GT.0) THEN
  IF (TGEN+CAP.LT.SENSEN) THEN
    SHORTAGE=SHORTAGE+SHORT
  ELSE
    SHORTAGE=SHORTAGE+SHORT
  END IF
ELSE
  SHORT=0
  SHORTAGE=SHORTAGE+SHORT
END IF

IF (CAP.LT.0) THEN
  CAP=0
END IF

IF (CAP.GT.QMAX*NumTanks) THEN
  HEATDUMP=CAP-QMAX*NumTanks
  CAP=QMAX*NumTanks
END IF
!SET THE OUTPUTS FROM THIS MODEL IN SEQUENTIAL ORDER AND GET OUT

OUT(1)=SENSEN
! LOSSSES
OUT(2)=LOSSSES
! HEATDUMP
OUT(3)=HEATDUMP
! CAP
OUT(4)=CAP
! CHPBIN1
OUT(5)=CHPBIN1
! CHPBIN2
OUT(6)=CHPBIN2
! CHPBIN3
OUT(7)=CHPBIN3
! SHORTAGE
OUT(8)=SHORTAGE

! EVERYTHING IS DONE – RETURN FROM THIS SUBROUTINE AND MOVE ON
RETURN
END
Appendix C

TRNSYS basic components used for the heating load prediction models

Weather Data: This component (Type 109) is the input for the weather data file. It reads from external files data such as ambient temperature, relative humidity, total radiation, beam radiation, sky diffuse radiation, etc. and performs calculations such as angles of solar incidence. Weather files provide the radiation on the horizontal only. However, when radiation is required as an input for a simulation, rarely refers to the horizontal but to other surfaces, either vertical (e.g. wall, window) or sloped (e.g. roof, PV, solar thermal). For this reason new surfaces were defined within this component, in terms of orientation and slope, and the radiation was re-calculated. It is a basic component which is linked to the most of the components in the simulation. The use of morphed weather data for the same location enabled the projection of future system behaviour based on predicted changes in climate.

Gains: This equation was used as an input for the gains of the house. It was linked to every thermal zone of Type 56 separately. Gains here refer only to those gains from electrical appliances and not gains from lighting or occupancy which were addressed in the building files.

Windows: For flexibility reasons it was chosen to define the glazing type as an input rather than having it fixed in each building file.
**Occupancy Data:** This is a data reader that reads ASCII files. The total (peak) number of occupants in the house was entered here.

**Boiler:** Heating profiles were provided in an ASCII file. The inputs were the desired temperature of the air set-point, the minimum heating threshold under which the heating is automatically turned on and the specific time profile that the heating is on, as described in Section 4.4.3.

**Infiltration:** Infiltration rates of each zone were given as inputs to Type 56.

**Import DHW Data:** An ASCII file data reader that provides the domestic hot water data. Section 4.4.1 explains in detail how this data is generated and the assumptions made.

**DHW_Synchronisation:** This was a new component created to synchronise the domestic hot water data with the occupancy profiles by shifting the demand. It is described in detail in Section 4.4.1.

**Psychrometrics:** This TRNSYS library component calculates moist air properties: dry bulb temperature, dew point temperature, wet bulb temperature, relative humidity, absolute humidity ratio and enthalpy, required inputs for Type 56.

**Sky temp:** A TRNSYS library component used to calculate an effective sky temperature. The effective sky temperature is always lower than the current ambient temperature and the heat losses from a surface exposed to the sky differ according the cloudiness, hence cloudiness should be also provided as an input to the model (TRNSYS, 2005).

**Turn:** It defined the orientation of “North” in a simulation.

**Lights:** The logical meaning of this component was to control the lighting in the house. Mathematically it is just a binary. The value of the control signal is a function of the difference between lower and upper irradiance differences $T_L$ and $T_U$ compared with two dead band irradiance differences and is determined from the total radiation on horizontal, which is set as lower input value for the controller. The value of the control function depends always from its value at
the previous time step. The controller has an hysteresis effect because the input control signal is connected to the output control signal.

**Lighting:** This equation contained a control strategy for lighting based on the occupancy and the total radiation on the horizontal. It defined at any time of the day in which zones artificial lighting was on. It was used as an input for the Type 56 component and it was linked to the gains due to artificial lighting.

**Occupancy:** Here a set of equations were used to input the occupancy profile of the house. A binary (In_the_House/Out_of_the_House) declared if there are any occupants in the building, two other variables were used to distinguish between work days and weekends, whilst a different occupancy was assumed for every zone according to the time of the day.

**Soil Temperature (Type 501):** This is a TRNSYS subroutine for modelling the ground’s vertical temperature distribution. The subroutine requires as inputs the mean ground surface temperature for the year, the amplitude of the ground surface temperature for the year, the time difference between the beginning of the calendar year and the occurrence of the minimum surface temperature, and the soil thermal diffusivity. These parameters were calculated for all the weather files used and they were provided manually as inputs to the subroutine. Ground temperature distribution was used to predict the cold water temperature from the mains. The pipes supplying with cold water were assumed to be buried at a depth of 1.5 m. The cold water temperature profile for the Southampton 2000 weather file is illustrated in Figure C.1.

**Valve (Type 11b):** This TRNSYS component models a tempering valve. It calculates the flowrate of the water diverted to the tank to be heated, and the flowrate of the water diverted to the rest of the building without being heated. The flowrates were calculated assuming a set point of 45°C for the domestic hot water that reaches the taps.

**Mixer (Type 11h):** This component models a mixer. It was used to calculate the temperature and the flowrate of the hot and cold water after being mixed.
CHAPTER C. TRNSYS basic components used for the heating load prediction models

Figure C.1: Cold water temperature profile for Southampton 2000 weather file and 1.5m pipes depth

**Tank (Type 4c):** This component models the thermal performance of a fluid-filled sensible energy storage tank, subject to thermal stratification (TRNSYS, 2005). The losses were assumed to be uniform and the tank was assumed to highly insulated. The technical characteristics of the tank used for the storage of the domestic hot water are given in Table C.1.

<table>
<thead>
<tr>
<th></th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tank volume</td>
<td>300 l</td>
</tr>
<tr>
<td>Tank loss coefficient</td>
<td>0.7 W/m(^2)K</td>
</tr>
<tr>
<td>Number of heating elements</td>
<td>1</td>
</tr>
<tr>
<td>Set point temperature</td>
<td>60 °C</td>
</tr>
<tr>
<td>Deadband for heating element</td>
<td>5 °C</td>
</tr>
</tbody>
</table>

Table C.1: Technical characteristics of the tank used for the domestic hot water

**Holiday (Type 95c):** The type 95c is a holiday calculator that performs a number of calendar computations based on the starting date of the TRNSYS simulation and the elapsed time. The outputs of this component was a binary indicating if it is a holiday period or not. When the binary was zero, then variables such as occupancy, heating and ventilation were also set to zero.
Appendix D

VBA program for electricity data analysis
Appendix E

Paper for ICE Energy Journal:
“Combined heat and power:
street-level domestic microgrids”
Residential housing in the UK accounts for about a quarter of the country’s carbon dioxide emissions. The major component of these emissions is associated with space heating, predominantly from gas. District heating schemes, at the community level, using combined heat and power (CHP) have the potential to deliver significant savings in carbon dioxide emissions. This paper considers various CHP schemes at both the individual house and the microgrid street level, where a cluster of up to ten houses are considered as a linked network. It seeks to address the benefits that may arise from each CHP scheme compared with a business as usual (BaU) scenario of individual condensing boilers and electricity from the utility grid. Three different types of housing stock condition have been combined with a range of occupancy profiles to produce a portfolio of hot water and space heating demand scenarios for two locations in the UK. Climate change adapted test reference year weather files have been applied to hourly timestep, domestic building stock simulations. It is shown that a housing cluster in conjunction with a ‘multi-stage’ CHP system may enable small-scale CHP technologies to deliver significant carbon and running cost savings over the BaU scenario.

1. INTRODUCTION

The UK government has set ambitious targets for low-energy housing, with new developments beyond 2016 required to be carbon neutral in operation. For large-scale residential developments, this implies the use of biomass combined heat and power (CHP) systems with potential contributions from photovoltaics or solar thermal systems. The economics of such systems will be driven by the availability of biomass feedstock which, as a commodity, could become more volatile in price as the supply–demand balance tips. Micro-wind power is unlikely to be suitable for the majority of developments due to the poor wind resource in the urban environment. To address shortfalls in the carbon balance of a development, mechanisms such as ‘windcrofting’ (i.e. a share in a large-scale wind farm is purchased) may be possible. In order to achieve the proposed carbon targets, the UK government plans to progressively tighten energy efficiency building regulations by 25% in 2010 and by 44% in 2013 relative to the current 2006 regulations. As of 1 May 2008, it is mandatory that all new homes are rated via the code for sustainable homes. In addition, it is envisaged that energy performance certificates and the low carbon buildings programme will contribute to the uptake of both energy efficiency and microgeneration technologies. The first report of the UK Committee on Climate Change estimates that CHP could deliver just over 1 Mt of carbon dioxide savings by 2020, while district heat schemes have the potential to save over 5 Mt of carbon dioxide by 2020. The report concludes that achieving significant carbon dioxide savings through CHP will be costly, but that it should be pursued given the government’s carbon targets.

This paper considers small-scale developments of fewer houses than would be typical for a developer-driven housing development. It seeks to identify possible CHP solutions at the street scale of ten houses, both in terms of new build and existing stock (Figure 1). If, as is possible with CHP, these houses could be linked through a shared heat network, they are termed a cluster. Such a cluster should deliver a better balanced heating–electrical profile than a single house, enabling a shared CHP system to deliver improved carbon savings.

2. DOMESTIC CHP SYSTEMS

As stated in the government’s standard assessment procedure (SAP), micro–CHP systems are assumed to be heat-led, meaning that they are allowed to operate only when there is a demand for space heating or hot water. This basis of operation assumption is valid for high heat:electricity ratio systems (>3:1). Therefore, CHP systems operate essentially as a thermally tracked process where electricity is produced as a by-product. CHP is widely seen as having the potential to make a significant contribution to carbon savings in the built environment. The high carbon intensity of UK grid electricity means that CHP may reduce the carbon footprint of a building compared with using electricity from the utility grid and a normal heating system without any change in user behaviour. Depending on the measure used, the UK grid is generally considered to have a carbon intensity of between 0.43 kgCO2/kWh (all-generator grid mix) and 0.586 kgCO2/kWh (avoided balancing generator mix or marginal plant), which electricity production through microgeneration has the potential to offset.

There are essentially two technology approaches to CHP at the individual house scale, where the device is considered to replace a ‘normal’ gas boiler. These individual house CHP units are commonly called micro-CHP.

(a) Stirling (reciprocating) engine type devices are characterised by a high thermal/electrical ratio. Manufacturers include...
Whispergen\textsuperscript{10} with a typical output of 6 kW\textsubscript{th} : 1 kW\textsubscript{e}. Baxi is also working on a micro-unit that is expected to be available for general domestic use in early 2009.\textsuperscript{11} (h) Fuel cell devices, which have an approximate 50:50 electrical:thermal split, are not yet commercially available.

Mini-CHP represents devices that are larger than micro-CHP units, with a thermal output of tens of kilowatts. They have a lower thermal/electrical ratio than micro-CHP units (around 1.5:1) and are suitable for businesses that have a well-defined heat demand (e.g. restaurants, hotels and leisure centres).\textsuperscript{7}

If a CHP system is considered for an individual house, the problem of thermal load matching becomes readily apparent. Various studies\textsuperscript{7,12} have shown that Stirling engine type CHP systems at this scale are really only appropriate for UK houses with significant heating demands – essentially large properties located in regions with harsh winters, such as Scotland. In addition, CHP plants must operate for prolonged periods to avoid inefficient start-up cycles where the device will operate at a very low electrical output, thus compromising its carbon intensity. Consistent operation without interruption for many hours per day also increases the lifetime of CHP units (mainly internal combustion engines), since the start-up of each running cycle is the most stressful activity and the point at which the engine suffers the most wear.\textsuperscript{7}

3. ASSESSING THE THERMAL: ELECTRICAL DEMAND OF A RESIDENTIAL HOUSING CLUSTER

This study considered a notional semi-detached house constructed from three different building fabrics – that is, poorly insulated ‘1980s fabric’ and more recent 2002 and 2006 building regulation compliant constructions. Table 1 gives an overview of the $U$-values of the building elements for the three considered building fabrics. Three user occupancy profiles were assumed: a retired couple, a professional working couple and a family with two children. The dynamic simulation package Trnsys\textsuperscript{13} was used to model the different building fabrics and the three occupancy profiles for two locations in the UK – Southampton in the south and Glasgow in the north. Custom building models were developed to create thermally coupled zones. The thermal zones considered for each house were the kitchen, ground-floor living space, first floor (bedrooms, bathroom) and loft space. Figure 2 illustrates the relationship between the main parameters used to predict thermal demand in Trnsys. The relevant signal flows and the main inputs and outputs are shown.

CHP operation is a dynamic process that requires sets of heat and electricity profiles in timesteps. In view of this, the SAP could not be used since it is an elemental approach that gives an annual estimate. Although the SAP was not used for calculating energy consumption in the various dwellings, all the models presented here are based on the building regulations to enable verification via an elemental approach.

3.1. Domestic hot water demand

Sets of load profiles developed by Jordan and Vajen\textsuperscript{14} were used for the domestic hot water demand. Each of these profiles consists of a domestic hot water flow rate value for every timestep of the year. However, the occupancy profiles considered by Jordan and Vajen are not related to the housing profiles considered in this study, thus creating a problem in synchronising the two datasets. To resolve this problem and give more flexibility to the models, a Fortran routine was developed within Trnsys; this synchronises the Jordan and Vajen domestic hot water data with any occupancy profile, defined by the user. The level of domestic hot water demand is

<table>
<thead>
<tr>
<th>$U$: W/m\textsuperscript{2}K</th>
</tr>
</thead>
<tbody>
<tr>
<td>External wall</td>
</tr>
<tr>
<td>Window</td>
</tr>
<tr>
<td>Floor</td>
</tr>
<tr>
<td>Ceiling</td>
</tr>
</tbody>
</table>

Table 1. Elemental $U$-values for notional semi-detached house (floor space area 90 m\textsuperscript{2}) constructed in the 1980s, 2002 and 2006
easily adjusted according to the specified occupancy density. The temperature of the incoming commercial water supply at each simulation timestep was estimated using a ground-temperature model within Trnsys incorporating a local weather data file.

3.2. Domestic electrical demand
This study simulated the thermal demand of houses (i.e. both space heating and domestic hot water) but used real data for the generation of electricity demand profiles. A typical UK household has an electricity consumption of around 4000 kWh per annum.\textsuperscript{15} Five-minute-interval electrical data from a set of nine low-energy houses in Havant, near Portsmouth, Hampshire have been collected since 2004.\textsuperscript{16} Three different datasets were chosen from the Havant trial in order to represent the three different occupancy profiles: retired couple (2800 kWh/year); working couple (3500 kWh/year); family with two children (4000 kWh/year).

4. CLIMATE CHANGE IMPACT
This paper includes an assessment of the impact of climate change on domestic heating demand and the implications for the various heating options considered. The performance of business as usual (BaU) condensing boiler and CHP systems under predicted future climates was estimated using ‘morphed’ weather files. These weather files are based on the 2002 UK climate impacts programme (UKCIP02)\textsuperscript{17} series of monthly estimates of climate change across the UK at a 50 km grid square resolution. The future UK climate is predicted across three decadal timeslices, the 2020s, 2050s and 2080s. This study considered only one emissions scenario, the medium–high emissions scenario, as this is considered a BaU projection, and only the 2020s timeslice.

The Microsoft Excel conversion tool CCWeatherGen,\textsuperscript{18,19} developed by the authors, was used to generate climate change adapted weather files. This tool takes the monthly UKCIP02 projections and applies them to hourly weather data by adopting the morphing approach outlined by Belcher \textit{et al.}\textsuperscript{20} Unmorphed Chartered Institution of Building Services Engineers (CIBSE)\textsuperscript{21} test reference year (TRY) weather files were used as the baseline present-day weather file. TRY weather files represent ‘average years’ and are typically used for the design of heating and mechanical cooling systems in buildings.

Climate change datasets are expected to have an impact on the heating demand of the various housing clusters and consequently to the technologies examined due to the projected rise in mean surface temperature. The Intergovernmental Panel on Climate Change (IPCC) states it is ‘very likely’ that cold nights, cold days and frost will become less frequent over most land areas.\textsuperscript{22} This will clearly lead to lower heating demands for domestic heating in temperate climates such as the UK.

5. CLUSTERING APPROACH: MICROGRIDS
The energy consumption of ten semi-detached houses was modelled. Semi-detached houses were chosen as they are the most common house type of the UK building stock. According to the 2001 national census,\textsuperscript{23} nearly a third of households in England lived in semi-detached houses, more than in any other type of home. The clustering of ten houses to form a microgrid was chosen as the basis of this study to assess the potential benefits of domestic microgrids over individual dwellings. These potential benefits are

\begin{itemize}
  \item[(a)] increased thermal load, allowing CHP technologies to operate under a better regime
  \item[(b)] smoother heating load profiles with less distinct peaks
  \item[(c)] peak demand of a CHP cluster expected to be proportionally smaller than that for a single dwelling, which translates to smaller total installed capacity.
\end{itemize}

Figure 3 shows the relationship between building fabric type and occupancy profiles within a cluster of semi-detached dwellings. For a particular location, this creates, for example, nine possible cluster types if an identical occupancy profile is assumed across all ten houses in a cluster. Different combinations of building fabric, occupancy profile, electricity and hot water demand, location and time period act together to
determine the heating demand for a particular semi-detached house simulation. The results from these individual house simulations were added together to create the heating demand for the desired ten-house cluster (a mix of occupancy profiles but the same building fabric condition).

6. HEATING OPTIONS: MODELLING

To assess the carbon emissions impact of various possible heating options to meet the thermal demand of a housing cluster, Fortran routines were developed within Trnsys. Figure 4 shows the four possible supply heating options that were considered.

(a) Option 1: current practice (BaU). Each house has its own dedicated gas boiler and electricity is imported from the utility grid.

(b) Option 2: micro-CHP household level. Each house has its own micro-CHP unit that follows the heating demand profile.

(c) Option 3: mini-CHP microgrid level. A single CHP device follows the heating demand of a cluster of ten houses. Electricity generation from the CHP unit is distributed across the microgrid with any excess/shortfall being accommodated by the utility grid.

(d) Option 4: multi-stage mini-CHP microgrid. Three CHP units of different capacities operate in series to provide the same peak thermal and electrical output capacity as the single mini-CHP device considered in option 3. Parallel operation strategies enable better thermal load matching than in option 3 and, for this study, a heuristic algorithm was developed for the parallel operation of the three-CHP units.

In order to justify installation of a CHP unit on the grounds of economics, its generated heating energy has to match the profile of the cluster of ten semi-detached houses.

Electricity is imported/exported from the utility grid as required.

Figure 3. Defining a residential housing cluster for present-day and future climate heating demand assessment

Figure 4. Possible thermal and electrical supply options for a cluster of ten houses
Therefore, the driving principle of the CHP model is that the heating demand of the microgrid is covered by the CHP unit(s) and consequently electricity generation is determined by the heating load and the heat/electricity ratio of the selected unit. For all three CHP schemes in this study, a variable-volume tank for thermal storage was considered. Specifically, for the micro-CHP option, a thermal storage tank of 150 litres was considered in every dwelling; for the mini-CHP and the three CHPs in series, an additional shared buffer of 1500 litres was added. Thermal storage enables longer operational periods and fewer start-up cycles for the CHP devices and minimises the intervals where excess or shortfall of heating energy is observed. Table 2 summarises the technical characteristics of the CHP units modelled.

| Option | BaU case – that is, the heating option for each house is assumed to be a gas condensing boiler of 90% efficiency. A condensing boiler was chosen as it represents common practice in current wet heating systems and therefore can be considered as competitive to CHP schemes. For the case of micro-CHP at household level (option 2), a WhisperGen engine micro-CHP system available on the market. For the single mini-CHP case (option 3) a ‘theoretical’ unit was chosen in order to match the technical characteristics of the three units deployed for the multi-stage scheme (option 4). These three units, which are commercially available and operate with natural gas, are the WhisperGen micro-CHP, the Baxi DACHS mini-CHP and the EC Power’s mini-CHP XRGI.

Although operation of the CHP units was adjusted to match heating demands, intervals with a shortage of heating energy do occur, principally at the beginning of the start-up cycle. However, this shortage was not predicted to affect the thermal comfort of the occupants. The minimum run time for the CHP units in this study was set to 3 h. While the primary objective of this study was to investigate the potential carbon savings from

### Table 2. Technical characteristics of CHP units in the three CHP schemes

<table>
<thead>
<tr>
<th>Capacity of mini-CHP theoretical unit</th>
<th>Capacity of WhisperGen micro (option 2)</th>
<th>Baxi DACHS (option 2)</th>
<th>EC Power CHP XRGI (option 2)</th>
<th>Mini-CHP theoretical unit (options 3 and 4)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermal output: kWth</td>
<td>7.0–12.0</td>
<td>12.5</td>
<td>30.0</td>
<td>51.0</td>
</tr>
<tr>
<td>Electrical output: kW</td>
<td>1.0</td>
<td>5.5</td>
<td>15.0</td>
<td>21.5</td>
</tr>
<tr>
<td>Fuel input: kW</td>
<td>10.0–17.0</td>
<td>22.8</td>
<td>50.0</td>
<td>83.0</td>
</tr>
<tr>
<td>Thermal efficiency (kWth/fuel input): %</td>
<td>70.0</td>
<td>55.0</td>
<td>60.0</td>
<td>60.0</td>
</tr>
</tbody>
</table>

### Table 3. Gas and electricity prices used in this study (100 p = £1)

<table>
<thead>
<tr>
<th>Import, rate 1</th>
<th>Import, rate 2</th>
<th>Export: p/kWh</th>
</tr>
</thead>
<tbody>
<tr>
<td>Usage: kWh</td>
<td>Cost: p/kWh</td>
<td>Usage: kWh</td>
</tr>
<tr>
<td>Natural gas</td>
<td>2680</td>
<td>6.860</td>
</tr>
<tr>
<td>Electricity</td>
<td>&lt;500</td>
<td>25.317</td>
</tr>
</tbody>
</table>

7. RESULTS

An estimation of the impact of climate change on the total heating demand of various cluster configurations of ten semi-detached houses was investigated as the first step. The heating demand was simulated for a single semi-detached house, for the three building fabrics, the three different occupancy profiles and two weather datasets for Southampton, UK (18 simulations in total). Present-day and climate change weather datasets were used for Glasgow for the three occupancy profiles, but only for the 1980s building quality fabric (six simulations in total). The results for the different occupancy profiles were combined and clusters of ten houses of the same building fabric were formed (as illustrated in Figure 3). Figure 5 shows the predicted annual heating demand for each cluster of ten semi-detached houses for the present day (2000) and the 2020s.

Future projections show that the heating demand in the 2020s can be expected to be ~6–7% lower than 1990 levels for Southampton (CIBSE TRY spans 1983 to 2004 for Southampton) and ~3–5% lower for Glasgow. The impact of building fabric condition is far greater. The cluster of semi-detached houses compliant to 2002 regulations was estimated to have an annual heating demand of 73 000 kWh – that is, 32% less than the
cluster of houses of 1980s quality fabric (107,000 kWh). This difference increases to 38% for the cluster compliant to 2006 regulations, with an annual heating demand of 66,000 kWh and 62,000 kWh for the present day and the 2020s respectively. Location also plays an important role in heating demand. Compared with Southampton, the harsher winter in Glasgow results in a 13% higher heating demand for the present day, rising to a 16% higher demand for the 2020s.

The related carbon emissions varied according to the heating option deployed. Figure 6(a) shows the carbon emissions for the three fabric-dependent clusters in Southampton. Figure 6(b) illustrates the carbon performance of the CHP schemes (options 2, 3 and 4 detailed in Section 6) compared with the BaU scenario of a condensing boiler and mains electricity (option 1). For the BaU scenario, emissions were estimated to be 37 t/year for the 1980s fabric cluster, 30 t/year for a cluster built according to 2002 regulations and 28 t/year for one built according to 2006 regulations. The performance of each CHP scheme proved to vary significantly, and not all the schemes were found to achieve carbon reductions relative to the BaU scenario.

For all three building fabric types in Southampton, for the present day, the micro-CHP option resulted in 5–10% higher carbon emissions than the condensing boiler option. This estimate agrees with the results of a micro-CHP field trial undertaken by the Carbon Trust. For clusters simulated with a high heating demand, the micro-CHP scheme performed better, but still did not achieve carbon savings. Even for the cluster located in Glasgow, the annual carbon dioxide emissions were estimated to be 2 t greater than for the BaU case. The low projected performance of the micro-CHP systems can be attributed to the low heating demand and the non-smooth heating profile of a single dwelling. Another important factor responsible for the low emissions performance of the micro-CHP is increased heat losses from the heat storage tanks. Ten storage tanks, one for each CHP unit, were assumed for the micro-CHP scheme, and a significant amount of produced heat was predicted to be lost (it was assumed that heat losses from the tank system did not contribute useful space heating to the houses). The two mini-CHP schemes (options 3 and 4) are assumed to operate using a highly insulated heat network so that the transmission losses across the microgrid (excluding tank storage losses) are negligible.

Significant savings were achieved when the ten houses were formed into a local network and the CHP units were operated as a common facility for the microgrid (option 3). In Southampton, the annual emissions for the mini-CHP scheme were estimated to be 29, 24 and 23 t for the three building fabric clusters for the present day, which translates to 18–24% better carbon performance over the BaU case. Further savings were achieved from the three mini-CHP units operating together (option 4), with carbon reductions of up to 32% over the BaU scenario. All the results were similar in terms of percentage carbon savings for the 2020s. Again, clusters located in Glasgow proved to be slightly more suitable for both mini-CHP schemes, underlying the strong correlation between high heating load and a scheme’s carbon performance.

This analysis also examined levels of electricity export and import from and to the utility grid for each cluster. Figure 7(a) shows electricity export as a percentage of electricity generated for the three CHP schemes. The data include all three fabric type clusters for both locations and both weather datasets and the export percentage is therefore given within a range for each CHP scheme. For the micro-CHP case, almost half of the electricity generated was consumed locally (45%), while for the other two schemes more than two-thirds of generated electricity was exported to the utility grid. This is due to the lower thermal/electrical ratio of mini-CHP schemes compared with micro-CHP. For all cases, it was observed that higher levels of export corresponded to higher levels of heating demand. Figure 7(b) shows imported electricity to all the microgrid schemes for the present-day weather case as a percentage of
It is clear that, as would be expected, higher levels of electricity from the utility grid were displaced from those CHP schemes with high heating demand.

Running costs in terms of gas and electricity were also investigated for each heating option and potential savings due to the CHP schemes were examined. Initial and capital costs were obtained from various case studies and costs for the microgrid pipe network were included. Figures 8(a) to 8(c) give an estimation of the annual savings compared with the BaU scenario for all the Southampton clusters for the present day, the three CHP options and three feed-in tariffs, while Figure 8(d) shows the 1980s fabric cluster in Glasgow. The payback period corresponding to these savings was calculated based on the capital and maintenance costs given in Table 4. The payback period for the CHP schemes is strongly dependent on the price paid for electricity exported to the grid. Figure 8 shows that the micro-CHP option is not predicted to achieve annual financial savings unless the high-tariff scenario is assumed. Even in this case, the corresponding financial payback period is high for all clusters, though it drops significantly for clusters with high heating demand, for example Glasgow. The two options in which the CHP(s) operate as a common facility for the microgrid achieved savings for all three feed-in tariff scenarios, but acceptable payback periods (<15 years) occurred only for the medium and high feed-in tariff scenarios. The three mini-CHP units in series were estimated to have similar payback periods to the one mini-CHP scheme. Although capital costs for three CHPs in series are higher than that for a single mini-CHP, the capital costs for the microgrid heating network are the same and account for about 50% of the total investment.

8. DISCUSSION
This paper has investigated the carbon performance of heating options for various clusters (occupancy profile, electricity and hot water demand, building fabric condition, location and

![Figure 6](https://example.com/figure6.png)

**Figure 6.** (a) Annual carbon dioxide emissions for clusters located in Southampton at the present day; (b) carbon performance of the CHP schemes studied.
climate) of ten semi-detached houses. Different levels of heating demand were simulated related to three different building fabric types, three occupancy profiles, two locations in the UK (Southampton and Glasgow) and two weather datasets (present-day and UKCIP02 medium–high 2020s emissions scenario). The investigated building fabrics reflect the evolution of UK building regulations, the occupancy profiles represent typical UK households and the two locations capture weather differences – that is, harsher winters in Glasgow. The heating options considered were a condensing boiler, a micro-CHP unit installed in each dwelling of the cluster, a mini-CHP unit operating as a common facility for a microgrid and three mini-CHP units connected in series, also operating as a common facility for the cluster.

All the CHP options in this work were considered as an alternative to a conventional boiler, therefore the process was assumed to be heat-led. Waste heat was avoided as an operating principle and only low levels of heat were dumped occasionally during winter when storage tanks reached capacity. This practice works well for countries with cooler climates such as the UK, where cooling for domestic purposes is not necessary. For warmer climates, where cooling is required during the summer months, an absorption chiller could be implemented, effectively creating a combined cooling, heating and power scheme (trigeneration). The extra heat required to drive an absorption chiller would result in higher levels of electricity generation during the summer months, when higher levels of electricity import are observed with the current practice.

The notion of combining a group of homes in a local microgrid incorporates a number of technical and regulatory issues that need to be considered before this concept can be applied. Due to the technical complexity of some of these issues (energy and power balance, energy storage, maintenance, monitoring, billing), a specialised energy company is expected to manage and maintain the microgrid. Regarding the billing, a ‘flat rate charging’ scheme may be adopted, thus avoiding complex and
expensive metering practices. As defined in SAP 2005, flat rate charging is a scheme where households pay a fixed monthly or annual amount, regardless of the heat actually used. This fixed charge may vary according to the size of the dwelling, its energy performance, the number of occupants, etc. Clearly, the weakness of this approach is that financial payment is no longer directly related to consumption. Another issue that needs to be considered when creating local microgrids is how big the microgrids may be. For this study, the heat network system was assumed to be highly insulated and therefore distribution losses low. Assuming the same heat network, the scheme could be expanded up to the scale of 1000 houses, for example, without significant losses.

When assessing the potential carbon savings from micro-technologies, the most important factor is electricity carbon intensity. Although there is not one value for electricity carbon intensity that suits all the technologies, two main options have been used for assessing micro-technologies: the UK grid mix and the marginal plant value. The UK grid mix emissions factor is based on the rolling average carbon intensity of the UK grid:

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national grid over a period of 5 years and is estimated to be 0.43 kg/kWh. This value has been widely used and is also suggested in government guidelines to greenhouse gas conversion factors for company reporting.25 The SAP suggests a similar value (0.422 kg/kWh). The marginal plant value is based on the assumption that certain types of plants, notably nuclear, will continue to generate regardless of total UK demand, therefore electricity from such plants will never be displaced. The SAP suggests a value of 0.586 kg/kWh for electricity displaced from the national grid. Though the marginal plant value benefits micro-technologies with higher potential to achieve carbon savings, the authors chose to use the UK grid mix value since it is more likely to reflect the carbon intensity of the UK grid in the future, when such microgrids may come to reality.7 The impact of the marginal plant approach is substantial in that, under this scenario, micro-CHP schemes achieve carbon savings for most of the housing clusters examined in this work.

Simulations were also undertaken for different minimum run times for the CHP units. A run time of 2 h gave similar results to those obtained with a minimum run time of 3 h. During periods of high heating demand, the CHP units were typically operating for 3 h or more, since the level of heating demand could not be met with only 2 h of operation. When the minimum run time was reduced to 1 h, the results were improved (<5%) mainly for the three CHPs in series scheme. More frequent switching results in less heat being diverted to heat storage and more heat being consumed directly in the dwelling. In this way, the heat losses due to heat storage are less than in the longer run cycles.

9. CONCLUSIONS

The carbon performance of the four heating options considered in this paper can be ranked, best to worst, as follows

(a) three mini-CHP units, connected in series, operating as a common facility for a microgrid
(b) one mini-CHP unit operating as a common facility for a microgrid
(c) condensing boiler of 90% efficiency (BaU scenario)
(d) micro-CHP installed at the single dwelling level.

This ranking order was noted to be the same for all the housing clusters, regardless of location or weather dataset used. This was also reflected in the annual financial savings achieved in terms of fuel (gas and electricity). The micro-CHP option did not achieve any carbon savings over the BaU scenario (condensing boiler and utility grid electricity). All the results demonstrate that the CHP schemes are more suitable for large dwellings (equivalent in heating profile to multiple numbers of the semi-detached dwellings considered here) or clusters with high heating demand. Higher heating demand corresponded to both improved carbon performance and proportionally higher savings in annual fuel bills. The estimated payback periods indicate that such schemes can be economically viable. Climate change will have a small negative impact on the potential market/benefit of CHP, reducing the heat demand of a dwelling by 4–7% by the 2020s. Finally, it was observed that high heating demand profiles resulted in higher levels of electricity export from the microgrid and lower levels of electricity import from the utility grid. Therefore, the need to move towards smart metering and financial mechanisms that reward electricity export is very important for such CHP systems.

This paper has not considered the issue of providing the heat network infrastructure in terms of its practicality. It has, however, shown that clustering is required to deliver a heating demand profile to enable small-scale CHP to yield carbon savings over the BaU case. Early adopter risk will inevitably reduce the economic viability of such systems, even if heat network infrastructure issues can be addressed. District heating across a range of scales is now becoming an increasingly important UK issue, which will be driven forward through new building regulation performance demands. In particular, the need to deliver carbon neutral homes by 2016 can be expected to drive CHP technology towards biomass-based systems.

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Appendix F

List of Publications

