Application of the Thermoelectric Heat Exchange Module Combined with Renewable Energy for UK Domestic Heating

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Declaration

I hereby declare that except where specific reference is made to the work of others, the contents of this dissertation are original and have not been submitted in whole or in part for consideration for any other degree or qualification in this, or any other university. This dissertation is my own work and contains nothing which is the outcome of work done in collaboration with others, except as specified in the text and Acknowledgements. This dissertation contains around 51,000 words include abstract and main chapters (i.e. bibliography and appendices are not counted), and has 86 figures.

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Publications

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Abstract

This thesis proposes a theoretical study which mainly utilizes experimental test, quantitative data statistics, case study and scenario simulation to ascertain the feasibility of developing a thermoelectric (TE) heating system powered by renewable energy to service for the UK domestic heating demands, and further compete with current domestic heating system to reduce the greenhouse gas emissions.

Experimental study results of the space heating application of TE modules in a laboratory environment (19 °C-21 °C) and outside courtyard low-temperature environment (1 °C-5 °C) demonstrate that sufficient temperature difference can be achieved with TE modules so as to satisfy UK thermal comfort levels. The heating COP test results of TE modules also suggest an acceptable heat pump efficiency for the domestic heating application.

In order to ascertain the potential feasibility of applying renewable energy to power TE modules for supporting the domestic heating, the detailed case study presents a simulated domestic heating application of TE modules to a Pre-1900s mid-terrace UK dwelling using hybrid renewable energy of solar energy and wind energy. Relevant calculation results reveal that a TE heating system, powered by local hybrid renewable energy and energy storage, can partly meet the domestic heating demand and could achieve a theoretical energy saving efficiency of 64.93% and reduce the CO_2 emission of 3927.72 kg/year compared with using generic electric heater for the domestic space heating whilst the average heating COP remains at 1.8. These suggest that TE modules can potentially be a solution for domestic indoor space heating whilst using renewable electricity.

Consequently and for further evaluating the feasibility of universally applying TE heating system in the UK domestic context, more scenario simulations regarding the domestic heating application of TE modules with hybrid energy supply in different properties across England and Wales are proposed. The simulation results show that with the heating support of TE modules powered by renewable energy, the domestic heating demands can be independently meet for 2-6 months per year (exclude June, July and August) in most common property types and 4-9 months per year in bungalows. Especially in some domestic scenarios of the UK southern regions, both of the domestic heating demands and hot water demands can be potentially meet without extra grid-supply throughout the year. More relevant estimation results suggest that the domestic heating application of TE modules with hybrid energy supply in various scenarios can save minimum 56.11% annual grid electricity consumption in comparison with employing generic electric heaters powered by the grid electricity, and can save 2.89%-84.82% CO_2 emission in comparison with condensing boiler heating by burning natural gas, respectively. Meanwhile,

during some warm months, the excess renewable energy outputs which are not requested by the domestic heating demands can potentially be used to supply the domestic hot water and electric demands which will contribute with more grid energy saving and CO_2 emission reduction.

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Nomenclature

Acronyms

ABS active building envelope

AC alternating current

ACP aluminum composite panel

AGM absorbent glass mat

AHP absorption heat pump

AR absorption refrigeration

CFC chlorofluorocarbon

COP coefficient of performance

DC direct current

DHW domestic hot water

GWP global warming potential

HAWT horizontal-axis wind turbine

HCFC hydrochlorofluorocarbon

HFC hydrofluorocarbon

ODP ozone depletion potential

PV photovoltaic

RTD resistance temperature detector

SLA sealed lead acid

SOC State of charge

STC standard test condition

TE thermoelectric

VAWT vertical-axis wind turbine

VC vapor compression

WT wind turbine

Symbols

$\Delta T_{airflow}$ temperature difference between the inlet airflow and outlet airflow (K)

α Seebeck coefficient ($\mathrm{V\,K^{-1}}$)

ΔT temperature difference between the junctions (K)

ΔT_{max} maximum temperature difference between hot side and cold side of TE module (°C)

η_b storage efficiency of battery (%)

η_{inv} inverter efficiency (%)

γ self-discharge influence value

κ thermal conductivity ($\mathrm{W\,cm^{-1}\,K^{-1}}$)

μ power law exponent

π_{Pel} Peltier coefficient (V)

ρ electric resistivity of N type semiconductor or P type semiconductor (Ω cm)

ρ_{flow} air density ($\mathrm{m^3/kg}$)

σ electric conductivity ($\Omega^{-1}\,\mathrm{cm^{-1}}$)

ε_c cooling COP

ε_h heating COP

ε_{max} maximum cooling COP

AD daily autonomy value

C specific heat capacity of the heated air ($\mathrm{J\,kg^{-1}\,K^{-1}}$)

C_{kwh} battery capacity (kW)

C_p power coefficient of the wind turbine

C_T temperature coefficient of PV cell (°C)

DOD depth of discharge of battery (%)

E_{BN} total capacity of battery (A h)

E_L average daily load energy demands (kW/day)

E_{min} maximum discharged capacity of battery (A h)

f_{pv} solar cell derating factor

G geometry factor of N type semiconductor or P type semiconductor (cm)

G_A solar radiation illuminating on solar cell (kW/m^2)

G_h local solar radiation in the horizontal surface (kW/m^2)

G_{STC} global solar radiation (kW/m^2)

I electric current (A)

I_0 electric current for reaching maximum cooling COP (A)

I_E electric current for reaching heating COP of 1.8 (A)

I_{max} maximum allowable current of TE module (A)

I_m electric current for reaching maximum cooling capacity (A)

K total thermal conductivity of TE module (W K^{-1})

$m_{airflow}$ net weight of the heated airflow (kg)

N number of thermocouples in TE module

P_h heat transfer power from TE modules to heating ambient (W)

P_{pv} power output of solar cell (W)

P_{STC} peak power of solar cell under the standard test condition (kW)

P_{WT} wind turbine power generation (W)

Q_{con} Fourier conduction heat (W)

Q_c cooling capacity (W)

Q_E equal power point cooling capacity (W)

Q_h heating capacity (W)

Q_J Joule heat generation rate (W)

Q_{max} maximum cooling capacity (W)

Q_{Peljc} Peltier cooling transferred at the cold junction (W)

$Q_{Pel\,jh}$ Peltier heating transferred at the hot junction (W)

Q_{Peltc} Peltier cooling transferred at the cold side of TE module (W)

Q_{Pelth} Peltier heating transferred at the hot side of TE module (W)

Q_{Pel} Peltier heat (W)

Q_P usable energy stored in the battery (A h)

R total internal electric resistance of TE module (Ω)

r radius of the wind turbine rotor (meter)

T absolute temperature of the thermoelectric material (K)

t heating time (s)

T_A ambient temperature (°C)

T_c cold side temperature of the TE modules (K)

t_d discharge time of battery (h)

T_h hot side temperature of the TE modules (K)

T_{jc} cold junction temperature (K)

T_{jh} hot junction temperature (K)

T_j junction temperature (K)

T_{pv} actual solar cell temperature (°C)

T_{STC} nominal temperature of solar cell under the standard test condition (°C)

U_{anem} wind speed at anemometer height (m/s)

U_{hub} wind speed at the hub height of the wind turbine (m/s)

U_{max} maximum working voltage of TE module (V)

U_s electric potential difference (V)

v wind speed (meter/s)

W power consumption (W)

Z figure-of-merit of thermoelectric material (K^{-1})

z_0 surface roughness length (m)

z_{anem} anemometer height (m)

z_{hub} hub height of wind turbine (m)

ZT dimensionless index for the heat exchange performance of the TE module

NOCT normal operating temperature of the solar cell (°C)

Chapter 1

Introduction

1.1 Research background

The energy consumption of domestic households in the UK usually occupies a large proportion of the national final energy consumption and is the significant contributor to the total carbon emission. The Department of Energy & Climate Change published that in 1990 and 2000 UK domestic dwellings energy consumption was 27.67% and 29.4% of the UK total energy consumption, and till 2013 the UK domestic residences had been response for 31.1% of the UK final energy consumed [1] and contributed to approximately 16.6% of the total CO_2 emissions [2]. This reveals an upward trend which is driven by factors such as population growth (i.e. the number of the UK households has risen by 40% since the 1970s [3]), proliferation of household electronic devices, and the increase of indoor thermal comfort level (i.e. average internal temperatures increased from 13 °C in 1970 to 18 °C in 2000 [4]) amongst others. Moreover, the specific profile of the UK domestic load energy-consumption in 2013 further shows over four fifths (83%) of the UK domestic total energy consumption was used for the space heating (66%) and the hot water heating (17%). And the rest energy consumption was used for the lighting & appliances (15%), and cooking (3%) respectively [2]. It is clear that space heating demand accounts for the largest proportion of the total domestic final energy-consumption. If no any more efficient actions are taken to further enhance the heat demand management of the UK dwellings but keep the historic upward trend, the worst result estimation in the 2050 Pathways Calculator shows that the energy demand for domestic heating and hot water can continually rise by up to about 50% by 2050 compared with the 2009's level [3], [5].

On the other side, the UK Government's Low Carbon Plan sets out ambitious targets to reduce UK greenhouse emissions by 80% of 1990 levels by the year 2050 [6]. This will be a significant challenge which requires substantial changes in both of the UK's buildings and energy supply infrastructures. For efficiently controlling the energy consumption for domestic heat demand factor, the government has taken many measures such as retrofit houses for reducing avoidable heat loss; improve the energy efficiency of heating systems; and develop heat networks [3]. Currently the UK is facing a huge retrofit challenge as some 25 million existing dwellings will need to be upgraded by 2050 as part of the UK's move towards a low carbon economy and built environment [7]. Moreover, the UK Government and Local Authorities are struggling to go beyond the so called "low-hanging fruit" energy efficiency measures such as double glazed windows and doors, loft, cavity and solid wall insulation when retrofitting the existing domestic stock. And the energy efficiency of existing heating systems are also more expected to be enhanced in future decades.

According to the latest statistics published by Department for Communities and Local Government [8], for meeting the domestic heating demand, till 2013 there are 91% UK homes have the central heating system, a further 6% dwellings utilize the storage heaters and 3% dwellings remain room heaters. Boilers are generally the cores of most central heating system. And the types of the boilers involve standard, back, combination, and condensing. Condensing boilers are the most efficient boiler type which generally have high heating efficiency between 85%-92% [9] compared with 79% of other non-condensing boilers [10]. As part of the UK government's low carbon plan, most of the 13 million remaining non-condensing boilers will be replaced by 2020 for maximizing the fossil fuel heating efficiency [3]. Additionally, looking forward to further developments, the government is expecting the natural gas combustion at individual building level will be completely phased out by 2050 and the natural gas will only allow to be consumed by some cases of the heat networks to provide heat to households. That means the electricity and bioenergy will play stronger roles to support future heat demands. Meanwhile as one of efficient heating devices which consume electricity to against the temperature gradient for achieving thermal comfort, the heat pump will be favored strongly by all individual buildings in the decarbonised scenarios [3].

1.2 TE heating module

Thermoelectric (TE) modules are typical solid-state heat pump devices which rely on the Peltier effect and their heat exchange performance can be characterized by a dimensionless index *ZT* in close relation to the thermoelectric material figure-of-merit (i.e. as a general rule, the larger *ZT* of the thermoelectric material is, the better heat pump performance (i.e. heating COP) [11]. The equation to derive the value of *ZT* can be found in section 2.1.3 of Chapter 2). Different from the traditional vapor compression (VC) heat pump system which consists of three basic components: a unit which permits the refrigerants to expand, vaporize, and absorb heat from surrounding ambient; a compressor; and condensers [12], TE modules do not require any fluid refrigerants or moving parts, and always work under a solid-state condition to transfer heat from the hot side to cold side. Thus, TE modules have zero ODP (Ozone Depletion Potential), low GWP (Global Warming Potential), higher levels of reliability, lower working noisy and lower maintenance costs [13]. Moreover, the volumes of TE modules are much smaller than both VC and absorption refrigeration (AR) equipment volume which could more easily be distributed in the building internal space; their total heating capacity can be augmented by simply increasing the total number of TE modules in the TE heat pump design; and TE modules have higher development potential as new material research improves figure-of-merit (e.g. Lincoln labs had improved the $ZT \geqslant 2.0$ [14]) and this will enable the development of TE modules with higher COP. The operation of the TE heat pump requires a DC power supply and its actual heat exchange capacity is more sensitive to the input power (voltage/current) changes. Thus, in comparison with both of the VC and AR heat pumps design, the TE heat pump could, theoretically, be smart controlled more easily by monitoring temperature and adjusting the input power level for optimizing the energy efficiency.

1.3 Study aim and objectives

The aims of this theoretical study are to ascertain the feasibility of developing a thermoelectric (TE) heating system powered by renewable energy to service for the UK domestic heating demands, and further compete with current domestic heating system to reduce the greenhouse gas emissions.

In order to achieve above study aims, specific research objectives are as follows:

1. review existing knowledge regarding the thermoelectric researches to determine the theoretical principle, relevant calculation methods and current TE research status so as to promote the thesis development.

2. determine the actual heating performance (e.g. reachable temperature difference for supporting indoor thermal comfort, achievable heating COPs and heating power) of TE modules when being tested under typical UK context.

3. determine the heating supply-demand relationship if applying TE modules combined with renewable energy to support the domestic heating throughout the year; estimate possible grid electricity saving efficiency in comparison with general electric heaters; and demonstrate appropriate application design in the domestic scenario, which intend to ascertain the feasibility of applying the entire system to service for the domestic heating demands.

4. expand the heating supply-demand and grid electricity saving efficiency estimations in more different domestic scenarios across England and Wales for further evaluating the feasibility of universally applying TE heating system with renewable energy supply in the UK domestic context.

5. estimate the possible CO_2 emission reduction caused by utilizing TE heating system to replace condensing boilers for domestic heating purpose and CO_2 emission reduction caused by rationally using excess renewable energy outputs, which intend to evaluate the carbon reduction potential of developing TE heating system with renewable energy supply in the domestic context.

1.4 Research methodology

In this thesis, the study mainly utilizes experimental test, quantitative data statistics, case study and scenario simulation methods to achieve the research aims.

To be more specific, in the first stage of the thesis development, literature review of existing knowledge regarding the thermoelectric researches are essential so as to confirm the theoretical principles (e.g. working principle of TE modules, TE material figure-of-merit) and determine basic equations refer to the TE heat exchange performance calculation. It can also understand current studies which have made efforts to explore the potential of TE modules for heating purposes such as [15], [16] and [17] (i.e. detailed research results of these studies are presented in section 2.3.3 of Chapter 2).

However, above studies also have shortcomings, mainly, there is a lack of experimentation data to validate the performance of TE module and its applicability. Hereby, in the second research stage, an experimental study is proposed to test the actual heating performance of TE module under typical UK context. Reachable temperature difference of TE module can be directly measured to compare with the UK domestic thermal comfort levels. Meanwhile based on relevant equations, parameters investigated in literature review stage and experimental measurement data, it can derive the achievable heating COPs, heating power of TE modules and analyze potential relationship regarding the achievable temperature differences, heating COPs change with operation times for ascertaining the heating applicability of TE module to indoor space.

Furthermore, although a lot of statistics and analysis regarding the UK domestic energy demands and renewable energy resources have been provided such as [18], [8], [19], [20], [21], [22], there are few UK-based reports could clearly discuss/evaluate the feasibility of employing heat pumps powered by renewable energy to supply the domestic heating demands. Thus in the third research stage, subsequent research development will carry out theoretical calculations in a realistic case study (i.e. a Pre-1900s mid-terrace UK dwelling) so as to ascertain the potential of a TE air-source heat pump when powered by renewable energy in the domestic context. During this study process, in the case studied dwelling, domestic energy consumption can be easily investigated and analyzed for determining the detailed domestic heating demands. Available renewable energy supply by suitable devices (i.e. solar panels and wind turbines) can be estimated by historical weather data statistics, equipment specifications investigations and software simulation calculations. Then combining with the experimental results regarding actual heating performance of TE module, it can theoretically estimate the heating supply-demand relationship when applying TE modules combined with renewable energy to support the domestic heating throughout the year, and further determine the entire system's energy saving potential in comparison with general electric heaters. Moreover, appropriate application design of TE heating system combined with renewable energy will also be visually demonstrated in the case study which is helpful to ascertain the feasibility of applying the entire system in the domestic context.

Additionally, in comparison with relevant data investigation results of the case study, the domestic heating demands and local available renewable energy resources in different domestic scenarios always have some differences depend on the influence factors involve dwelling types, floor areas, ages, locations and occupant number. Hence for evaluating the feasibility of universally applying TE heating system with renewable energy supply in the UK domestic context, in the fourth research stage, the study will verify necessary baseline data and change trends of domestic heating demands and renewable energy resources in various domestic scenarios based on quantitative data statistics and investigations. Hereby, it can expand theoretical calculations refer to the domestic heating demands and available renewable energy supply in more different domestic scenarios across England and Wales. Then utilizing similar simulation methods with case study, different domestic heating results regarding heating supply-demand relationship and grid energy saving efficiency can be explored.

Finally, the thesis intends to evaluate the potential advantages of developing TE heating system with renewable energy supply in the domestic context to reduce the greenhouse gas emissions. Hence the CO_2 emission factors of various energy sources and basic equations refer to the CO_2 emission calculations are necessary to be investigated and studied. Then based on theoretical calculation results of the domestic heating demands and available renewable energy supply in various domestic scenarios, the study can further classify and estimate the potential CO_2 emissions caused by the entire system application in the domestic context. Hereby it would be able to compare and ascertain the CO_2 emission reduction efficiency caused by utilizing TE heating system to replace common condensing boilers for the domestic heating purpose and possible CO_2 emission reduction caused by rationally using excess renewable energy outputs to partly supply the domestic electric demands.

1.5 Thesis outline

The structure of the rest of the thesis is as follows:

- Chapter 2 presents a detailed background study which introduces the working principle of TE modules, the TE material figure-of-merit, basic equations refer to the TE heat exchange performance calculations, and the development status of existing TE research. The particular features of TE modules are also thoroughly evaluated in comparison with VC and AR heating system.

- Chapter 3 proposes a specific experiment to test and study the actual space heating performance of TE modules in the UK context. Three pieces of TEC1-12706 modules are utilized to heating a 1 m^3 enclosed space under different test conditions (i.e. different input voltages levels and different external ambient). Relevant test results regarding achievable heating temperature, temperature difference, heating COP, and heating power are detected and analyzed for ascertaining the feasibility of applying TE modules to support the UK domestic heating.

- Chapter 4 presents a detailed case study for exploring the potential application of TE heating system if further being powered by renewable energy to support the domestic heating. Relevant heating demands and available renewable energy supply (i.e. solar and wind energy supply) in a typical pre-1900s mid-terraced property with 180 m^2 floor area located in Newcastle upon Tyne are investigated for supporting the estimation of heating supply-demand relationship when utilizing TE heating system powered by renewable energy to service for the domestic heating. Moreover, rational comparison between TE heating system and general electric heater is helpful to identify the TE system's advantages which contribute with both of the grid energy saving and carbon saving for supporting the dwelling heating.

- in Chapter 5, the specific application design of TE heating system combined with hybrid energy supply (i.e. solar/wind renewable energy and utility grid supply) are demonstrated in the typical mid-terraced property same with the case studied dwelling. Main system components' specifications and costs are investigated for supporting simple estimations of the system total cost and lifecycle. Correspondingly, the achievable energy/carbon saving contributions during minimum system lifecycle in comparison with general electric heater can be identified.

- Chapter 6 further proposes more domestic heating scenario simulations by employing TE heating system with hybrid energy supply in different properties across England and Wales. Relevant baselines and estimation methods are defined and studied respectively. The specific heating supply-demand relationships and potential energy saving efficiencies in various scenarios are estimated as important arguments to evaluate the feasibility of universally applying TE heating system with hybrid energy supply in the UK domestic context,

- in Chapter 7, the CO_2 emission factors of various energy sources are studied and the potential CO_2 emissions caused by applying TE heating system with hybrid energy supply in the UK domestic context are further classified and estimated. Relevant estimation results in terms of the CO_2 emission reduction compared with condensing boiler heating by burning natural gas and possible CO_2 emission reduction caused by rationally using excess renewable energy outputs will be helpful to evaluate the carbon saving potential of the entire system.

- Finally, in Chapter 8, main study results and limitations are summarized and evaluated, and further works are suggested.

Table 1.1 provides a summary of how the research objectives map with the methodology and chapter structure.

Objective	Methodology	Chapters
Objective 1	Literature review	Chapter 2
Objective 2	Experimental study	Chapter 3
Objective 3	Case study & Simulation	Chapter 4 & Chapter 5
Objective 4	Simulation	Chapter 6
Objective 5	Simulation	Chapter 7

Table 1.1 Mapping objectives to methodology and chapters

1.6 Study contribution to existing research

This thesis presents a number of contributions to knowledge of existing research in the form of a detailed experimental study validates the actual heating performance of TE module and its applicability in the UK context. All the test results should be useful data references for supporting others' future studies in relation to TE heating application in buildings. Quantitative data statistics regarding the heating demands and available renewable energy supply in typical UK domestic context are investigated to support relevant heating supply-demand relationship simulations in a specific case study and more other UK domestic scenarios, which ascertains the feasibility of employing TE heating system powered by renewable energy to service for some domestic heating demands of the UK. Both of the grid energy consumption in comparison with general electric heater and CO_2 emission in comparison with condensing boiler have been estimated, allowing an evaluation of potential energy/carbon saving advantages of TE heating system with hybrid energy supply to compete with existing heating systems. Detailed application design of TE system combined with hybrid energy supply (i.e. solar/wind energy and grid energy supply) in the domestic scenario are also proposed and demonstrated.

Chapter 2

Literature Review

This chapter mainly introduces five main aspects: the working principles of TE module; the thermoelectric material figure-of-merit index *ZT* regarding to TE heat exchange performance; the TE heat exchange performance calculations derived by basic equations; comparison between TE modules, VC and AR/AHP systems; and the development status of TE cooling/heating application researches reviewed in other's studies.

2.1 Background study

2.1.1 Working principle of thermoelectric module

When the same two conductors are respectively connected with each end of a different conductor and keep the intersections at different temperatures, then this will generate an electric potential difference between the junctions [23]. This phenomenon is known as Seebeck effect discovered by German physicist Thomas Johann Seebeck in 1821 and its equation is defined in Equation 2.1.

$$U_s = \alpha \times \Delta T \tag{2.1}$$

Where U_s is electric potential difference (V) caused by the Seebeck effect, α is the Seebeck coefficient ($\mathrm{V\,K^{-1}}$) which is determined by the properties of conductor materials and ΔT is temperature difference (K) between the junctions.

The Peltier effect was firstly discovered by French physicist Jean Charles Athanase Peltier in 1834. This effect is the opposite of the Seebeck effect and it is described as providing a direct current to through junctions of dissimilar materials so it can build up a temperature gradient capable of transporting heat from the low-temperature end to the high-temperature end [24].

That is, connected two conductors A (e.g. bismuth) with conductor B (e.g. copper) as shown in Figure 2.1, if electric current flows from junction 1 to junction 2, the internal electrons (e-carriers) will across junction 2 and move towards to junction 1, which is opposite to electric current flow direction. The heat around the junction 2 (lower potential) will be absorbed by the electrons and cause a boost of electric potential energy of these electrons. When electrons pass through junction 1 (higher potential), the electric potential energy of electrons will drop whilst releasing heat at this junction. In this way, it can apply the electric current (electrons/e- carriers) to transport heat from junction 2 to junction 1 [25].

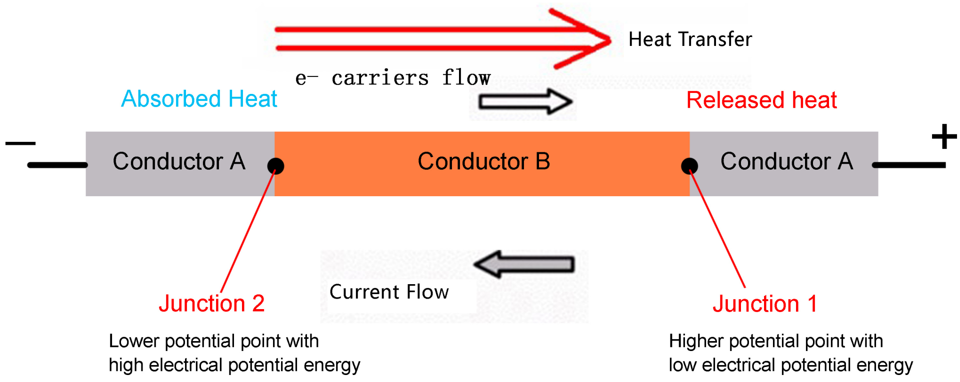


Fig. 2.1 Schematic of the Peltier effect

The heat transfer caused by the Peltier effect is defined by Equation 2.2. Where Q_{Pel} is the Peltier heat (W), I is the input electric current (A), π_{Pel} is the Peltier coefficient (V) which is further determined by the Seebeck coefficient α (V K^{-1}) and the junction temperature T_j (K) as shown in Equation 2.3.

$$Q_{Pel} = \pi_{Pel} \times I \tag{2.2}$$

$$\pi_{Pel} = \alpha \times T_j \tag{2.3}$$

Combining Equation 2.2 and Equation 2.3, it could define the Peltier cooling $Q_{Pel\,jc}$ (W) transferred at the cold junction (i.e. junction 2) and the Peltier heating $Q_{Pel\,jh}$ (W) transferred at the hot junction (i.e. junction 1) by Equation 2.4 and Equation 2.5 respectively.

$$Q_{Pel\,jc} = \alpha \times I \times T_{jc} \tag{2.4}$$

$$Q_{Pel\,jh} = \alpha \times I \times T_{jh} \tag{2.5}$$

Where T_{jc} is the cold junction temperature (K) and T_{jh} is the hot junction temperature (K).

The Peltier effect is the working principle of TE modules which became available in commercial application since the 60's benefited from the development of advanced semiconductor thermocouple materials in combination with ceramics substrates [26]. Typical TE module usually consists of a large number of N type semiconductor pellets, P type semiconductor pellets, conductor tabs (e.g. copper), two wires and ceramic substrates as shown in Figure2.2.

The main ingredient of both N type semiconductor and P type semiconductor is bismuth telluride [25]. To be specific, the most common N type materials are Bi_2Te_3-Bi_2Se_3 and P type materials are Bi_2Te_3-Sb_2Te_3 [27]. The difference of specific compositions result in the N type

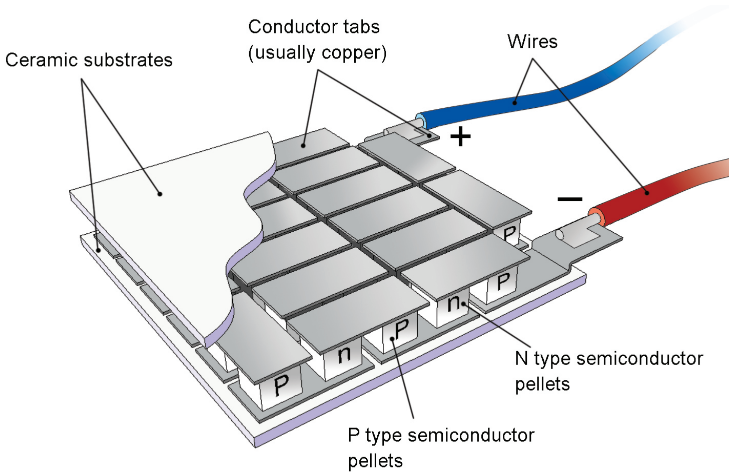


Fig. 2.2 Schematic of the typical TE module

material and the P type material are doped with different types of carries respectively and further demonstrate different properties.

As shown in Figure 2.3(a), the N type semiconductor material doped with an abundant number of free electrons (e- carriers) is sandwiched between two copper conductors. When they are connected to an closed DC circuit, electrons will move towards to the positive end of the power supply under the external electric force. Meanwhile following the Peltier effect, at the cold end (junction with lower electric potential), electrons will firstly absorb heat from surrounding ambient to boost their energy levels and then pass through the semiconductor. When these electrons leave the hot end (junction with higher electric potential), they will drop back to lower energy levels and release heat. In this way, it can build up a temperature gradient between two ends of the N type semiconductor, and the Peltier heat transfer direction is opposite to the electric current flow direction.

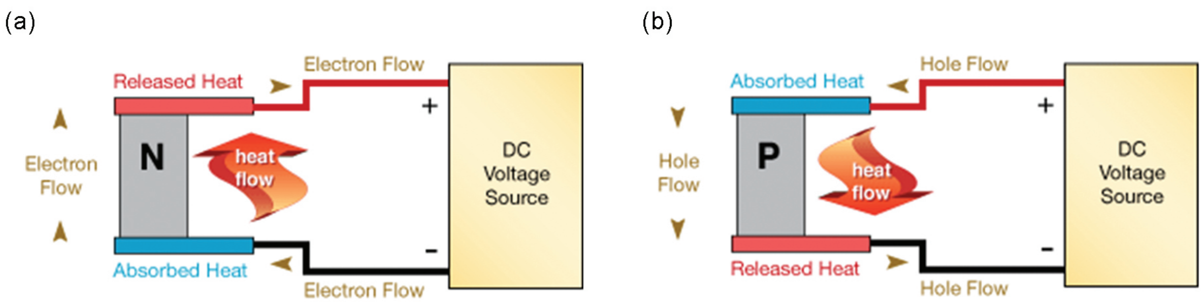


Fig. 2.3 (a) rationale of the N type semiconductor (b) rationale of the P type semiconductor (pictures source from [25])

The P type semiconductor material is doped with a lot of electron holes (e+ carriers) as shown in Figure 2.3(b). The movement of holes is same with the electric current flow direction in the DC circuit (i.e. in the closed DC circuit, electrons always moves towards to the opposite direction of the electric current flow. When a electron moves to fill a hole whilst it creates a new hole at the original position of this electron. Hereby it can be deemed as the holes and electrons move in opposite directions). According to [25], when electrons enter the hot end (junction with lower electric potential) of the P type semiconductor and fill into the holes, they will drop to lower energy levels whilst releasing heat to surrounding ambient. Then these electrons will move towards to the cold end (junction with higher electric potential), and absorb heat when leaving the cold end (junction with higher electric potential) for boosting back to higher energy levels. In above processes, even though the actual heat is firstly released at the hot end and then be absorbed at the cold end, the total amount of heat release is equal to the heat absorption. Therefore it can be deemed as the Peltier heat transfer caused by the P type semiconductor follows the same direction of the electric current flow (e+ carrier movement direction).

In summary, the N type semiconductor doped with e- carriers is able to absorb heat at the lower potential junction and release heat at the higher potential junction, but the P type semiconductor doped with e+ carriers releases heat at the lower potential junction and absorb heat at the higher potential junction. Utilizing these opposite properties, it could connect a N type semiconductor and a P type semiconductor in electric series to further compose a thermocouple as shown in Figure 2.4.

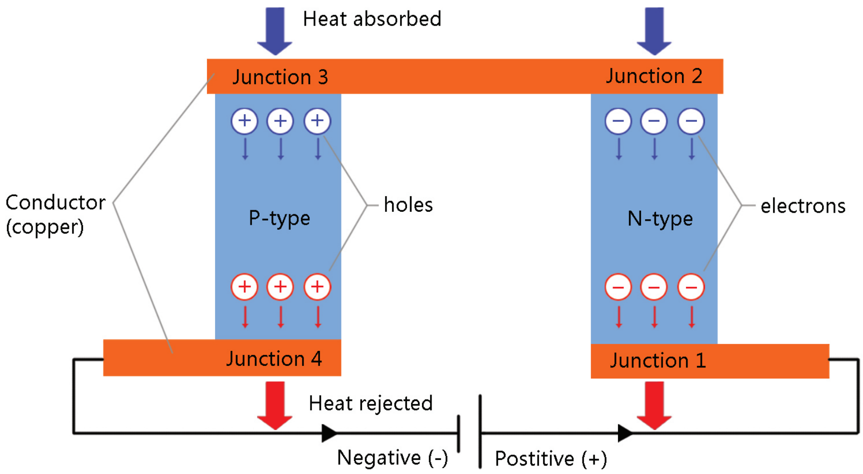


Fig. 2.4 Schematic diagram of the thermocouple

Figure 2.4 shows that in the closed DC circuit, the sequence of electric potential strengths between four junctions is: junction 4 $<$ junction 3 $<$ junction 2 $<$ junction 1. Based on the property of the N type semiconductor, the e- carriers (electrons) move in opposite direction of the electric current flow to cross the junction 2 and junction 1 will result in heat is absorbed at junction 2 (lower potential) and released at junction 1 (higher potential). On the contrary, in the P type semiconductor, it can be deemed as the e+ carriers (holes) move in the same direction of the electric current flow to cross junction 3 and junction 4. And heat will be absorbed at junction 4 (lower potential) and be released at junction 3 (higher potential). It can summarize both junction 2 and 3 are heat release ends; junction 1 and 4 are heat absorption ends. In this way, the thermocouple consists of a N type semiconductor and a P type semiconductor can build a temperature gradient between the cold side and the hot side in closed DC circuit, and the temperature gradient direction can be easily reversed by reversing the direction of electric current [16].

Moreover, since the heat exchanged by single thermocouple is usually very few, typical single-stage TE module commonly employs a number of same thermocouples which are connected electrically in series and thermally in parallel as shown in Figure 2.5 to ensure enough total heat exchange in most actual applications. And the outer case of the TE module generally utilizes the ceramic material (e.g. alumina) with the electric insulation and higher thermal conductivity.

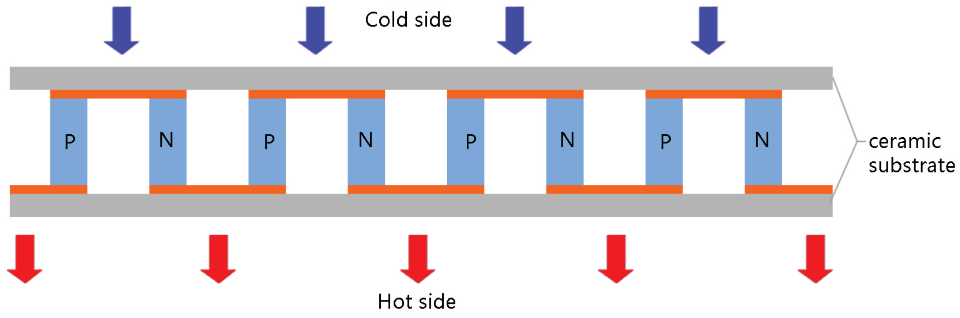


Fig. 2.5 Schematic diagram of TE module

2.1.2 TEC1-127 modules

Currently the most popular TE heat exchange modules in the market should be the TEC1-127 modules which involve a series of different models named from TEC1-12703 till TEC1-12715. The basic naming regulations of these series modules generally contain six sections [28]:

- In the first section where "TE" is abbreviation of "Thermo-Electric".
- In the second section where "C" indicates the cross-sectional area of each N type/P type semiconductor pellet is larger than 1 mm^2 whilst the TE module utilizes ceramic material as its outer case (i.e. if the semiconductor pellet cross-sectional area $\leqslant$ 1 mm^2, the indicator "C" would be replaced to "S". Another different type of TE module with a metal structure uses "M" as the indicator).
- In the third section where "1" indicates the single-stage TE module (i.e. multi-stage TE module is stacked/cascaded by up to 6 layers of single-stage TE modules. As general rules, multi-stage TE modules always can achieve higher temperature difference than single-stage TE modules but have lower COP. The indicator "1" will increase corresponds to the total layers in the multi-stage TE module).
- In the forth section, the total number of thermocouples in each module is demonstrated (e.g. "127" indicates there are total 127 thermocouples being connected in each module).
- In the fifth section, the two digits behind the thermocouples number indicate the maximum allowable current (unit in A) when TE module works under its maximum working voltage

and has optimal heat dissipation performance at both hot side and cold side (e.g. "06" in the name of TEC1-12706 indicates the maximum allowable current of this type of TE module can reach 6 A. The working current of TE module will decline as the temperature increase of the whole module).

- In the sixth section, if there are additional metal layers covering on the outer case of TE module, one more indicator "T" (represents single layer of metal cover) or "TT" (represents double layers of metal covers) would be added to the end of model name (e.g. TEC1-12706T or TEC1-12706TT).

All types of TE modules in the TEC1-127 series have the same rated voltage of 12 V and maximum working voltage of 15.4 V which are mainly related to the total number of thermocouples in these modules (i.e. the maximum working voltage can be calculated by: thermocouples number 127 $\times$ 0.12 $\approx$ 15.4 V; the rated voltage of TE module is generally about 78% of its maximum working voltage calculated by: 15.4 V $\times$ 0.78 $\approx$ 12 V). Moreover, different types of TE modules in the TEC1-127 series respectively utilize different dimensions of thermocouple pellets or different semiconductor material compositions. Hereby these modules have different outer case dimensions, maximum allowable currents and maximum cooling power as shown in Table 2.1.

Model name	**Dimensions** length×width×thickness (mm)	**Maximum current** (A)	**Rated voltage** (V)	**Maximum voltage** (V)	**Cooling power max** (W)	ΔT **max** (K)
TEC1-12703	40 × 40 × 4.0	3	12	15.4	27	65
TEC1-12704	40 × 40 × 4.0	4	12	15.4	36	65
TEC1-12705	40 × 40 × 3.9	5	12	15.4	45	65
TEC1-12706	40 × 40 × 3.9	6	12	15.4	53	65
TEC1-12707	40 × 40 × 3.4	7	12	15.4	65	65
TEC1-12708	40 × 40 × 3.6	8	12	15.4	72	65
TEC1-12709	40 × 40 × 3.4	9	12	15.4	80	65
TEC1-12710	40 × 40 × 3.4	10	12	15.4	89	65
TEC1-12711	50 × 50 × 4.0	11	12	15.4	98	67
TEC1-12712	40 × 40 × 3.3	12	12	15.4	107	65
TEC1-12713	50 × 50 × 3.4	13	12	15.4	116	67
TEC1-12714	50 × 50 × 4.0	14	12	15.4	125	67
TEC1-12715	40 × 40 × 3.3	15	12	15.4	134	65

Table 2.1 Specifications of different types of TE modules in the TEC1-127 series (data investigated from [29])

2.1.3 Figure-of-merit of thermoelectric materials

The heat exchange performance of the TE module is basically characterized by the dimensionless index of *ZT* where the figure-of-merit *Z* (K^{-1}) is determined by the thermoelectric material property and usually changes with temperature *T* (K) [30], [16], [31]. As a general rule shown in the Figure 2.6, when the temperature difference between the hot side and cold side of the TE module is consistent, the larger *ZT* of the TE material is, the better heat pump performance (i.e. heating COP and cooling COP) of the TE module can be achieved. Equally, a larger *ZT* is beneficial to obtain the larger temperature difference between two sides of the TE module whilst remaining same energy efficiency [16].

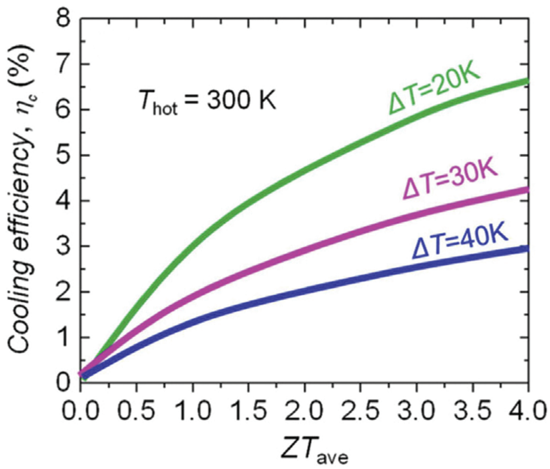


Fig. 2.6 Cooling efficiency as a function of average *ZT* (Figure is copied from [11])

The value of (*ZT*) can be derived by Equation 2.6 [16]. Where α is the Seebeck coefficient ($V\,K^{-1}$), σ is the electric conductivity ($\Omega^{-1}\,cm^{-1}$), T is the absolute temperature of the thermoelectric material (K), and k is the thermal conductivity ($W\,cm^{-1}\,K^{-1}$).

$$ZT = \frac{\alpha^2 \sigma T}{\kappa} \tag{2.6}$$

Based on the Equation 2.6, there are three obvious ways to promote *ZT* to higher level: both Seebeck coefficient α and electric conductivity σ of the TE materials should be increased as large as possible, whilst the material thermal conductivity k (thermal conductivity is the sum of lattice thermal conductivity and electric thermal conductivity), especially the lattice thermal conductivity should be reduced as much as possible [32], [33].

The relationship between the TE cooling COP and the material figure-of-merit is further given by Equation 2.7. Where ε_c is the cooling COP, T_h and T_c are the hot side temperature and cold side temperature (unit in K) of the TE modules respectively [34], [35], [11].

$$\varepsilon_c = \frac{T_h}{T_h - T_c}\left[\frac{\sqrt{1+ZT} - T_h/T_c}{\sqrt{1+ZT}+1}\right] \tag{2.7}$$

[36] defines the materials which have *ZT* > 0.5 can be potentially used as the TE materials. As shown in Figure 2.7 of the historical development of the TE materials, the *ZT* values of early materials (e.g. ZnSb in room temperature test, MnTe in high temperature test) were commonly lower than 0.5. In 1954, [37] firstly proposed the bismuth telluride (BiTe) alloys to develop the TE material with higher *ZT*. It was found that Bi_2Te_3 material in room temperature test exhibited a significant reduction in the lattice thermal conductivity in 1958. Then in the following around 40 years, this material remained unchanged and was always the best bulk TE material in comparison with other materials to be widely employed in commercial TE modules (e.g. the TAGs material in high temperature test exhibited higher *ZT* than the BiTe material but was not applicable in the TE module applied at near room temperature) [16], [30]. According to [38], the maximum *ZT* value of state-of-the-art bulk Bi_2Te_3 material is capable of reaching up to 1.1, but if consider the overall performance of the TE devices in the practical applications, the effective *ZT* is generally around 0.7.

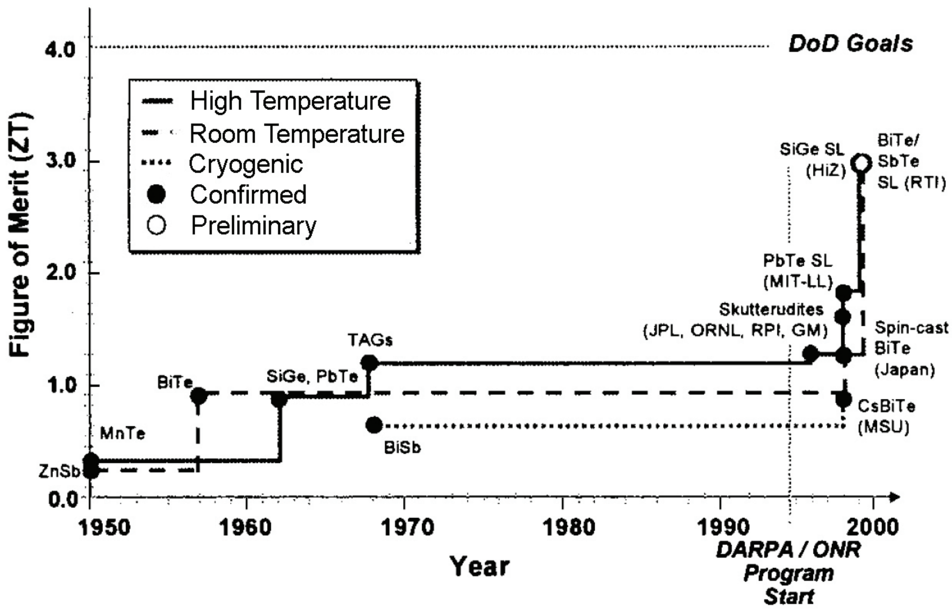


Fig. 2.7 History of TE figure of merit *ZT* adapted ([39])

[38], [40], and [41] report that the *ZT* values of most existing TE materials commonly vary between 0.8-1.1 in the near room temperature applications. But for promoting the cooling COP of the TE cooling device to become comparable with the VC air-conditioner, the *ZT* reaches 3 at least is required [14]. Take a simple calculation example, when the hot side temperature has reached 313.15 K and there is a consistent temperature difference of 30 K between the hot side and cold side of the TE cooling device. The *ZT* is assumed as 0.8 in this near room temperature operation. Then the cooling COP of this device can be theoretically calculated as 1.05 by Equation 2.7 which is much less than the general cooling COP around 3.0 of existing VC air-conditioner. But if the *ZT* value of the TE material is boosted up to 3.0 whilst holding the temperature of both hot side and cold side unchanged, the corresponding cooling COP would

correspondingly increase to 3.11 which is capable of competing to the energy efficiency of the VC air-conditioner.

Many researchers and institutions made efforts to develop materials with higher *ZT* for stimulating the advancement and contributions of TE materials and devices. In 1995 the Defense Advanced Research Projects Agency (DARPA) initiated a program aimed to quadruple the *ZT* of TE materials [39]. [36] introduces the potential methods of enhancing *ZT* of the TE materials involve lower the material dimensional structures, thermionic emission and control the nanoscale transport effect of phonons and electrons. For instances, the Bi_2Te_3/Sb_2Te_3 superlattices (produced by alternately depositing thin films of 1 nm-4 nm in depth of Bi_2Te_3 & Sb_2Te_3) and Bi_2Te_3 nanowires are able to increase the material *ZT* up to 2-3 times [42], [43]. [44] from Research Triangle Institute in USA reports that $ZT = 2.4$ for the p-type Bi_2Te_3/Sb_2Te_3 superlattices at room temperature and $ZT = 1.2$ for the n-type superlattices have become available. [41] demonstrates the available *ZT* value of 1.6 for PbSeTe/PbTe quantum dot superlattice. Harmon from the Lincoln labs in MIT reports the quantum dot superlattices could achieve $ZT \geqslant 2$ near room temperature [14]. According to more latest reports in terms of the TE materials development, the quantum well materials can achieve the *ZT* value around 4.1 at the high temperature of 523.15 K [36], and the *ZT* values of quantum dots TE materials under optimum conditions are even predicted as potential high as 10 at near room temperature of 300 K [45]. [39] fairly summarizes that the *ZT* near 2.0 for the TE materials are reliable and reproducible based on current technology, and the value approaches 3 or higher will also be potentially obtained with technology development.

2.1.4 The heat exchange performance calculations of TE module

The heating/cooling process of the TE module involves four types of heat caused by the Peltier effect, Joule effect, Fourier heat conduction, and Thomson effect [46].

For calculating the specific heat transfer performance of the TE module, the Peltier cooling Q_{Peltc} (W) transferred at the cold side of the TE module is defined by Equation 2.8; the Peltier heating Q_{Pelth} (W) transferred at the hot side of the TE module is defined by Equation 2.9; Equation 2.10 calculates the Joule heat Q_J (W) generated by the internal electric resistance of the TE module; and Equation 2.11 calculates the Fourier conduction heat Q_{con} (W) due to the temperature gradient between the hot side and cold side.

$$Q_{Peltc} = 2N \times \alpha \times I \times T_c \tag{2.8}$$

$$Q_{Pelth} = 2N \times \alpha \times I \times T_h \tag{2.9}$$

$$Q_J = 2N \times \rho \times I^2/G \tag{2.10}$$

$$Q_{con} = 2N \times \kappa \times G \times \Delta T \tag{2.11}$$

Where N is the total number of thermocouples in TE module, α is the Seebeck coefficient ($\mathrm{V\,K^{-1}}$), I is the input electric current (A), ρ, κ and G are, respectively, the electric resistivity (Ω cm), thermal conductivity ($\mathrm{W\,cm^{-1}\,K^{-1}}$), and geometry factors (cm) of N type semiconductor and P type semiconductor in each thermocouple.

Except above Peltier heat, Joule heat and Fourier conduction heat, [47] notes the heat transferred by the Thomson effect is usually ignored regarding Seebeck coefficients are assumed to be constant in general TE cooling/heating power calculations (i.e. most TE studies and simplified analysis involve [48], [49], [50], [51], [52] follow establish convention and regard the TE module's parameters Seebeck coefficient α, electric resistivity ρ and thermal conductivity κ as constant even though the value of these parameters will be have slight variations as the average temperature change of the TE module in time [15]). It can be further assumed that 50% of the Joule heat transfers to the cold side and the other 50% transfers to the hot side [36], [16]. Therefore the net cooling power, i.e. cooling capacity Q_c (W), at the cold side of the TE module can be expressed in Equation 2.12 which includes the Peltier cooling, half of the Joule heat, and the Fourier conduction heat back from the hot side. Similarly, the total heat rejection, i.e. heating capacity Q_h (W), at the hot side of the TE module can be obtained by use of Equation 2.13.

$$Q_c = Q_{Peltc} - 1/2 \times Q_J - Q_{con} = 2N \times (\alpha \times I \times T_c - \rho \times I^2/2G - \kappa \times G \times \Delta T) \tag{2.12}$$

$$Q_h = Q_{Pelth} + 1/2 \times Q_J - Q_{con} = 2N \times (\alpha \times I \times T_h + \rho \times I^2/2G - \kappa \times G \times \Delta T) \tag{2.13}$$

$$W = Q_h - Q_c = 2N \times (\alpha \times I \times \Delta T + \rho \times I^2/G) \tag{2.14}$$

$$\varepsilon_c = \frac{Q_c}{W} = \frac{\alpha \times I \times T_c - \rho \times I^2/2G - \kappa \times G \times \Delta T}{\rho \times I^2/G + \alpha \times I \times \Delta T} \tag{2.15}$$

$$\varepsilon_h = \frac{Q_h}{W} = \frac{Q_c + W}{W} = \varepsilon_c + 1 \tag{2.16}$$

During the operation process, the input electric power W (W) of the TE module is given by Equation 2.14 which is converted to heat 100% and released at the hot side of TE module. The cooling COP ε_c and heating COP ε_h of the TE module are calculated in Equation 2.15 and Equation 2.16 respectively. These show that, in the rated working range, the cooling COP at the cold side of the TE module will always be greater than zero so as to an effective heat pump application. Therefore, the corresponding heating COP at the hot side will be always greater than 1.

2.2 Comparison between TE modules, VC and AR/AHP systems

Traditional VC heat pump system comprises four basic components: a compressor, a condenser, a thermal expansion valve (also called a throttle valve), and an evaporator which together to build an enclosed circulating system, whilst it must require liquid refrigerants (e.g. CFC, HCFC or HFC) as the medium of heat transport included in this circulation. The heat pump working principle of the VC system is mainly based on the alternating conversion between liquid and vapor states of the refrigerant under low-pressure and high-pressure respectively to absorb, transport and release heat. Both of the cooling and heating applications can be provided by this heat pump system. For the specific cooling cycle:

As shown in Figure 2.8a, firstly the saturated hot vapor released from the indoor coil (acts as the evaporator) enters the compressor. The gas volume is reduced under the compression and further become the superheated vapor. Then the compressed hotter vapor releases heat and be condensed into a high-pressure saturated liquid state via the outdoor coil (acts as the condenser). The saturated liquid refrigerant is next routed through the expansion valve where it undergoes an abrupt reduction in pressure. The pressure reduction results in the adiabatic flash evaporation of a part of the liquid refrigerant which promotes the liquid to become the mixture of liquid and vapor with a lower temperature. The cold mixture flows back into the evaporator and absorbs heat from indoor space, which accelerates the evaporation of rest liquid part of the mixture. Eventually the mixture refrigerant will be completely transformed into saturated hot vapor state for starting next cycle.

For the heating cycle, the circulation direction of the refrigerant is reversed to the cooling as shown in Figure 2.8b:

Firstly the liquid refrigerant released from the indoor coil (acts as the condenser) passes through the expansion valve and changes into a low-pressure and low-temperature liquid/vapor mixture. Then the mixture flows into the outdoor coil (acts as the evaporator), absorbing heat from outdoor environment and further evaporating to completely become a low-temperature vapor. The vapor is next compressed by the compression to become high-pressure gas with a higher temperature. Finally the high-temperature gas is sent back into the indoor condenser to release heat to indoor air for heating purpose and be condensed into liquid state for starting next cycle.[53]

The absorption refrigeration (AR) system mainly applies the basic principles of liquid refrigerant evaporation for heat absorption and gaseous refrigerant absorbed by absorbent for heat release. The unique feature of this system is utilizing external heat sources (e.g. solar, kerosene-fueled flame, waste heat from factories or district heating systems) as the primary motive energy to drive the heat exchange system which can save traditional electricity consumption. Additionally, similar to VC heat pump system, the AR system also needs to utilize internal fluid circulation (liquid/gas states) to complete heat exchange and transfer processes. The working fluid in an AR system is a binary solution consisting refrigerant and absorbent, and the

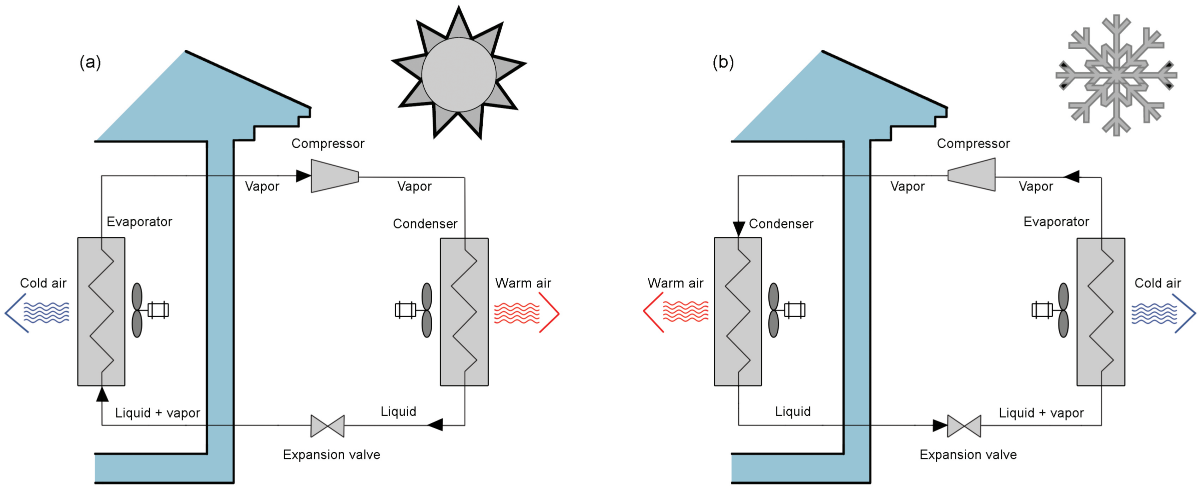


Fig. 2.8 Typical single stage vapor compression air conditioning system: (a) Cooling cycle (b) Heating cycle

common solutions selection are water (absorbent)/NH_3 (refrigerant) or LiBr (absorbent)/water (refrigerant).

Common single-effect AR system comprises four main components: evaporator, absorber, generator and condenser. The specific absorption refrigeration cycle is shown in Figure 2.9: firstly, the liquid refrigerant can easily absorb heat and switch into vapor state in the evaporator to achieve cooling effect; secondly, the refrigerant vapor is absorbed by absorbent whilst releases heat in the absorber side; thirdly, the diluted absorbent solution which is mixed with high content of refrigerant is pumped into generator and further be dried by external heat source in order to separate out the refrigerant vapor; fourthly, the separated absorbent will be sent back to absorber, likewise the refrigerant vapor will through condensation and depressurization processes in condenser and finally be restored into evaporator for starting next absorption cycle. During above refrigeration circulation, the COP of the system is obtained in Equation 2.17:

$$\text{Cooling COP} = \frac{\text{cooling capacity obtained at evaporator}}{\text{heat input for the generator} + \text{work input for the pump}} \tag{2.17}$$

The AR system generally cannot be directly reversed for heating applications. But based on similar working principle, the absorption heat pump (AHP) system which has similar components with the AR system was developed for the heating demands. The main system structure difference is that an expansion device installed between the condenser and the evaporator in the AR system is replaced by a pump in the AHP system. The specific absorption heat pump cycle is shown in Figure 2.10: firstly the binary solution consists refrigerant and absorbent pumped from the absorber is heated by external heat source at a relatively low temperature level in the generator for separating refrigerant. The separated gaseous refrigerant is next condensed into liquid state in the condenser and then be pumped into the evaporator with elevated pressure. The liquid refrigerant will be vaporized with heat absorption in the evaporator which is drived by external low temperature waste heat (the generator and evaporator temperatures are usually equal in the

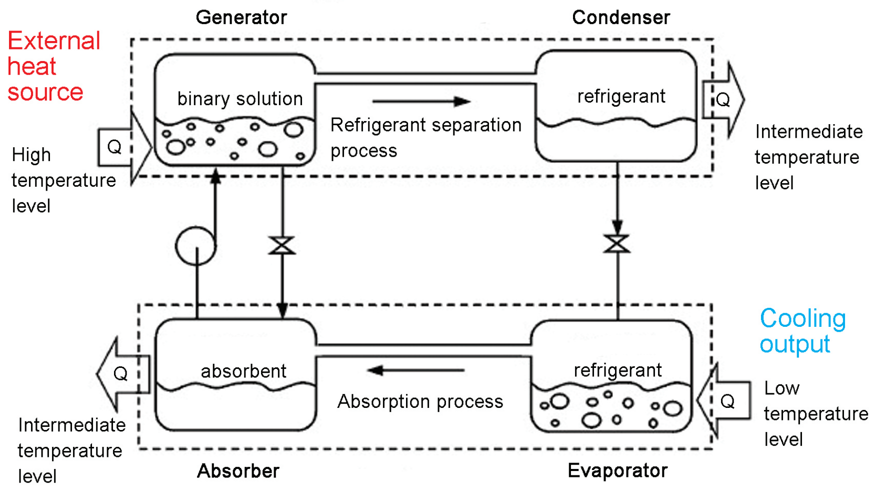


Fig. 2.9 A continuous absorption refrigeration cycle

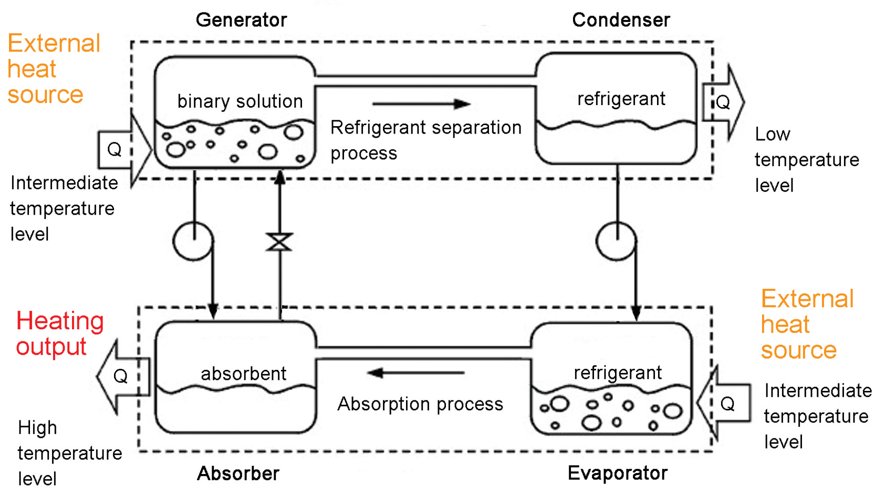


Fig. 2.10 A continuous absorption heat pump cycle

operation process of the AHP system). Finally the vapor refrigerant flows into to the absorber and be absorbed by absorbent to produce the binary solution again for next cycle whilst release the useful heat at a high temperature level for heat purpose [54].

Compared with the VC and AR/AHP system, the fundamental difference and unique features of the TE system are given by [55]:

- The working of the TE module requests no refrigerants (such as CFCs, HCFCs or HFCs which are potentially harmful to environment) and the module usually has long life expectancy (i.e. typically exceeds 100,000 hours: mean time between failures [56]) and can keep continuous working.
- The TE module can achieve both heating and cooling by simply switching the electric current direction (the TE cooling coefficient is generally not high, but the TE heating coefficient is always greater than 1). Therefore one piece of this module can simultaneously replace separate heating and cooling systems.
- The output power (both cooling/heating power) of TE module is controllable by changing either voltage or current. Maintaining voltage stability and control the intensity of input electric current, it can achieve precision temperature control.
- The thermal inertia of the TE module is very low, thus the rates of both heating and cooling are very quick. In cooling test if keep a good heat dissipation at the hot side whilst no load connected with the cold side, the cold side will be able to research the maximum temperature difference after being activated one minute.
- The highest temperature of the hot side can research 90 °C and the lowest temperature of the cold side is able to achieve −130 °C.

More detailed comparisons between the features of VC, AR/AHP systems and TE modules are summarized in Table 2.2, Table 2.3, Table 2.4, and Table 2.5. .

System type \ Features	Power requirements	Refrigerant requirements		Equipment components
VC	100 V-240 VAC, 50Hz-60Hz.	CFC, HCFC or HFC [57], [58].		Compressor, Condenser, Expansion valve, Evaporator, Liquid circulation pipeline [53].
		Absorbent	Refrigerant	
AR	External heat sources (e.g. solar energy, kerosene fueled flame, industrial waste heat or district heating systems, etc) usually 80 °C-230 °C [59], [60], [61], [54].	Water LiBr $LiNO_3$ LiBr + $ZnBr_2$ $LiNO_3$ + KNO_3 + $NaNO_3$ LiCl Glycerol	NH_3 [62], [63] Water [64] NH_3 [65] CH_3OH [66] Water [67] Water [68] Water [69]	Evaporator, Absorber, Generator, Condenser, Pump, Fluid distribution pipe [54].
AHP		LiBr LiBr + $ZnBr_2$ DMETEG DMF KHO	Water [70] CH_3OH [71] R21/R22 [72] R21 [73], [74] Water [75]	
TE	Usually 0-16.4 VDC for most popular commercial modules [76].	N/A		Solid-state TE module.

Table 2.2 The Comparison between VC, AR/AHP and TE systems 1

Features / System type	Cooling effect	Heating effect	EER (cooling COP)	Heating COP
VC	$\geqslant$ 18 °C for indoor cooling [58].	25 °C-45 °C air flow at outlet for indoor heating [53].	Usually 2.6-5.0, Max 7.0 [57].	Mostly around 3.0, may requires auxiliary electric heating device in some colder weather [57].
AR	Water/ NH_3 can get minimum -60 °C [77], LiBr/Water usually $>$ 5 °C [54].	N/A	Commonly 0.5-1.2, Max 1.5-4.5 [54].	N/A
AHP	N/A	Up to 65 °C for hot water heating [78].	N/A	Approximate 1.3-1.5 [78].
TE	Usually $>$ 0 °C Single-stage cooling effect cannot freeze in room temperature [55].	Up to approximate 60 °C for hot water heating [17].	Usually 0.4-0.7, Max around 1.5 in most practical applications [79].	For air heating can easily reach near 2.0 [15]. For hot water heating is always higher than 1.0 [17].

Table 2.3 The Comparison between VC, AR/AHP and TE systems 2

Features / System type	Ozone depletion potential	Global warming potential	Flammable or toxic substances	Mechanical volume	Working noise (Db)
VC	High	High	Involved	Medium	35-48 indoor
AR/AHP	N/A	N/A	Involved	Big	N/A
TE	N/A	N/A	N/A	Small	N/A

Table 2.4 The Comparison between VC, AR/AHP and TE systems 3 [57], [54]

Features / System type	Maintenance difficulty	Life expectancy	Primary application occasions
VC	Refrigerant leak & Compressor mechanical failure [80].	10-12 years [57]	Suitable for meeting various enclosed building space cooling/heating demands. (small, medium and large power outputs depend on actual cooling/heating floor areas and thermal comfort demands).
AR/AHP	Solution crystallization & Metal corrosion [54].	∼15 years [57]	Suitable for the centralized cooling/heating demands in many public places with large building space such as hotels, office buildings, hospitals, stadiums and theaters, etc.
TE	N/A	∼23 years *	Be applied into a wide range of the military, aeronautic, medical, industry and domestic fields: [79], [81], [82] • Train, vehicle and submarine air conditioning systems for both cooling and heating. • Portable TE refrigerators for food preservation. • TE refrigeration and cooling apparatuses for medical applications, such as diagnostic medical equipment, blood vessel, heart and eye surgery and physical therapy. • Small enclosed space cooling/heating (e.g. Laboratory).

Table 2.5 The Comparison between VC, AR/AHP and TE systems 4

* The manufacturer [76] introduces the optimal life expectancy of 200,000 hours of the TE module which is used as the core of the TE heat exchange system. If assuming 10 hours operation time per day, the module could totally work 20,000 days equals to 55 years. But based on a comprehensive assessment involves the life expectancies of other auxiliary accessories, working ambient and operation status, the designed life expectancy of an existing TE air conditioner (model: MAA1200E-115) is finally suggested as 23 years [57].

2.3 TE researches for actual applications

2.3.1 Relationships between TE cooling temperature and working current

[83] designs an experiment to explore the cooling temperature changes of TE module under different input electric current levels. The test-rig employs two pieces of TEC1-12704 modules connected in electric series with the power supply (18 V, 200 W), heat sinks, axial flow fans, and circuit control system (i.e. control input electric current level). As shown in Figure 2.11, the dimensions of internal test space are 450 mm × 300 mm × 300 mm and this experiment totally installs 8 digital thermometers to monitor the temperature changes of TE cold/hot surfaces, internal test space and external ambient respectively.

The tests remain the heat sink at TE hot side unchanged, and input different levels of electric current (involve 1.23 A, 1.67 A, 2 A and 2.5 A) to test the cooling temperature of TE modules

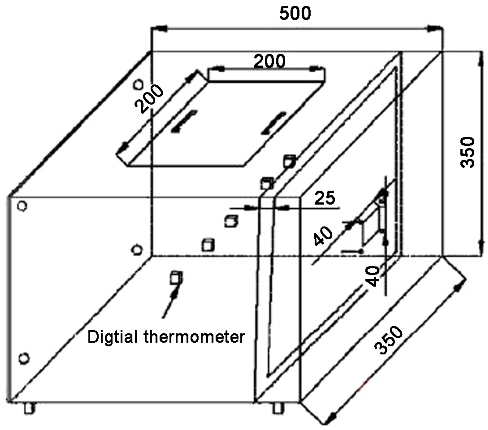


Fig. 2.11 The dimensions of the test cooling box

respectively. The continuous cooling test time of TE modules under each electric current level is set as 80 minutes. All the experimental results are shown in Figure 2.12 and Figure 2.13.

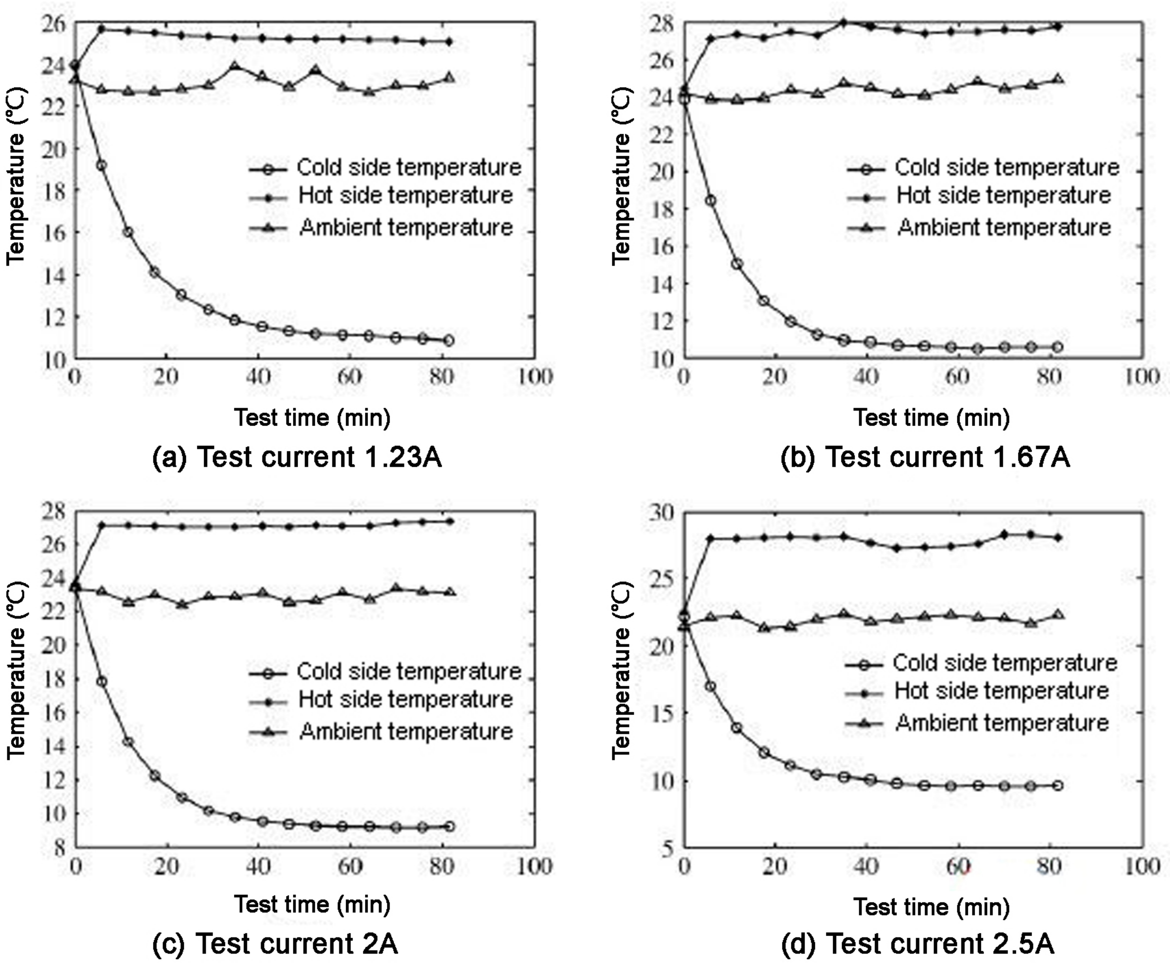


Fig. 2.12 Surface temperature of TE cold side/hot side, and ambient temperature monitored in tests under different currents input levels

Figure 2.12 shows that when external ambient temperature is relatively stable between 22 °C and 24 °C, after 80 minutes of cooling test, the TE cold side can reach the lowest temperature of 9 °C with 2 A input. Moreover, the test results reveal that the TE cold side firstly can reach lower temperature as the increase of input electric current level (i.e. the reachable minimum temperature at the cold side surface drops down from 11 °C with 1.23 A input to 9 °C with 2 A input). But then the cold side temperature change shows an upward trend to 10 °C despite the input electric current level is continually increased to 2.5 A.

For explaining the reason of above changes, according to Equation 2.13 studied in Section 2.1.4, the total heat generation (involves Peltier heat and Joule heat) at TE hot side will increase as the input electric current rises. But due to limited heat dissipation performance at the hot side, more increased heat generation cannot be released to external ambient in time and will cause the hot side temperature continues to rise. Then following the Fourier heat conduction law, the overmuch heat will conduct back to TE cold side and result in a poor cooling performance (i.e. higher cooling temperature with higher power consumption).

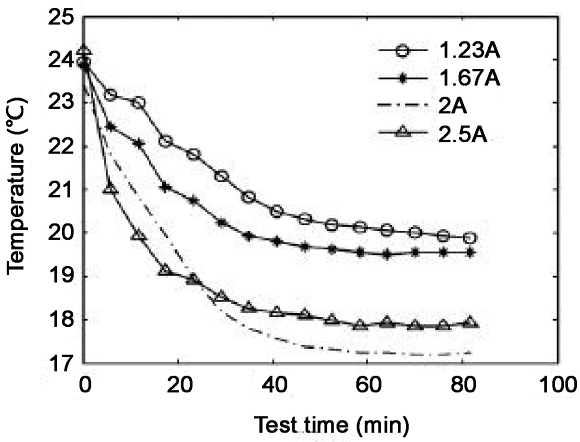


Fig. 2.13 Variation curves of the average temperature of internal test space air

Results in Figure 2.13 further prove TE module with 2 A input can achieve the lowest average temperature (i.e. 17.1 °C) of air cooling in the internal test space compared with 1.23 A (20 °C), 1.67 A (19.7 °C), and 2.5 A (18 °C) inputs. Hereby it can summarize that TE module cannot always achieve lower cooling temperature as the increase of the input electric current. And there is an optimal electric current range operating TE modules which can achieve better cooling performance (i.e. lower cooling temperature with lower power consumption). Furthermore, if the heat dissipation performance at TE hot side is limited in reversal TE heating application, it would also suggests operating TE modules with optimal electric current inputs for avoiding too much useful heat generation at TE hot side conducts back to TE cold side.

2.3.2 Relationships between the COP, cooling capacity, heat generation and working current of TE module

[84] designs a specific experiment in terms of the optimal working status research of TE modules. The test totally employs four pieces of TEC1-12706 modules to cooling the internal space of one plastic foam box (dimensions of internal space: 400 mm × 400 mm × 230 mm). Moreover, the heat dissipation methods at the hot side respectively apply water-filled cooling and forced air cooling:

(1) The hot sides of TE modules utilize room-temperature (30 °C) water to enhance the heat dissipation. The cross-sectional dimensions of the square tube are 25 mm × 12 mm; the water flow rate is 13.4 kg/min. The cold sides are connected with a large size of aluminum-fin heat sink (262 mm × 40 mm × 20 mm, fin height 15 mm, fin thickness 2 mm, fins interval 3 mm) to promote natural heat exchange with internal air.

(2) Total eight aluminum-fin heat sinks combine with axial flow fans are employed to connect with hot side and cold side of each TE module respectively for achieving the forced air cooling. The dimensions of each aluminum-fin heat sink are 60 mm × 55.5 mm × 25 mm, fin thickness 1 mm, fins interval 3 mm. The rated power of axial fan is 2.04 W.

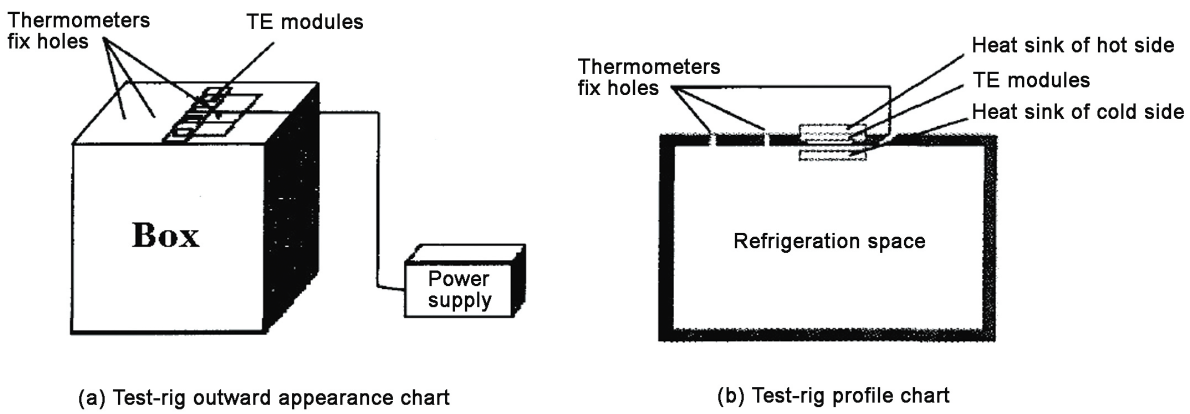


Fig. 2.14 Test-rig description charts

The test-rig described in Figure 2.14 show that the experiment utilizes digital thermometers (accuracy: 0.1 °C) to measure the TE hot side temperature and fixes glass mercury thermometers (accuracy: 0.1 °C) to measure the TE cold side temperature and internal air temperature of the box respectively.

During all test processes, the input electric current is gradually increased, and the corresponding changes of cooling capacity (curve Q/I, unit in W) at TE cold side, cooling COP (curve ε/I), and power consumption (curve W/I, unit in W) of TE module change with input electric current increase are recorded in Figure 2.15.

The test results in Figure 2.15 show that as continuous increase of the input electric current, both of the cooling capacity and cooling COP of TE modules will firstly increase and then

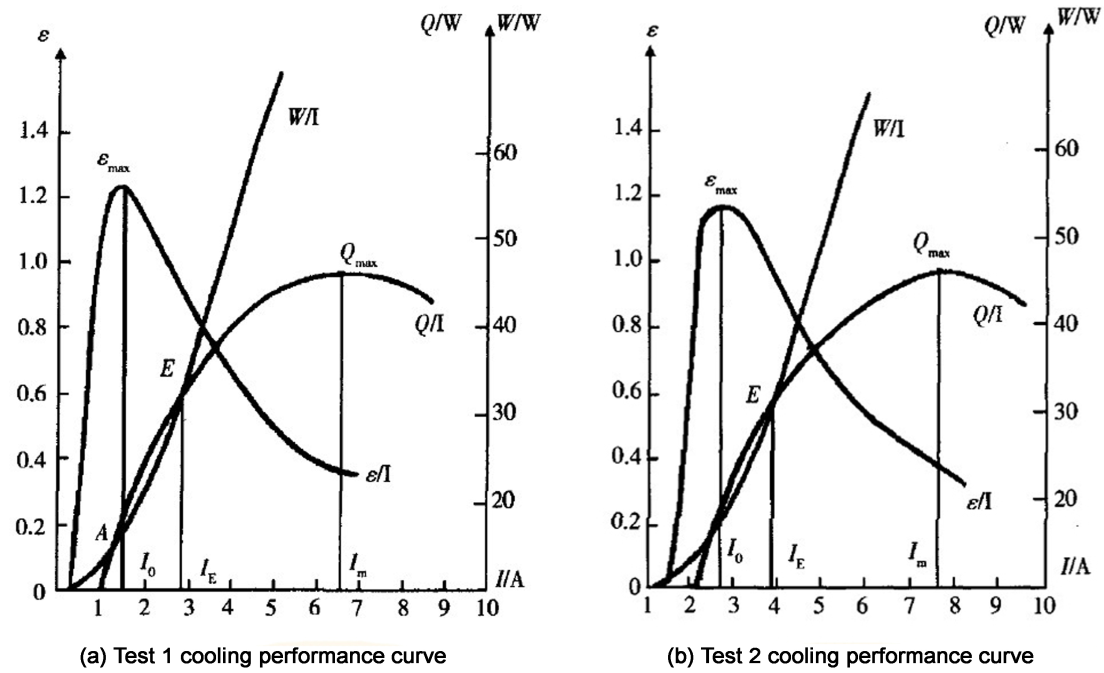


Fig. 2.15 Cooling performance curves of test1 and test2

decrease whilst the total power consumption of TE modules always remains a increase trend. Moreover, it notes that the cooling capacity and cooling COP cannot reach the maximum values under same input electric current level. Specifically, as gradual increase of the input electric current, the cooling COP will firstly get its maximum value ε_{max} when the input electric current value reaches I_0; then the cooling COP starts to decline but the cooling capacity can continue to increase till its maximum output value Q_{max} when the input electric current increases to I_m.

However, in most actual TE cooling applications, if TE modules are always operated with the input electric current I_0 for keeping the maximum cooling COP, the corresponding cooling capacity is usually very small (i.e. in this case, it needs to employ more number of TE modules to increase the total cooling capacity for getting a satisfied cooling temperature). But if operating TE modules with the electric current I_m input for achieving the maximum cooling output, the corresponding cooling COP would decline to a very low value which will causes more energy waste. Hereby it suggests inputting an optimal working current range between I_0 and I_m to operate TE modules which is capable of balancing an acceptable cooling COP and higher cooling capacity for the best economic efficiency. Similarly, if in reversal TE heating applications, it would also exists an optimal working current range to operate TE modules for achieving higher heating output whilst keeping an acceptable heating COP.

Additionally, there is a special point E which is the intersection of curve Q/I and curve W/I. At this point, the cooling capacity Q_E is equal to the energy consumption W, and the corresponding cooling COP is equal to 1. Thus the E point is called as equal power point, which means if the TE module consumes one unit of electricity, the cold side can absorb one unit of heat whilst the hot side will totally release two units of heat [85].

Finally, the experiments find that the water-filled cooling method utilized in test1 is helpful to achieve lower TE hot side temperature (i.e. T_h = 307.0 K) and smaller temperature difference (i.e. ΔT = 19.8 K between two sides of TE module) than the forced air cooling method utilized in test2 (i.e. T_h = 309.5 K, ΔT = 20.9 K). Meanwhile TE module can always consume less electric current in test1 than in test2 when producing same cooling capacity. These comparison results reveal that better heat dissipation performance at the TE hot side will be helpful to promote higher cooling COP in cooling applications. Similarly, in reversal TE heating applications, it will also suggests enhancing the heat exchange between TE hot side and surrounding ambient in time for avoiding too high temperature at the TE hot side surface and too large temperature difference between two sides of TE module, which are helpful to keep higher heating COP.

2.3.3 Development status of TE cooling/heating application researches

Lots of research studies relating to TE cooling applications have been provided in past years. [86] designed an outdoor solar PV/battery TE refrigerator which could maintain the inside temperature at 5 °C-10 °C with cooling COP about 0.3. An experimental study of the optimal working status of TE cooler showed the cooling COP of TE module could reach 0.36 to 1.21 when input electric current was reduced from 6.57 A till 1.49 A per module [84]. [13] employed eight Ultra TE modules (UT8-12-20-RTV) operated with optimum electric current 4.8 A for each module to cooling airflow and test results showed that when the temperature difference between the inlet air and outlet air reached around 7 °C, the practical cooling COP were 0.43 and 0.45 tested under different room temperature of 34.2 °C and 38.9 °C respectively. [87] designed a novel air conditioning combined TE modules with thermosyphon to cooling a truck cab. The test result showed that when the outside temperature was 34 °C and maintain 6 °C temperature difference in the cab lower than ambient temperature, the corresponding cooling COP was 0.7. [88] tested a TE system powered by solar to cooling 0.125 m^3 internal space of a model room. It reported that minimum internal temperature of 17 °C with a cooling COP higher than 0.45 could be achieved. Meanwhile the system could heat 18.5 L of tank water to rise up 9 °C. [89] experimentally studied a TE chiller driven by solar cells and summarized the system was able to cool 250 mL of water from 18.5 °C to 13 °C with the corresponding cooling COP between 0.55 and 1.05. [90] redesigned a TE air-conditioner with water cooling pipe replaced at the TE module hot side to service the train compartment. The simulation analysis results showed that when the internal temperature dropped 12 °C in comparison with 40 °C of external ambient temperature, the cooling COP was 1.50 in theory.

However, limited by relatively low *ZT* of most existing thermoelectric materials, [91], [79] summarize that in most practical cooling applications, the cooling COPs of common single-stage TE devices are typically around 0.4-0.7. Compared with existing absorption refrigeration (AR) air conditionings (i.e. general cooling COPs are around 0.5-1.2 [54]) and vapor-compression (VC) air conditionings (i.e. cooling COP $\geqslant$ 2.6 [57]), the TE cooling system with lower cooling COP has to consume more energy than AR and VC cooling systems to achieve equivalent cooling capacity. Thus, the developed applications of TE module for cooling the large-scale architectural space are still not popular as the other two types of air-conditioners although the concept of TE air conditioning already was proposed since 1960s [16]. Currently TE cooling applications are mostly preferred in the military, aeronautic, medical, industry and domestic fields for meeting some special cooling requirements (such as the submarine internal air conditioning, portable TE refrigerator, and medical cooling apparatuses, etc) which pursue reliability, simplicity, safety, eco-friendship to replace the conventional bulky, noisy cooling equipment but does not criticize the energy efficiency as priority [36], [92], [93], [52], [94], [82], [81].

Additionally, in the heating mode, it seems that the differences of heating COPs between TE devices, absorption heat pump (AHP) and VC air-conditioners are not as large as the gap of their cooling COPs comparisons: gas absorption air heat pump and gas absorption ground source heat pump generally have maximum heating COPs approximate 1.3-1.5 [78]; [57] tests the heating COP of a typical VC air-conditioner (Brand: Hitach; Model: KFR-26) is 2.6-3.0 which is similar with its cooling COP values; [15] designs a air-conditioning system which employs TE modules (model: CP2-127-06L) to cooling or warming airflow, and its performance analysis reveals heating COP near 2.0 can be easily reached when the temperature difference between two sides of TE module is about 10 °C; simulation analysis of a novel TE radiant air-conditioning system which intends to cooling/heating a virtual office space with 70 m^2 floor area and 3.5 m height shows that it can produce a temperature difference of 30.1 °C between two sides of TE modules with theoretical maximum heating COP of 1.77 when external ambient temperature is 0 °C and electric current input is 2.2 A to per module [16]; [17] studies an active building envelope (ABS) window-system which integrates photovoltaic (PV) and TE technologies, and test results reveal that the transient-state heating COP of this system measured at the end of 2-hour test can range from 1.83 to 3.10 with different electric connection designs and power inputs.

In summary, [15] indicates that when the temperature difference unchanged, TE module can always achieves higher COP in heating mode than in cooling mode, which enables relatively good comparability between TE system and other types of heat pump systems in heating applications. Moreover, higher COP of TE module can potentially be achieved as new material research improves ZT (e.g. Lincoln laboratory has improved the $ZT \geqslant 2.0$ which is much higher than ZT around 0.8-1.1 of common thermoelectric materials [14], [38]) and this will promote a great development potential of TE module for the space heating. [83] and [84] further reveal the actual heat exchange capacity of TE module is more sensitive to the input power (e.g. input electric current) changes. Thus, in comparison with both of the VC and AR heat pumps design, the TE heating system could, theoretically, be smart controlled more easily by monitoring temperature and adjusting the input power level for optimising the energy efficiency in cooling/heating applications. Finally, [13] indicates that TE modules can be powered by DC electricity which solar panels could provide the power for, without inverter or distribution losses. Hence, if the TE heating system can be fully/partially powered by renewable energy sources to service the households, it should potentially compete with the traditional heating system (e.g. gas boiler or VC heat pump) whilst contributing to a lower carbon, securer and fairer future.

Chapter 3

Experimental Study of the TE Module

3.1 Introduction

In this experimental study, a 1 m^3 independent and enclosed test container with better thermal insulation is built to test the performance (i.e. achievable heating temperature, temperature differences, COP values and heating power) of TEC1-12706 module operated under different input voltage levels for space heating. Detailed experimental set-up, technical supports and experimental methodology will be presented. The experimental results are provided both for a laboratory and a low-temperature courtyard environment.

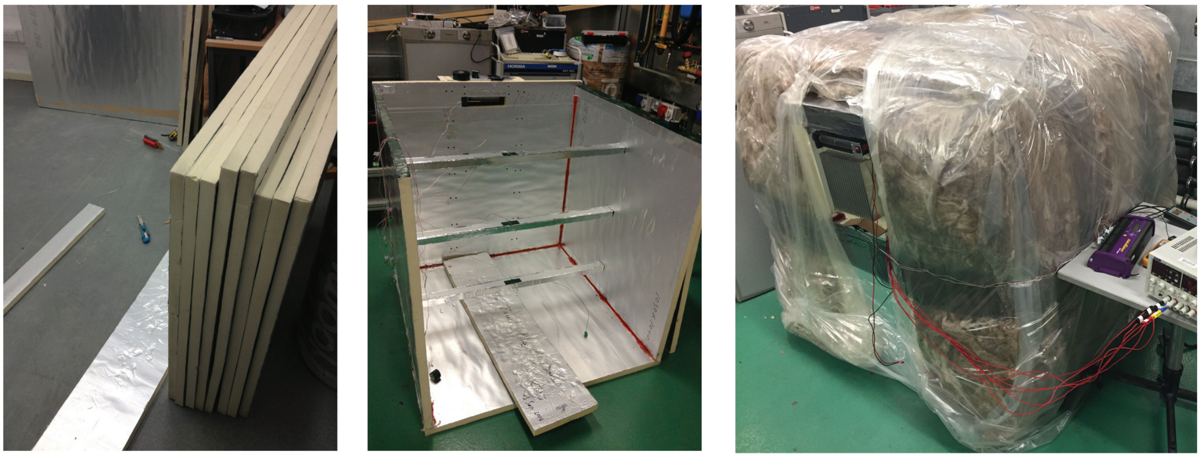
In order to ascertain the potential feasibility of TE module applied for the domestic heating, the experimental data analysis and discussion demonstrate that sufficient temperature difference can be achieved with TE modules so as to satisfy domestic thermal comfort levels. It also suggests an acceptable heat pump efficiency and sufficient heating power for the domestic heating application. Moreover, the relationships with regard to temperature difference and heating COP change with the operating time can be further explored for better guiding the application of TE module for actual building space heating. Relevant experimental verification and uncertain analysis are provided at the end of this chapter.

3.2 Experimental set-up

This section demonstrates the specific materials selection for building test-rig, experimental measurement devices pre-test and distribution, and test sites preparation in advance of the test start.

3.2.1 Test-rig and experimental apparatus

The experimental set-up is designed to utilize three pieces of TEC1-12706 heat exchange modules powered by DC electricity to absorb heat from external ambient so as to heat a 1 m^3 enclosed space (i.e. length 1 m; width 1 m; height 1 m). The basic framework of the test container is built by 30 mm-thick phenolic foam boards (see Figure 3.1a) which have a fine closed cell structure with the low thermal conductivity. The splicing method between the boards is bonded by double sided self-adhesive tape foam (30 mm width and 1 mm thickness) and further firmed by screws. Meanwhile the main surfaces of all foam boards are covered by foil and all the commissures are sealed by silica gel and tinfoil tape for reducing possible radiation, conduction and convection heat loss from internal test space to external ambient (see Figure 3.1(b)). Moreover, the whole container is further covered by the loft roll (width 1.2 m, thickness 150 mm) for strengthening the thermal insulation between the internal test space and external ambient (see Figure 3.1c).



(a) (b) (c)

Fig. 3.1 (a) 30 mm-thick Phenolic foam panels cutting (b) Boards splicing & commissure seal (c) Loft roll covering

The three TEC1-12706 modules (see Table 3.1) are fixed in a row by the thermal insulation pad and sandwiched by two aluminum fin heat sinks (dimensions: 182 mm × 44.5 mm × 200 mm; fins number: 19; thickness of the outer fin: 3 mm; thickness of main fin: 2 mm; thickness of the bottom plate: 5 mm). The two heat exchange surfaces of TEC1-12706 modules are placed with thermal grease for promoting thermal contact with the bottom plate of heat sinks. Two cross flow fans (see Table 3.2) are utilized to match to the heat sinks at each side respectively for enhancing heat exchange between air flow and surfaces of heat sinks. All above components are framed by one piece of aluminum composite panel (ACP) which has a lower thermal conductivity to together constitute the core of the TE heat exchange test device (see Figure 3.2).

Furthermore, the test-rig design embeds the TE core device into an independent small compartment which is fixed on the outer wall of the test container whilst contacting with the internal space via an inlet and a outlet. In this way, the internal air of the container can be continuously absorbed into the small compartment by the cross flow fan, then be heated by TE modules and flows back to the container for completing each heating cycle. During the whole cycle process, there is no airflow exchange with outside ambient. The specific structure and dimensions of the test-rig are shown in Figure 3.3.

Finally, the experiment employs a DC power supply (model: CPX400DP, parameter see Table 3.3) which is capable of supporting a fixed range power supply by providing optional

Specification	Range	
Hot Side Temperature (°C)	25	50
Q_{max}(W)	50	57
ΔT_{max}(°C)	66	75
I_{max}(A)	6.4	6.4
U_{max}(V)	14.4	16.4
Resistance (Ω)	1.98	2.30
Length (mm)	40	
Width (mm)	40	
Thickness (mm)	3.9	

Table 3.1 Summary of TEC1-12706 module's specification ([76])

Model	Dimensions (mm)	Number	DC Voltage (V)	Current (A)	Speed (RPM)	AirFlow (CFM)	Max. Pressure (mmH_2O)
AXL30150HC-12O1	195 x 50 x 48	2	12	0.28 ±10%	1750±10%	34.5	2.5

Table 3.2 Cross flow fan parameters

Model	Power range (W)	Voltage output range (V)	Voltage setting accuracy	Current output range (A)	Current setting accuracy
CPX400DP	up to 420	0.1 to 60	10mV Resolution 0.1% of reading ± 2 digits	0.01 to 20	10mA Resolution 0.3% of reading ± 2 digits

Table 3.3 Power supply parameters

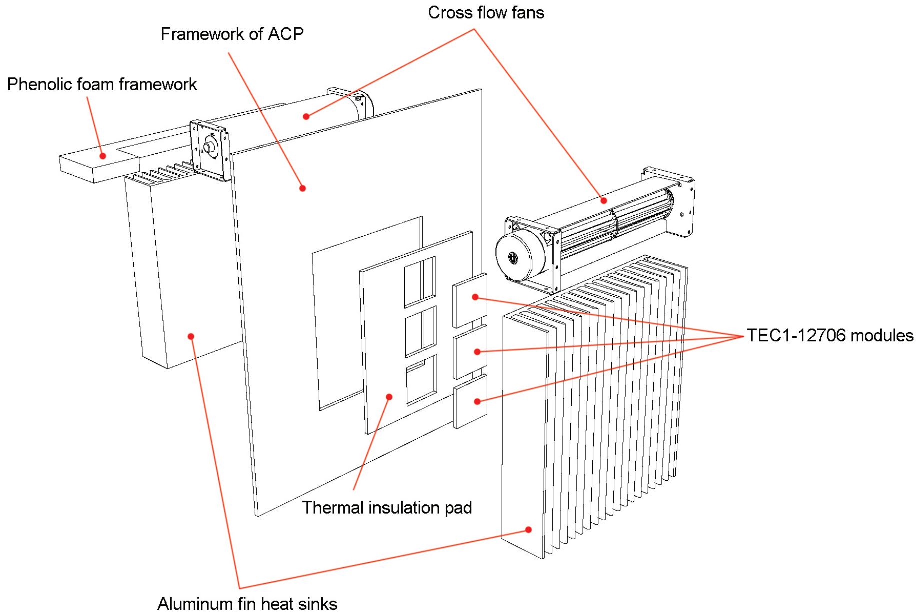


Fig. 3.2 The core of the TE heat exchange test device

constant voltage output or constant current output. All the TEC1-12706 modules are connected electrically in parallel with this power supply.

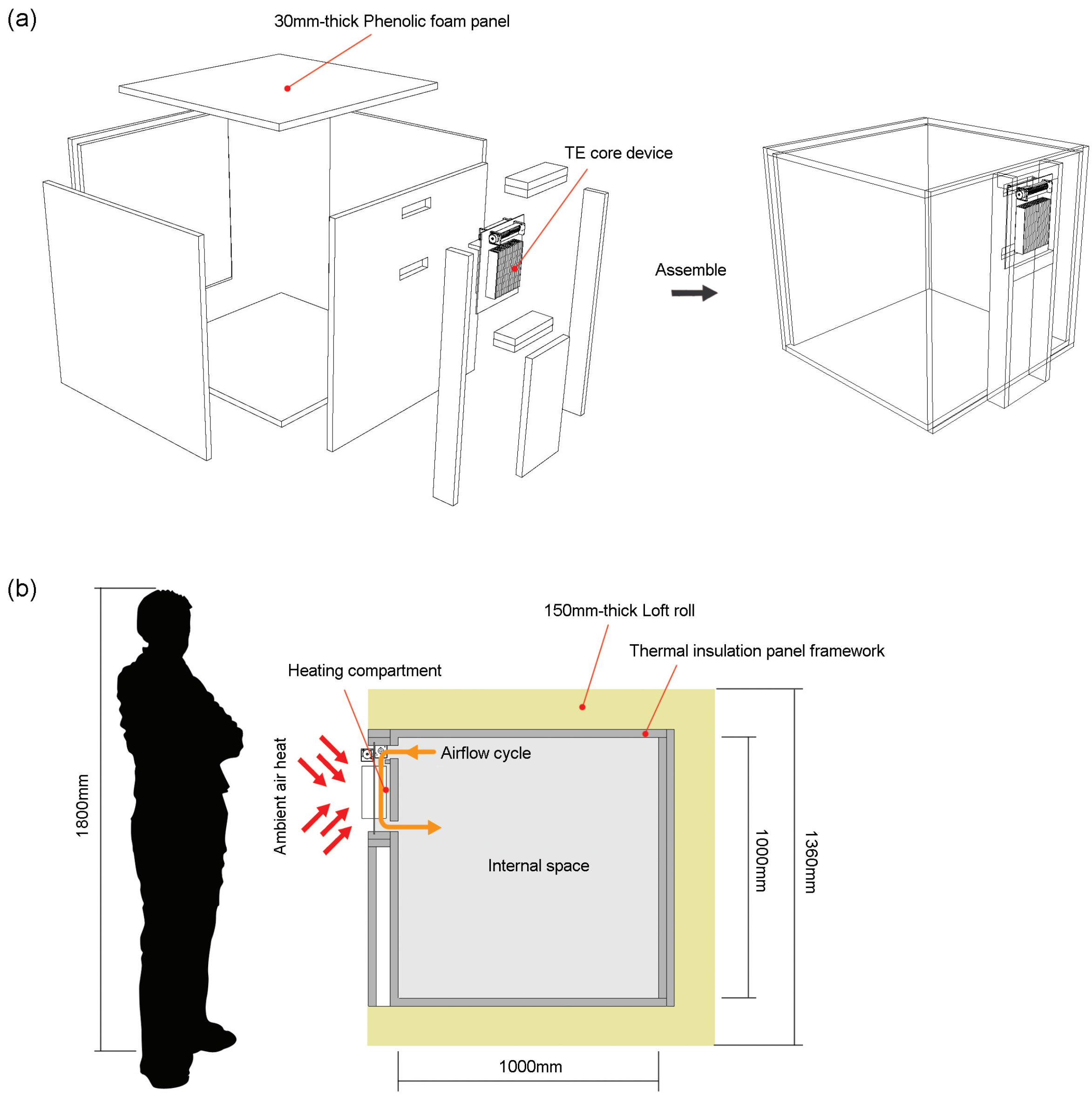


Fig. 3.3 (a) Assembly of the test-rig (b) Structure, scale and dimensions

3.2.2 Measurement devices for tests

For the temperature measurement purpose, the experiment totally utilizes eight 3-wire platinum resistance temperature detector (RTD) sensors (model: PT100, parameters see Figure 3.4a) as the primary measure device to monitor the ambient temperature, internal average temperature, inlet airflow temperature, outlet airflow temperature, temperatures of the hot side and cold side of TE module respectively. This type of temperature sensor commonly has resistance changes of 100 Ω at 0 °C and 138.4 Ω at 100 °C. And the relationship between temperature and resistance is approximately linear (every 1 °C temperature change will cause a 0.384 Ω change in resistance) over a small temperature range (i.e. 0 °C-100 °C). During the test process, all the temperature changes can be measured by the RTD sensors with a higher measurement accuracy (see Table 3.4) and further recorded by a data logger (model: DT85 series3, parameter see Table 3.5) in unit of °C.

Additionally, a digital air pressure, temperature and humidity monitor (model: FZ-2012C, parameters see Figure 3.4b) and two digital thermometers (model:TL8009, parameters see Figure 3.4c) are added to monitor the air pressure, temperature and humidity changes of the internal test space and external ambient temperature change for checking any unexpected experimental statuses in time. For instance, at random time point of the test process, the temperature values measured by above two types of measurement devices can be used to compared with the RTD sensors' measurement results: if both of the similar temperature values measured by the FZ-2012C monitor and TL8009 thermometer are quite different (i.e. more than 1 °C-2 °C difference) with the measurement results of the RTD sensors in the internal test space, it would judge the RTD sensors or the data logger may meet some errors; if the temperature changes measured by all devices are abnormal to expected change trend (i.e. the temperature of internal test space starts to continuously decline when the heating test still carries on), it should check whether the TE modules are damaged caused by overheat or the circuit connection meets breakage; if the external ambient temperature values measured by the TL8009 thermometer and RTD sensor are quite different, the test should also be suspended to check any potential device problems.

The specific parameters of all the temperature measurement devices are shown in Table 3.4.

Fig. 3.4 Measurement devices: (a)PT100 RTD sensor (b)FZ-2012C digital air pressure, temperature and humidity monitor (c)TL8009 digital thermometer

Model	Dimensions (mm)	Number	T range (°C)	T accuracy (°C)	Air pressure range (kPa)	Air pressure accuracy (kPa)	Humidity range (%)	Humidity accuracy
PT100	probe: 4 ∅× 100; length of cable: 1000	8	-80 to 50	0.00001 ±0.15(*ClassA*) 0.00001 ±0.3(*ClassB*)	N/A	N/A	N/A	N/A
TL8009	probe: 4 ∅ × 25; length of cable: 1000	2	-50 to 110	0.1 ±1	N/A	N/A	N/A	N/A
FZ-2012C	N/A	1	-40 to 80	0.1 ±0.4	30 to 110	0.01 ±0.3%	5 to 95	0.1 ±2%

Table 3.4 Temperature measurement devices parameters

Model	External power supply DC(V)	Power output to sensors DC(V)	Analog input channels Number	Accuracy	Software support
DT85 series3	10 to 30	12	16	0.1% to 0.35% (Measurement at DC resistance)	dEX

Table 3.5 Data logger parameters

3.2.3 Measurement devices calibrations and distributions

The temperature measurement accuracy of the RTD sensor is mostly depended on its resistance which sensitively changes with temperature. But limited by the actual production technology, it is unrealistic to produce the RTD sensors with absolutely equal resistances. Although these production deviations have been controlled within an allowable range of the industrial standards, it is still necessary to pre-test all the RTD sensors for calibrating their measurement deviations and further make rational test adjustments in the experimental preparation phase.

Firstly, the devices calibrations request a constant measurement environment. But the natural convection usually causes different air temperatures distributed in the ambient space. Thus as shown in Figure 3.5, all the applied RTD probes are fixed on a horizontal frame, and keep only 2.5 cm interval distance between neighboring probes which try to measure the same ambient temperature (i.e. if in the same ambient temperature, the measurement results of all the RTD sensors should be equivalent in ideal).

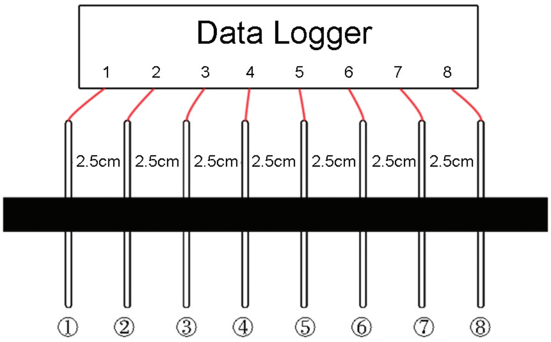


Fig. 3.5 RTD sensors test

Secondly, operating all the RTD sensors with the data logger to measure the same ambient temperature (i.e. the auto data record is 5s interval, the total test time is 150s). The original measurement results are recorded in Table 3.6.

Thirdly, for simplifying the data analysis process, the means of the temperature measurement results of eight RTD sensors are calculated respectively and be arranged follow the order from low temperature to high temperature as shown in Table 3.7.

Table 3.7 shows that there are obvious measurement deviations up to 0.43 °C difference between the eight RTD sensors when measuring the same temperature around 21 °C. In order to reduce as much as possible negative influences caused by these measurement deviations in experimental study of the heat exchange performance of TE module (e.g. the temperature difference results between two sides of TE module or between internal test space and external ambient will have to contain above potential measurement deviations), the specific distributions of all the RTD sensors in the test-rig are shown in Figure 3.6.

As shown in Figure 3.6, RTD⑦ and RTD⑧ are applied to monitor the cold side temperature and hot side temperature of TE module. RTD④, RTD③ and RTD⑤ are fixed at the midpoint positions of the top one-third space, middle one-third space and bottom one-third space respectively

Time \ Temperature	RTD① (°C)	RTD② (°C)	RTD③ (°C)	RTD④ (°C)	RTD⑤ (°C)	RTD⑥ (°C)	RTD⑦ (°C)	RTD⑧ (°C)
31:20	20.87	20.81	20.95	20.70	21.13	20.95	21.05	21.12
31:25	20.88	20.80	20.94	20.70	21.15	20.96	21.06	21.11
31:30	20.89	20.81	20.95	20.70	21.14	20.95	21.05	21.12
31:35	20.89	20.82	20.97	20.72	21.15	20.97	21.06	21.11
31:40	20.90	20.81	20.97	20.71	21.14	20.97	21.08	21.12
31:45	20.91	20.84	20.98	20.74	21.16	20.99	21.09	21.13
31:50	20.91	20.83	20.99	20.73	21.17	21.01	21.09	21.13
31:55	20.92	20.85	20.99	20.74	21.16	21.00	21.08	21.13
32:00	20.93	20.83	20.98	20.74	21.17	20.99	21.08	21.14
32:05	20.91	20.83	20.99	20.74	21.16	21.00	21.11	21.13
32:10	20.92	20.83	20.99	20.74	21.17	21.01	21.10	21.14
32:15	20.94	20.83	20.99	20.73	21.16	21.01	21.10	21.12
32:20	20.91	20.83	20.97	20.73	21.15	21.00	21.10	21.14
32:25	20.92	20.82	20.97	20.73	21.14	20.99	21.09	21.11
32:30	20.91	20.80	20.96	20.71	21.14	20.98	21.09	21.11
32:35	20.90	20.80	20.95	20.72	21.14	20.98	21.08	21.11
32:40	20.92	20.80	20.96	20.70	21.13	20.97	21.08	21.09
32:45	20.91	20.80	20.96	20.72	21.14	20.97	21.08	21.09
32:50	20.91	20.81	20.96	20.73	21.15	20.99	21.09	21.10
32:55	20.92	20.80	20.96	20.73	21.14	20.98	21.08	21.10
33:00	20.92	20.81	20.95	20.72	21.15	20.98	21.08	21.10
33:05	20.92	20.78	20.95	20.72	21.14	20.98	21.08	21.11
33:10	20.91	20.78	20.95	20.72	21.14	20.97	21.07	21.10
33:15	20.92	20.78	20.94	20.71	21.12	20.96	21.06	21.08
33:20	20.90	20.76	20.93	20.70	21.12	20.94	21.06	21.08
33:25	20.90	20.76	20.93	20.70	21.10	20.94	21.05	21.08
33:30	20.89	20.75	20.93	20.69	21.11	20.95	21.05	21.09
33:35	20.90	20.74	20.93	20.69	21.12	20.96	21.06	21.09
33:40	20.90	20.76	20.93	20.69	21.12	20.96	21.06	21.09
33:45	20.90	20.75	20.92	20.68	21.11	20.95	21.06	21.09
33:50	20.89	20.75	20.92	20.68	21.10	20.95	21.05	21.09
Mean	20.91	20.80	20.96	20.71	21.14	20.97	21.07	21.11

Table 3.6 Ambient temperature results measured by all RTD sensors for supporting devices calibrations

RTD	Temperature mean (°C)
RTD④	20.71
RTD②	20.80
RTD①	20.91
RTD③	20.96
RTD⑥	20.97
RTD⑦	21.07
RTD⑧	21.11
RTD⑤	21.14

Table 3.7 Means of ambient temperature results measured by all RTD sensors

to monitor the internal air temperature changes. Thus the average temperature of internal space at any time is considered as the mean value of these three temperature measurement results. RTD⑥

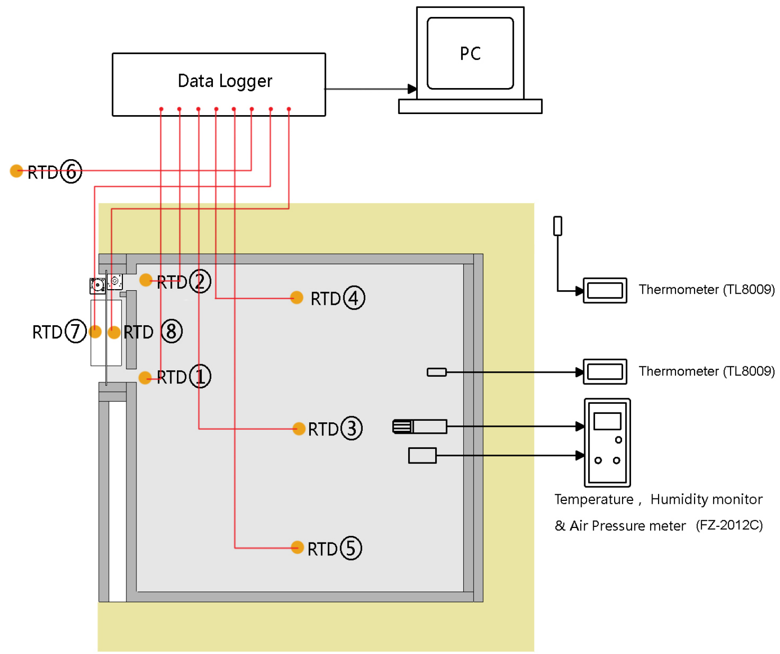


Fig. 3.6 Distribution of all the measurement devices in the test-rig

is used to monitor the external ambient temperature change. RTD② and RTD① are applied to measure the airflow temperature of the inlet and outlet respectively.

Depending on above device distributions, it can reduce the deviations in test results (e.g. temperature difference between two sides of TE module or between internal test space and external ambient) much lower than possible maximum deviation value of 0.43 °C. Take for examples, in the ambient temperature around 21 °C, according to the measurement results in Table 3.7, the measured temperature difference between the TE hot side temperature (i.e. 21.11 °C measured by RTD⑧) and the TE cold side temperature (i.e. 21.07 °C measured by RTD⑦) has 0.04 °C deviation in comparison with the ideal result of 0 °C. Similarly, the measured temperature difference between internal space (i.e. average value measured by RTD④, RTD③ and RTD⑤ is: (20.71 °C + 20.96 °C + 21.14 °C) ÷ 3 ≈ 20.94 °C) and external ambient (i.e. 20.97 °C measured by RTD⑥) will have 0.03 °C deviation.

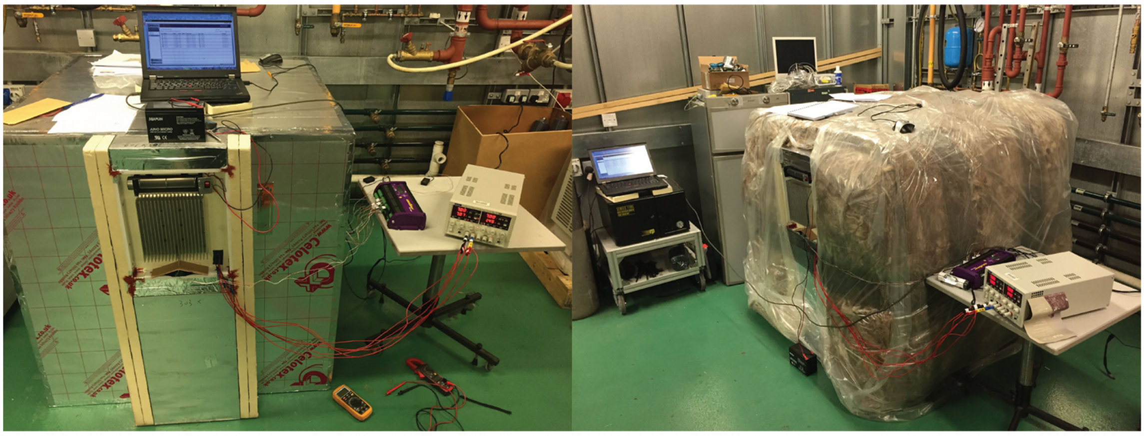
Additionally, since any poor contact between the cold/hot side surface of TE module and heat sink will reduce the heat transfer performance and may cause overheating phenomenon to damage whole TE module. Therefore the test design is hard to fix the probes of RTD sensors to directly touch with the cold and hot surfaces of TE module before heat sinks. RTD⑦ and RTD⑧ are fixed with the bottom plate of aluminum heat sink at each side respectively to monitor the temperature change of the hot side and cold side of TE module. As a result, the corresponding measurement results may be subject to very minor deviations with the real temperature values of the hot side and cold side of TE module because of the uncertain thermal resistance of the bottom plates of heat sinks. This may result in further calculated results of the heating COP being slightly higher than real COP values.

3.3 Experimental methodology

The main purposes of the experiment in this study are to confirm achievable heating temperature, temperature differences, COP values and average heat transfer power of TEC1-12706 module operated under different input voltage levels, and to further explore the relationships with regard to temperature difference and heating COP change with the operating time in actual space heating application.

Moreover, for better demonstrating the heating performance differences (i.e. achievable heating temperature, temperature difference and heating COP) of TE module when working in warm ambient and cold ambient, the test ambient contains lab (see Figure 3.7a, ambient temperature range: 19 °C to 21 °C) and open-air courtyard (see Figure 3.7b, the enclosed test container is placed at the shadow area of the courtyard without direct sunlight for reducing the effect of solar radiation on the heating performance during test period. Ambient temperature range: 1 °C to 5 °C). The test months are December and January which usually are amongst the coldest months of the year in the UK.

(a)



(b)

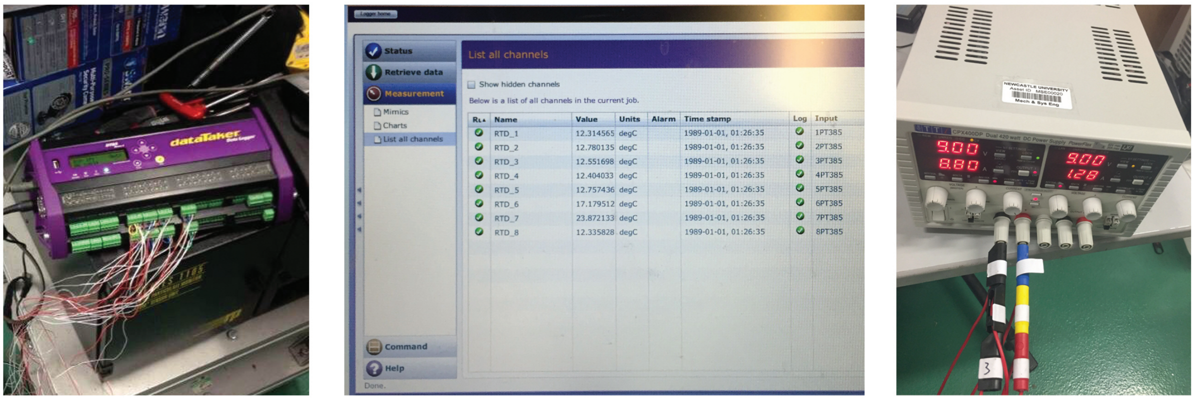
Fig. 3.7 Test ambient: (a) Heating test in lab ambient (b) Heating test in open-air courtyard ambient

The specific voltage input range selected to test TE module in this experiment are: 4 V to 9 V for the laboratory environment; and 6 V to 9 V for the low temperature open-air courtyard environment (see Table 3.8).

Test time	Test site	Input voltage					
Dec 2014	lab ambient	4 V	5 V	6 V	7 V	8 V	9 V
Jan 2015	open-air courtyard	N/A	N/A	6 V	7 V	8 V	9 V

Table 3.8 Test plan

During each test process, the CPX400DP power supply keeps a constant voltage output value, and the electric current consumption changes with operating time. All the temperature changes of TE cold side surface, TE hot side surface, inlet airflow, outlet airflow, internal space and external ambient are monitored by RTD sensors whilst being recorded by the DT85 series3 data logger (see Figure 3.8a). Specifically, the time interval setting of the data logger is 5 seconds per record. The recorded temperature data (in unit of °C) can be checked on the laptop screen in time via the dEX software (see Figure 3.8b) and be further saved as the csv file format which supports the Excel data analysis. The electric current values change with time can be directly read from the digits screen of the power supply and recorded by notes (see Figure 3.8c). For the operation time control of each heating test, the test will continue till the temperature of the cold sides of TE modules is close to the ambient temperature.



(a) (b) (c)

Fig. 3.8 Experimental devices: (a) Data logger (model: DT85 series3) connects with RTD sensors (b) Interface of the dEX software (c) DC power supply (model: CPX400DP) connects with TE modules

Then in the experimental analysis phase, firstly, [95] states that "one of the most important parameters for defining comfort is air temperature and it is possible to use indoor temperature as a measure of thermal comfort". Currently, the figure of 21 °C is employed by the UK government as an adequate level of warmth for living rooms and 18 °C for all other areas of a domestic house [96]. The Chartered Institution of Building Services Engineers has more precise guidelines [97] and recommends that a suitable temperature range during winter is approximately 18 °C-21 °C in occupied areas of a house and approximately 16 °C-18 °C for transient occupancy [95]. Hence, based on all relevant temperature data recorded by the data logger, the achievable air heating temperature, temperature differences of TEC1-12706 module operated under different input voltage levels and in different ambient are easily confirmed to compare with above standards, which is helpful to ascertain the heating performance of TE module for meeting the domestic thermal comfort.

Secondly, for studying the heating COP, the following assumptions have been adopted: (1) the Thomson effect, and heat losses caused by convection and radiation are ignored as suggested by [46]; (2) the thermal conductivity and electric resistance of TE modules are considered as constant values; (3) the Seebeck coefficient of the n-type element and p-type element in TE modules are constant and equivalent; (4) the thermal resistance between the bottom plate of heat sink and surfaces of TE module is disregarded, thus consider the measurement values of the RTD⑦ and RTD⑧ are equal to the temperature of the hot side and cold side respectively. Hereby the specific power consumption, heat generation and heating COP of TE module can be determined by Equation 2.14, Equation 2.13 and Equation 2.16 studied in Section 2.1.4 of Chapter 2.

When making the calculations based on above equations, the specific parameters of the tested TEC1-12706 module are given by [84]: the number of the thermocouples of is N = 127; the Seebeck coefficients of the n-type semiconductor and p-type semiconductor are considered as constant values $\alpha_n = \alpha_p = 2 \times 10^{-4}\,\mathrm{W\,K^{-1}}$; the internal electric resistance $R = 2N \times \rho / G = 2.22\,\Omega$; total thermal conductivity $K = 2N \times \kappa \times G = 0.5808\,\mathrm{W\,K^{-1}}$; the figure-of-merit $Z = 2.3608 \times 10^{-3} K^{-1}$. All the hot/cold side temperature values of TE module and its corresponding electric current consumption values are depended on the actual test results.

Further comparing different heating COP changes of TE module during the whole test processes, the minimum heating COP in the satisfied experiments (i.e. the heating temperature meet the thermal comfort) can be determined. And this value will be utilized as an important parameter assumption in next chapter for estimating the minimum heat generation of TE heating system powered by local renewable energy in the specific UK domestic heating context. Moreover, in this experimental analysis, it can also draw detailed data change curves by Excel to study the relationships of temperature difference and heating COP change with the operating time.

Thirdly, for confirming the average heat transfer power (in unit of W) by the forced convection of the cross flow fan from TE modules to the heating ambient (i.e. the 1 $\mathrm{m^3}$ of internal space of the test container) during the test process, it can utilize the Equation 3.1 [98].

$$P_h = C \times m_{airflow} \times \Delta T_{airflow} \div t \tag{3.1}$$

Where P is the heat transfer power (W), C is the specific heat capacity of the heated air ($\mathrm{J\,kg^{-1}\,K^{-1}}$); $m_{airflow}$ is the net weight of the heated airflow (kg); t is the heating time (s); $\Delta T_{airflow}$ is the temperature change (K) during the heating time t which can be determined by the monitored temperature difference between the inlet airflow and outlet airflow.

The experimental heat transfer power results of TE module operated under different input voltage levels and in different ambient can be used to estimate the heating power (in unit of $\mathrm{W\,m^{-2}}$) of TE system in the building space heating application and compared with general heating load of residential building for further ascertaining potential feasibility of TE module for the domestic heating.

Finally, it can verify the heating test results (i.e. measured temperature difference and actual electric current consumption when reaching the minimum heating COP) in comparison with the theoretical derivation results (i.e. achievable maximum temperature difference in theory when keeping the minimum heating COP and theoretical electric current consumption when reaching the tested heating temperature and temperature difference with minimum heating COP) and detects potentially uncertain factors in this experiment.

3.4 Experimental results

This section reports on the experiments conducted to investigate the heating effect of the tested TE modules. The tests were carried out in a laboratory ambient and in a low-temperature courtyard ambient, respectively.

3.4.1 Laboratory tests

Ambient	Voltage input (V)	Air pressure (kPa)	Humidity (%)	Test date	Test time span
Laboratory	4	101.57	50.2	2nd Dec 2014	10:14−11:13
	5	100.78	49.7	1st Dec 2014	10:18−11:46
	6	100.60	49.0	1st Dec 2014	14:11−15:14
	7	101.76	47.6	2nd Dec 2014	14:11−15:04
	8	102.06	50.4	3rd Dec 2014	10:26−11:12
	9	101.88	48.4	3rd Dec 2014	14:22−15:18

Table 3.9 Data record of the internal test space before the testing

Relevant data records of the internal test space before laboratory testing and corresponding test date are shown in Table 3.9. Table 3.10 shows data recorded at the end of the laboratory testing.

Figure 3.9 shows all the original temperature monitor records between the hot side and cold side of the TE module for 4 V to 9 V voltage inputs during the laboratory tests. Specifically, these data curves show the recorded temperature 1-2minutes before the test started (i.e. TE module off. Minor fluctuations in the graphs), during test process (i.e. TE module on. Gradual rise of temperature till it reaches a peak value), and 4-7minutes after the test has ended (i.e. TE module off. A rapid decline of temperature). Thus, Figure 3.9 demonstrates that the tested TE modules are able to achieve a range of temperature differences (i.e. at the end of the test) between the hot and cold side which goes from 8.72 °C with an input voltage of 4 V, till 22.79 °C with an input voltage of 9 V.

Figure 3.10 records the average temperature changes of the internal space, lab ambient temperature, and the temperature difference changes for all voltage inputs during the laboratory tests. The results demonstrate that the tested TE modules are able to achieve a range of temperature (i.e. at the end of the test) changes which goes from 8.52 °C with an input voltage of 4 V, till 20.18 °C with an input voltage of 9 V. Moreover, it also obviously shows a gradual increase trend of the temperature difference between the internal space and outside lab ambient as the

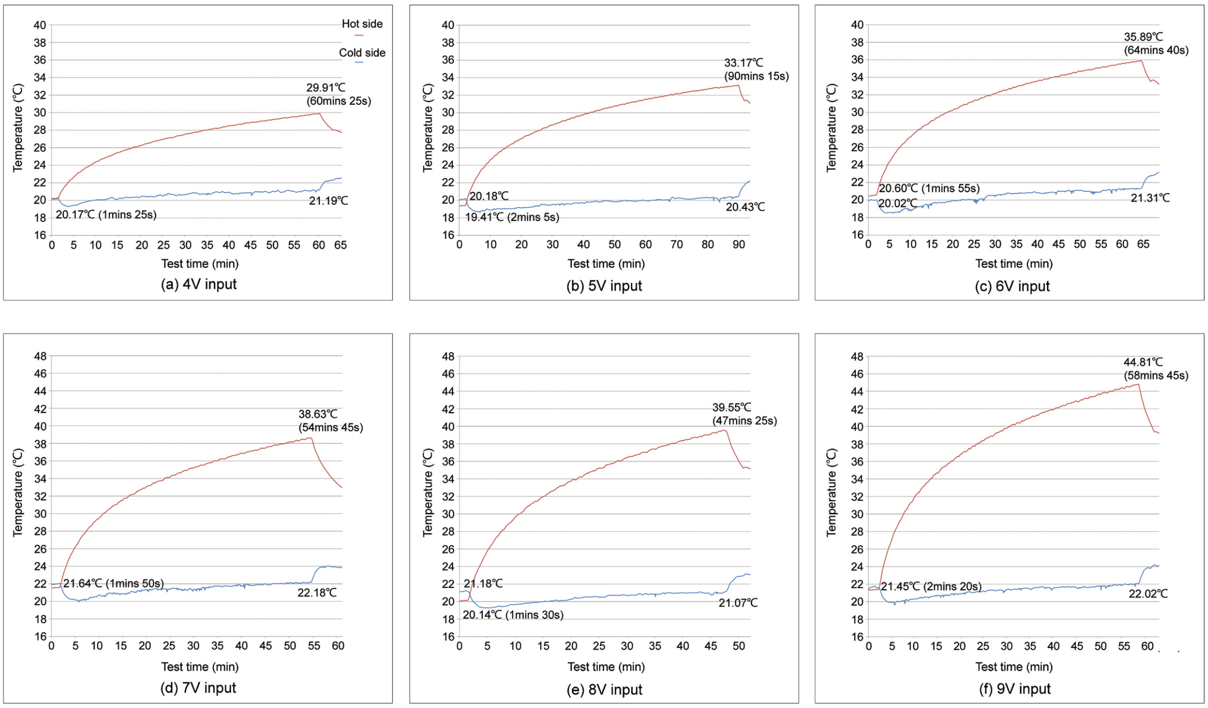


Fig. 3.9 Temperature changes of hot side and cold side under 4 V, 5 V, 6 V, 7 V, 8 V, 9 V input in lab ambient

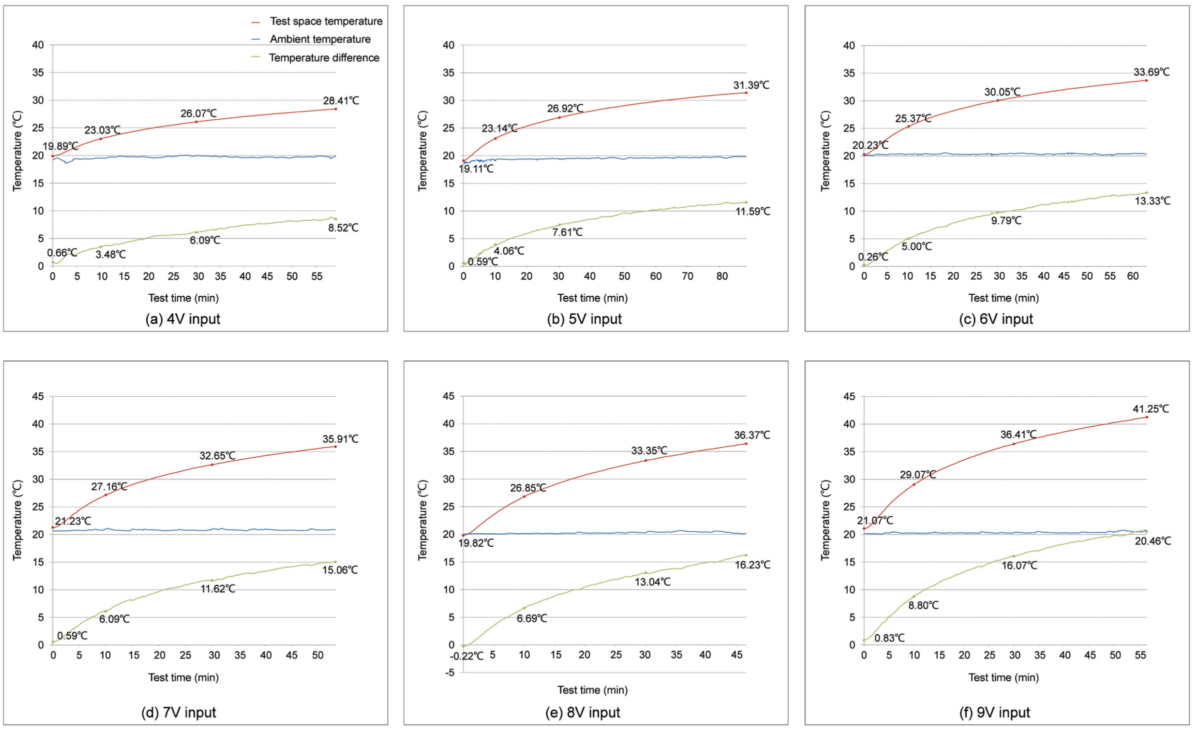


Fig. 3.10 Average temperature of the internal test space, lab ambient temperature and temperature difference changes in 4 V, 5 V, 6 V, 7 V, 8 V, 9 V input tests

test time goes on. To further compare the heating effects under the same conditions, within Figure 3.10 the temperature values for four points in time are annotated: when TE modules were powered up to start the heating test; 10 and 30 minutes after the start of test; and end of test. These temperature differences are achieved gradually with ranges from 3.48 °C with an input voltage of 4 V, till 8.80 °C with an input voltage of 9 V at 10 minutes interval; and from 6.09 °C with an input voltage of 4 V, till 16.07 °C with an input voltage of 9 V at 30 minutes interval. This suggests that TE modules could produce larger temperature difference within same time when input higher voltage whilst the ambient temperature only remains minor fluctuations.

Ambient	**Voltage input** (V)	**Air pressure** (kPa)	**Humidity** (%)
Laboratory	4	101.63	32.1
	5	100.73	27.5
	6	100.60	26.3
	7	101.81	24.8
	8	102.04	24.3
	9	101.87	21.3

Table 3.10 Data record of the internal test space at the end of laboratory testing

3.4.2 Open-air courtyard tests

Relevant data records of the internal test space before open-air courtyard testing and corresponding test date are shown in Table 3.11. Table 3.12 shows data recorded at the end of the open-air courtyard testing.

Ambient	**Voltage input** (V)	**Air pressure** (kPa)	**Humidity** (%)	**test date**	**test time span**
Courtyard	6	96.53	57.4	29th Jan 2015	14:38−16:26
	7	96.83	60.0	29th Jan 2015	10:39−12:09
	8	96.76	48.6	30th Jan 2015	14:28−15:34
	9	96.87	59.8	30th Jan 2015	10:30−11:34

Table 3.11 Data record of the internal test space before the testing

Figure 3.11 records all the original temperature monitor data between the hot side and cold side for 6 V to 9 V voltage inputs during the open-air courtyard tests. Similar with Figure 3.9, the data curves in Figure 3.11 record all the temperature changes of 2-4 minutes before the test started, during test process, and 4-5minutes after the test has ended. Thus, Figure 3.11 demonstrates that the tested TE modules are able to achieve a range of temperature differences (i.e. at the end of the test) between the hot and cold side which goes from 18.08 °C with an input voltage of 6 V, till 23.80 °C with an input voltage of 9 V.

Figure 3.12 records the average temperature changes of the internal space, courtyard ambient temperature, and the temperature difference changes between the internal space and outside courtyard ambient for all voltage inputs during the open-air courtyard tests. To further illustrate the gradual temperature change during the test and to enable heating effects comparisons under the same conditions, within Figure 3.12 the temperature values for four points in time are also annotated: when TE modules are powered up to start the heating test; 10 and 30 minutes after the start of test; and end of test.

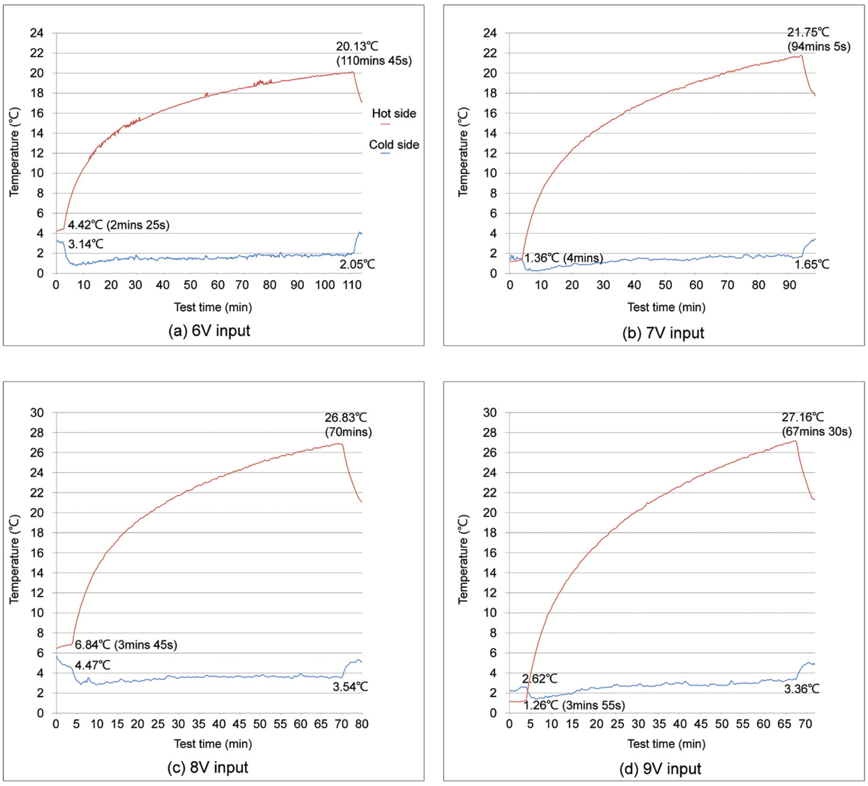


Fig. 3.11 Temperature changes of hot side and cold side under 6 V, 7 V, 8 V, 9 V input in courtyard ambient

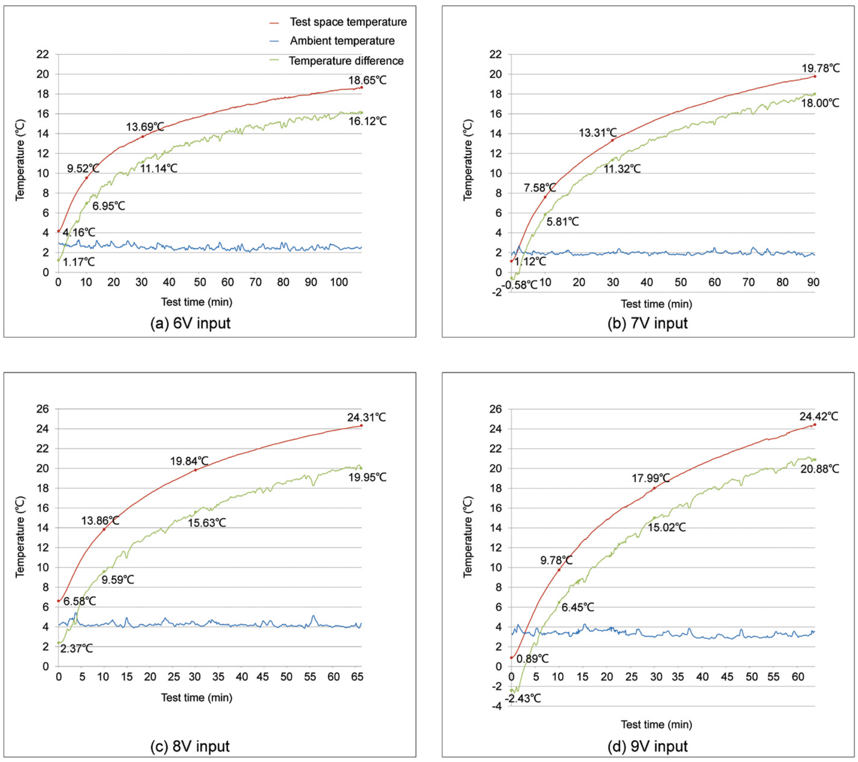


Fig. 3.12 Average temperature of the internal test space, courtyard ambient temperature and temperature difference changes in 6 V, 7 V, 8 V, 9 V input tests

The results of the courtyard tests as showed in Figure 3.12 proved that the internal average temperature can be heated to reach 18.65 °C when 6 V input, 19.78 °C when 7 V input, 24.31 °C when 8 V input and 24.42 °C when 9 V under a low-temperature outdoor ambient (vary between 1 °C-5 °C). This suggests that sufficient thermal comfort could be reached by using TE modules to generally service for the domestic heating scenario.

Ambient	**Voltage input** (V)	**Air pressure** (kPa)	**Humidity** (%)
Courtyard	6	96.57	27.2
	7	96.69	24.8
	8	96.77	21.6
	9	96.87	20.9

Table 3.12 Data record of the internal test space at the end of open-air testing

3.5 Date analysis and discussion

Figures 3.9, 3.10, 3.11, and 3.12 show the results of the internal space average temperatures, hot sides temperature and cold sides temperature of TE modules in a typical transient test for the heating application. This section will utilizes these results to ascertain TE feasibility by exploring the relationships between heating COP, input power, and temperature.

Furthermore, in order to discuss TE modules performance, it should be noted that in the experimental process all the air of the internal space needs to be heated by TE modules so as to reach the maximum temperature value (i.e. TE modules have to heat 1,000 liters of air by continuously transmitting heat till a maximum temperature is reached). This means that only when the total heat conduction (i.e. material thermal conductivity $\mathrm{W\,m^{-1}\,K} \times \Delta T$) is equal, at any time, to the total heat generated by TE modules, both the internal space air temperature and the TE hot side temperature will not change with time. At this point, the heating then can be defined as reaching a steady-state regime. However, all test results of this study show that TE modules are able to reach temperatures sufficiently high from a thermal comfort perspective before reaching a steady-state. From the domestic heating application perspective, if the temperature difference ΔT is sufficient to satisfy thermal comfort but TE modules are operating in a transient-state, then the indoor temperature will continue to rise until reaching a steady-state condition. Thus, in order to prevent the indoor temperature from exceeding thermal comfort level whilst avoiding energy waste, TE modules input voltage should be reduced so that the TE operation is near a steady-state condition. This is substantiated further in the next sections.

3.5.1 The relationship between input voltage level and temperature difference

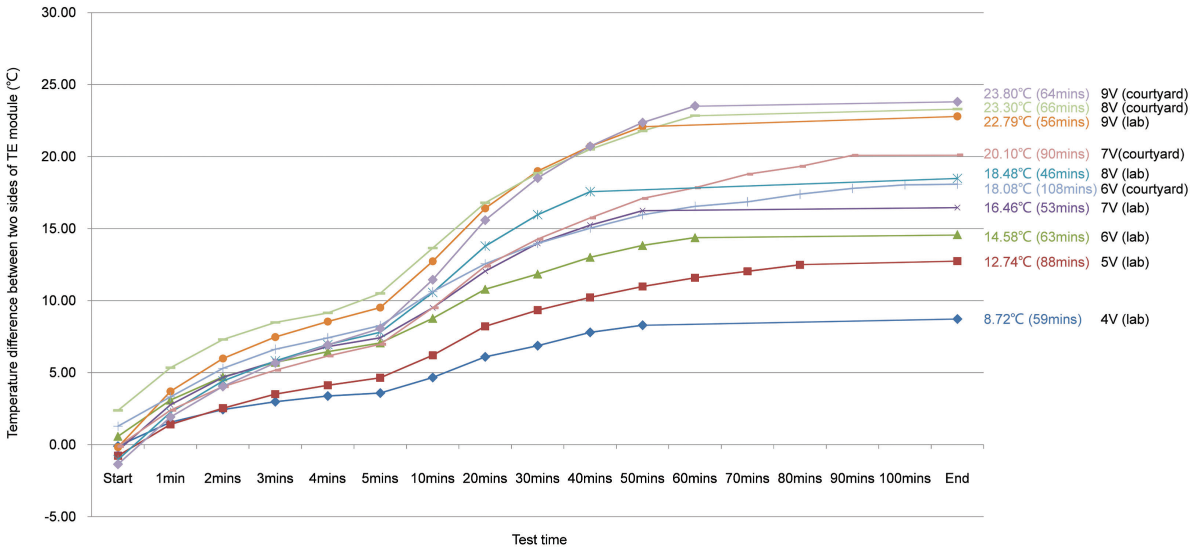


Fig. 3.13 The monitored temperature differences between the two sides of TE module at different test time intervals

The monitored temperature differences between the hot side and cold side of TE module tested under different voltages in both lab and courtyard ambient are shown in Figure 3.13. The results reveal a general trend that TE modules powered by higher voltages could produce larger temperature differences in shorter operation time than lower voltages (e.g. 3 V-5 V range). For example, after 40 minutes a 8 V input produces a ΔT 17.56 °C whereas a 4 V input produces a ΔT 7.80 °C. The experimental results also show that TE modules can reach 8.72 °C-23.80 °C temperature difference with different voltage inputs which are able to meet the indoor thermal comfort level under the UK domestic heating demand context. If the heating time was to be extended longer than the test time in this study, larger temperature difference would potentially be produced. Moreover, the results suggest that TE modules commonly achieve greater temperature difference in a courtyard low-temperature ambient 1 °C-5 °C than in a warm lab ambient 19 °C-21 °C during same heating time. This further indicates the potential of TE modules for a domestic heating application.

3.5.2 The relationship between input voltage level and heating COP

Figure 3.14 shows a comparison of the different heat generation and heating COP under various voltage inputs during a transient-state at the 10 minutes after test start-up. The results show that both of the heating generation of TE modules will increase as the input voltage is elevated and that the heating COP values changes show a decline trend when the input voltage is increased. This declining COP trend is confirmed at the end of the test results (Figure 3.15).

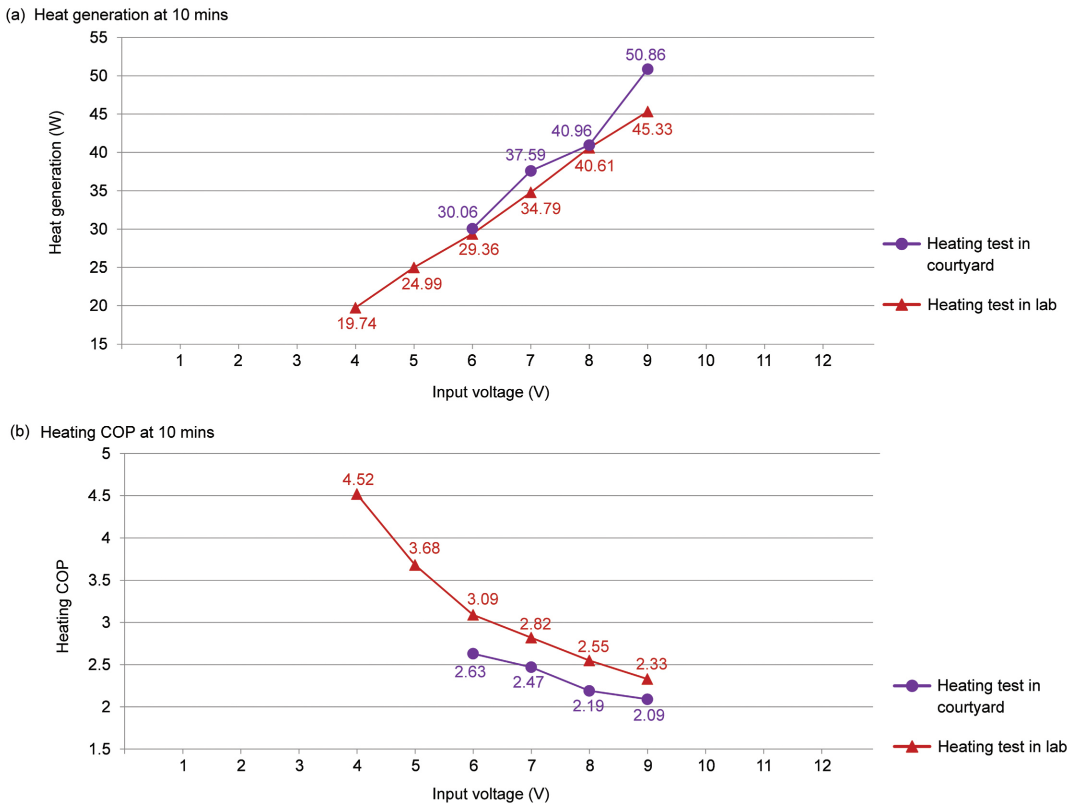


Fig. 3.14 (a)Heating generation comparison under different input voltage levels at 10 minutes after test start-up (b) Heating COP comparison under different input voltage levels at 10 minutes after test start-up (Relevant calculation data see Table A.1 in Appendix A)

Moreover, Figure 3.14 also reveals that during the transient-state, TE modules with same voltage input usually can generate a little more heat in the low-temperature environment than in the lab environment. However, the corresponding heating COP in the low-temperature environment is lower than that in lab environment. This implies that TE modules may cause a faster heating effect in the low-temperature environment than in the warm environment at the period of time of heating start-up. But, as expected, in the low-temperature environment TE modules will cost more power than in warm environment. From the test results of this study, the application perspective suggests that if the external environment is not too cold (i.e. above 10 °C), it would be better to operate TE modules with lower voltage inputs (e.g. 3 V-5 V range) so as to benefit from a higher COP and ensure maximum energy efficiency. On the other hand, when the external environment is cold (i.e. below 10 °C), then higher voltage input might be preferred to operate TE albeit with a lower COP. Furthermore, even though COP will drop down as the temperature difference increases, Figure 3.15 shows that between 4 V-9 V inputs (in lab and courtyard environments) the average heating COP of TE modules can remain above 1.8 during the whole test heating process. This suggests acceptable heat pump efficiency for a domestic heating application albeit as new material research develops (e.g. Lincoln labs had improved the $ZT \geqslant 2.0$ [14]) higher COP will be feasible.

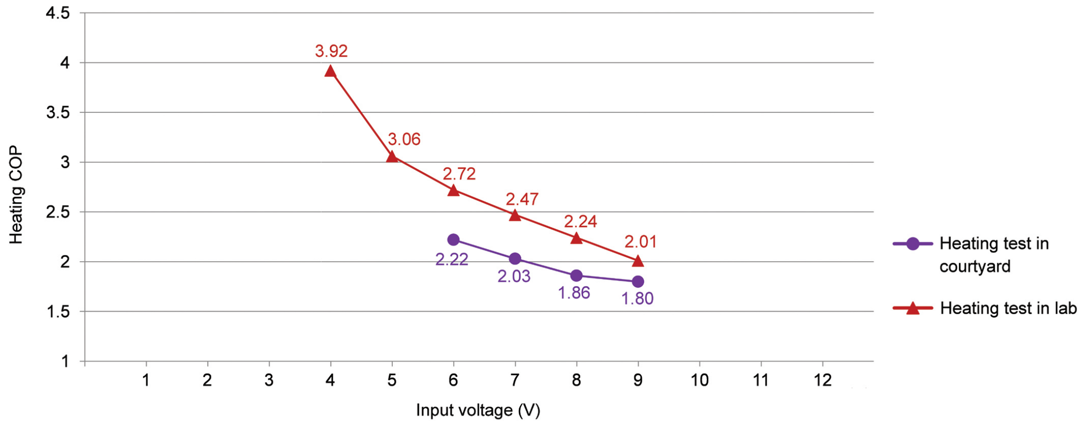


Fig. 3.15 Heating COP measured at the end of experiment for different ambient and input voltage levels (Relevant calculation data see Table A.2 in Appendix A)

3.5.3 The relationship between heating COP, temperature difference, and operation time

In this section, the study analyzed TE modules heating test results with an 8 V input in lab environment and courtyard low-temperature environment as a way of representative example to analyze the relationship between the temperature difference, heating COP and the heat generation.

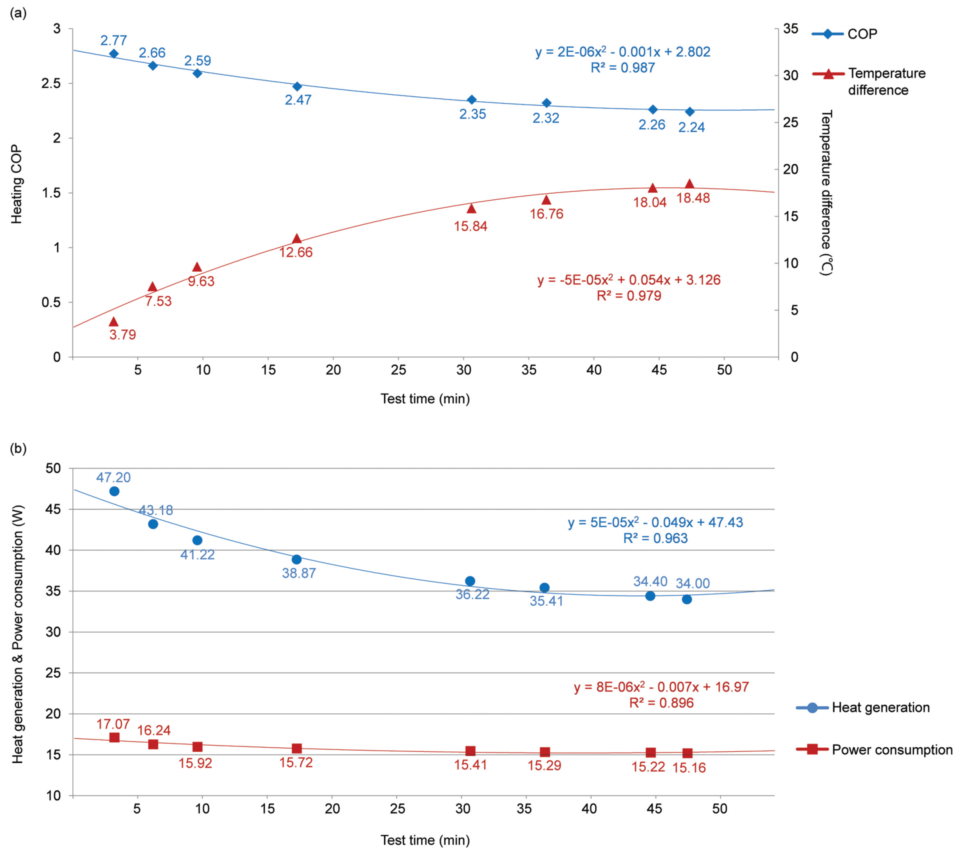


Fig. 3.16 (a) Heating COP and temperature difference under 8V input in lab environment (b) Heat generation and power consumption under 8V input in lab environment (Relevant calculation data see Table A.3 in Appendix A)

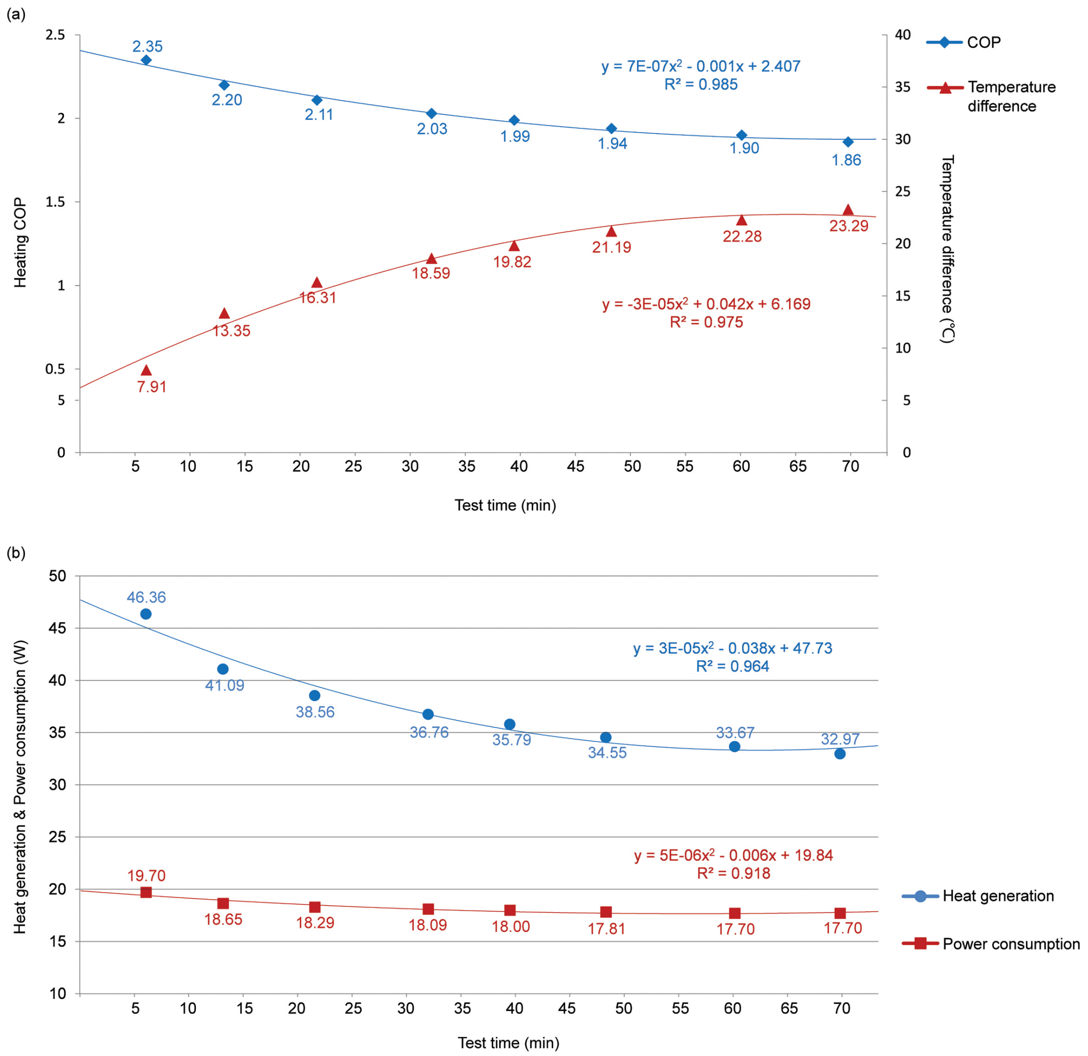


Fig. 3.17 (a)Heating COP and temperature difference under 8V input in courtyard environment (b)Heat generation and power consumption under 8V input in courtyard environment (Relevant calculation data see Table A.4 in Appendix A)

Figure 3.16 and Figure 3.17 reveal that during the whole transient-state process of the heating test, both of the heating generation and the heating COP of TE modules will reduce as temperature difference increases between the two sides of TE module. This is consistent with other TE module studies. Specifically, the results shown in Figure 3.16(a) that when the temperature difference between the two sides of TE modules expand to 18.48 °C from 3.79 °C, the heating COP drops 19.13% (changes from 2.77 to 2.24). Similarly, Figure 3.17(a) shows that when the temperature difference between the two sides of TE modules expand to 23.29 °C from 7.91 °C, the heating COP drops about 20.85% (changes from 2.35 to 1.86). Regarding heat generation, Figure 3.16(b) and Figure 3.17(b) show that although there is an initial drop in heat generation (e.g. -23.26% (changes from 47.20 W to 36.22 W)) after 30 minutes heat generation is stable (changes from 36.22 W to 34.00 W) with a slight decline in power consumption. Thus, minor changes of the heating COP during the whole heating process and a stable heat generation further suggests that TE module could be used for domestic heating.

3.5.4 Average heat transfer power of TE module

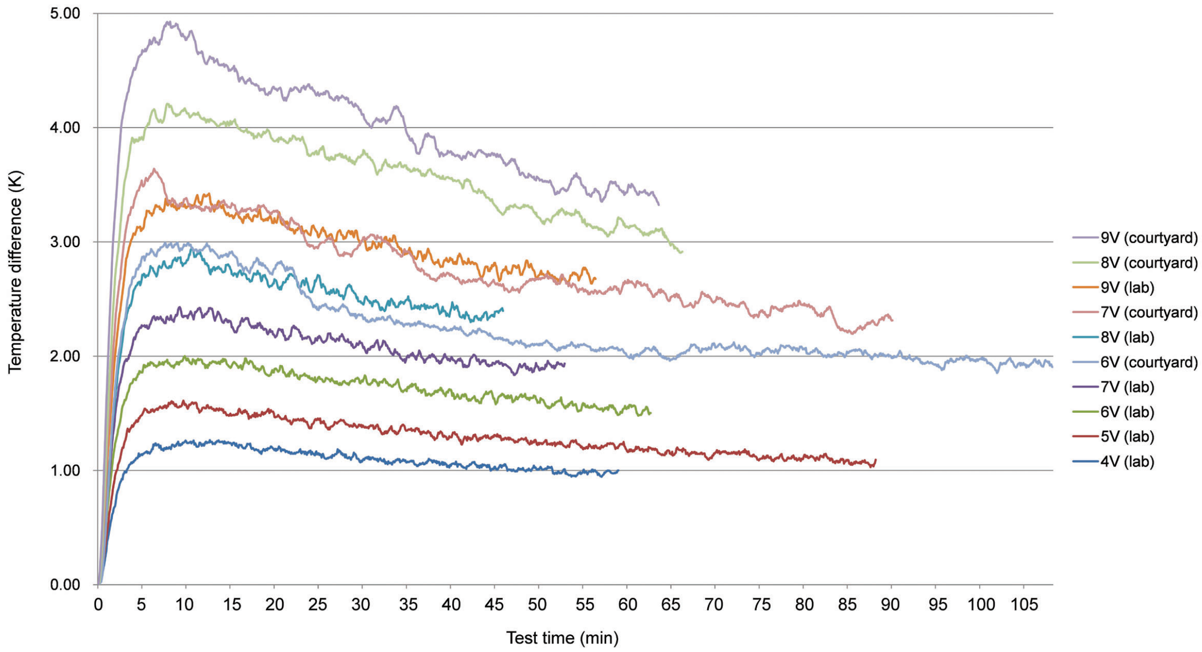


Fig. 3.18 Experimental temperature difference changes between outlet airflow and inlet airflow

During all heating test processes, the monitored temperature difference results between the inlet airflow and outlet airflow are shown in Figure 3.18. Moreover, the specific heat capacity of air in this study is assumed as a constant value of $1004\,\mathrm{J\,kg^{-1}\,K^{-1}}$ [99]. The airflow of the cross flow fan employed in the experiment is equal to $0.016\,28\,\mathrm{m^3\,s^{-1}}$ whilst the air density is considered as the standard value of $1.225\,\mathrm{kg\,m^{-3}}$. Hereby, the net weight of the heated airflow is calculated as $0.016\,28\,\mathrm{m^3\,s^{-1}} \times 1.225\,\mathrm{kg\,m^{-3}} \approx 0.019\,943\,\mathrm{kg\,s^{-1}}$.

Based on above data and assumption, it can confirm the average temperature difference between inlet airflow and outlet airflow in all tests (i.e. under different input voltage levels and in different ambient) and can further utilize Equation 3.1 (listed in Section 3.3) to calculate the average heat transfer power (in unit of W) by the forced convection of the cross flow fan from three TE modules to the $1\,\mathrm{m^3}$ internal test space. Furthermore, If assuming the standard height of a room is $3\,\mathrm{m}$, then it would employ nine pieces of TE modules to heating each $1\,\mathrm{m^2}$ floor area (i.e. space volume of $1\,\mathrm{m^2}$ floor area is equal to $3\,\mathrm{m^3}$), and the corresponding heating power (in unit of $\mathrm{W\,m^{-2}}$) would be estimated as: the average heat transfer results of the tests $\times$ 3. All the test and estimation results are shown in Table 3.13.

Table 3.13 shows higher input voltage level can always promote larger temperature difference between inlet airflow and outlet airflow due to the increase of total heat generation at the TE hot side as the input voltage level is elevated. Moreover, when keeping same input voltage level in different test ambient, the TE module usually can cause more obvious heating effect (i.e. larger temperature difference) in the low-temperature environment (e.g. $3.52\,^{\circ}\mathrm{C}$ airflow temperature difference under 8 V input in the open-air courtyard ambient) than in the warm environment (e.g.

	Average temperature difference between outlet and inlet (°C)	**Average heat transfer to** 1 m^3 **space** (W)	**Average heating power for each** 1 m^2 **floor area** (W m^{-2})
4 V (lab)	1.07	21.47	64.41
5 V (lab)	1.27	25.45	76.35
6 V (lab)	1.70	34.02	102.06
7 V (lab)	2.05	41.14	123.43
8 V (lab)	2.49	49.89	149.66
9 V (lab)	2.92	58.44	175.33
6 V (courtyard)	2.21	44.28	132.84
7 V (courtyard)	2.73	54.71	164.12
8 V (courtyard)	3.52	70.41	211.22
9 V (courtyard)	3.96	79.25	237.74

Table 3.13 Average heat transfer power by forced convection from TE modules to heating 1 m^3 space

2.49 °C airflow temperature difference under 8 V input in the lab ambient) during whole heating period.

Additionally, by the rule-of-thumb of load estimation [100] the heating load of UK residential building is suggested as 60 W m^{-2}. Experimental estimation results (see Table 3.13) show that nine TEC1-12706 modules can produce minimum 64.41 W m^{-2} under 4 V input to heating the building ambient. Thus, if the TE heating system design can employ every three pieces of TEC1-12706 modules to heating each 1 m^3 building space, it should be able to meet the basic domestic heating load with all tested voltages. More comparisons between the heating power of TE system and detailed domestic heating load will be demonstrated in the specific case study of next chapter.

3.5.5 Uncertainty

This section verifies the heating test results in comparison with the theoretical derivation results and detects uncertain factors.

Assuming the heating COP of TE module is equal to 1.8, the heating capacity at the hot side will be $Q_h = 1.8 \times W$ whilst the cooling capacity at the cold side $Q_c = Q_h - W = 0.8 \times W$. Consequently in accordance with Equation 2.12 and Equation 2.14 it has Equation 3.2. Where I_E is the input electric current (A) when the heating COP of TE module gets 1.8.

$$2N \times (\alpha \times I_E \times T_c - \rho \times I^2/2G - \kappa \times G \times \Delta T) = 0.8 \times [2N \times (\rho \times I^2/G + \alpha \times I_E \times \Delta T)] \quad (3.2)$$

Further defining the internal electric resistance (Ω) of TE module $R = 2N \times \rho/G$; the total thermal conductivity (W K^{-1}) of TE module $K = 2N \times \kappa \times G$. Then Equation 3.2 can be developed as $2N \times \alpha \times I_E \times T_c - 1/2 \times I_E^2 \times R - K \times \Delta T = 0.8 \times (I_E^2 \times R + 2N \times \alpha \times I_E \times \Delta T)$, which is simplified as:

$$1.3 \times I_E^2 \times R - 2N \times \alpha \times I_E \times (T_c - 0.8 \times \Delta T) + K \times \Delta T = 0 \quad (3.3)$$

As shown in Equation 3.4, there are two different solution values to Equation 3.3 (i.e. the literature review studied in Section 2.3.2 has revealed a general rule that the COP of TE module will firstly increase and then decrease as continuous increase of the input power when both hot side and cold side temperature keep unchanged. Thus except the maximum value of COP, there usually are two different input power values corresponding to same COP but different heating/cooling capacities).

$$I_{E1,2} = \frac{2N \times \alpha \times (T_c - 0.8\Delta T) \pm \sqrt{(2N \times \alpha)^2 \times (T_c - 0.8\Delta T)^2 - 5.2R \times K \times \Delta T}}{2.6R} \tag{3.4}$$

Here in order to get more heat generation at the hot side, the calculated input electric current should utilize the larger value result in Equation 3.5.

$$I_E = \frac{2N \times \alpha \times (T_c - 0.8\Delta T) + \sqrt{(2N \times \alpha)^2 \times (T_c - 0.8\Delta T)^2 - 5.2R \times K \times \Delta T}}{2.6R} \tag{3.5}$$

For assuring the I_E is always a valid value (i.e. if the I_E is not a valid value in the calculation, the heating COP of 1.8 could not be achieved when TE module reaches the expected temperature settings and it would merely achieve lower heating COP < 1.8), it must keep $\sqrt{(2N \times \alpha)^2 \times (T_c - 0.8\Delta T)^2 - 5.2R \times K \times \Delta T} \geq 0$. Hereby the available maximum temperature difference between two sides of TE module can be estimated by Equation 3.6.

$$(2N \times \alpha)^2 \times (T_c - 0.8\Delta T)^2 - 5.2R \times K \times \Delta T \geq 0 \tag{3.6}$$

Then if importing the specific parameters of TEC1-12706 module into Equation 3.6 and assuming the outside ambient is 276.51 K (3.36 °C) (i.e. when the cold side temperature of TE modules is equal to the ambient temperature), then it is able to calculate the maximum theoretical temperature difference is $\Delta T \leq 25.27$ °C with a corresponding input electric current of 2.31 A whilst the heating COP keeps at 1.8. This encouraging theoretical result can meet the indoor thermal comfort demand with an acceptable heat pump efficiency.

Compared with above theoretical calculation results, the real experimental results show that when the TE module achieves a heating COP result of 1.8 with cold side temperature of 3.36 °C at the end of 9 V input test in courtyard environment, the measured temperature difference between the two sides of TE module is 23.80 °C which is lower than the theoretically maximum value of 25.27 °C. Conversely, if importing the real experimental results of the cold side temperature T_c of 3.36 °C with temperature difference ΔT of 23.80 °C back into the Equation 3.5, the ideal current consumption I_E would be equal to 2.85 A in theory. Compared with the real current measurement result of 2.88 A, there is a minor deviation of 1.05% between the theoretical result and the experimental result which may be caused by some uncertain factors such as the minor changes of the internal electric resistance of TE module due to temperature changes and potential influences of other circuit components. This deviation should be an acceptable result in generic experimental analysis.

3.6 Summary

In this experimental study, a heating test apparatus has been built to test the performance (i.e. achievable heating temperature, temperature differences, COP values and heating power) of TEC1-12706 module for space heating. The experimental results have been provided both for a laboratory and a low-temperature courtyard environment, which can be utilized as useful indicators to ascertain the potential feasibility of TE module for the domestic heating application and to support further studies with regard to the feasibility of TE module combined with renewable energy for UK domestic heating in next chapters. Main conclusions of this experimental study are drawn as follows:

1. This experimental study has shown that TE module(s) could be potentially used for indoor space heating in the UK ambient temperature context.

2. TE modules can achieve the required temperatures differences so as to potentially satisfy domestic thermal comfort levels. Furthermore, experimental results analysis also indicates potential operational modes for TE modules as suggest that when the ambient temperature is between 1 °C and 10 °C, TE module would require higher working voltage level (i.e. 6 V to 8 V) so as to ensure an adequate temperature level can be achieved. For temperatures above 10 °C, it would be better to have a higher number of TE modules working under lower voltage level (i.e. 3 V to 5 V) so as to be more energy efficient (i.e. because of the higher heating COP which could be obtained).

3. The heating COP of the selected TEC1-12706 modules during the whole space heating process can be remained above 1.8 with all voltage input tests (i.e. 4 V to 9 V) in both in lab and courtyard environments. This suggests an initial good heat pump efficiency for a domestic heating application. However, as new material research develops (e.g. Lincoln labs had improved the $ZT \geqslant 2.0$ [14]), TE modules with higher COP will be feasible.

Chapter 4

TE Module Combined with Renewable Energy for the Domestic Heating in a Mid-terraced House

4.1 Introduction

Pre-1900s mid-terraced property is one of the most common housing type in the UK and one of the most difficult to retrofit with new energy efficiency measures such as solid wall which go beyond the "low-hanging fruit" measures (i.e. loft insulation) already installed in the majority of properties. Hence, any technologies which can alleviate the heating demand are expected. In this chapter, a detailed case study will be provided to explore the possible technical application of combining TE modules with renewable energy to supply the domestic heating in a typical pre-1900s mid-terraced house. The cased studied house is located in Newcastle upon Tyne in the North East of England, it has a total floor area of 180 m^2 and the project area of the exposed roof is 90.32 m^2 as measured off surveyed drawings (see Figure 4.1). Relevant investigation results and data analysis regarding the energy consumption, heating load and available renewable energy supply (i.e. solar energy and wind energy) in this domestic context will be presented in following sections. Moreover, based on the experimental results of TE heating performance tested in Chapter 3 and detailed investigation results of domestic gas demands for supplying heating purpose and local renewable energy supply in this chapter, it could further simulate the specific heating supply-demand relationship throughout the year if utilizing the TE heating system powered by renewable energy to service for the domestic heating. Finally, in comparison with employing general electric heater, the possible energy saving efficiency and carbon saving caused by the whole TE heating & renewable power supply system will be estimated as helpful indications for ascertaining the potential application of TE heating system powered by renewable energy for meeting future domestic heating demands.

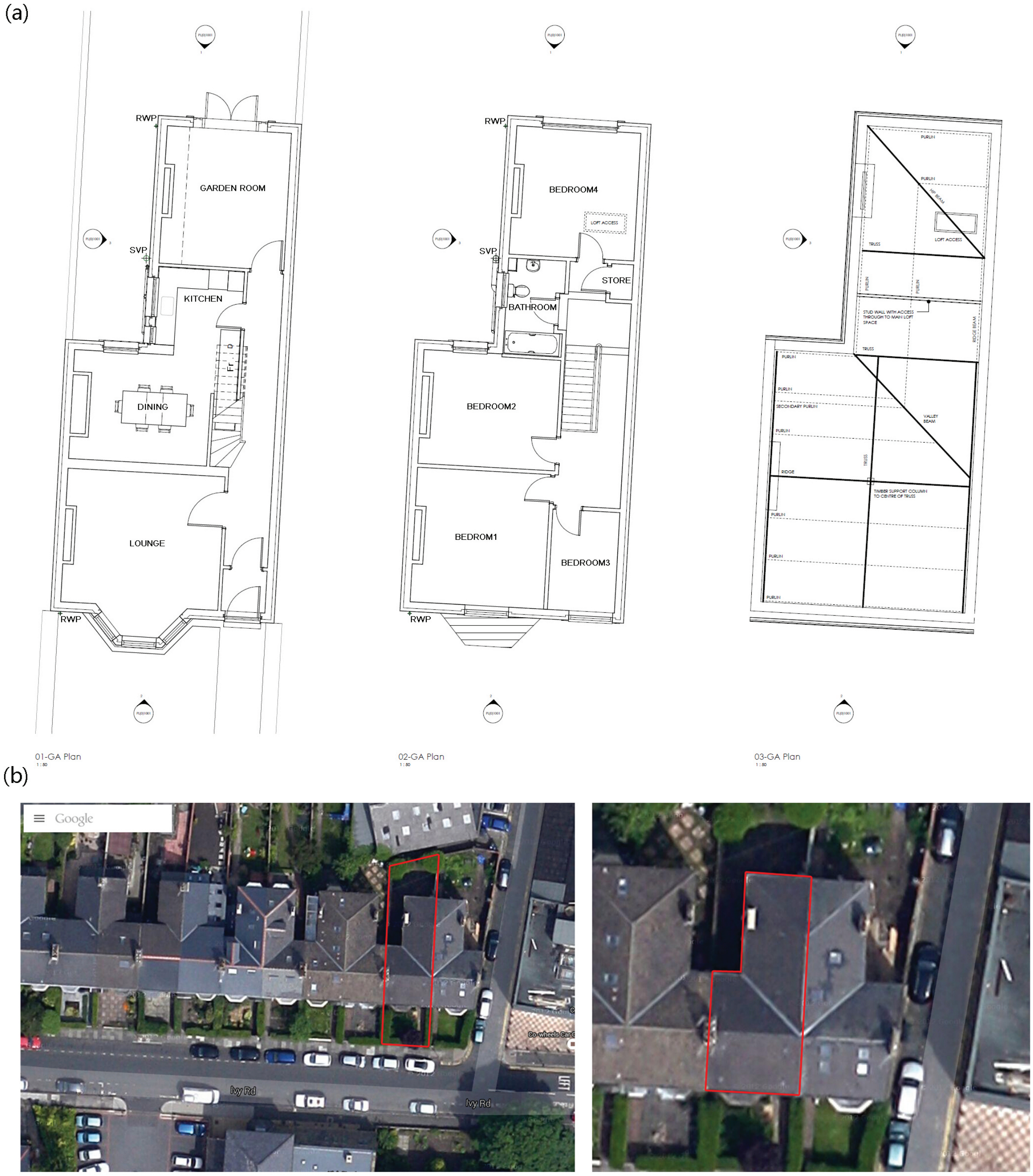


Fig. 4.1 Case study house: (a) Surveyed plan drawings by an architect (b) House areal view on Google®

4.2 Gas demands for supplying domestic heating of the mid-terraced property

4.2.1 Energy consumption investigation of the mid-terraced property

Both of the gas and electricity consumptions have been recorded from Nov 2012 till Mar 2015 by using British ®smart energy meter reading. The raw data of the energy consumption are shown in Table 4.1. Additionally, the classification of seasons by months throughout the year have been marked as shown in Table 4.2.

Start date	**End date**	**Record days**	**Gas consumption** (kWh)	**Average gas consumption** (kWh/day)	**Electricity consumption** (kWh)	**Average electricity consumption** (kWh/day)
30-Nov-12	8-Dec-12	9	1349	149.89	N/A	N/A
9-Dec-12	11-Jan-13	34	3460	101.76	358	10.53
12-Jan-13	9-Feb-13	29	4670	161.03	307	10.59
10-Feb-13	8-Mar-13	27	3615	133.89	271	10.04
9-Mar-13	11-May-13	64	N/A	N/A	4	0.06
12-May-13	9-Jun-13	29	1582	54.55	710	24.48
10-Jun-13	7-Jul-13	28	385	13.75	188	6.71
8-Jul-13	15-Jul-13	8	148	18.50	47	5.88
16-Jul-13	14-Aug-13	30	472	15.73	164	5.47
15-Aug-13	15-Aug-13	1	11	11.00	5	5.00
16-Aug-13	12-Sep-13	28	184	6.57	250	8.93
13-Sep-13	9-Oct-13	27	934	34.59	235	8.70
10-Oct-13	8-Nov-13	30	2175	72.50	315	10.50
9-Nov-13	9-Dec-13	31	3149	101.58	306	9.87
10-Dec-13	9-Jan-14	31	2295	74.03	283	9.13
10-Jan-14	7-Feb-14	29	3138	108.21	400	13.79
8-Feb-14	8-Mar-14	29	2718	93.72	290	10.00
9-Mar-14	13-Apr-14	36	2612	72.56	286	7.94
14-Apr-14	9-May-14	26	1255	48.27	207	7.96
10-May-14	9-Jun-14	31	776	25.03	204	6.58
10-Jun-14	11-Jul-14	32	433	13.53	239	7.47
12-Jul-14	10-Aug-14	30	222	7.40	137	4.57
11-Aug-14	9-Sep-14	30	378	12.60	206	6.87
10-Sep-14	15-Oct-14	36	1104	30.67	317	8.81
16-Oct-14	13-Nov-14	29	810	27.93	292	10.07
14-Nov-14	15-Nov-14	2	79	39.50	24	12.00
16-Nov-14	17-Nov-14	2	79	39.50	30	15.00
18-Nov-14	15-Dec-14	28	2790	99.64	274	9.79
16-Dec-14	11-Jan-15	27	1418	52.52	309	11.44
12-Jan-15	10-Feb-15	30	3180	106.00	330	11.00
11-Feb-15	12-Feb-15	2	215	107.50	26	13.00
13-Feb-15	15-Mar-15	31	2958	95.42	342	11.03
16-Mar-15	17-Mar-15	2	147	73.50	21	10.50
Total days		838				

Table 4.1 The energy consumption counted by British ®smart energy meter reading

Spring	Summer	Autumn	Winter
March, April and May.	June, July and August.	September, October and November.	December, January and February.

Table 4.2 Classification of seasons by months throughout the year

Gas consumption

According to Table 4.1 and Table 4.2, during the whole monitoring period, the domestic gas consumption changes in this case studied property can be further visually demonstrated as shown in Figure 4.2. It reveals that during the coldest months of winter season, the gas consumption level per day is usually the highest throughout the year, and followed by the months of spring and autumn. The lowest gas consumption level in summer season is likely caused by the hot weather with no heating demand.

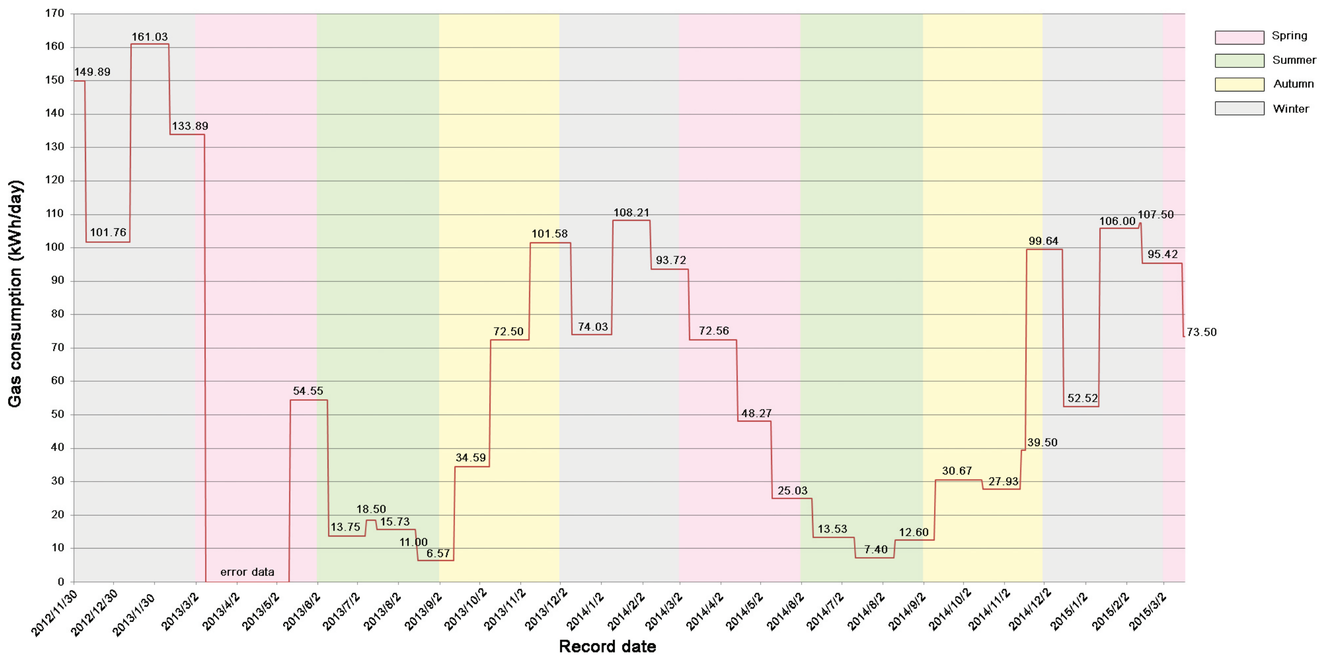


Fig. 4.2 The gas consumption change between 30th Nov 2012 and 17th Mar 2015 * Data records between 18th Mar 2013 and 20th May 2013 were missing.

Furthermore, for calculating the average daily gas consumption level (in unit of kWh/day) in each specific month, based on Table 4.1 and Figure 4.2, the calculation can sum all the gas results consumed in same months of different years, and divide the sum value by corresponding total record days. Take for example as shown in Table 4.3, during the same months of January in 2013, 2014 and 2015, there is total 10084.65 kWh gas consumption and the corresponding total record time are 93 days.

Hence, the average daily gas consumption in January is calculated as: 10084.65 kWh $\div$ 93days $\approx$ 108.44 kWh/day. Utilizing the same method, more calculation results of average daily gas consumption levels in other months throughout the year can be carried out as shown in Table 4.4.

Start Date	**End Date**	**Average gas consumption** (kW h/day)	**Record days**	**Total gas consumption** (kW h)
1-Jan-13	11-Jan-13	101.76	11	1119.41
12-Jan-13	31-Jan-13	161.03	20	3220.69
1-Jan-14	9-Jan-14	74.03	9	666.29
10-Jan-14	31-Jan-14	108.21	22	2380.55
1-Jan-15	11-Jan-15	52.52	11	577.70
12-Jan-15	31-Jan-15	106.00	20	2120.00
Total			93	10084.65

Table 4.3 Total gas consumption record of January

Months	**Jan**	Feb	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
Gas consumption sum (kW h)	10084.65	9520.56	5067.97	1763.80	2076.17	1289.16	792.83	675.01	1458.92	2813.23	4781.12	8417.57
Record days	93	84	56	30	51	60	62	62	60	62	61	93
Average daily gas (kW h/day)	108.44	113.34	90.50	58.79	40.71	21.49	12.79	10.89	24.32	45.37	78.38	90.51

Table 4.4 Average daily gas consumption levels in each month between 30th Nov 2012 and 17th Mar 2015

It needs to indicate that all the calculation results in Table 4.4 have involved the occupants' behavior influence. For instances, the gas record of 149.89 kW h/day between 30th Nov 2012 and 8th Dec 2012 is much higher than the calculated December average level of 90.51 kW h/day, which may be caused by more domestic heating & hot water demands and longer home stay time during the extremely cold weather period in that year. However, the gas record between 14th Nov 2014 and 15th Nov 2014 with higher resolution is 39.50 kW h/day which is much lower than the calculated November average level of 78.38 kW h/day. The less actual gas consumption during these two days may be caused by the reason of some residents leave away for business trips. Hence, the calculated average daily gas consumption levels in each month should have some deviations away from the actual consumptions.

Electricity consumption

In this case studied property, the domestic heating, hot water supply and cooking are fuelled by the gas, electricity is only consumed for supplying indoor lighting and electric appliance using. Monitored domestic electricity consumption changes are visually demonstrated as shown in Figure 4.3 which reveals that the electricity consumption level per day in summer is the lowest throughout the year, and followed by spring and autumn, which may be caused by longer sunshine time with less indoor lighting hours and occupants' behaviors (i.e. leaving home for holidays or business trips). During winter, the electricity consumption level is the highest which may be caused by longer indoor lighting hours and more indoor activities with higher using frequency of electric appliance (i.e. TV, game console and computer) during the colder weather.

Moreover, similar with the gas consumption investigation and analysis, relevant calculation results of the average daily electricity consumption level in each month of one year are carried out as shown in Table 4.5.

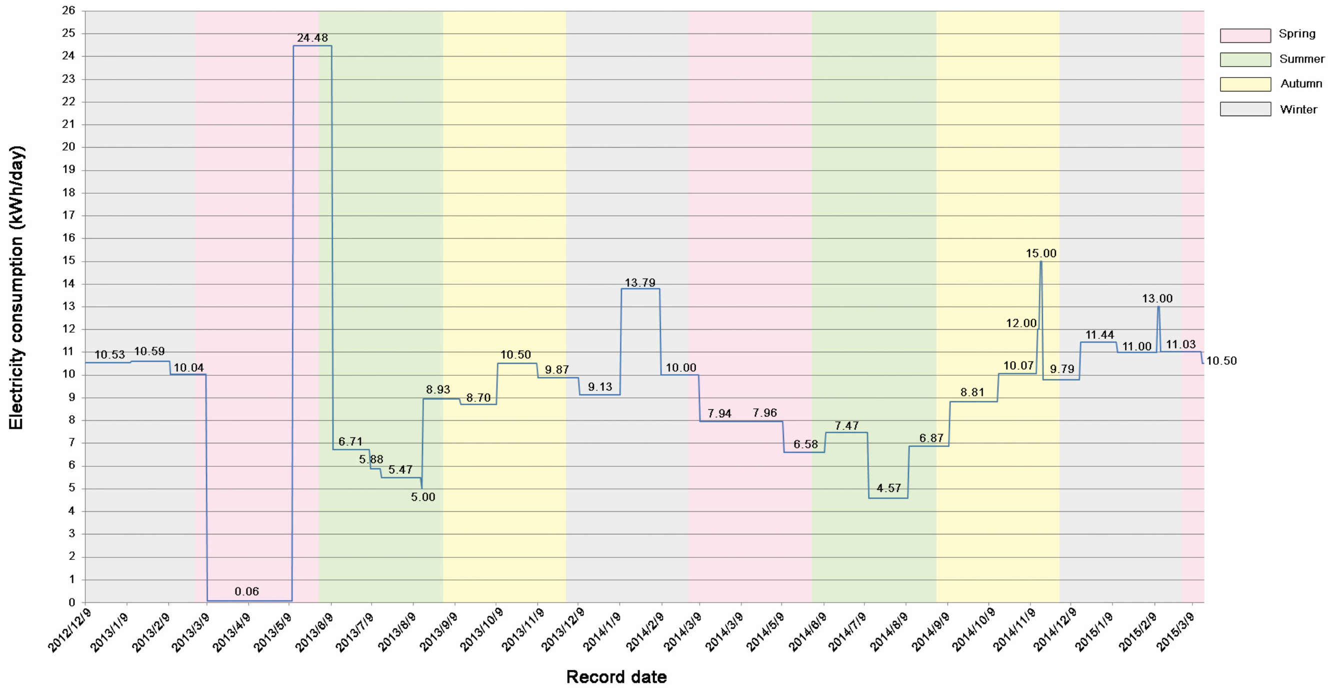


Fig. 4.3 The electricity consumption change between 9th Dec 2012 and 17th Mar 2015 * Abnormal data records between 9th Mar 2013 and 9th June 2013 were considered as the invalid data and excluded since too low/high electricity consumption without reasonable explanations.

Months	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Ele consumption sum (kWh)	1059.05	905.05	529.50	238.62	216.43	357.07	354.96	414.26	510.53	602.52	613.27	861.75
Record days	93	84	56	30	31	51	62	62	60	62	60	85
Average daily ele (kWh/day)	11.39	10.77	9.46	7.95	6.98	7.00	5.73	6.68	8.51	9.72	10.22	10.14

Table 4.5 Average daily electricity consumption levels in each month between 9th Dec 2012 and 17th Mar 2015

4.2.2 Estimations of monthly gas demands for supplying domestic heating and hot water & cooking, and electricity demands in the mid-terraced property

Based on the average daily gas/electricity consumption levels in each month calculated in Table 4.4 and Table 4.5, the monthly total gas and electricity demands (in unit of kWh/month) in this investigated property are capable of being estimated by: average daily gas/electricity consumptions in each specific month (kWh/day) $\times$ standard days of the corresponding month. For instances, the monthly total gas demand in February is estimated: 113.34 kWh/day (average daily gas consumption level in February) $\times$ 28 days (standard days of February) $\approx$ 3173.52 kWh/month; the monthly total electricity demand in January is estimated: 11.39 kWh/day (average daily electricity consumption level in January) $\times$ 31 days (standard days of January) $\approx$ 353.02 kWh/month. All the estimation results of monthly total gas/electricity demands are given in Table 4.6.

Furthermore, in most months of the year, the household needs to consume gas to meet the domestic heating, hot water and cooking demands. But during the summer season (i.e. June, July and August) there is generally no indoor heating demand. Hence, In this case study, it could consider utilizing the average daily gas consumption in these summer months as a reference value to represent the average level of the domestic hot water & cooking gas demands throughout the year. Based on the statistical data in Table 4.4, the average daily gas consumption during summer months is calculated by: $(1289.16\,\text{kWh} + 792.83\,\text{kWh} + 675.01\,\text{kWh}) \div (60 + 62 + 62)\text{days} \approx 14.98\,\text{kWh/day}$. Then if estimating the monthly gas demands (in unit of kWh/month) for supplying hot water & cooking as: $14.98\,\text{kWh/day} \times$ standard days of each month (exclude June, July and August) and further separating these results from the estimated monthly total gas demands, the specific monthly gas demands for supplying domestic heating throughout the year would be finally identified. All estimation results regarding the monthly gas demands for supporting both of hot water & cooking and domestic heating have been summarized in Table 4.6.

Months	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual (kWh)
Total gas demand (kWh/month)	3361.55	3173.52	2805.49	1763.80	1261.98	644.58	396.41	337.51	729.46	1406.62	2351.37	2805.86	21038.15
Gas for hot water & cooking (kWh/month)	464.38	419.44	464.38	449.40	464.38	644.58	396.41	337.51	449.40	464.38	449.40	464.38	5468.04
Gas for domestic heating (kWh/month)	2897.17	2754.08	2341.11	1314.40	797.60	0	0	0	280.06	942.24	1901.97	2341.48	15570.11
Total electricity demand (kWh/month)	353.02	301.68	293.12	238.62	216.43	210.04	177.48	207.13	255.26	301.26	306.64	314.29	3174.97

Table 4.6 Monthly gas demands for supplying domestic heating, hot water & cooking and electricity demands in the mid-terraced property

Table 4.6 estimates the annual gas demand in the case studied property is 21 038.15 kWh which is close to the median gas consumption level of 22 900 kWh of the properties with $151\,\text{m}^2$ to $200\,\text{m}^2$ floor area located in North East region (data statistics by [101] and updated in 2015). Moreover, it can analyze the detailed energy demands profile in this house as: the domestic heating, hot water & cooking and lighting & electric appliance (i.e. annual electricity demand) account for 64.3%, 22.6% and 13.1% of total energy demand respectively. These energy consumption patterns are also most likely close to the statistics results by [2]: 66% of UK domestic energy consumption is used for indoor heating, 20% for hot water & cooking, and 15% for lighting & electric appliance. Hence, this case studied house can be seen as a typical representative of pre-1919 mid-terraced dwellings with $151\,\text{m}^2$ to $200\,\text{m}^2$ floor area located in North East region, and the specific monthly heating demands of this household (i.e. heating demands can be calculated by: gas demands for supplying domestic heating $\times$ boiler efficiency) can be utilized as important baseline data reference to further estimate possible monthly domestic heating demands in other types of dwellings in next chapters.

4.3 Relationship between monthly gas demand for supplying domestic heating and monthly climate temperature change

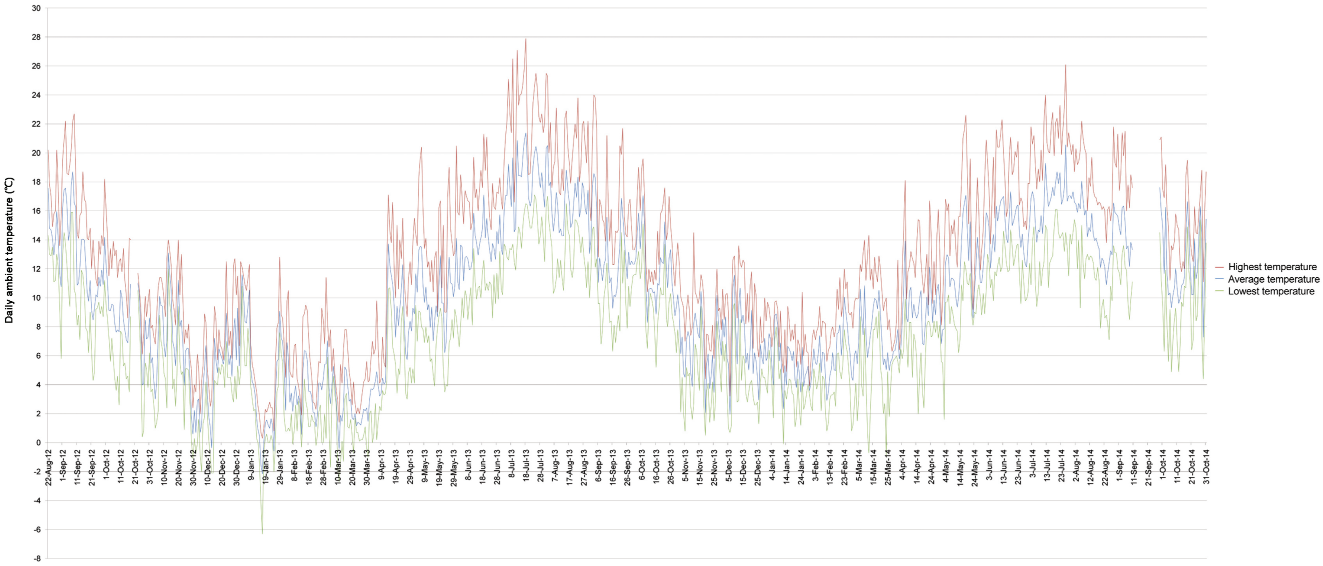


Fig. 4.4 The temperature monitoring data of Newcastle upon Tyne from 22nd Aug 2012 till 31st Oct 2014 * Data between 19th Oct 2012 and 22nd Oct 2012, 11th Sep 2014 till 28th Sep 2014 were missing.

Based on domestic gas consumption records of the case studied household (see Table 4.2) and historical climate temperature monitoring records of Newcastle upon Tyne (see Figure 4.4), it can particularly extract relevant gas consumption and climate temperature data recorded between 30th Nov 2012 and 30th Oct 2014 to analyze the relationship between monthly gas demands for supplying domestic heating and climate temperature changes as shown in Figure 4.5.

Figure 4.5 shows that the change of monthly gas demands for supplying domestic heating is inversely proportional to the monthly average climate temperature change. Moreover, it presents that there is usually no gas consumption for domestic heating purpose when the monthly average climate temperature is above 14 °C. The minimum monthly gas demands for supplying domestic heating is 280.06 kW h/month in September while the monthly average climate temperature is 13.49 °C (i.e. there are relatively few cold days requesting domestic heating demands during this month). Additionally, compared the monthly average climate temperature of 5.05 °C in March with 8.18 °C in April, the gas demand for supplying domestic heating reduces 995.04 kW h/month as the monthly average climate temperature roses by 3.13 °C. More similar comparisons are presented in Table 4.7, and corresponding analysis results can roughly summarize a relationship that the monthly gas demands for supplying domestic heating will increase 200 kW h/month-400 kW h/month as each 1 °C decline of the monthly average climate temperature. This can provide some helpful references to estimate the gas demands of domestic heating in any similar dwelling scenarios rely on the local climate temperature in a certain range.

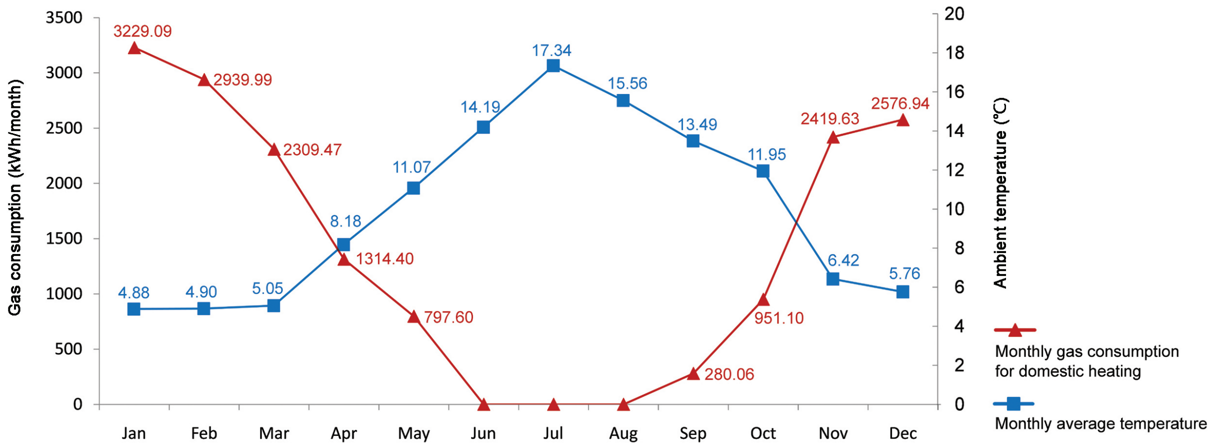


Fig. 4.5 The relationship between monthly gas demands for supplying domestic heating and monthly average climate temperature change * The domestic hot water & cooking demands are assumed as 14.98 kWh/day and have been excluded from the calculated monthly total gas consumption results for finally estimating the monthly gas demands for supplying domestic heating.

Monthly climate temperature change (°C)		**Climate Temperature increase** (°C)	**Gas demand** (kWh/month)		**Gas demand decrease** (kWh/month)	**The change of monthly gas demand as each 1 °C rise** (kWh/month)
from	**to**		**from**	**to**		
5.05	8.18	3.13	2309.47	1314.40	995.07	317.91
8.18	11.07	2.89	1314.40	797.60	516.80	178.82
11.07	13.49	2.42	797.60	280.06	517.54	213.86
13.49	11.95	-1.54	280.06	951.10	-671.04	435.74
11.95	6.42	-5.53	951.10	2419.63	-1468.53	265.56
6.42	5.76	-0.66	2419.63	2576.94	-157.31	238.35

Table 4.7 The monthly gas demands for supplying domestic heating change with different monthly average climate temperature

Additionally, it notes the drastically declines of the monthly gas demands for supplying domestic heating (i.e. reduce from 3329.09 kWh/month till 2309.47 kWh/month) between January and March but with minor climate temperature changes (i.e. monthly average climate temperature changes from 4.88 °C to 5.05 °C) may be caused by some uncertain factors such as occupants' behavior pattern, and have been excluded from the analysis in Table 4.7.

4.4 Heat load estimation in the mid-terraced property

The detailed heating load in the case studied mid-terrace house can be estimated by utilizing a "whole house" procedure called: domestic heating sizing method which has been developed by the Energy Saving Trust [102], a non profit organization funded by the UK government. This procedure is a heat balance method which provides a realistic estimate of the heating demand so that any heat generator can be sized correctly for a whole dwelling [103]. The domestic heating sizing method relies on a number of assumptions [103] and input parameters for heat loss calculations. In the case of this study, the location factor value of 30 is comprehensively determined by an allowance for design indoor temperatures of 19.2 °C under the ambient context of North England region, intermittent heating (10%), distribution losses (5%), pipe losses, and a partial allowance for thermal bridging and inter-floor gaps. Furthermore, heat loss through the building envelope has been calculated based on the case study's building materials' U-values and internal measurements (see Table 4.8). The infiltration/ventilation rate of air changes per hour uses an average value of 0.5 [104] as all chimneys of the case study property are blocked.

	Parameters	**Total area** (m^2)	**U-values** ($W\,m^{-2}\,K^{-1}$)
Windows	Single glazing	2.55	4.80 *
	Double glazing	9.00	2.00 *
	Triple glazing	7.50	1.00 **
Doors	Solid wooden door	2.64	3.00 ***
	UPVC half glazed with double glazing	5.52	2.50 ***
External walls	225mm solid wall / 25mm internal wet plaster	88.89	2.01 **
Party walls	Brick 215mm	136.80	1.33 *
Indoor roof	Pitched, 150mm insulation	79.08	0.29 *
Indoor floors	Ground floor (suspended, 25mm floor boards, carpet)	79.08	0.66 *
	First floor (200 × 50mm softwood floor joists [105], carpet)	77.18	1.02 *

Table 4.8 Case study's building materials' U-values and internal measurements. U-values obtained from: * [103], ** [104], *** [106]

The detailed heat losses through the building envelope are calculated as shown in below:

(1) Heat loss from single windows: $2.55\,m^2 \times 4.80\,W\,m^{-2}\,K^{-1} = 12.24\,W\,K^{-1}$

(2) Heat loss from double windows: $9.00\,m^2 \times 2.00\,W\,m^{-2}\,K^{-1} = 18.00\,W\,K^{-1}$

(3) Heat loss from triple windows: $7.50\,m^2 \times 1.00\,W\,m^{-2}\,K^{-1} = 7.50\,W\,K^{-1}$

(4) Heat loss from solid wooden doors: $2.64\,m^2 \times 3.00\,W\,m^{-2}\,K^{-1} = 7.92\,W\,K^{-1}$

(5) Heat loss from solid wooden doors half glazed with double glazing: $5.52\,m^2 \times 2.50\,W\,m^{-2}\,K^{-1} = 13.80\,W\,K^{-1}$ (As indicated by [106], a solid wooden door (U-value of $3.00\,W\,m^{-2}\,K^{-1}$ [106]) half glazed with double glazing (U-value $2.00\,W\,m^{-2}\,K^{-1}$ [103]) could has a resultant U-value: $0.5 \times (3.00\,W\,m^{-2}\,K^{-1} + 2.00\,W\,m^{-2}\,K^{-1}) = 2.50\,W\,m^{-2}\,K^{-1}$)

(6) Heat loss from net external walls exclude windows is: $88.89\,\mathrm{m}^2 \times 2.01\,\mathrm{W\,m^{-2}\,K^{-1}} \approx 178.67\,\mathrm{W\,K^{-1}}$

(7) Heat loss from indoor roof: $79.08\,\mathrm{m}^2 \times 0.29\,\mathrm{W\,m^{-2}\,K^{-1}} \approx 22.93\,\mathrm{W\,K^{-1}}$

(8) Heat loss from indoor floor: $79.08\,\mathrm{m}^2 \times 0.66\,\mathrm{W\,m^{-2}\,K^{-1}} \approx 52.19\,\mathrm{W\,K^{-1}}$

(9) Ventilation heat loss: $(79.08\,\mathrm{m}^2 + 77.18\,\mathrm{m}^2) \times 3.00\,\mathrm{m}$ (room height of each floor) $\times\, 0.5 \times 0.33 \approx 77.35\,\mathrm{W\,K^{-1}}$

Therefore the total heat loss from external surface and infiltration/ventilation can be summarized by: $(12.24\,\mathrm{W\,K^{-1}} + 18.00\,\mathrm{W\,K^{-1}} + 7.50\,\mathrm{W\,K^{-1}} + 7.92\,\mathrm{W\,K^{-1}} + 13.80\,\mathrm{W\,K^{-1}} + 178.67\,\mathrm{W\,K^{-1}} + 22.93\,\mathrm{W\,K^{-1}} + 52.19\,\mathrm{W\,K^{-1}} + 77.35\,\mathrm{W\,K^{-1}}) \times 30$ (location factor) $= 11\,718.25\,\mathrm{W}$

Moreover, in this calculation case, it notes that heat losses to adjacent dwellings via party walls are completely ignored as adjacent properties can be heated to the same standards.

Hereby the estimation result of average heat load demand in the whole property will finally be: $11\,718.25\,\mathrm{W} \div (79.08\,\mathrm{m}^2 + 77.18\,\mathrm{m}^2) \approx 74.99\,\mathrm{W\,m^{-2}}$

in comparison with the heating load of $60\,\mathrm{W\,m^{-2}}$ of UK residential building estimated by the rule-of-thumb [100], the detailed heat load estimation result of $74.99\,\mathrm{W\,m^{-2}}$ in this case studied property is much higher than the rule-of-thumb result due to it is a worse case scenario estimation (i.e. the location factor utilizes the value of 30 in the cold North England region which is larger than the value of 25 in the warm South West England region [103].).

Additionally, the domestic heating demand (i.e. calculated by: gas demands for supplying domestic heating × boiler efficiency) is always determined by the heat losses of the house and can be utilized to calculate the average heating power demand for further verifying above theoretical heating load result. In this case studied property, assuming the efficiency of condensing boiler is 90% suggested by [107] and the average heating time per day is 8 hours suggested by [108]. The actual heating floor area is measured as $147.94\,\mathrm{m}^2$ (i.e. porch and storeroom are non-heating floor area and excluded). Then based on the monthly gas demand results for supplying domestic heating (see Table 4.6) studied in Section 4.2.2, it could simply calculate the average heating power demand (in unit of $\mathrm{W\,m^{-2}}$) in each month as: monthly gas demands (kWh/month) × boiler efficiency (90%) ÷ standard days of the corresponding month ÷ 8 hours/day ÷ heating floor area ($147.94\,\mathrm{m}^2$) × 1000. As a satisfied validation result, the calculated highest heating power demand is $74.80\,\mathrm{W\,m^{-2}}$ in February which is very close to the theoretical heating load of $74.99\,\mathrm{W\,m^{-2}}$.

Finally, the experimental results (see Table 3.13) studied in Section 3.5.4 already reveal that for the domestic heating application, the TE system can transfer minimum $76.35\,\mathrm{W\,m^{-2}}$ heat to the heating ambient when the input voltage level is equal to 5 V, and higher heating power can be produced by the TE system with higher input voltage level. Thus in this case studied property, the heating power of the TE system should be able to meet the domestic heating load with operating voltages equal and above 5 V. For meeting relatively lower domestic heating load during warm seasons, lower operating voltages might be feasible (i.e. lower heating power of $64.41\,\mathrm{W\,m^{-2}}$ can be produced by the TE system with operating voltages of 4 V).

4.5 Renewable energy supply

Both solar energy and wind energy are abundant renewable source which can be directly converted into electricity via PV panels and wind turbines respectively in the urban domestic context. Moreover, [13] shows that TE modules are capable of powering by DC electricity generated from renewable energy. Thus, combining TE modules with hybrid energy of solar & wind power supply for domestic heating is a theoretical possibility with game-changing potential in the way heating demand is met in the UK domestic sector.

4.5.1 Solar energy supply in the case study context

In this case study, for assessing the feasibility of applying the TE system combined with renewable energy to support the domestic heating, firstly the available solar energy resource in the local context can be investigated by using I-Scope ®[109], an online tool specifically designed by Newcastle City Council to estimate local roof irradiance data i-scope. The roof irradiance results measured by i-scope have involved the possible solar energy loss caused by the roof orientation, tilt angle, shadow, geographical location and elevation which further determine the estimation results of the roof PV energy output. The estimated irradiator maps are shown in Figures 4.6.

Based on the basic data harvested from i-Scope, the monthly total irradiation (in unit of kWh/month) on the case house roof (i.e. total projected area is $90.32\,m^2$) can be directly estimated. Moreover, if employing PV panels to cover all the roof area of the case house for power supply purpose and assuming necessary frames of PV panels and installation will occupy 10% roof area, the actual area of available PV arrays will be equal to 90% total roof area. Correspondingly 90% roof total irradiation can be effectively collected by the PV arrays for generating electricity. Further considering the conversion efficiency of the Polycrystalline panel is typical 15.5% as suggested by i-scope calculation, then the corresponding electricity generation calculation in each month throughout the year could be simplify as: Monthly roof total irradiation (kWh/month) × available PV arrays area ratio (90%) × PV arrays conversion efficiency (15.5%). All the detailed monthly electricity generation results by the roof PV panels are finally given by Table 4.9.

Months	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	**Annual** (kWh)
Monthly roof irradiation (kWh/month)	1215.08	2361.05	4648.93	6452.62	8753.43	8660.36	8442.07	7817.63	5083.70	3103.53	1477.97	831.89	58848.26
Monthly PV power output * (kWh/month)	169.50	329.37	648.53	900.14	1221.10	1208.12	1177.67	1090.56	709.18	432.94	206.18	116.05	8209.33

Table 4.9 Monthly electricity generation by roof PV panels of mid-terraced dwelling
* total projected area of the dwelling roof is $90.32\,m^2$, available area of PV arrays is estimated as: total roof area × 90% which excludes 10% areas loss by frames of PV panels and installation.
** The conversion efficiency of the Polycrystalline panel is generally considered as a average value of 15.5%.

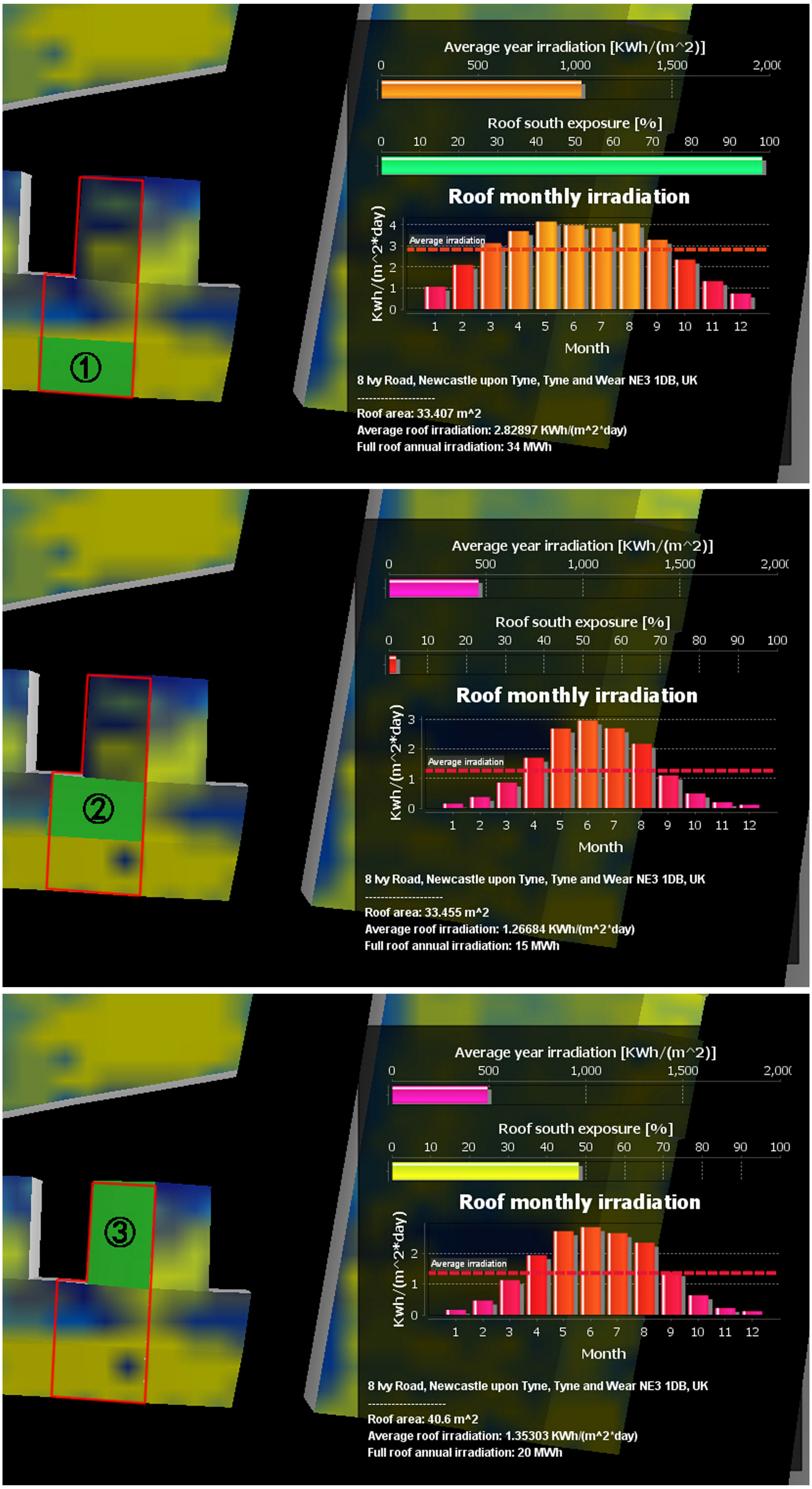


Fig. 4.6 Case study house. Local roof irradiance data collected from the online i-scope irradiator map

4.5.2 Wind energy supply in the case study context

In additional to potential solar energy supply, the possible wind energy supply is also considered in this case study. The system design intends to utilise the SM-1000 wind turbine as it is suitable for the domestic context (i.e. SM-1000 wind turbine is more suitable to fix and operate in the urban domestic context benefit from its relatively smaller rotor diameter than other types of wind turbines which have higher rated outputs). Table 4.10 and Figure 4.7 have summarized the performance parameters of the SM-1000 wind turbine.

Model	Type	Rated output (kWh)	Peak output (kWh)	Start-up speed (m/s)	Cut-in speed (m/s)	Rated speed (m/s)	Rotor diameter (m)
SM1000	HAWT	1.0	1.2	2.0	2.5	12.0	1.96

Table 4.10 Wind turbine parameters

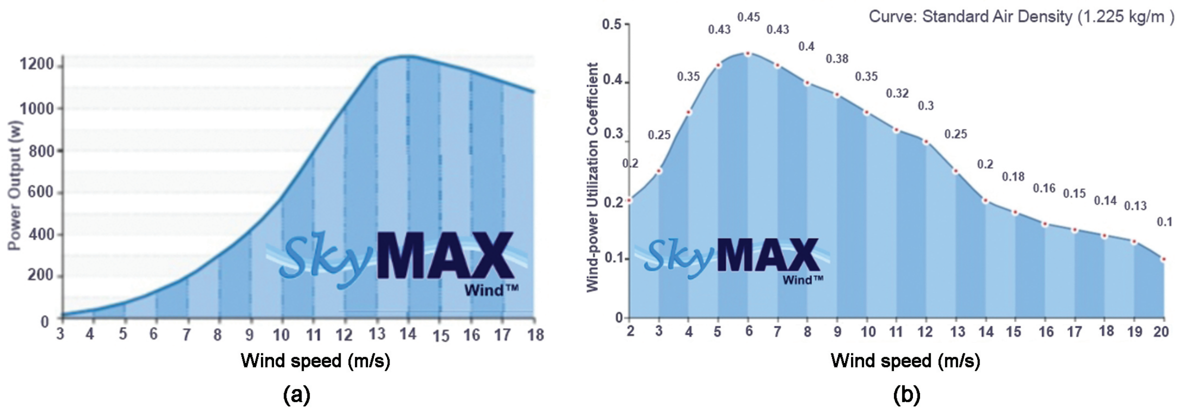


Fig. 4.7 Performance parameters of SM-1000 wind turbine

For investigating available wind energy resource, it can import the specific Latitude & Longitude of Newcastle city into the NASA meteorological database [19], the local historical weather data (involve the monthly mean wind speed and horizontal solar radiation) can be obtained as shown in Table 4.11.

Based on the obtained monthly wind speed data, it can employ the HOMER (Hybrid Optimization Model for Electric Renewables) simulation software tool to synthesize more detailed daily wind speed data with hourly resolution in each month (see Figure 4.8).

Then both of the SM-1000 wind turbine's performance parameters (see Figure 4.9) and the synthetic daily wind speed data have been imported into HOMER so as to calculate the daily wind power output (in unit of kW) at an hourly resolution throughout every month in one year (see Figure 4.10).

Finally, it can summarize the monthly average wind power output (in unit of kW, see Figure 4.11) and the monthly electricity generation (in unit of kWh/month, see in Table 4.12) throughout the year by empolying one SM-1000 wind turbine in this case studied context.

Additionally, Figure 4.12(a) demonstrates the average daily gas demand for supplying domestic heating in each month. It shows that the case studied property always has the highest

Location	North East (Newcastle upon Tyne)				
Latitude (°N)	54.97				
Longitude (°E)	-1.61				
Elevation (m)	90				
Month	**Air temperature** (°C)	**Relative humidity** (%)	**Daily solar radiation horizontal** (kWh/(m^{2}day))	**Atmospheric pressure** (kPa)	**Wind speed** (m/s)
Jan	4.5	79.40	0.63	100.1	5.8
Feb	4.5	77.00	1.31	100.3	5.5
Mar	5.7	76.00	2.32	100.2	5.5
Apr	7.2	74.10	3.53	100.2	4.7
May	10.2	70.80	4.67	100.5	4.3
Jun	13.3	68.20	4.73	100.4	4.0
Jul	15.8	68.00	4.62	100.4	3.9
Aug	16.0	68.50	3.92	100.4	4.1
Sep	13.7	70.20	2.72	100.3	4.7
Oct	10.7	74.90	1.57	100.0	5.1
Nov	7.3	80.30	0.77	100.0	5.3
Dec	5.4	80.50	0.47	100.2	5.6
Annual	9.5	74.00	2.60	100.3	4.9
Measured at (m)					10

Table 4.11 Historical weather data statistics of Newcastle upon Tyne by NASA meteorological database (sources from [19])

Region	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	**Annual** (kWh)
Newcastle	146.94	113.49	127.10	78.05	61.92	48.32	45.69	53.67	78.26	102.45	110.71	133.71	1100.31

Table 4.12 The simulation results of the monthly electricity generation by one SM-1000 wind turbine employed in Newcastle upon Tyne

gas demand level for heating purpose in February, and followed by January and December when the solar energy output levels (i.e. electricity converted by the PV panels which cover all the roof area) are very low (see Figure 4.12(b)). During May, June, July and August, the roof PV panels can generate much more electricity than in cold months due to higher monthly irradiance levels while the household has few and even no gas demands for heating. Moreover, Figure 4.12(b) also reveals that the wind energy output levels (i.e. electricity converted by two SM-1000 wind turbines) during cold months (i.e. Jan, Feb, Mar, Oct, Nov and Dec) are always higher than in warm months (i.e. Apr to Sep). This suggests wind resource should be a potential renewable energy candidate to power the TE heating system for domestic heating especially during the cold months when the monthly solar energy outputs are shortage.

Fig. 4.8 Parameters used in HOMER for converting monthly wind speed data into daily wind speed data

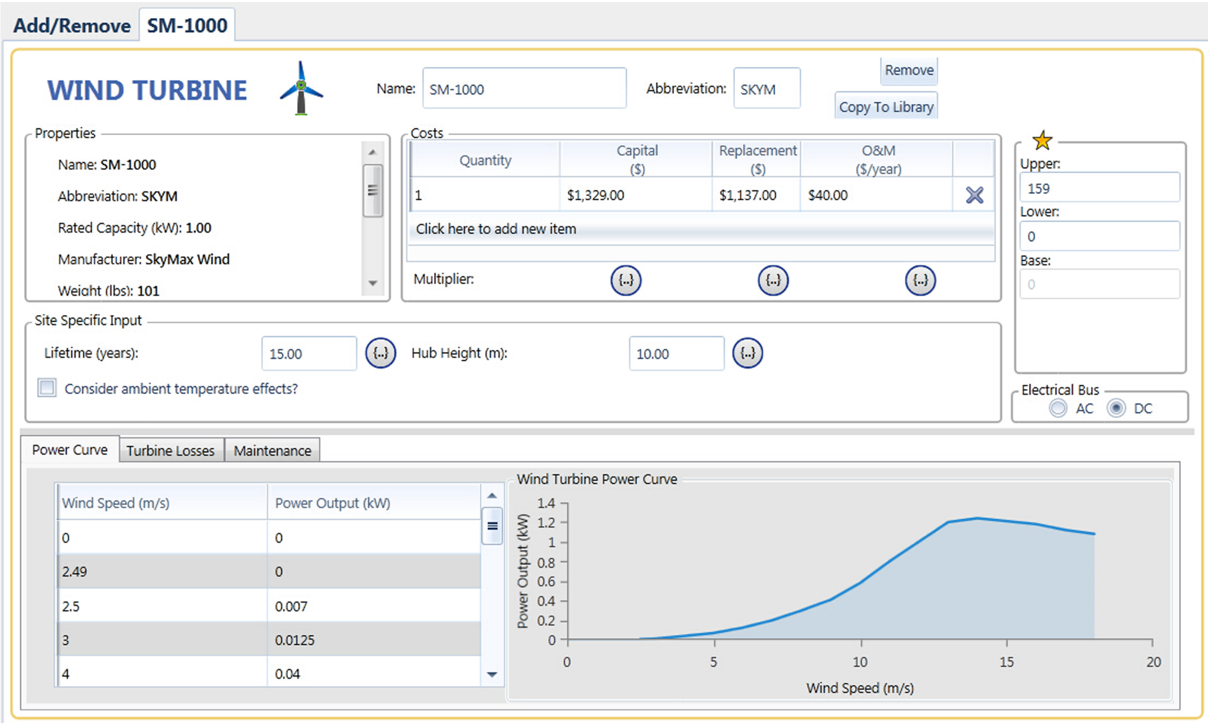


Fig. 4.9 SM-1000 wind turbine specifications in HOMER interface

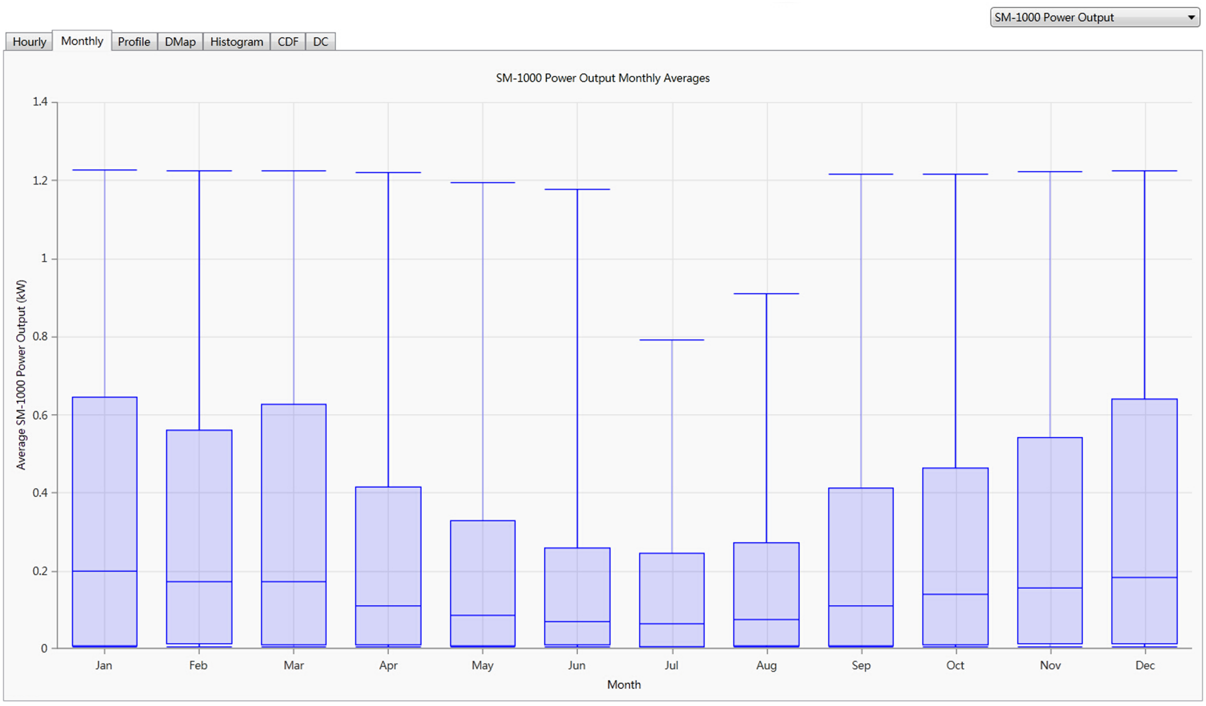


Fig. 4.10 HOMER simulation results of SM-1000 wind power output daily profile

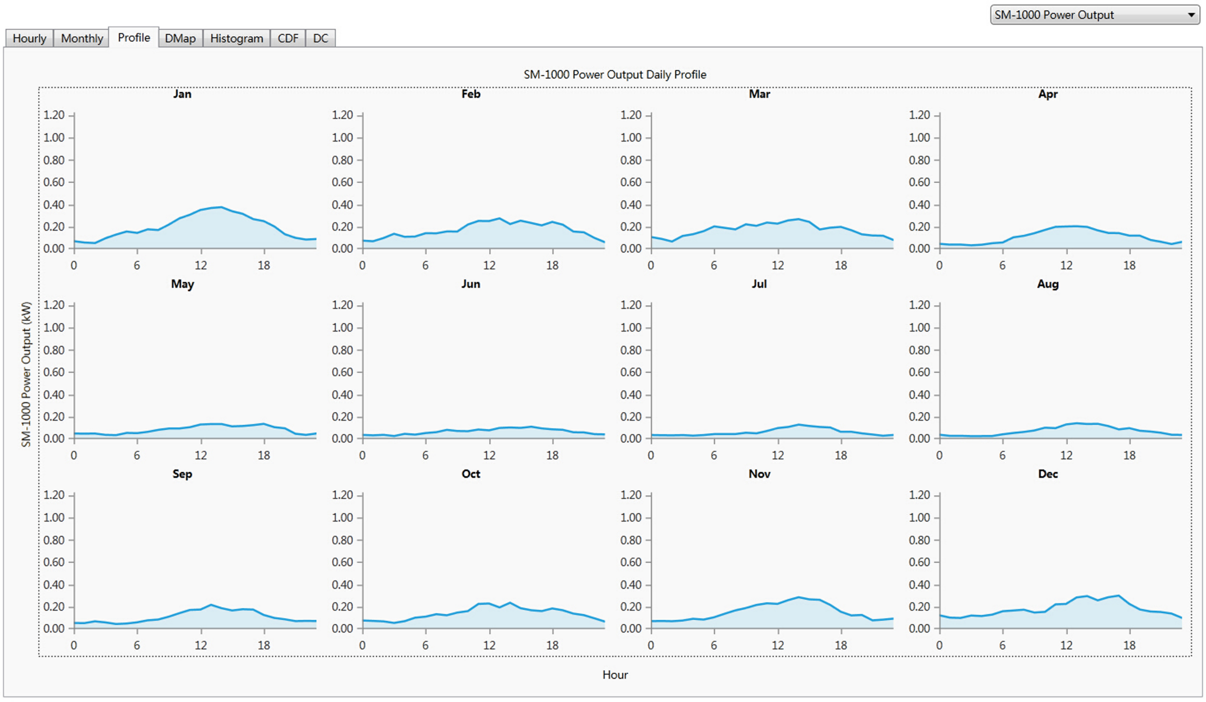


Fig. 4.11 HOMER simulation results of monthly average wind power output by SM-1000 wind turbine

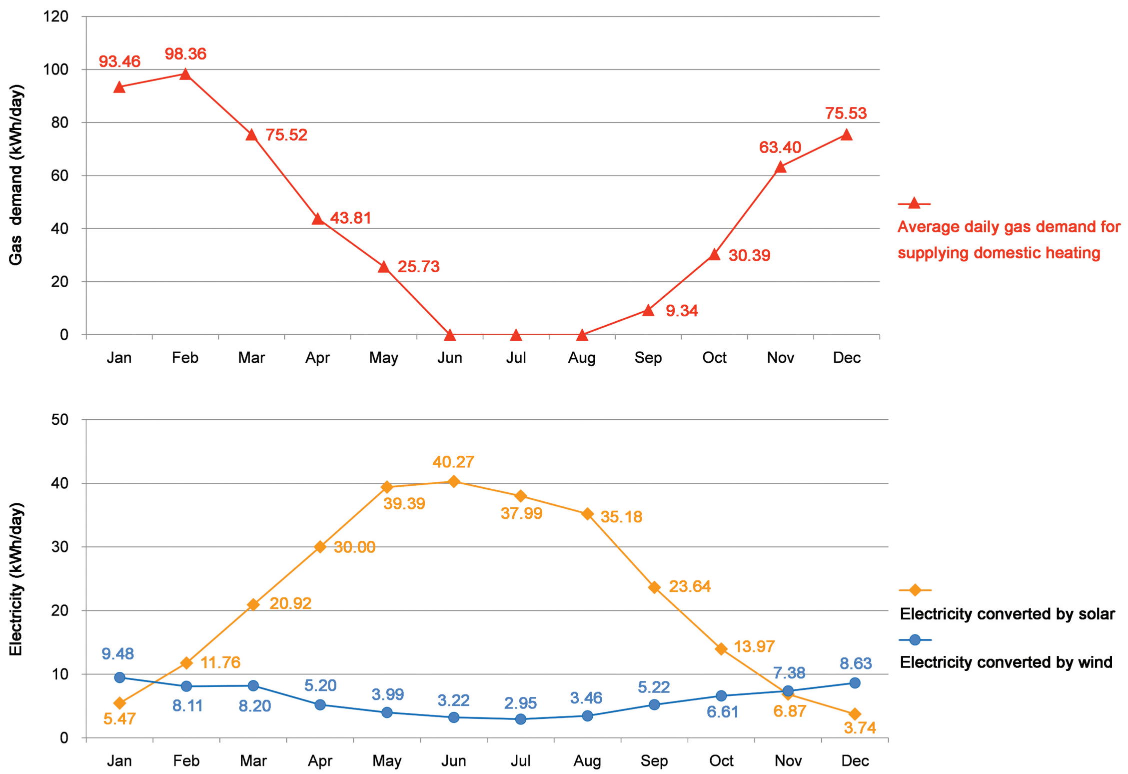


Fig. 4.12 (a) Average daily gas demand for supplying domestic heating in each month (b) Average daily electricity converted by roof PV panels and two SM-1000 wind turbines in each month

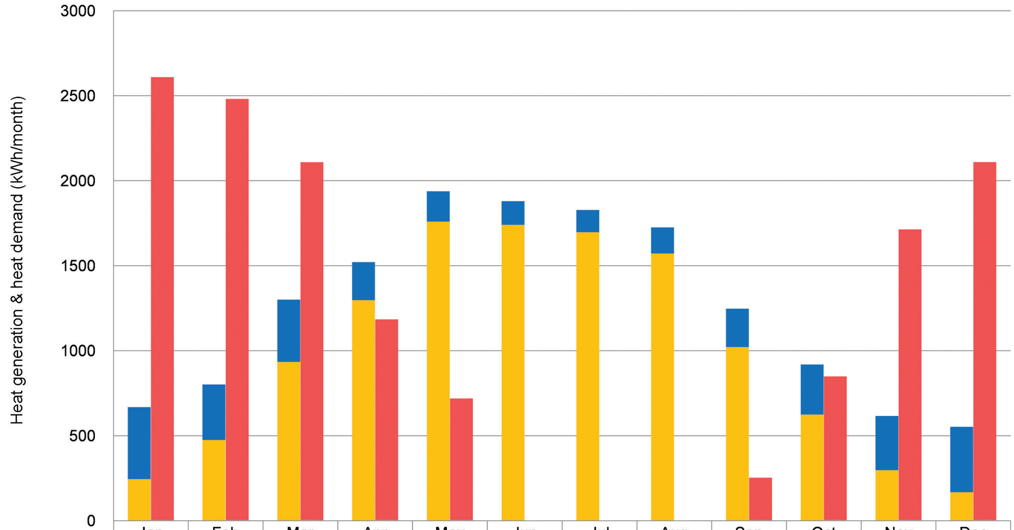
4.6 TE modules combined with renewable energy supply for domestic heating demand

Heating supply-demand relationship and energy saving efficiency estimations

In this case study, the system design intends to employ both of PV panels and SM-1000 wind turbines to power the TEC1-12706 modules for the domestic heating purpose. For estimating detailed supply-demand relationship between the heat supply of TE modules powered by hybrid renewable energy and the domestic heating demands, the following assumptions have been adopted:

- PV panels cover all the roof area (i.e. total projected area of the roof is 90.32 m^2, necessary frames of PV panels and installation will occupy 10% available roof area) and the PV panel efficiency can be generally considered as 15.5% suggested by I-Scope ®[109];
- the employment number of SM-1000 wind turbines in this domestic scenario is two which will be fixed at the open space around the house;
- the average heating COP of TE modules is assumed as a minimum test value of 1.8;
- for delaying the use of electricity converted from PV panels and wind turbines if needed (e.g. lots of solar energy can be collected during day-time for powering the TE heating system during night-time), the system design should include suitable battery units. The average energy loss caused by the storage efficiency of batteries and peripheral equipment efficiency (i.e. DC/DC converters to optimize the output voltage of the PV panels and control the charging voltage of batteries. More relevant studies regarding both of the battery efficiency and peripheral equipment performances can be checked in next Chapter 5) is assumed as 20% of initial power production of the hybrid renewable energy (i.e. solar and wind energy);
- if TE heating system needs additional power from the utility grid during any shortage periods of the renewable energy supply, the AC current supplied by the grid would be required to be converted into DC current to operate TE modules. The energy conversion efficiency between AC power and DC power is assumed as constant 80% in this estimation (More relevant studies regarding the AC/DC rectifier performance are also presented in next Chapter 5);
- condensing boilers generally have heating efficiency between 85%-92% [9]. In this estimation assuming the heating efficiency of condensing boiler installed in the case studied dwelling is typical 90% suggested by [107].
- the energy efficiency of a general electric heater is typically considered as 100% [110].

The monthly heating supply-demand results can be estimated as shown in Figure 4.13.



	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Monthly heat generation poweref by wind	423.19	326.85	366.05	224.78	178.33	139.16	131.59	154.57	225.39	295.06	318.84	385.08
Monthly heat generation poweref by solar	244.09	474.29	933.88	1296.20	1758.39	1739.69	1695.84	1570.41	1021.21	623.44	296.89	167.11
Domestic monthly heating demand	2607.45	2478.67	2107.00	1182.96	717.84	0.00	0.00	0.00	252.05	848.02	1711.77	2107.33
Monthly excess heating supply	-1940.18	-1677.53	-807.07	338.03	1218.88	1878.85	1827.43	1724.98	994.55	70.48	-1096.03	-1555.14

Fig. 4.13 The supply-demand relationship of the domestic heating by using TE heating system with the hybrid renewable energy supply

Figure 4.13 shows that the TE heating system powered by the hybrid renewable energy in the local context is likely to act as a sole domestic heating in Apr, May, Sep and Oct. However, during the colder months of Jan, Feb, Mar, Nov and Dec, the shortage of usable renewable energy is severe due to local climatic and weather conditions. Meanwhile, the actual heating demands in these months will substantially increase to excess the annual average heating demand level of 1167.76 kW h/month since the fall down of ambient temperature. As a result, the TE heating system powered by the renewable energy can partly meet the domestic heating demand, and it has to require more additional electricity supply from the utility grid for remedying the rest heating demand vacancy during any renewable energy supply shortage period.

Furthermore, and based on the results of Figure 4.13, the total energy requirement of the TE system to the utility grid throughout the year (in the months of Jan, Feb, Mar, Nov, and Dec) should be calculated as: (1940.18 kW h + 1677.53 kW h + 807.07 kW h + 1096.03 kW h + 1555.14 kW h) ÷ 1.8 ÷ (1 − 20% of energy loss by the AC/DC conversion) ≈ 4913.86 kW h/year. Then if compared with the potential grid electricity consumption of the general electric heater which is equal to the total heating demand of 14013.10 kW h/year due to its energy efficiency of 100%, the energy saving efficiency of the TE system with hybrid energy supply (solar/wind energy and the grid power) can be calculated by: (14013.10 kW h/year − 4913.86 kW h/year) ÷ 14013.10 kW h/year ≈ 64.93%.

Carbon saving estimation

Solar and wind power are not zero-carbon due to the carbon usually will be emitted during manufacture, construction, maintenance and decommissioning processes throughout the devices' life cycles [111]. Therefore in order to ascertain potential carbon saving contributions of the TE heating system combined with renewable energy for domestic heating, possible CO_2 emissions caused by the entire system (i.e. uses of roof PV panels, wind turbines and additional grid power supply) will be simply estimated and further compared with the estimation results of CO_2 emission if employing generic electric heaters in the same domestic heating scenario.

The necessary assumptions have been adopted before the start of relevant calculations:

- the average CO_2 emission factor in terms of the UK grid electricity consumption will utilize the value of 0.46 kgCO_2/kWh (involves imported electricity and grid transmission/distribution losses) which was calculated based on the data year of 2014 and newly updated by UK government in 2016 [112];

- before connect into batteries or the grid, the CO_2 emission factor in terms of the electricity generation of roof PV panels is assumed as 0.058 kgCO_2/kWh [113] and the CO_2 emission factor in terms of the electricity generation of micro wind turbines is assumed as 0.045 kgCO_2/kWh [111]. It notes above carbon footprint values are most likely the maximum values detemined by the power farms in the UK context but these values may still be disputed when using to support the small-scale power estimations in domestic scenario.

Thus, in the case studied domestic scenario, the annual CO_2 emission (kgCO_2/year) caused by TE modules when being powered by the hybrid energy system can be simply calculated as: solar energy output which is consumed for the domestic heating purpose throughout the year $\times$ CO_2 emission factor of electricity generation by PV panels + wind energy output which is consumed for the domestic heating purpose throughout the year $\times$ CO_2 emission factor of electricity generation by wind turbines + additional grid electricity consumed for the domestic heating purpose during the renewable energy supply shortage periods $\times$ average CO_2 emission factor of grid electricity supply $\approx$ 2518.31 kgCO_2/year.

Similarly, the annual CO_2 emission (kgCO_2/year) caused by employing generic electric heaters in the same case studied domestic scenario can be simply calculated as: the annual grid electricity consumption of the generic electric heater $\times$ average CO_2 emission factor of grid electricity supply $\approx$ 6446.03 kgCO_2/year. Consequently, a potential estimation of CO_2 emission reduction is 3927.72 kg$CO_2/year$.

4.7 Summary

In order to ascertain the potential application of TE heating system powered by renewable energy for meeting domestic heating demands, a realistic case study has been presented in this chapter. Detailed heating demands and available renewable energy supply in the case studied domestic scenario are estimated for supporting the simulation of heating supply-demand relationship and relevant calculations of possible energy saving efficiency and carbon saving caused by the whole TE heating & renewable power supply system. Main conclusions can be drawn as follows:

1. It reveals a relationship of rough 200 kW h/month – 400 kW h/month increase of the gas demand for supplying domestic heating as each 1 °C decline of the monthly average climate temperature in the case studied property.
2. In the case studied domestic context, the TE heating system powered by the hybrid renewable energy can fully meet the monthly domestic heating demands in Apr, May, Sep and Oct. But during some renewable energy supply shortage periods (i.e. Jan, Feb, Mar, Nov and Dec), the TE heating system has to require additional electricity supply from the utility grid for meeting higher monthly heating demands.
3. An energy saving efficiency of 64.93% and a reduction of CO_2 emission of 3927.72 kg/year could be potentially achieved by utilizing the TE heating system powered by hybrid renewable energy instead of using a generic electricity heater for the domestic space heating. This suggests that the entire system has potential for both energy and carbon savings.

Furthermore, during some rich renewable energy supply periods, the renewable energy supply equipment usually can produce more electricity than the power demand of domestic heating. These excess renewable energy can be self-consumed by the domestic electric demands or feed into grid to supply other grid-connected consumers which will potentially save more grid energy consumption whilst reduce more CO_2 emission.

Chapter 5

Application Design of TE Heating System with Hybrid Energy Supply in Domestic Scenario

In this chapter, relevant performance of components included in the system configuration will be studied. The specific application design of TE heating system combined with hybrid energy supply (i.e. solar/wind renewable energy and utility grid supply) in the domestic scenario will also be demonstrated and discussed (i.e. components installment positions, grid-connection, smart control for adjusting indoor heat distribution, and domestic hot water supplement, etc).

5.1 System configuration

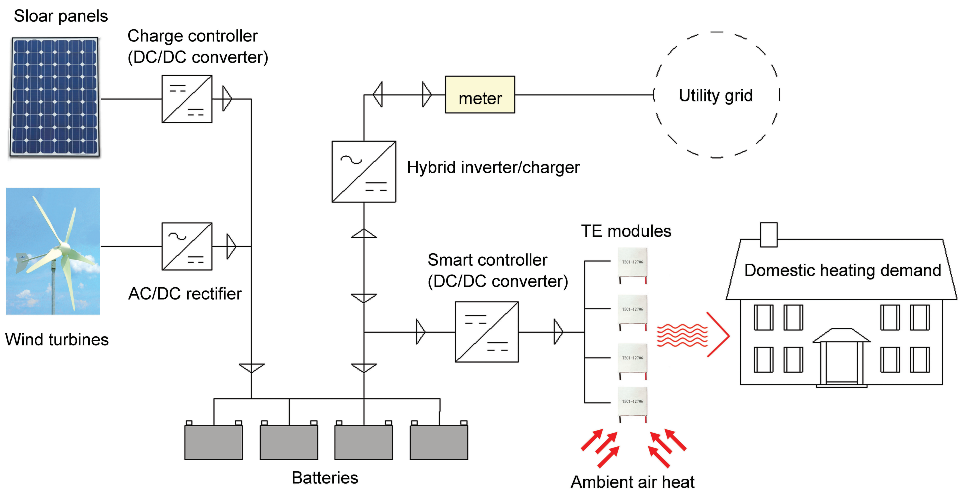


Fig. 5.1 System configuration of TE modules with hybrid energy supply & energy storage for domestic heating

Figure 5.1 demonstrates the entire domestic heating system configuration by employing TE modules, hybrid renewable energy supply (i.e. solar panels and micro wind turbines), batteries and peripheral equipment. The ideal expectation of this study is the domestic heating demands could be fully meet by the TE heating system with the local hybrid renewable energy supply throughout the year whilst off the utility grid supply. However, in Chapter 4, the case study results in the typical pre-1900s mid-terraced property located in Newcastle upon Tyne have revealed that the poor renewable power generation during the winter months always cannot meet the higher domestic heating demands. Thus the system configuration is suggested rationally connecting with the utility grid which can provide extra electricity supply in any renewable energy supply shortage periods. Incidentally any excess renewable energy generation during summer time which cannot be fully stored by batteries or self-consumed by the dwelling is potentially traded into the utility grid for getting payments. More relevant discussions will be presented in later sections.

5.2 System components studies and investigations

5.2.1 Photovoltaic component

Basic studies of photovoltaic cells

Solar radiant energy can be directly converted into electricity by solar cells relies on the photovoltaic effect. Existing solar cells are mostly produced by semi-conductor materials (e.g. silicon crystals). A typical Silicon cell generally consists of two different silicon lays: one silicon lay is mixed with lots of Phosphorus atoms to generate the n-type semi-conductor and the other silicon lay is mixed with lots of Boron atoms to generate the p-type semi-conductor. Under suitable solar irradiation level, it will be able to absorb the irradiation energy and generate electric current and voltage between the p-n junctions (also call p-n diodes) [114].

Moreover, the Silicon cells can be further classified into three different types: monocrystalline (mono-Si) cell, polycrystalline (poly-Si) cells and amorphous (a-Si) cells. The monocrystalline cells produced by high-purity silicon material with the highest production cost usually can achieve the highest energy conversion efficiency (i.e. the highest efficiency has reached 24% in laboratory). The polycrystalline cells produced by the melting and casting techniques have relatively lower energy conversion efficiency (i.e. the efficiency is usually lower than 18%) than monocrystalline cells. But this type of solar cells currently occupy the largest market share (around 85%) due to lower production cost. The amorphous cells produced by the thin film technology with the cheapest production cost are widely used by existing electronics products benefit from they can adapt to poor working ambient with lower irradiation level and higher temperature. But the achievable energy conversion efficiencies of amorphous cells are the lowest (i.e. 5% - 13%) in all types of Silicon cells [114]. In addition to the Silicon cell technology, there are some other materials such as Cadmium Telluride (CdTe), Copper Indium Dieseline (CIS), and Gallium Arsenide (GA) being used in current solar cell industry [115], [116].

The actual energy output of solar cell is mainly determined by the solar radiation intensity: PV arrays generally can convert more electricity from higher irradiance. Additionally, temperature is another important factor to influence the energy output efficiency of solar cells. Figure 5.2 reveals that the PV power output will decline 0.5% - 0.6% as each 1 °C rising when the cell temperature exceeds 25 °C. [117] presents a field experiment in UK which also reveals the peak power of residential PV arrays will decline 1.1% for 1 °C degree rising once the cell temperature exceeds 42 °C.

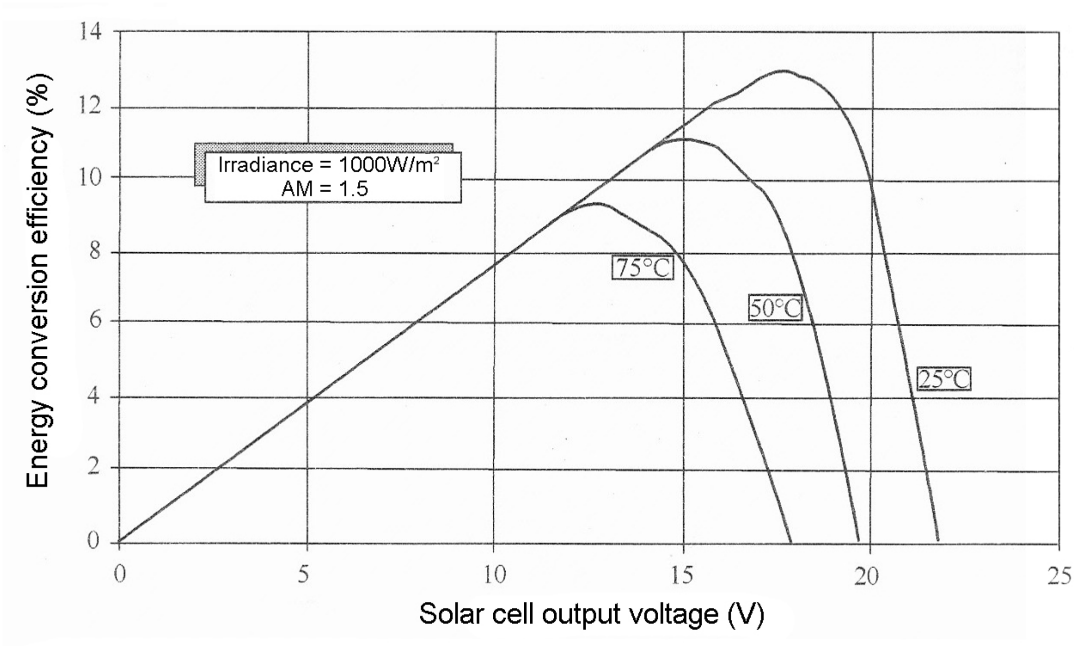


Fig. 5.2 Influence of the cell temperature to PV power output efficiency (Photo copied come from [114])

The realistic power output calculation of solar cell is generally determined by Equation 5.1 [118].

$$P_{pv} = f_{pv} \times P_{STC} \times \frac{G_A}{G_{STC}} \times [1 + (T_{pv} - T_{SCT}) \times C_T] \tag{5.1}$$

Where P_{pv} is the power output (W) of solar cell; f_{pv} is the solar cell derating factor (usually range from 70% to 90%) influenced by ambient factors (e.g. dust and dirt, array shading); P_{STC} is the peak power (kW) of solar cell measured under the standard test condition (STC, ambient irradiation: 1000 W/m^2, cell temperature: 25 °C, AM: 1.5); G_A is the local solar radiation (kW/m^2) illuminating on solar cell; G_{STC} is the global solar radiation of 1 kW/m^2 whilst T_{SCT} is the nominal cell temperature of 25 °C under the STC condition; C_T refers to the temperature coefficient of solar cell (i.e. -0.011 °C for Si).

Moreover, T_{pv} is the actual cell temperature (°C) which can be further calculated by Equation 5.2. Where T_A is the ambient temperature (°C) and G_h is the local solar radiation (kW/m^2) measured on the horizontal surface. NOCT is the normal operating temperature of the solar cell (i.e. generally set as 48 °C).

$$T_{pv} = T_A + \frac{(NOCT - 20)}{0.8} \times G_h \tag{5.2}$$

According to historical weather data collected by NASA database [19], it shows that the annual average climate temperature in most England and Wales regions are usually range from 9 °C to 12 °C. In summer months, the highest monthly average temperature changes between 16 °C and 19 °C which are still lower than the STC temperature requirement (i.e. 25 °C). Hereby it suggests that the solar cells are likely to remain in the normal operation scope with minor efficiency loss influenced by the temperature factor when working in the England and Wales regions.

PV panel specifications and cost

The system design intends to employ the polycrystalline cells designed as the tile to cover as more as possible the dwelling roof area, more existing design cases can be found in Figure 5.3.

Fig. 5.3 Different design cases of fixing PV system with the building roof (Photos come from [119])

Additionally, the costs of the PV panels have declined sharply in recent years benefit from the industrial production technology progress. In 2016, Power NI estimates the average cost of typical 4kWp domestic solar PV system is around \$6,109 inc VAT [120], which is about half of the cost (around \$12,156 inc VAT) estimated by the Energy Saving Trust in August 2012 [121]. Till August 2016, the latest market survey results on world.taobao.com recommend the 100 Watt 12 Volt polycrystalline solar panel (specifications see Table 5.1; market investigation see Appendix G) with an optimal capital price around \$40.42/piece which could potentially be mounted on roof by large quantity for supplying the domestic energy demands. Furthermore, based on the criterion proposed in [122], the O&M (Operations & Maintenance) cost of the PV panels can be assumed as 1% of total capital cost. Relevant costs of the PV panels are summarized in Table 5.2 which can be utilized to further support the simplified capital cost estimation and analysis of the entire system design in last section of this chapter.

Maximum Power	100 W
Operating voltage (Vmp)	19.0 V
Peak current (Imp)	5.0 A
Open-circuit voltage (Voc)	20.0 V
Short-circuit current (Isc)	5.4 A
Maximum conversion efficiency	18%
Power tolerance	3%
Dimensions	1200 × 540 × 30 mm
Weight	8.0 kg

Table 5.1 Specifications of 100 Watt 12 Volt polycrystalline solar panel (sources from [123])

Price (US$/unit)	**Number**	**Replacement cost** (US$/unit)	**O&M cost per year** (%/year)	**Lifecycle** (year)
40.42	1	40.42	1%	25

Table 5.2 Relevant costs and lifecycle of PV panel

5.2.2 Wind turbine component

Relevant studies of wind turbines

Wind turbine can utilize the aerodynamic lift caused by rotations of the blades to capture and convert the kinetic energy in wind to electricity. Existing wind turbines are commonly divided into two different types: horizontal-axis wind turbine (HAWT) and vertical-axis wind turbine (VAWT) (see Figure 5.4) [124]. Compared with VAWTs, the HAWTs usually have lower production costs benefit from simple design configuration. Moreover, when the input wind speed is high enough, the HAWTs typically can achieve higher wind energy conversion efficiency than the VAWTs which have equivalent swept areas. Hence, the HAWTs are most universally employed in the commercial utility-scale wind power market during past decades. However, it needs to note that the VAWTs also have distinctive advantages such as low noise level associated with their slower rotation rates and lower start-up wind speed requirement in comparison with the HAWTs. Thus as the technological development in recent years, the VAWTs start to extent more potential applications for attracting the attention of current wind power market [125].

In terms of the energy output regular pattern of wind turbine, [126] introduces that wind turbine operation can be divided into three stages depend on different wind speed levels: cut-in speed, rated speed, and cut-out speed (see Figure 5.5). To be specific, before reaching the cut-in speed, the wind turbine cannot generate any usable power. Then start from the cut-in speed, the energy output of wind turbine will gradually increase as the wind speed up, and the wind

(a) (b)

Fig. 5.4 (a) Horizontal-axis wind turbine (b) Vertical-axis wind turbine (Photos come from google web)

turbine can achieve its rated power output when reaching the rated speed. If the actual wind speed exceeds the rated speed, a potential peak output which is higher than the rated power would be achieved. But when reaching the cut-out speed, the wind turbine has to be shut down and cease the power generation because of the device safety and protection considerations. Moreover, between the cut-in wind speed and cut-out speed, the turbine also demonstrates different coefficients corresponding to various wind speed levels.

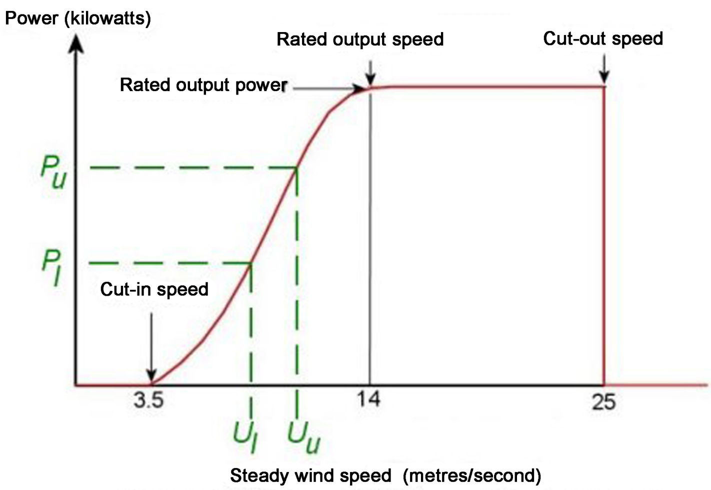


Fig. 5.5 Typical wind turbine power output with steady wind speed (source from [126])

According to [127], the general output power generated by the wind turbine can be estimated by Equation 5.3.

$$P_{WT} = 0.5 \times C_p \times \rho_{flow} \times \pi \times r^2 \times v^3 \tag{5.3}$$

Where ρ_{flow} is the air density (m^3/kg), r is the radius of the wind turbine rotor (unit in meter), and v is the wind speed (m/s).

C_p is the power coefficient of the wind turbine varies with wind speed. It notes that limited by the basic aerodynamic principles, the typical wind turbine design cannot extracts the entire kinetic energy from the wind stream. And there is a Betz Limit of maximum 59.3% of the wind energy can be captured by the wind turbine [128]. Practically if considering all the energy loss during the processes of capturing the wind kinetic energy and converting the mechanical energy into electricity by the wind generator, the actual power coefficient C_p of the wind turbine is typically lower than the Betz Limit.

Additionally, common wind speed database are measured at typical anemometer heights of 10 m, 25 m and 50 m respectively. [126] indicates that the wind speed generally increases with height above ground due to the decreases of obstacles (i.e. vegetation, buildings, and topographic features). Thus when calculating the power output of wind turbine, the wind speed data collected at the anemometer height must be corrected to the actual hub height of wind turbine by one of two mathematical models: the logarithmic profile or the power law profile [129].

Logarithmic profile

The logarithmic profile (or log law) assumes that the wind speed is proportional to the logarithm of the height above ground. Equation 5.4 gives the ratio of the wind speed at hub height to the wind speed at anemometer height:

$$\frac{U_{hub}}{U_{anem}} = \frac{\ln(z_{hub}/z_0)}{\ln(z_{anem}/z_0)} \tag{5.4}$$

Where U_{hub} is the wind speed (m/s) at the hub height of wind turbine, U_{anem} is the wind speed (m/s) at anemometer height, z_{hub} is the hub height (m) of the wind turbine, z_{anem} is the anemometer height (m), z_0 is the surface roughness length parameter (m) which characterizes the roughness of the surrounding terrain (i.e. Table 5.3 lists representative surface roughness lengths taken from Manwell, McGowan, and Roger), ln(..) is the natural logarithm.

Terrain Description	z_0 (m)
Very smooth, ice or mud	0.00001
Calm open sea	0.0002
Blown sea	0.0005
Snow surface	0.003
Lawn grass	0.008
Rough pasture	0.01
Fallow field	0.03
Crops	0.05
Few trees	0.10
Many trees, few buildings	0.25
Forest and woodlands	0.5
Suburbs	1.5
City center, tall buildings	3.0

Table 5.3 Various representative surface roughness lengths (sources from [129])

Power law profile

The power law profile assumes that the ratio of wind speeds at different heights is given by the Equation 5.5:

$$\frac{U_{hub}}{U_{anem}} = \left[\frac{z_{hub}}{z_{anem}}\right]^{\mu} \tag{5.5}$$

Where μ is the power law exponent which is a dimensionless parameter depends on terrain roughness, atmospheric stability, and several other factors in practice. Foundational research in fluid mechanics shows that its value is equal to 1/7 for turbulent flow over a flat plate [129].

Wind turbine specifications and cost

The system design considers employing the SM-1000 micro wind turbine (see Figure 5.6) which has a rotor diameter of 1.96 m with swept area of 3.0 m^2 to collect wind energy for potentially supplying the domestic energy demands during any solar energy shortage periods (e.g. cold months or rainy weather). The cut-in speed of this type of the wind turbine is required at a relatively lower wind speed level of 2.5 m/s. Its rated power output and achievable peak output are 1000 W at wind speed of 12 m/s and 1200 W at wind speed of 14 m/s respectively. All the specifications of this wind turbine are able to meet the installation requirements of micro wind turbines which are suggested by the UK government's existing planning legislation (see Table 5.4) [130].

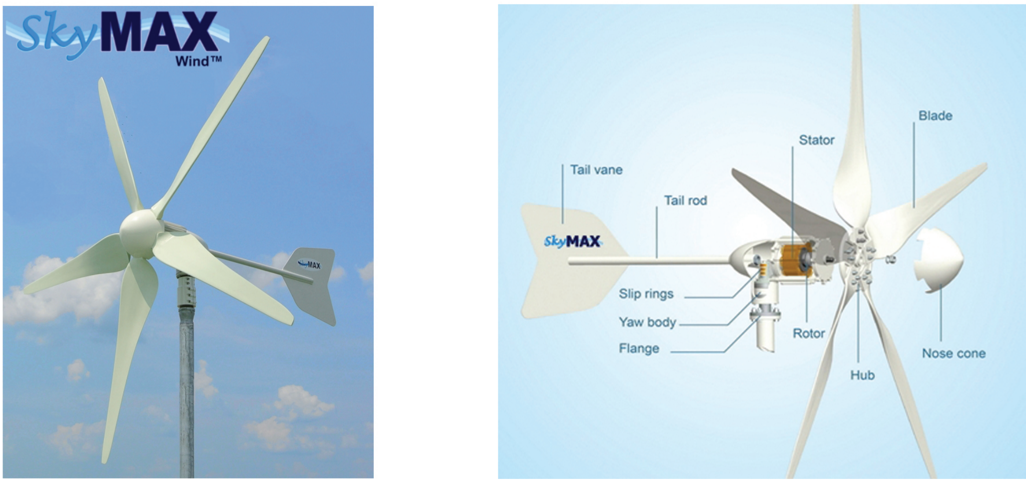


Fig. 5.6 SM1000 wind turbine design structure (photos from [131])

According to the device price survey results, the total price of each SM-1000 in come with the charge controller (Module: SM-C10-48AWM) is \$1329/unit. And its O&M cost is generally assumed as around 3% of total capital costs [122]. Hereby relevant costs of the wind turbine are summarized in Table 5.5.

Rooftop mounted turbines	Stand alone turbines
Wind Turbines on normal buildings permitted if: • <3 m above ridge (including the blade) and diameter of blades <2 m • internal noise <30 dB • external noise <40 dB • "garden" noise <40 dB • up to 4 turbines on buildings >15 m (as with antennas) • vibration <0.5 mm/s. No roof top mounted turbines will be permitted on buildings in conservation areas or world heritage sites.	Wind Turbines on normal buildings permitted if: • <11 m (including the blade) high and diameter of blades <2 m • at least 12 m from a boundary • internal noise <30 dB • external noise <40 dB • "garden" noise <40 dB • vibration <0.5 mm/s. Stand alone turbines will be permitted beside buildings in conservation areas or in world heritage sites as normal except in front of principal elevation.

Table 5.4 Summary of Planning Guidelines suggested by the UK Government for the installation of micro wind turbines ([132])

Price (US$/unit)	**Number**	**Replacement cost** (US$/unit)	**O&M cost per year** (%/year)	**Lifecycle** (year)
1329.00	1	1137.00	3%	15

Table 5.5 Relevant costs and lifecycle of SM-1000 micro wind turbine

5.2.3 Battery component

Figure 5.7 demonstrates the 24-hrs energy consumption load profiles (include electric appliance, DHW and space heating) in various typical dwellings. It can see that there are usually two surge load periods during the whole day which are most likely focused on the time periods of 5:00 - 10:00 and 16:00 - 21:00 respectively.

However, real monitoring results by [134] indicates that typical solar energy output peak period is usually between 10:00 - 14:00. Figure 5.8 obviously shows that PV power output peaks and household energy consumption peaks most likely do not take place at the same moment in one day which may result in lots of electricity generated by PV panels cannot be consumed in time and will be wasted. Thus any efficient energy storage devices are necessarily considered to store the intra-day renewable energy production for meeting the delayed energy consumption demands of household.

Relevant studies of batteries

Common batteries used for the hybrid system contain the nickel-cadmium battery and the sealed lead-acid battery. Compared with the sealed lead-acid batteries, the nickel-cadmium batteries can better bear overloads, work in wider temperature permissible range, and have longer lifecycle. However, the sealed lead-acid batteries also have advantages such as having much lower production cost and higher reliability of SOC (state of charge) than the nickel-cadmium batteries. Moreover, [135] reveals that fully charged lead-acid batteries generally have higher

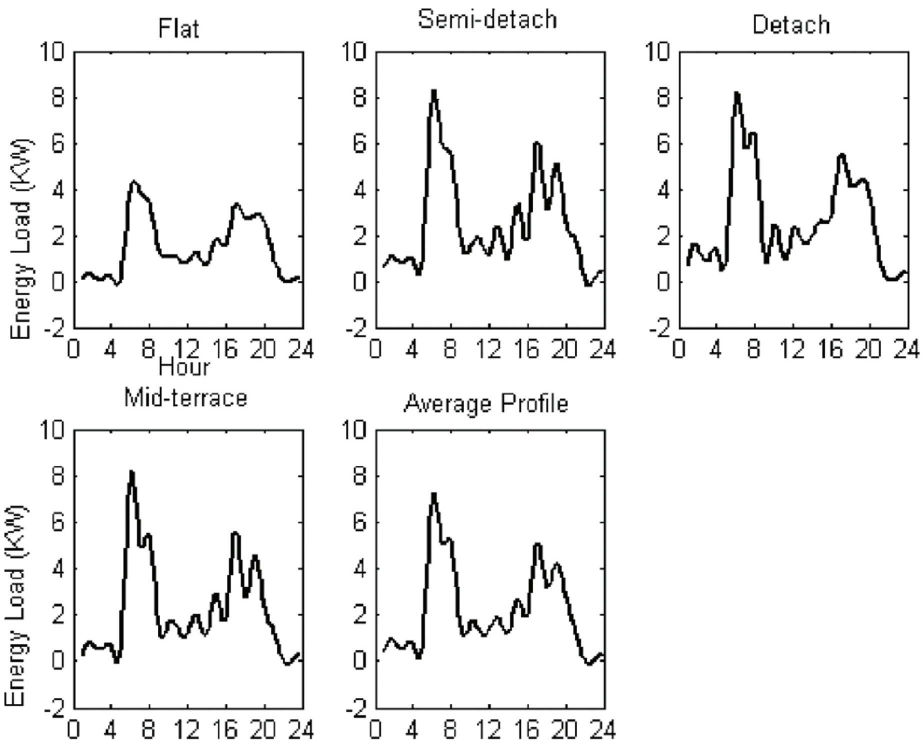


Fig. 5.7 Typical energy consumption load profiles (include electric appliance, DHW and space heating) detected in various typical dwellings (sources from [133])

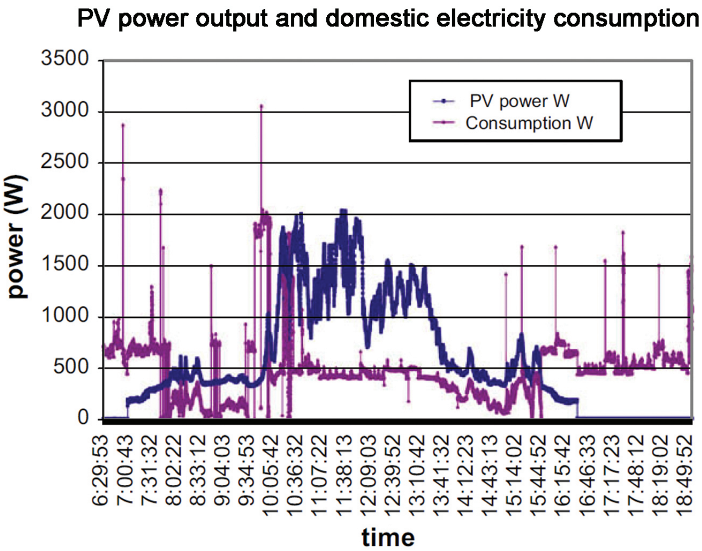


Fig. 5.8 Power output profile of PV panels on a day in October and electricity consumption profile of the household on the same day (sources from [134])

output capacities and lower self-discharge rates (i.e. average 2% self-discharge per month tested at 20 °C) than nickel-cadmium batteries (i.e. average 7% self-discharge per month tested at 20 °C). Hence the sealed lead-acid batteries are most likely better choice for the applications which require equipment to keep in a dormant state for an extended period of time before operation.

Moreover, the optimal working temperature of the lead-acid batteries is 25 °C and low temperature will typically cause the reduction of the battery capacity. [136] reports that the capacity of lead-acid batteries will generally declines around 20% at a freezing temperature of 0 °C and drops 50% when temperature reduces to approximately −27 °C. But it seems that the temperature influence is minor to the performance changes of these batteries if applied in the context of typical UK climate with mild temperature changes.

In terms of relevant calculations of the energy storage system, total demand of the battery capacity can be estimated by Equation 5.6

$$C_{kwh} = \frac{(E_L + AD)}{\eta_{inv} \times \eta_b \times DOD} \tag{5.6}$$

Where C_{kwh} is the needed battery capacity(kW), E_L is the average daily load energy demands (kW/day), AD is the daily autonomy value ranges from 0.1 to 1.0, η_{inv} is the inverter efficiency, η_b is the actual energy storage efficiency of the battery (i.e. is generally between 70% and 95% [137], [134]), DOD is the depth of discharge of the battery (i.e. maximum DOD of the sealed lead-acid battery is typically allowed around 80%). If the lead-acid battery is discharged more than its allowable depth of discharge or even be fully discharged, it would cause a risk of permanent damage of the battery and cannot be recharged for recycle using [135].

The relationship between discharge time, total energy storage and discharge electric current can be given by Equation 5.7

$$t_d = \frac{Q_P}{I^\gamma} \tag{5.7}$$

Where t_d represents the discharge time (h), Q_P is the usable energy (A h) stored in the battery, I is the allowable maximum electric current output (A) of the battery, and γ is a constant value of around 1.3 which involves the self-discharge influence to the I output.

The usable capacity of a battery can be calculated as in Equation 5.8.

$$E_{min} = E_{BN} \times (1 - DOD) \tag{5.8}$$

Where E_{min} is the maximum capacity (A h) allowed to be discharged without damaging the battery, E_{BN} is the total capacity (A h) of the battery.

Battery specifications and cost

Base on either cost consideration or specific application requirements, the system design prefers to employ large number of stand-alone SLA/AGM batteries (model: 6FM-200, specifications see Table 5.6) as the primary energy storage to store the electricity generated by both roof PV panels and wind turbines for supplying any delayed energy consumptions in the domestic scenario. The market price of this type of battery is $180.99/unit with 3 years warranty provided by the Resden battery manufacturer (market investigation see Appendix G). Additionally, it notes batteries commonly have no O&M requirements during their lifecycles [122]. Hereby relevant costs of batteries are summarized in Table 5.7.

Dimensions	522mm × 239mm × 219mm (total height: 244mm)
Weight	58 kg
Rated voltage	12.0 V
Rated capacity	200 A h
Charging capacity	10hrs(10 A): 100%
	5hrs(45 A): 90%
	1hr(80 A): 80%
Internal resistance	≤ 3.4 mΩ
Charging voltage	14.4 V
Float voltage	13.5 V
Capacity changes with different temperature	40 °C: 102%
	25 °C: 100%
	−10 °C: 90%
	−30 °C: 78%
Storage capacity	After 3 months: 96%
	After 6 months: 90%
	After 12 months: 82%

Table 5.6 Specifications of 6FM-200 battery (sources from [138])

Price (US$/unit)	**Number**	**Replacement cost** (US$/unit)	**O&M cost per year** (US$/year)	**Lifecycle** (year)
180.99	1	153.84	0	3

Table 5.7 Relevant costs and lifecycle of 12.0 V 200 A h SLA/AGM battery

5.2.4 Peripheral equipment

In order to address the energy storage and grid-connected issues, the DC/DC converters, DC/AC inverter, and AC/DC rectifier are indispensable system components to connect the hybrid renewable energy supply equipment (i.e. PV panels and micro wind turbines), batteries, utility grid and the TE heating equipment. During the renewable energy generation and storage processes, reasonable charging voltage control between the renewable energy supply equipment (i.e. PV panels or micro wind turbines) and batteries will be able to increase the renewable energy output efficiency. [139] reports that the optimal voltage tracking and adjustment can increase the power output of the PV arrays by 20% in comparison with a fixed voltage. Hence the converters are generally employed to optimize the charging voltage level for achieving maximum renewable energy output efficiency. Additionally, the DC/AC inverter and AC/DC rectifier are mainly used for the grid-connected purpose. To be specific, the DC/AC inverter is purposed to feed any excess renewable energy outputs (i.e. cannot be fully stored by batteries or self-consumed by the dwelling) into the utility grid. Conversely, in the system design, the AC/DC rectifier can potentially be used to convert AC power traded from the utility grid into DC power for operating the TE heating modules during the local renewable energy shortage periods. [134] reports that the efficiencies of the converters and inverters commonly range between 85% and 97% depend on various device qualities. For the efficiency introduction of the AC/DC rectifier, the maximum efficiency of typical full wave rectifier is proved as 81.2% [140].

Bidirectional inverter specifications and cost

Grid-tied inverter, generally known as bidirectional inverter which incorporates both of the DC/AC inverter and AC/DC rectifier functions could potentially meet the system design requirements of supporting either stand-alone mode or grid-connected mode. Hence, the XW series hybrid inverter/charger - 230Vac/50Hz modules involve the basic bidirectional inverter and optional solar charge controller with maximum power point tracking function will be employed in this system design. Moreover, the XW series hybrid inverter/charger modules have three different models: XW4024-230-50 (continuous output power: 4.0 kW/unit), XW4548-230-50 (continuous output power: 4.5 kW/unit), and XW6048-230-50 (continuous output power: 6.0 kW/unit) can be selected according to the actual requirements (i.e. different nominal loads, surge loads and maximum renewable energy output powers in various domestic scenarios) and optimal economic considerations. All detailed specifications of above inverter/charger modules can be checked in Figure G.6 and Figure G.7 of Appendix G. Additionally, the O&M cost of the inverter will generally take up 1% of the capital cost [141]. Table 5.8 exhibits relevant cost estimation results for the bidirectional inverters.

Model	**Price** (US$/unit)	**Number**	**Replacement cost** (US$/unit)	**O&M cost per year** (US$/year)	**Lifecycle** (year)
XW4024-230-50	2772.90	1	2356.97	1%	15
XW4548-230-50	3123.90	1	2655.32	1%	15
XW6048-230-50	3474.90	1	2953.67	1%	15

Table 5.8 Relevant costs and lifecycle of bidirectional inverter/charger

5.2.5 TE heating equipment

The TE heating equipment mainly consists of TE modules, metal heat sinks, cross flow fans, and smart controllers. Where TE modules are the core of heat pump; metal heat sinks are indispensable components which are closely associated to the heating efficiency of TE modules whilst can prevent any module damages caused by overheating; additional cross flow fans are expected in the TE heating equipment design to promote the convective heat exchange between heat sinks and surrounding air which potentially contribute to higher heating COP of TE modules; the smart controllers are purposed to automatically adjust the working voltage levels for optimizing the heat exchange efficiency of TE modules depends on ambient temperature monitoring results and to flexibly change the heat transfer direction in indoor space according actual demands (i.e. the heat transfer direction can be easily reversed by reversing the circuit current direction). It notes that the market survey results didn't find any existing smart controller can be directly employed to achieve above expected functions. Thus the cost estimation in terms of the smart controller is uncertain and all the relevant investigation results of the other three components are presented in next sections.

TE module cost

According to latest market investigation results in August 2016, the price of TEC1-12706 module has generally declined to 1.15$/piece from historical price of 1.66$/piece in 2013 (market investigation see Appendix G). The O&M cost of TE module can be generally assumed as 1% of the capital cost. Additionally, the specifications investigation in Chapter 2 has shown that the optimal life expectancy of TEC1-12706 module is about 200,000 hours. If assuming 10 hours operation time per day, the TE module could totally work 20,000 days equals to 55 years. Hereby relevant costs of TE module can be summarized as in Table 5.9.

Price (US$/piece)	**Number**	**Replacement cost** (US$/piece)	**O&M cost per year** (%/year)	**Lifecycle** (year)
1.15	1	1.15	1%	55

Table 5.9 Relevant costs and lifecycle of TEC1-12706 module

Heat sink specifications and cost

The market prices comparison results show the optimal price of the aluminum heat sink (module: FL49-022; dimensions: $125 \times 125 \times 45$ mm; fins number: 37; thickness of the bottom plate: 8 mm) is 5.28$/piece (market investigation see Appendix G) and relevant costs of heat sink are summarized in Table 5.10.

Price (US$/piece)	**Number**	**Replacement cost** (US$/piece)	**O&M cost per year** (%/year)	**Lifecycle** (year)
5.28	1	0	0	

Table 5.10 Relevant costs and lifecycle of heat sink

Cross flow fan specifications and cost

The general life expectancy of the cross flow fan (model: CYF-6043, specifications see Table 5.11) provided by the manufacturer is around 30,000 hours which can be deemed as about 12 - 15 years relies on actual using conditions. The market price of this cross flow fan is 25.34$/piece (market investigation see Appendix G) and the O&M cost is assumed as 1% of the capital cost. Relevant costs of cross flow fan can be summarized in Table 5.12.

Model	**Dimensions** (mm)	**AC Voltage** (V)	**Power** (W)	**Air Flow** (m^3/hour)
CYF-6043	539 x 102 x 91	220	45	402

Table 5.11 Cross flow fan parameters

Price (US$/piece)	Number	Replacement cost (US$/piece)	O&M cost per year (%/year)	Lifecycle (year)
25.34	1	25.34	1%	15

Table 5.12 Relevant costs and lifecycle of CYF-6043 cross flow fan

5.3 System application design in domestic scenario

System installation and application designs in mid-terraced property

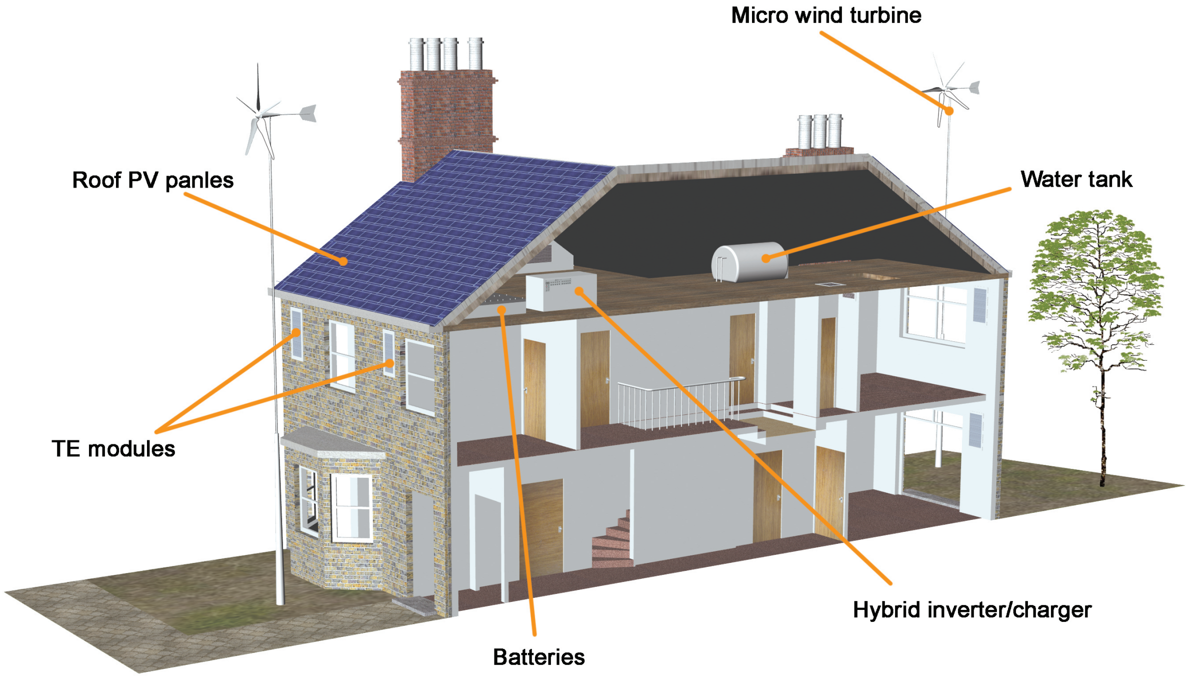


Fig. 5.9 TE heating system with hybrid renewable energy applied in a typical mid-terrace dwelling

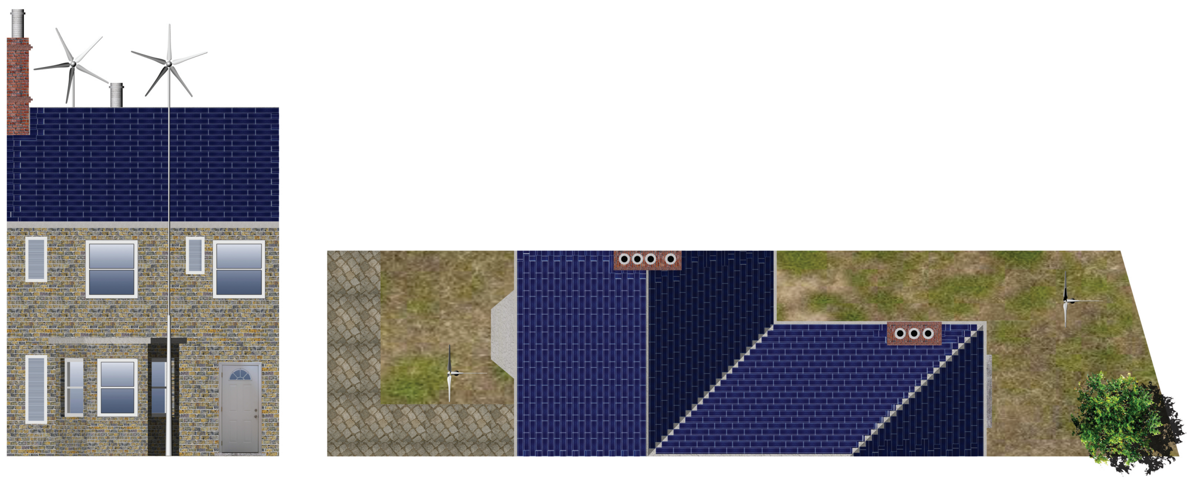


Fig. 5.10 Front view and plan view of the scenario

As shown in Figure 5.9 and Figure 5.10, to apply TE heating system with hybrid renewable energy supply serving in the typical mid-terraced property with 180 m^2 floor area investigated in Chapter 4, the PV panels ought to cover as more as possible roof area for maximizing solar energy collection whilst two stand-alone micro wind turbines (i.e. hub height is 10 m, diameter of blades is 1.96 m) are mounted on the space of front and rear of the house respectively for collecting potential wind energy.

TE modules ought to be inlaid in the exterior wall of the building for absorbing outside ambient heat and heating the indoor space (see Figure 5.9). Experimental study results in Chapter 3 have revealed that when the heat absorbing side of TE module is exposed to a warmer external ambient, the heating COP is always higher than in a relatively colder external ambient (such as the north-facing shadow area). Thus, the preferred mounting positions of TE modules should be selected on the south-facing building exterior wall which intends to maximize the COP of TE modules.

TE modules and auxiliary components inlaid in exterior wall are specifically shown in Figure 5.11. The metal heat sinks are indispensable to closely touch with each sides of TE module, and additional cross flow fans are expected in both hot side and cold side to promote the convective heat exchange with air which can also contribute to the high heating COP value of TE module.

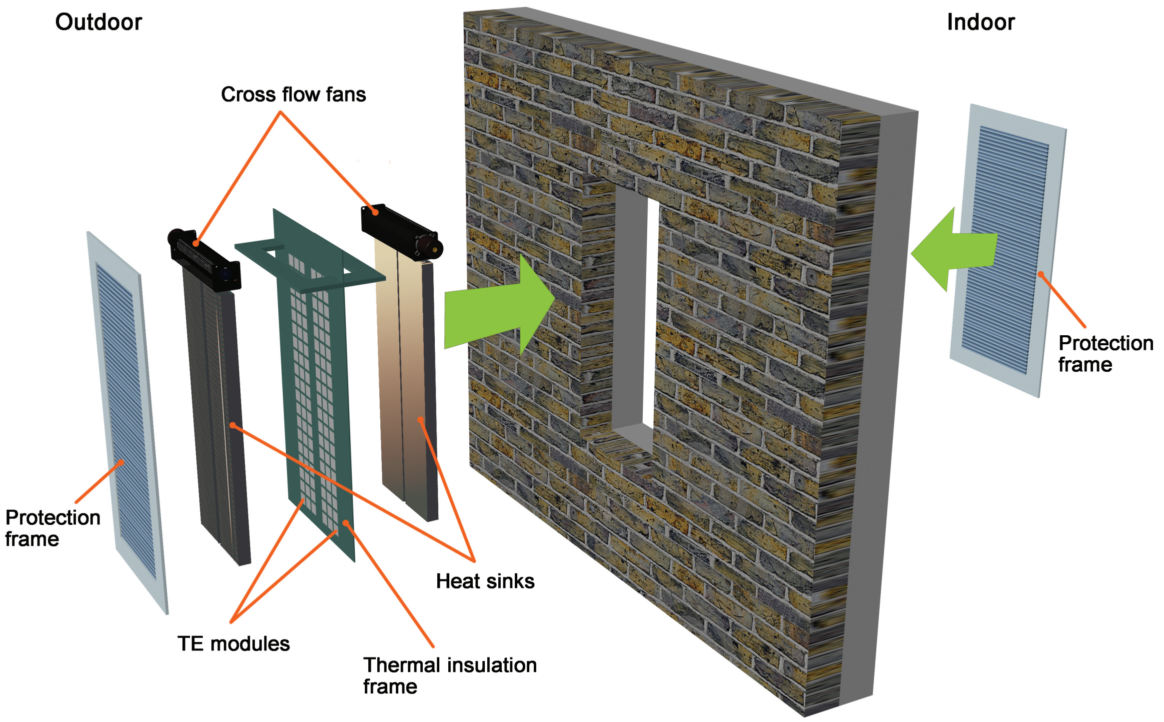


Fig. 5.11 Components of TE heating system inlaid in exterior wall

Additionally, case study results in Section 4.4 have proved that it can produce a satisfied heating power to meet the domestic heating load by employing 9 pieces of TE modules to heating each 1 m^2 floor area. Hereby for heating a total floor area of 180 m^2 of the mid-terrace dwelling, the system design will require 1620 pieces of TEC1-12706 modules (dimensions: 40 × 40 ×

3.9 mm) which should occupy minimum 2.6 m^2 of the exterior wall area. It needs to note that TE modules cannot occupy too much area on the single south-facing exterior wall for avoiding damage to the load-bearing structure of the wall. Hence the design should also consider making rational distribution of parts of TE modules at the north-facing and west-facing exterior wall of the dwelling (see Figure 5.14).

The system application design further considers inlaying a certain amount of TE modules in the building interior walls for adjusting the heat distribution in building interior space. As shown in Figure 5.12, the south-facing rooms easily capture more passive heat/sunshine as to have higher indoor average temperature (i.e. 1 °C - 5 °C) than the north-facing rooms. If operating these TE modules inlaid in the interior walls under a minor voltage level (i.e. 3 V - 5 V inputs should be enough for minor temperature difference adjustments) with high COP (i.e. higher than 3.0) to accelerate heat exchange between the two types of rooms in time, it would be helpful to contribute to a well-distributed indoor thermal comfort in the whole building.

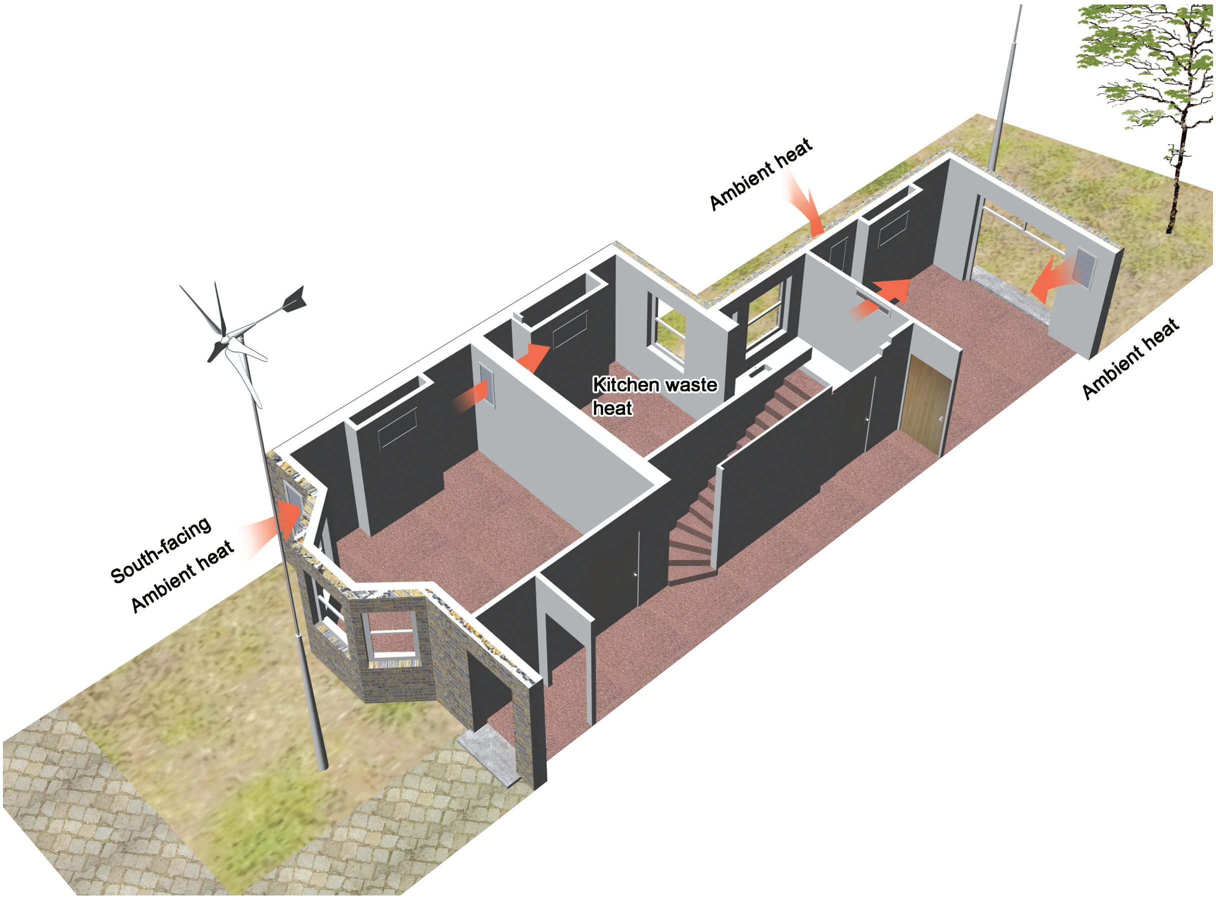


Fig. 5.12 Heating method 1 of the TE heating system in typical mid-terrace scenario

Figure 5.13 presents TE modules inlaid in interior walls can collect the waste heat from bathroom or kitchen (after use) to focus on heating other occupied rooms. They can also be operated to prevent more effective heat loss from occupied room to unoccupied rooms/external ambient in some extents. Figure 5.14 demonstrates that TE modules can transfer the potential indoor waste heat between different floors via the indoor fireplace tubes. New smart heat control implementations should benefit from TE modules' capability of switching heat flow transfer

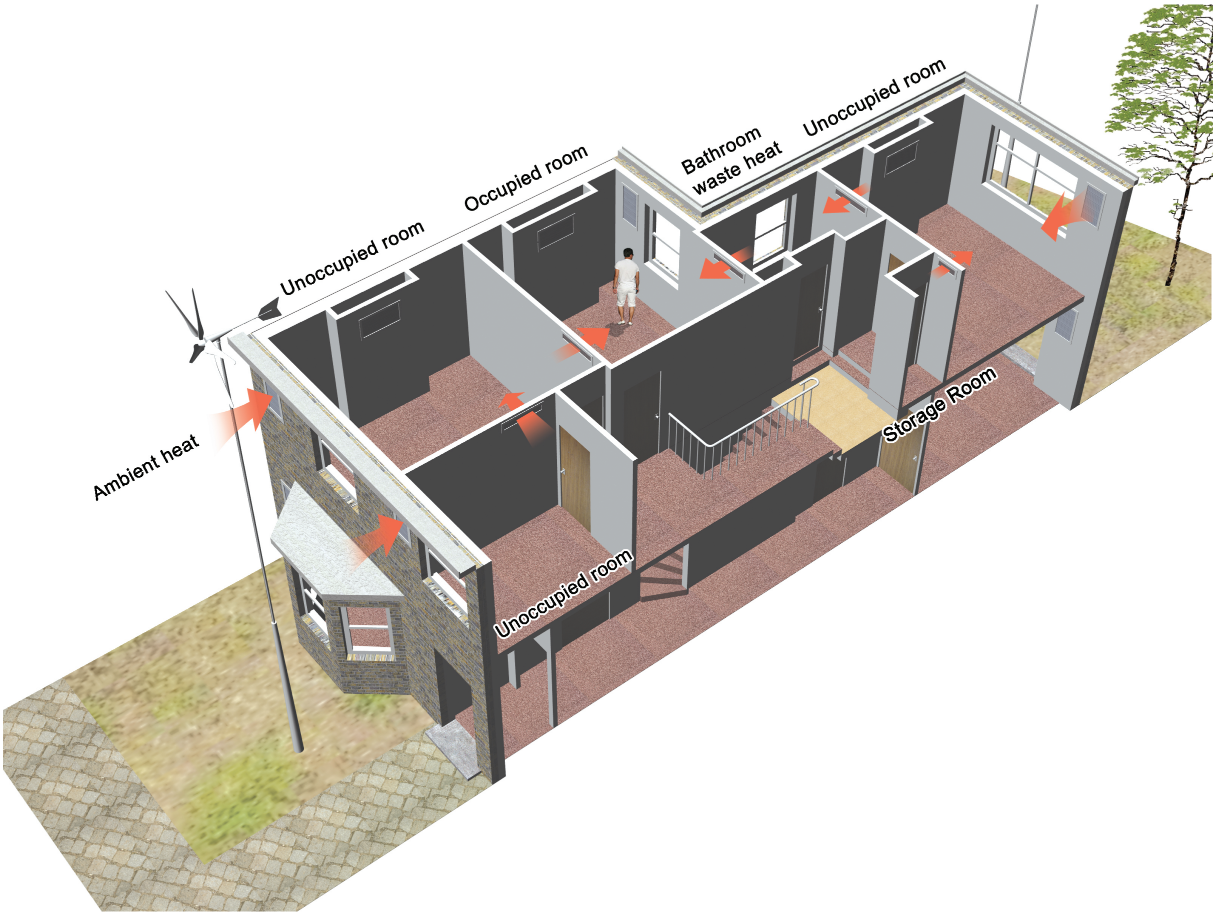


Fig. 5.13 Heating method 2 of the TE heating system in typical mid-terrace scenario

direction by simply revising the electric current direction. Moreover, the hot sides of TE modules inlaid in both exterior and interior walls should be positioned carefully, similarly to standard panel radiators, as potential high surface temperature may cause thermal discomfort due to radiant asymmetry.

Finally, the mean value of domestic hot water delivery temperature is 51.9 °C ± 1.3 °C despite a boiler is normally expected to provide water at 60 °C [142], [143], [144]. [17] studies TE modules (model: CP1.4-127-045L and PT4-12-40) in heating mode with maximum 7 V input can reach near 60 °C at the hot side when ambient temperature is about 20 °C and the heating COP are always higher than 1. This result implies the feasibility of TE modules apply for pre-heating the domestic hot water when the renewable energy supply is excess to meet the inter-day heating demand. Thus the system design could consider adding additional TE modules to heating the water tank located in the loft. These TE modules will daily absorb heat from the loft space to potentially supply the domestic hot water. Meanwhile the average temperature reduction of the roof caused by these TE modules is helpful to promote higher energy output efficiency of roof PV cells.

Fig. 5.14 Heating method 3 of the TE heating system in typical mid-terrace scenario

System circuit design

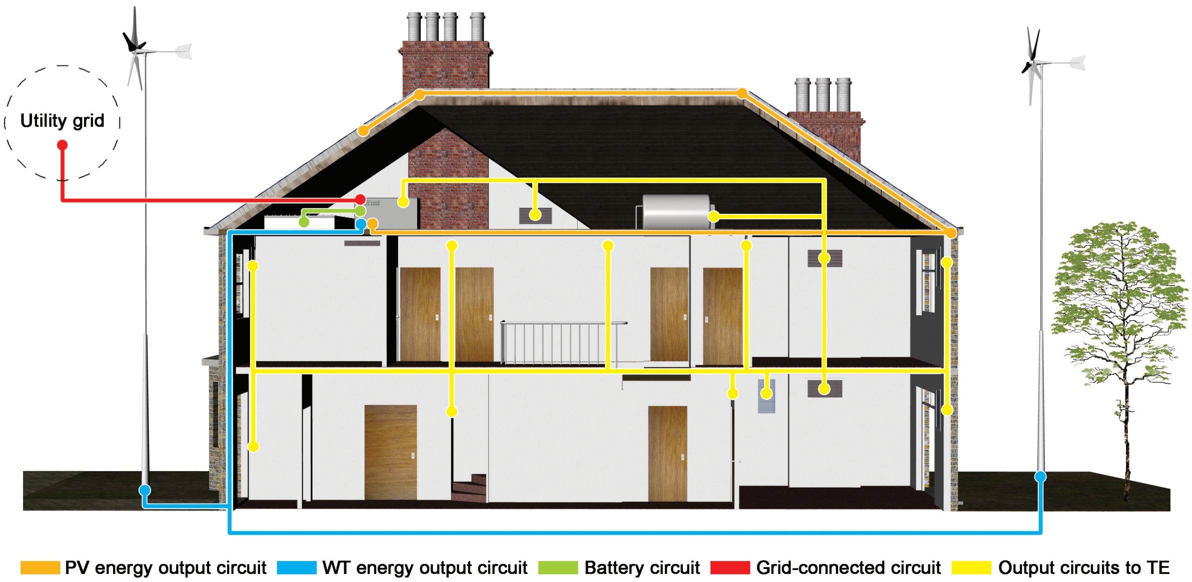


Fig. 5.15 Profile of the TE heating system with hybrid renewable energy in typical mid-terrace scenario

Figure 5.15 demonstrates the circuit distribution of the entire system design: Both PV and wind turbine energy output circuits should be connected with the hybrid inverter/charger which consists of a bidirectional inverter and solar charge controller. Simultaneously two separate circuits are set at the power exchange terminals of the hybrid inverter/charger: one is connected with the batteries stored in the loft of the building, and the other is connected with the external utility grid power system. Finally, the power output terminals of the hybrid inverter/charger are connected with the smart controllers distributed in the building space and further optimally operating the TE heating modules. Depend on these circuit connections, it can optimal the power efficiency of the PV devices and wind turbines, whilst the grid-connected circuit ought to be able to be used to provide additional power supply or trade excess renewable energy generation. Moreover, during the renewable energy shortage periods, although the battery units cannot obtain adequate energy from the PV panels and wind turbines, they also can be used to store a certain amount of electricity from the utility grid during the load trough period with cheap imported electricity tariffs and then supply the domestic heating demand during the load peak period which could save more economic costs to some extents.

Heating power of the designed system

The experimental results studied in Section 3.5.4 of Chapter 3 have estimated the average heating power (in unit of $W\,m^{-2}$) of TE modules by forced convection under different operating voltage levels (see Table 3.13). Hereby, for heating 180 m^2 floor area of the mid-terraced property, the TE heating system design in the exterior walls which totally employ 1620 pieces of TEC1-12706 modules should be able to provide minimum 11 593.80 W and maximum 42 793.20 W of heat to meet the building space heating load. More detailed heating powers of this TE system under different operating voltage levels are shown in Table 5.13.

Operating voltage (V)	**Total heating power** (W)
4	11593.80 *
5	13743.00 *
6	18370.80 - 23911.20 **
7	22217.40 - 29541.60 **
8	26938.80 - 38019.60 **
9	31559.40 - 42793.20 **

Table 5.13 Total heating power of TE heating system designed for the mid-terraced property with 180 m^2 floor area

* these heating powers are estimated rely on the TE heating results tested in lab ambient (i.e. 19 °C to 21 °C).

** these heating power ranges are estimated rely on the TE heating results tested in both lab ambient and open-air courtyard (i.e. 1 °C to 5 °C).

5.4 Simplified system cost estimation and discussion

Based on market investigation results of relevant system components in section 5.2, the total cost of the entire system designed for heating the typical mid-terraced dwelling (i.e. case studied in Chapter 4) will be simply estimated and discussed in this section.

Before estimating the entire system cost, some necessary assumptions ought to be defined as below:

- if employing the 100 Watt 12 Volt polycrystalline solar panels (dimensions: 1200 × 540 × 3 cm) to cover as more as possible of the roof surface area (i.e. around 108 m^2) of the mid-terraced house, it would be able to install maximum 166 pieces of solar panels.

- it will totally employ two micro wind turbines (model: SM-1000) in this domestic scenario as the description in Section 5.3.

- three hybrid inverter/chargers (model: XW6048-230-50) will be employed to support continuous renewable power output of 18 kW and surge load of 36 kW.

- the estimation results of domestic heating demands in Chapter 4 have revealed a maximum daily heating demand of 98.36 kW h/day during February. If operating TE modules with a average heating COP of 1.8 to fully meet the domestic heating demands, it would require a maximum electricity supply of 54.64 kW h/day. Hereby the system design suggests employing minimum 29 pieces of SLA/AGM batteries (model: 6FM-200) which can store adequate electricity to potentially supply TE heating system for meeting the domestic heating demands throughout the year.

- the system design require 1620 pieces of TEC1-12706 modules inlaid in the exterior walls for heating the total floor area of 180 m^2 in the mid-terraced property. In here if assuming inlaying equivalent number of TE modules in the interior walls to optimize the heat distribution in the building interior space (i.e. collect waste heat from kitchen or bathroom, transfer heat from unoccupied rooms to occupied rooms), the total number requirement of the TEC1-12706 modules will be 3240 pieces.

- in the system design, if assuming the area ratio between the heat sink and TE module is 2:1, it would require total area of 20.8 m^2 of the heat sink to maintain good heat dissipation performance at both hot sides and cold sides of TE modules. Hereby it needs to purchase 1332 pieces of aluminum heat sinks (model: FL49-022) for meeting the system design requirements.

- the system design suggests distributing 32 pieces of cross flow fans (model: CYF-6043) on the exterior walls and 52 pieces on the interior walls to promote the convective heat exchange of the heat sink surfaces.

Hereby the total capital cost and O&M cost of the entire system consists of TE heating equipment, renewable energy supply devices, batteries and peripheral equipment can be simply summarized in Table 5.14. It notes that all initial prices of the system components surveyed from the international market don't involve the potential VAT (Value Added Tax), transportation and installment costs. Moreover, possible costs of the smart controller and basic cable connected between all electric components are also uncertained. Thus the estimation results of relevant system costs should be rationally tasted as reference values.

Component	**Number**	**Total capital cost** (US$)	**Replacement cost** (US$)	**O&M cost** (US$/year)	**Lifecycle** (year)
PV panel (100 W 12 V polycrystalline)	166	6709.72	6709.72	67.10	25
Wind turbine (SM-1000)	2	2658.00	2274.00	79.74	15
Hybrid inverter/chargers (XW6048-230-50)	3	10424.70	8861.01	104.25	15
Battery (6FM-200)	29	5248.71	4461.36	0.00	3
TE module (TEC1-12706)	3240	3726.00	3726.00	37.26	55
Heat sink (FL49-022)	1332	7032.96	0.00	0.00	N/A
Cross flow fan (CYF-6043)	84	2128.56	2128.56	21.29	15
Total		37928.65		309.63	

Table 5.14 System cost estimation for mid-terraced property with 180 m^2 floor area

Furthermore, refer to the life expectanies of most system components involve the cross flow fans, wind turbines and hybrid inverter/chargers are estimated as around 15 years, thus the lifecycle design of the entire system ought to be assumed as minimum 15 years. Hereby the cumulative costs involve initial investments and O&M costs of various system components during the minimum lifecycle are compared as shown in Figure 5.16.

Daily energy consumption for domestic heating demand is usually much higher than daily electricity consumption for household electric appliances. Thus the system design has to employ as more as possible renewable energy supply devices and batteries to assure adequate energy supply for daily heating demands. Figure 5.16 reveals that during minimum system lifecycle of 15 years, the batteries' costs (i.e. cumulative cost of batteries is estimated as $23,094.15) will potentially account for nearly a quarter of total cumulative cost (i.e. is estimated as $60,418.54) of the entire system. This is mainly caused by relatively short lifecycle and expensive replacement cost of batteries (i.e. it notes that the lifecycle of the lead-acid battery is suggested as around 3 years in this estimation. Hereby all batteries will be replaced by 4 times during the entire system lifecycle).

For relieving the argument of expensive battery cost, [134] indicates that more and more hybrid cars are employed in current society and be encouraged by governments which will cause massive demands of battery industry. This is helpful to lower the battery production cost and further results in the appearance of additional second-hand battery markets. Many batteries installed in hybrid cars will be replaced or even be abandoned when their capacity drops after a

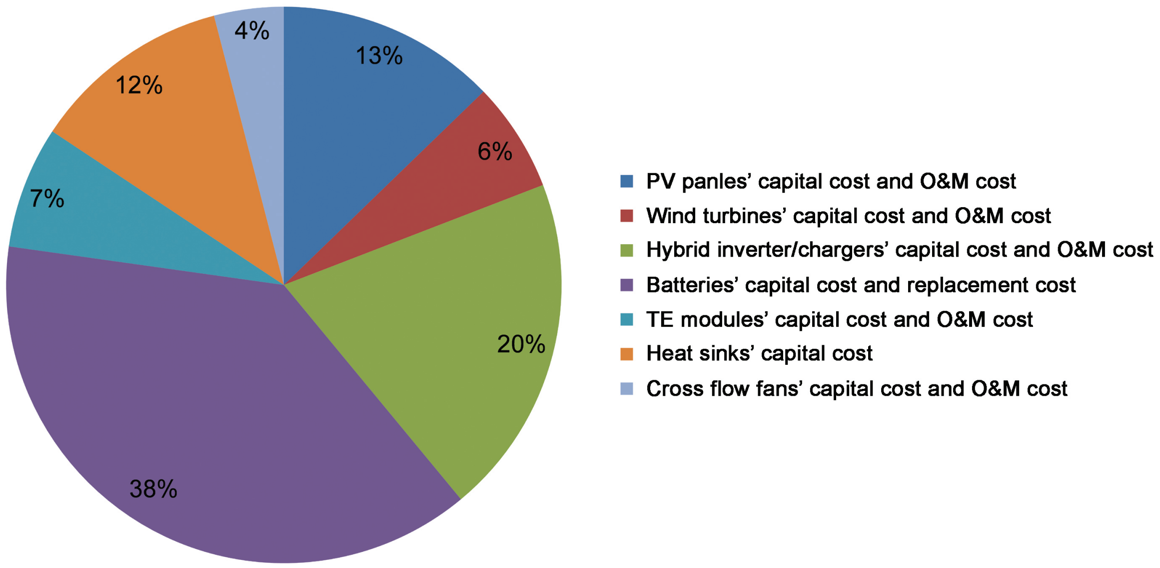


Fig. 5.16 Cumulative costs comparison between various system components during expected lifecycle

period of using. But they can still be recycled for domestic applications, where storage place is less critical.

Additionally, Figure 5.16 also indicates the hybrid inverter/chargers' costs (i.e. cumulative cost of hybrid inverter/chargers is estimated as $11,988.41) are the second most expensive which accounts for 20% of total cumulative cost of the entire system. It suggests reasonably measuring domestic nominal/surge loads and estimating renewable energy power peak level for selecting suitable hybrid inverter/chargers which may potentially optimize relevant costs caused by hybrid inverter/chargers. It also expects any more technical innovations for lowering the production cost of hybrid inverter/chargers in future.

Finally, based on relevant estimation results in Chapter 4, in comparison with using general electric heaters in the same mid-terraced property, the entire system can save 136488.60 kW h grid electricity consumption (i.e. annual electricity saving is estimated as 9099.24 kW h/year) whilst can contribute to the CO_2 emission reduction of 58915.80 kg (i.e. annual reduction of CO_2 emission is estimated as 3927.72 kg/year) during the minimum system lifecycle of 15 years. In addition to meet the domestic heating purpose, the renewable power supply equipment (i.e. solar panels and wind turbines) can also be used to supply additional domestic electricity demands and hot water demand when the dwelling has no heating demands. These applications will potentially save more grid energy consumptions and CO_2 emissions during the entire system lifecycle.

5.5 Summary

In this chapter, main system configurations of the TE heating system combined with hybrid energy supply (i.e. solar/wind renewable energy and utility grid supply) have been identified. Relevant performance studies of system components can provide reliable reference data (e.g. the power output efficiencies of solar cells and wind turbine, the lead-acid battery efficiency and depth of discharge, and generic conversion loss of the converter and inverter, etc) to support the estimations of supply-demand relationship between TE heating system and domestic heating demands in other chapters.

Detailed system application design in typical mid-terraced dwelling scenario further demonstrated the main system components installment positions in building space and system circuit connection for supporting both stand-alone mode and grid-connected mode. The free indoor heat distribution smart control is benefited from the simplified configuration of TE module which is hard to achieve by vapor compression air-conditionings. Additional design applications potentially for domestic hot water was also suggested.

The designed heating power of the entire system was estimated as minimum 11 593.80 W and maximum 42 793.20 W for meeting the heating load of typical mid-terraced property with 180 m^2 floor area. Additionally, during the minimum system lifecycle of 15 years, the simple system cost estimation results summarized a total cumulative cost of $60,418.54 of the entire system which involved higher costs of battery components and hybrid inverter/chargers (note: uncertain costs regarding smart controllers' costs and main system components' VAT, transportation and installment costs weren't included in the cumulative cost estimation). Finally, in comparison with using general electric heaters, it could estimate 136 488.60 kW h grid electricity saving and 58 915.80 kg CO_2 emission reduction caused by the entire system application for meeting the domestic heating loads during the minimum system lifecycle.

Chapter 6

The Feasibility of Applying the TE Domestic Heating System across England and Wales

6.1 Introduction

In Chapter 4, based on the investigations of domestic heating demands in a typical pre-1900s mid-terraced property and local renewable energy supply levels (i.e. solar and wind energy supplies) at Newcastle upon Tyne, the case study results have estimated a minimum energy saving efficiency of 64.03% caused by applying the TE heating system with hybrid energy supply to service for the domestic heating throughout the year.

Relevant statistic results by NEED (National Energy Efficiency Data-Framework [145]) indicate that the households in the UK southern regions commonly have less heating demands than most households in the UK northern regions which is benefited from the relatively mild climate in south England and Wales throughout the year. Meanwhile historical weather data statistics by the Surface Meteorology and Solar Energy Data Set [19] show that both of local irradiance level and wind speed will gradually enhance as the decrease of the latitude from the UK northern regions to the UK southern regions. Therefore in comparison with the case study results in North East England, it would potentially cause higher energy saving efficiencies if employing the TE heating system with hybrid energy supply to service for some domestic scenarios in the UK southern region due to more available renewable energy can be easily collected by PV panels/wind turbines and lower level of heating demands are requested. Moreover, specific domestic heating demands are also determined by different floor areas, occupant number, property types and ages [145]. Hence, in the same region with consistent renewable energy supply level, the application of TE heating system with hybrid energy supply will also capable of causing higher energy saving efficiencies in some other different domestic scenarios which may have lower heating demands.

In this chapter the study intends to explore specific heating supply-demand relationships in various domestic scenarios across England and Wales. It expects the TE heating system powered by local renewable energy can fully meet the domestic heating demands throughout the year whilst off the utility grid supply in some scenarios. Meanwhile all the scenario simulation results will be important arguments to ascertain the feasibility of universally applying the TE system in the UK domestic heating context.

6.2 Scenario simulation methodology

In order to estimate as more as possible heating supply-demand relationships and energy saving efficiencies caused by applying the TE heating system with hybrid energy supply in various UK domestic scenarios, firstly it is necessary to determine the detailed domestic heating demands in different domestic contexts.

In most UK households who have connected into the public gas grid, the annual gas consumption is usually a valuable indication to detect the domestic heating demands. Moreover, the domestic gas consumption is usually influenced by three main factors: Property attributes (i.e. floor area, number of bedroom, property type, and property age), Household characteristics (i.e. tenure, household income and number of adult occupants), and Geographic area (i.e. region and output area classification). In here according to 2013 domestic energy consumption statistics which is newly updated by [18] in June 2015, this study could investigate the median domestic gas consumption levels in various cross-variations categories involve floor area/property type, floor area/occupant number, floor area/property age, and floor area/region. For example, in the cross-variations category of floor area/occupant number, it can investigate the median domestic gas consumptions in all specific dwelling classifications which have different floor areas (i.e. $50\,m^2$ or less, $51\,m^2$ to $100\,m^2$, $101\,m^2$ to $150\,m^2$, $151\,m^2$ to $200\,m^2$, over $200\,m^2$) and different occupant numbers (i.e. 1 adult, 2 adults, 3 adults, 4 adults, and 5 or more adults) respectively.

Then based on the investigation results of the median gas consumptions in each cross-variations category, the study can utilize the median gas consumptions in specific dwelling classifications of 3 adult occupants, mid-terraced property type, pre-1919 built, and North East regional location as the baselines, and to further calculate different percent changes caused by comparing domestic gas consumptions of other dwelling scenarios with the baseline scenarios.

Furthermore, it has argued that the detailed domestic heating demands studied in Chapter 4 can be used to potentially represent the common domestic heating demand level of typical pre-1919 mid-terraced dwellings with $151\,m^2$ to $200\,m^2$ floor area, 3 adult occupants and located in North East region (note: the case studied dwelling in Chapter 4 totally has four occupants involve two adults and two children. In here all occupants are treated as equivalent to three adults due to children usually have less energy demands than adults). Hereby, if importing the case study results as the representative of monthly heating demands in corresponding baseline scenario, it would be able to rationally combine with different scale plates of gas consumption change percents for reckoning the specific monthly heating demands in any other domestic scenarios.

Secondly, solar energy is an abundant renewable source which can be directly converted into electricity via solar panels to power the TE heating system, and the solar energy outputs are generally proportional to local irradiance level and total area of available PV arrays. In here for estimating possible solar energy outputs in various domestic scenarios, the study will utilize the annual irradiance level of the North East as a baseline and compared with the irradiance levels of other regions to calculate the regional irradiance change percents. Then if importing relevant monthly solar energy output results estimated in Chapter 4 as the typical roof solar energy output levels of properties with roof areas of 90 m^2 and located in North East region, it would be able to estimate more monthly roof solar energy outputs in various dwelling scenarios by scaling the corresponding roof areas change ratios and regional irradiance change percents.

Thirdly, the wind energy outputs by wind turbines are closely related to regional wind speed level. The case study in Chapter 4 ever investigated monthly average wind speed in Newcastle upon Tyne depended on NASA meteorological database and further applied HOMER software tool to simulate the wind energy outputs by employing SM-1000 wind turbine in the local context. In here it can also utilize similar methods to investigate more regional wind speed levels and simulate possible wind energy outputs by employing SM-1000 wind turbine in other various domestic scenarios.

Fourthly, based on all estimation results regarding the monthly heating demands, solar energy outputs by roof PV panels and wind energy outputs by wind turbines in various domestic scenarios, the study can utilize same assumptions (i.e. define the minimum heating COP of TE module and the energy loss of battery and peripheral equipment) and calculation methods as in the case study of Chapter 4 to estimate the specific monthly heating supply-demand relationships and energy saving efficiencies when employing TE heating system with hybrid energy supply to service for various domestic scenarios across England and Wales.

Additionally, the domestic hot water demand is mainly determined by the number of occupants. [133] study has analyzed the specific profile of domestic hot water (DWH) consumption in typical three-people household of the UK as shown in Table 6.1. The results show a average energy consumption level around 2.3 kW h/day per people for meeting the daily DWH demand. Hereby if this study further assumes the average DWH demand as 2.5 kW h/day per people, it would be able to estimate specific DWH demands according to the number of occupants in various domestic scenarios, and further analyze whether the excess renewable energy outputs (i.e. do not need to be consumed by heating demands) during some warm months could fully supply the monthly DWH demands.

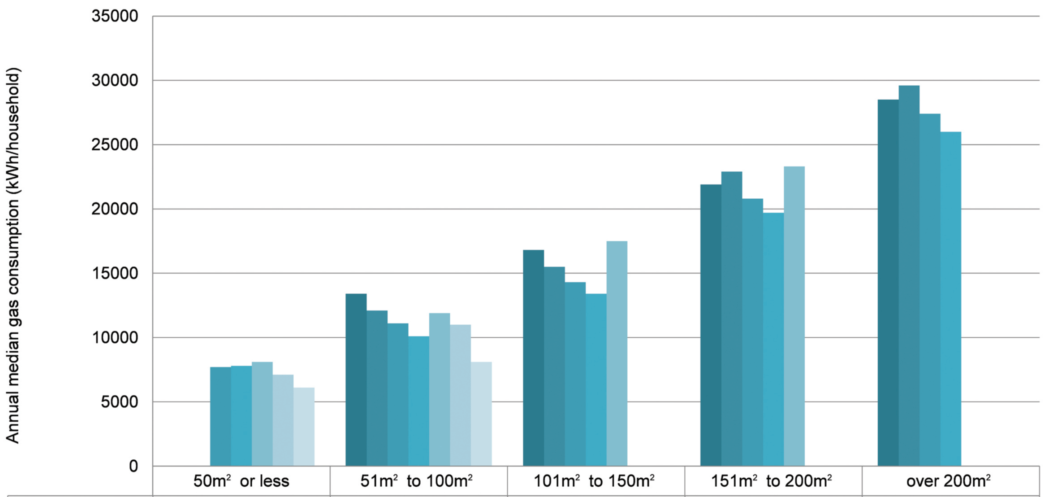
Appliance/use	DHW load consumption (kWh/day)
Bath/shower	1.1
Wash hand basin	1.4
Dish washing	2.3
Clothes washing 50%	2.0
Clothes washing 50%	0
Total	6.8

Table 6.1 Energy-consumption for domestic hot water of a three-person family

6.3 UK domestic heating demands investigation

6.3.1 Domestic gas consumptions by different cross-variable influences

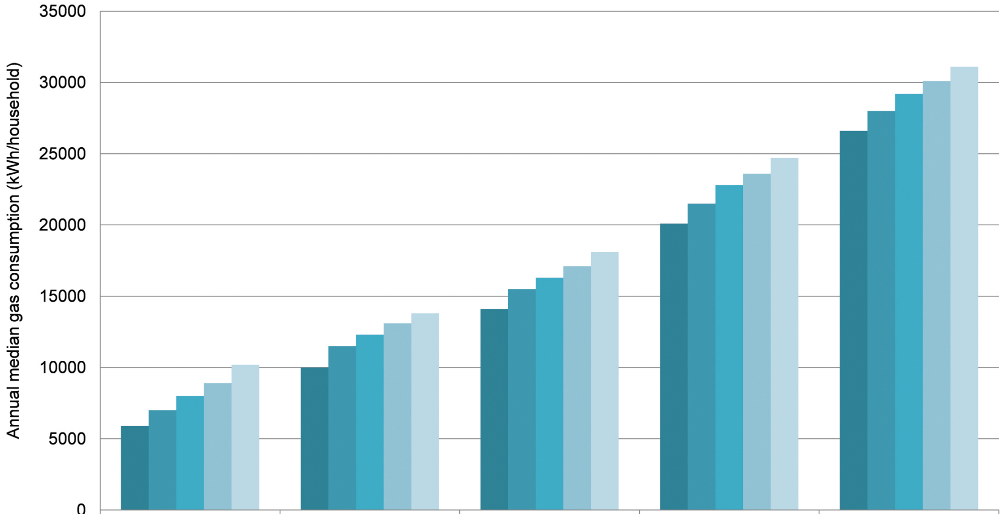
Based on 2013 domestic energy consumption statistics which is newly updated by [18] in June 2015, the median domestic gas consumption levels in various cross-variations categories involve floor area/property type, floor area/occupant number, floor area/property age, and floor area/region have been presented in Figure 6.1, Figure 6.2, Figure 6.3 and Figure 6.4 respectively. It notes that the occupants' behavioral determinants regarding the domestic gas consumption have been involved in above cross-variations of the quantitative statistics and will not be discussed as an independent factor.



	50m² or less	51m² to 100m²	101m² to 150m²	151m² to 200m²	over 200m²
Detached	N/A	13400	16800	21900	28500
Semi detached	N/A	12100	15500	22900	29600
End terrace	7700	11100	14300	20800	27400
Mid terrace	7800	10100	13400	19700	26000
Bungalow	8100	11900	17500	23300	N/A
Converted flat	7100	11000	N/A	N/A	N/A
Purpose built flat	6100	8100	N/A	N/A	N/A

Fig. 6.1 Annual median gas consumption in 2013, by floor area and property type * When the observation number in the NEED sample is fewer than 2000, the consumption figure should be treated with caution and excluded from this analysis to show N/A in the table.

Figure 6.1 shows that in each same floor area band, the median gas consumption levels in detached, semi-detached properties and bungalows are usually more than the end terrace and mid terrace which are potentially caused by their different compositions of housing stocks. Moreover, when the floor area excesses 100 m^2 in above five property types, bungalows likely have the most gas demands whilst the median gas consumption levels in mid-terraced properties are always the lowest. Additionally, it notes that relevant analysis of the median gas consumptions in the converted flat and purpose built flat are excluded in this study due to poor statistics data refer to these two types of properties.

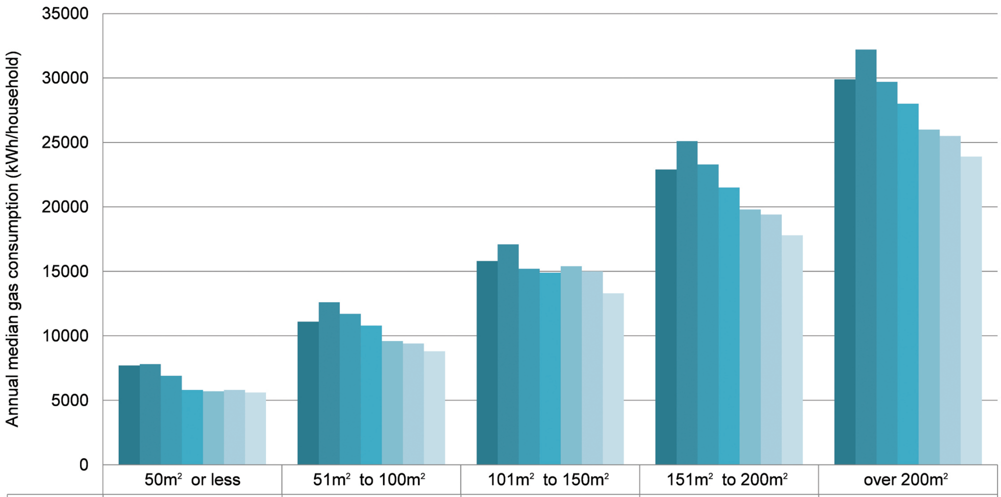


	50m² or less	51m² to 100m²	101m² to 150m²	151m² to 200m²	over 200m²
1 adult	5900	10000	14100	20100	26600
2 adults	7000	11500	15500	21500	28000
3 adults	8000	12300	16300	22800	29200
4 adults	8900	13100	17100	23600	30100
5 or more	10200	13800	18100	24700	31100

Fig. 6.2 Annual median gas consumption in 2013, by floor area and number of adults

Figure 6.2 shows that there is a strong relationship between the gas consumption and floor area and occupant number in all properties. The results reflect the gas consumptions of properties typically increase as the increase of either floor area or occupant number. Moreover, it notes that the total gas consumptions in a smaller floor area band with maximum number of occupants (e.g. 5 or more) are commonly less than the gas consumptions in a larger floor area band with minimum number of occupants (e.g. only 1 adult), which implies the variation of floor area can cause larger influence to determine the domestic gas consumption than the variation of number of occupants.

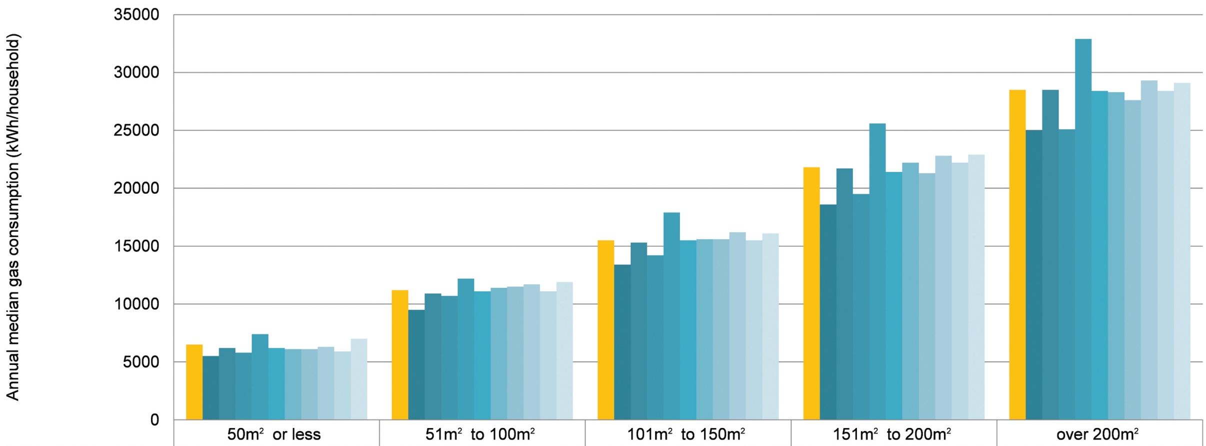
Figure 6.3 shows the median gas consumption levels in properties built before 1944 are commonly higher than properties built in later periods due to there was no minimum energy efficiency requirement to the building standards before 1962. Then as the implementation of building standard regarding energy efficiency becomes more stringent over time, the gas consumptions shows obvious reduction trends in more dwellings which are newly built with better insulation performances [145]. It notes that in 101 m^2 to 150 m^2 floor area band, the median gas consumption level of properties built between 1993-99 is higher than older properties built between 1983-92 which may be caused by different housing structure characteristics (e.g. the average floor area for properties built in 1993-99 is commonly larger than properties built in 1983-92 which will cause more domestic heating demands) or uncertain household



	50m² or less	51m² to 100m²	101m² to 150m²	151m² to 200m²	over 200m²
Pre 1919	7700	11100	15800	22900	29900
1919-44	7800	12600	17100	25100	32200
1945-64	6900	11700	15200	23300	29700
1965-82	5800	10800	14900	21500	28000
1983-92	5700	9600	15400	19800	26000
1993-99	5800	9400	15000	19400	25500
Post 1999	5600	8800	13300	17800	23900

Fig. 6.3 Annual median gas consumption in 2013, by floor area and property age

characteristics. Additionally, in 50 m^2 or less floor area band, there are minor differences between the gas consumptions of all properties built after 1964, which suggests the variation of property age has less influence to determine the domestic gas consumptions in dwellings which have small floor areas and are built after 1964.



	50m² or less	51m² to 100m²	101m² to 150m²	151m² to 200m²	over 200m²
All dwellings	6500	11200	15500	21800	28500
South West	5500	9500	13400	18600	25000
South East	6200	10900	15300	21700	28500
Wales	5800	10700	14200	19500	25100
London	7400	12200	17900	25600	32900
East of England	6200	11100	15500	21400	28400
West Midlands	6100	11400	15600	22200	28300
East Midlands	6100	11500	15600	21300	27600
Yorkshire & Humber	6300	11700	16200	22800	29300
North West	5900	11100	15500	22200	28400
North East	7000	11900	16100	22900	29100

Fig. 6.4 Annual median gas consumption in 2013, by floor area and region

Figure 6.4 shows that all properties located in South West usually have the lowest median gas consumption level, and followed by Wales. On the contrary, the median gas consumptions of all properties located in London region always keep the highest level across England and Wales, which may be caused by the regional high income level and high quality of life requirements. Otherwise, in each same floor area band, there are very slight fluctuations between the gas consumptions of properties located in the other regions, which suggests that variation of floor area should be able to cause larger influence to determine the domestic gas consumption than the variation of geographic difference.

6.3.2 Heating demands estimations in different UK domestic scenarios

In each cross-variations category (see section 6.3.1), the study can utilize the median gas consumptions in specific dwelling classifications of mid-terraced property type, 3 adult occupants, pre-1919 built, and North East regional location as the baselines, and further compared with domestic gas consumptions of other dwelling scenarios for detecting different gas consumption change percents as shown in Table 6.2, Table 6.3, Table 6.4 and Table 6.5.

Property type / Floor area	Mid terrace (kWh)	End terrace	Semi detached	Detached	Bungalow
50 m^2 or less	7800	-1.28%	N/A	N/A	+3.85%
51 m^2 to 100 m^2	10100	+9.90%	+19.80%	+32.67%	+17.82%
101 m^2 to 150 m^2	13400	+6.72%	+15.67%	+25.37%	+30.60%
151 m^2 to 200 m^2	19700	+5.58%	+16.24%	+11.17%	+18.27%
over 200 m^2	26000	+5.38%	+13.85%	+9.62%	N/A

Table 6.2 The change trend of the gas consumption by floor area and property type * The gas consumptions of the mid-terraced properties with different floor area categories are utilized as the baselines to compare with the other property types.

Adult number / Floor area	3 adults (kWh)	1 adult	2 adults	4 adults	5 or more
50 m^2 or less	8000	-26.25%	-12.50%	+11.25%	+27.50%
51 m^2 to 100 m^2	12300	-18.70%	-6.50%	+6.50%	+12.20%
101 m^2 to 150 m^2	16300	-13.50%	-4.91%	+4.91%	+11.04%
151 m^2 to 200 m^2	22800	-11.84%	-5.70%	+3.51%	+8.33%
over 200 m^2	29200	-8.90%	-4.11%	+3.08%	+6.51%

Table 6.3 The change trend of the gas consumption by floor area and number of adults * The gas consumptions of properties with 3 adults in different floor area categories are utilized as the baselines to compare with the other numbers of adults.

Finally, if importing the monthly heating demands results (see Table 6.6) studied in Chapter 4 as the typical representative of domestic heating demands in one specific baseline scenario which is pre-1919 mid-terraced dwelling with 151 m^2 to 200 m^2 floor area, 3 adult occupants and located in North East region, it would be able to rationally combine with different scale

Floor area \ Property age	Pre 1919 (kWh)	1919-44	1945-64	1965-82	1983-92	1993-99	Post 1999
50 m^2 or less	7700	+1.30%	-10.39%	-24.68%	-25.97%	-24.68%	-27.27%
51 m^2 to 100 m^2	11100	+13.51%	+5.41%	-2.70%	-13.51%	-15.32%	-20.72%
101 m^2 to 150 m^2	15800	+8.23%	-3.80%	-5.70%	-2.53%	-5.06%	-15.82%
151 m^2 to 200 m^2	22900	+9.61%	+1.75%	-6.11%	-13.54%	-15.28%	-22.27%
over 200 m^2	29900	+7.69%	-0.67%	-6.36%	-13.04%	-14.72%	-20.07%

Table 6.4 The change trend of the gas consumption by floor area and property age * The gas consumptions of properties built in pre 1919 with different floor area categories are utilized as the baselines to compare with the other property ages.

Floor area \ Region	North East (kWh)	North West	Yorkshire & Humber	East Midlands	West Midlands	East of England	London	Wales	South East	South West
50 m^2 or less	7000	-15.71%	-10.00%	-12.86%	-12.86%	-11.43%	+5.71%	-17.14%	-11.43%	-21.43%
51 m^2 to 100 m^2	11900	-6.72%	-1.68%	-3.36%	-4.20%	-6.72%	+2.52%	-10.08%	-8.40%	-20.17%
101 m^2 to 150 m^2	16100	-3.73%	+0.62%	-3.11%	-3.11%	-3.73%	+11.18%	-11.80%	-4.97%	-16.77%
151 m^2 to 200 m^2	22900	-3.06%	-0.44%	-6.99%	-3.06%	-6.55%	+11.79%	-14.85%	-5.24%	-18.78%
over 200 m^2	29100	-2.41%	+0.69%	-5.16%	-2.75%	-2.41%	+13.06%	-13.75%	-2.06%	-14.09%

Table 6.5 The change trend of the gas consumption by floor area and region * The gas consumptions of the North East region with different floor area categories are utilized as the baselines to compare with the other regions.

plates of gas consumption change percents for reckoning possible monthly heating demands in any other UK domestic scenarios.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Monthly heating demand (kWh/month)	2607.45	2478.67	2107.00	1182.96	717.84	0.00	0.00	0.00	252.05	848.02	1711.77	2107.33	14013.10

Table 6.6 Monthly heating demands of typical baseline scenario: pre-1919 mid-terraced dwellings with 151 m^2 to 200 m^2 floor area, 3 adult occupants and located in North East region

For instance to estimate possible monthly heating demands in a specific domestic scenario which is a post 1999 end-terraced property with 151 m^2 to 200 m^2 floor area, 4 adult occupants and located in North West region. According to relevant estimation results of gas consumption change percents, in 151 m^2 to 200 m^2 floor area band, Table 6.2 shows median gas consumption of end-terraces is 5.58% more than mid terraces; Table 6.3 indicates typical gas consumption of dwelling with 4 adults will increase 3.51% more than dwellings with 3 adults; Table 6.4 shows properties built in post 1999 can save 22.27% gas consumption less than properties built in pre-1919; Table 6.5 shows the gas consumption of properties located in North West region usually reduce 3.06% less than properties located in North East region. Hence, the specific monthly heating demands in this end-terraced scenario will be reckoned by: monthly heating demands of typical mid-terraced baseline scenario $\times$ $(1 + 5.58\%) \times (1 + 3.51\%) \times (1 - 22.27\%) \times (1 - 3.06\%)$. Relevant estimation results are shown in Table 6.7.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Monthly heating demand (kW h/month)	2147.20	2041.15	1735.08	974.15	591.13	0.00	0.00	0.00	207.56	698.33	1409.62	1735.36	11539.58

Table 6.7 Monthly heating demands estimation in post 1999 end-terraced dwelling with 151 m^2 to 200 m^2 floor area, 4 adult occupants and located in North West region

6.4 Renewable energy sources investigation and power output estimation

6.4.1 Solar energy output simulations in various UK domestic scenarios

The irradiance distribution in the UK territory is usually not uniform. [22] has demonstrated the annual irradiance changes in different regions as show in Figure 6.5. In here the study can utilize the annual irradiance level of the North East as a baseline and compared with the irradiances of other regions to calculate the regional irradiance change percents (see Figure 6.6).

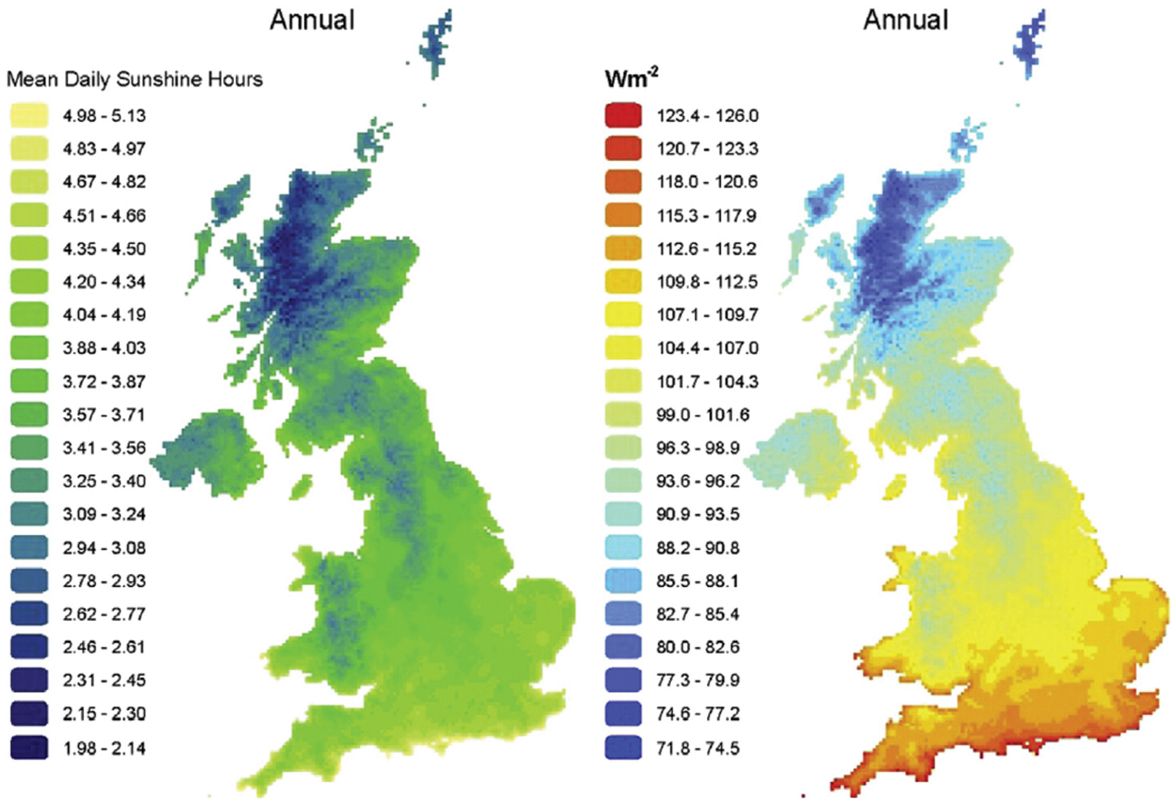


Fig. 6.5 Average daily annual sunshine hours and converted solar irradiance over the baseline time period

If importing the specific monthly roof irradiations (in unit of kW h/month, see Table 6.8) estimated in Chapter 4 to represent the typical roof irradiation levels of properties with roof areas of 90 m^2 and located in North East region, the monthly electricity outputs (in unit of kW h/month) by applying roof PV panels in various domestic scenarios of other regions can be estimated by:

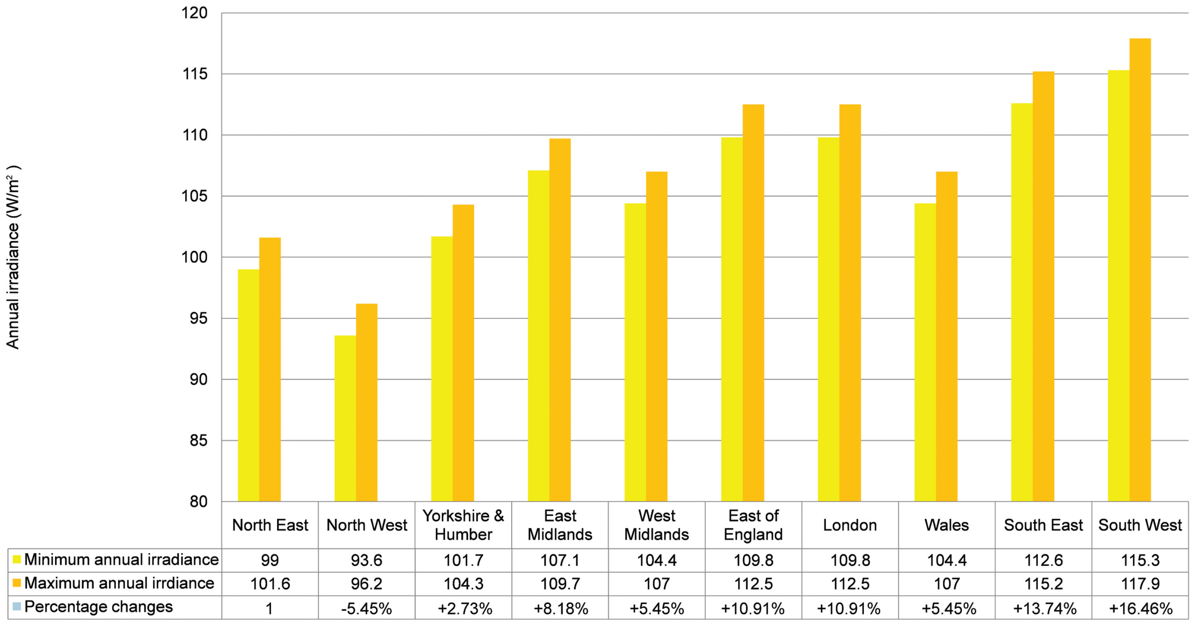


Fig. 6.6 The change trend of the regional irradiance * The irradiance of the North East is utilized as the baseline to compare with the other regions, and the percentage changes are calculated rely on the minimum annual irradiance level of each region.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Monthly roof irradiation (kW h/month)	1215.08	2361.05	4648.93	6452.62	8753.43	8660.36	8442.07	7817.63	5083.70	3103.53	1477.97	831.89	58848.26

Table 6.8 Monthly roof irradiations of typical baseline scenario: mid-terraced property with roof areas of 90 m^2 and located in North East region

- the specific electricity outputs by applying roof PV panels in detached, semi-detached, mid-terraced and end-terraced properties with 151 m^2 to 200 m^2 floor area (i.e. corresponding roof areas are around 90 m^2) are calculated by: roof irradiation of baseline scenario × (1 + regional irradiance change percent) × available PV arrays area ratio (90%) × PV panel efficiency;

- When the PV panels are applied on the roof of detached, semi-detached, mid-terraced and end-terraced properties with 50 m^2 or less floor area, the available roof areas for installing PV panels will correspondingly reduce to about 22.5 m^2. Thus the specific solar energy outputs can be calculated by: roof irradiation of baseline scenario × 1/4 × (1 + regional irradiance change percent) × available PV arrays area ratio (90%) × PV panel efficiency;

- the specific electricity outputs by applying roof PV panels in detached, semi-detached, mid-terraced and end-terraced properties with 51 m^2 to 100 m^2 floor area (i.e. corresponding roof areas are around 45 m^2) are calculated by: roof irradiation of baseline scenario × 1/2 × (1 + regional irradiance change percent) × available PV arrays area ratio (90%) × PV panel efficiency;

- the specific electricity outputs by applying roof PV panels in detached, semi-detached, mid-terraced and end-terraced properties with 101 m^2 to 150 m^2 floor area (i.e. corresponding roof areas are around 67.5 m^2) are calculated by: roof irradiation of baseline scenario $\times$ 3/4 $\times$ (1 + regional irradiance change percent) $\times$ available PV arrays area ratio (90%) $\times$ PV panel efficiency;

- it notes that available roof areas of bungalows where allow installing PV panels are always twice as large as the other types of properties when their total floor areas are equivalent. Thus based on above calculation results, the corresponding electricity outputs by applying roof PV panels in bungalows with various floor areas should be calculated as doubled.

6.4.2 Wind energy output simulations in various UK domestic scenarios

For estimating the possible wind energy outputs in various UK domestic scenarios, it needs to firstly investigate the wind resource distributions across England and Wales where are divided into ten different regions: North East, North West, Yorkshire & Humber, East Midlands, West Midlands, East of England, London, Wales, South East, and South West. In each region the investigation will select a typical city as the regional representative, then via importing the specific city coordinate information (i.e. Latitude & Longitude) into the Surface meteorology and Solar Energy Data Set [19], it can finally collect historical weather data (involve monthly mean wind speed and horizontal solar radiation) of various regions (see Appendix B).

Based on the investigated monthly wind speed levels in different regions, it can apply the HOMER software tool (see Figure 6.7) and same simulation methods utilized in the case study of Chapter 4 to synthesize detailed daily wind speed data with hourly resolution in each month, and further combine with specific wind turbine performance parameters (model: SM-1000) to simulate the monthly wind energy outputs (in unit of kW h/month) throughout the year by empolying one SM-1000 wind turbine in various regions (see Table 6.9).

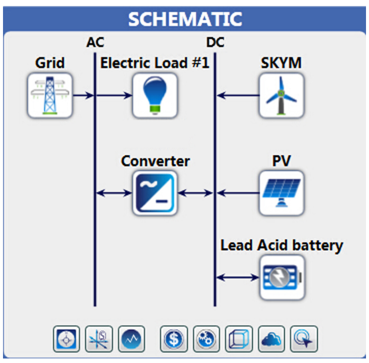


Fig. 6.7 Simulation interface of HOMER

Region \ Monthly output	Jan (kWh)	Feb (kWh)	Mar (kWh)	Apr (kWh)	May (kWh)	Jun (kWh)	Jul (kWh)	Aug (kWh)	Sep (kWh)	Oct (kWh)	Nov (kWh)	Dec (kWh)	Annual (kWh)
North East (Newcastle)	146.94	113.49	127.10	78.05	61.92	48.32	45.69	53.67	78.26	102.45	110.71	133.71	1100.31
North West (Greater Manchester)	108.11	77.21	108.08	68.30	57.44	48.12	38.70	39.00	59.82	75.37	93.22	102.22	875.59
Yorkshire & Humber (York)	133.58	103.20	120.65	73.17	57.64	48.29	42.17	49.74	73.42	96.71	104.78	127.10	1030.45
East Midlands (Lincoln)	168.46	131.91	134.09	83.40	62.14	48.49	49.53	57.94	83.59	114.77	123.31	147.62	1205.25
West Midlands (Birmingham)	180.98	131.33	166.53	99.14	80.55	68.65	61.50	66.39	99.30	126.74	155.50	174.94	1411.55
East of England (Great Yarmouth)	239.63	196.65	196.90	136.68	109.02	83.79	91.77	97.79	130.23	189.39	190.85	218.48	1881.18
London (London)	181.59	131.77	160.06	99.47	80.82	64.44	66.16	62.15	94.10	127.17	149.20	168.37	1385.30
Wales (Cardiff)	306.66	244.16	257.62	181.99	146.41	116.55	114.41	127.11	161.26	230.30	256.70	290.00	2433.17
South East (Southampton)	196.59	157.41	160.40	111.31	86.20	69.03	66.31	66.77	88.90	140.62	149.51	175.89	1468.94
South West (Plymouth)	334.02	277.21	279.21	217.97	174.51	128.75	127.91	141.16	169.24	259.73	283.39	318.53	2711.63

Table 6.9 The simulation results of monthly wind energy outputs of one SM-1000 wind turbine in various regions

Furthermore, in various UK domestic scenarios, the allowable installment number of wind turbines are assumed as:

- mid-terraced, end-terraced, semi-detached and detached properties with 100 m^2 or less floor areas can merely employ one stand-alone SM-1000 wind turbine in each domestic scenario;
- mid-terraced, end-terraced, semi-detached and detached properties with 101 m^2 to 200 m^2 floor areas can employ two stand-alone SM-1000 wind turbines;
- bungalows with 100 m^2 or less floor areas can employ two stand-alone SM-1000 wind turbines;
- bungalows with 101 m^2 to 200 m^2 floor areas can employ four stand-alone SM-1000 wind turbines.

Hence, the total wind energy outputs in various UK domestic scenarios can be simply calculated by: regional wind energy outputs by one wind turbine $\times$ wind turbine number employed in the corresponding domestic scenario.

6.5 Heating supply-demand relationship in various UK domestic scenarios

Section 6.3.2, section 6.4.1 and section 6.4.2 have confirmed relevant baselines and estimation methods regarding the monthly heating demands, solar energy outputs by roof PV panels and wind energy outputs by wind turbines in various domestic scenarios respectively. Hereby in this section it can further estimate possible heating supply-demand relationships and energy saving efficiencies caused by applying TE heating system powered by hybrid energy (i.e. solar/wind renewable energy and utility grid supply) to service for more UK domestic scenarios.

Before the start of relevant estimations, some necessary assumptions are adopted as following:

- necessary frames of PV panels and installation will occupy 10% available roof area and PV panel efficiency can be generally considered as 15.5% suggested by I-Scope ®[109];
- the average heating COP of TE modules is assumed as a minimum test value of 1.8;
- in order to address the renewable energy storage issue, the circuit design commonly requires two necessary DC/DC converters to optimize the output voltage of PV panels (so-called maximum power point tracker) and control the charging voltage of batteries respectively [134]. It notes that the overall circuit efficiency is calculated by multiplying all individual efficiencies of participated system components. For instance, if employing two DC/DC converters with 95% efficiency to connect lead-acid batteries with 90% efficiency, the corresponding energy storage efficiency should be calculated by 95% $\times$ 95% $\times$ 90% $\approx$ 81.23%. In here the average energy throughput from batteries to power TE heating system is assumed as 80% of initial power production of renewable energy (i.e. solar and wind energy);
- if TE heating system needs additional power from the utility grid during any shortage periods of the renewable energy supply, the AC current supplied by the grid would be required to be converted into DC current by AC/DC rectifier to operate TE modules. The energy loss in the conversion process between AC power and DC power is assumed as constant 20% in this simulation;
- the domestic hot water demand is mainly determined by the number of occupants. If assuming the average domestic hot water (DWH) consumption is 2.5 kWh/day per people, the corresponding monthly DWH demands (kWh/month) in various domestic scenarios would be calculated as shown in Table 6.10. In following simulations, in any months if the renewable energy production is capable of fully meeting the monthly domestic heating demands and still has a surplus, the excess energy could be considered for the hot water supply purpose with energy efficiency is assumed as 100% (i.e. heating COP = 1);
- the energy efficiency of a general electric heater is typically considered as 100% [110].

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1 occupant (kW h/month)	77.50	70.00	77.50	75.00	77.50	75.00	77.50	77.50	75.00	77.50	75.00	77.50
2 occupants (kW h/month)	155.00	140.00	155.00	150.00	155.00	150.00	155.00	155.00	150.00	155.00	150.00	155.00
3 occupants (kW h/month)	232.50	210.00	232.50	225.00	232.50	225.00	232.50	232.50	225.00	232.50	225.00	232.50
4 occupants (kW h/month)	310.00	280.00	310.00	300.00	310.00	300.00	310.00	310.00	300.00	310.00	300.00	310.00

Table 6.10 Domestic hot water demands

Hereby the study can firstly detect the heating supply-demand relationship, energy saving efficiency and DHW supply caused by employing TE heating system with hybrid energy supply in a Pre-1919 mid-terraced property with 151 m^2 to 200 m^2 floor area, 3 adult occupants and located in North East region which is similar with the case study scenario in Chapter 4. All detailed estimation results involve monthly domestic heating demands, monthly renewable energy outputs (i.e. solar and wind energy outputs), reachable maximum heat generation of TE heating system if merely powered by local renewable energy in each month, energy saving efficiency in comparison with using general electricity radiator, and feasibility of DHW supplied by excess monthly renewable energy outputs have been summarized in Table 6.11.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total	Energy saving
Monthly heating demand (kW h/month)	2607.45	2478.67	2107.00	1182.96	717.84	0.00	0.00	0.00	252.05	848.02	1711.77	2107.33	14013.10	64.93%
Roof PV panels outputs (kW h/month)	169.50	329.37	648.53	900.14	1221.10	1208.12	1177.67	1090.56	709.18	432.94	206.18	116.05	8209.33	
Two wind turbines outputs (kW h/month)	293.88	226.98	254.20	156.10	123.84	96.64	91.38	107.34	156.52	204.90	221.42	267.42	2200.62	
Renewable final output * (kW h/month)	370.71	445.08	722.18	844.99	1075.95	1043.81	1015.24	958.32	692.56	510.27	342.08	306.77	8327.96	
Heat generation (COP=1.8)	667.27	801.14	1299.93	1520.99	1936.72	1878.85	1827.43	1724.98	1246.60	918.49	615.74	552.19	14990.33	
Excess heat (kW h/month)	-1940.18	-1677.53	-807.07	338.03	1218.88	1878.85	1827.43	1724.98	994.55	70.48	-1096.03	-1555.14	977.23	
Feasibility of monthly self-heating	×	×	×	✓	✓	✓	✓	✓	✓	✓	×	×	✓	
Hot water supply **				★ (blue)	★ (red)	★ (red)	★ (red)	★ (red)	★ (red)	★ (blue)				

Table 6.11 Simulation of domestic scenario which is Pre-1919 mid-terraced property with 151 m^2 to 200 m^2 floor area, 3 occupants and located in North East region

* final renewable energy output is calculated by: (monthly solar energy output by roof PV panels + monthly wind energy output by wind turbines) × overall efficiency (80%) of renewable energy storage.

** ★ (red) indicates the monthly hot water demand can be fully meet by using the excess renewable energy production; ★ (blue) indicates the monthly hot water demand can be partly meet by using the excess renewable energy production.

Utilizing similar simulation methods, it can further estimate heating supply-demand relationship, energy saving efficiency and DHW supply in more different scenarios such as a Pre-1919 end-terraced property with 151 m^2 to 200 m^2 floor area, 3 occupants, and located in North East region. Table 6.12 demonstrates that both heating supply-demand relationship and available

DHW supply period caused by employing TE heating system with hybrid energy supply in this end-terraced dwelling are mostly close to the estimation results in above mid-terraced dwelling which is also located in North East region and has similar floor area, property age and same number of occupants. Meanwhile the annual energy saving efficiency is finally estimated as 63.02% which only reduces 1.01% due to the minor increase of heating demands in the end-terraced type of property.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total	Energy saving
Monthly heating demand (kW h/month)	2752.95	2616.98	2224.57	1248.97	757.90	0.00	0.00	0.00	266.12	895.34	1807.29	2224.92	14795.03	63.90% *
Roof PV panels outputs (kW h/month)	169.50	329.37	648.53	900.14	1221.10	1208.12	1177.67	1090.56	709.18	432.94	206.18	116.05	8209.33	
Two wind turbines outputs (kW h/month)	293.88	226.98	254.20	156.10	123.84	96.64	91.38	107.34	156.52	204.90	221.42	267.42	2200.62	
Renewable final output (kW h/month)	370.71	445.08	722.18	844.99	1075.95	1043.81	1015.24	958.32	692.56	510.27	342.08	306.77	8327.96	
Heat generation (COP=1.8)	667.27	801.14	1299.93	1520.99	1936.72	1878.85	1827.43	1724.98	1246.60	918.49	615.74	552.19	14990.33	
Excess heat (kW h/month)	-2085.68	-1815.84	-924.64	272.02	1178.82	1878.85	1827.43	1724.98	980.48	23.16	-1191.55	-1672.73	195.30	
Feasibility of monthly self-heating	×	×	×	✓	✓	✓	✓	✓	✓	✓	×	×	✓	
Hot water supply				★	★	★	★	★	★					

Table 6.12 Simulation of domestic scenario which is Pre-1919 end-terraced property with 151 m^2 to 200 m^2 floor area, 3 occupants and located in North East region
* compared with using generic electric heaters powered by the grid electricity supply, the energy saving efficiency of TE heating system with hybrid energy supply is estimated by similar calculation method utilized in the case study in Chapter 4.

Moreover, in section 6.3.2, the statistical results of median gas consumptions in the cross-variations category of floor area/region (see Figure 6.4) demonstrate that the properties located in North East region mostly have the most gas demands, and followed by the properties located in Yorkshire & Humber region (note: the London is excluded as a special case due to its special household characteristics such as high income level, high life quality requirements and high population density, etc). Meanwhile the properties located in South West region always have the least gas demands. Furthermore, the regional irradiance investigation results (see Figure 6.6 in section 6.4.1) and regional wind speed statistical results (see section 6.4.2) reveal South West region always keeps the highest irradiance level and the highest wind speed whilst North West region usually has the lowest irradiance level and the lowest wind speed, and followed by North East and Yorkshire & Humber regions. Hence, it seems that the application of TE heating system with hybrid energy supply can most likely reach the highest energy efficiency and the lowest energy saving efficiency respectively in some domestic scenarios located in above regions.

Hereby this study will focus on simulating the applications of TE heating system with hybrid energy supply in various domestic scenarios located in North East, North West, Yorkshire & Humber, and South West regions respectively as shown in Table 6.13. All detailed simulation results in corresponding scenarios can be checked in Appendix C, Appendix D, Appendix E and Appendix F.

	Floor area	Number of adults	Property type	Property age	Region
Scenario 1	151 m^2 to 200 m^2	3	Various	Pre-1919	North East
Scenario 2	151 m^2 to 200 m^2	4	Various	Pre-1919	North East
Scenario 3	151 m^2 to 200 m^2	4	Various	1919-44	North East
Scenario 4	151 m^2 to 200 m^2	4	Various	Post 1999	North East
Scenario 5	101 m^2 to 150 m^2	3	Various	Pre-1919	North East
Scenario 6	101 m^2 to 150 m^2	3	Various	1919-44	North East
Scenario 7	101 m^2 to 150 m^2	3	Various	Post 1999	North East
Scenario 8	51 m^2 to 100 m^2	2	Various	Pre-1919	North East
Scenario 9	51 m^2 to 100 m^2	2	Various	1919-44	North East
Scenario 10	51 m^2 to 100 m^2	2	Various	Post 1999	North East
Scenario 11	50 m^2 or less	1	Various	Pre-1919	North East
Scenario 12	50 m^2 or less	1	Various	Post 1999	North East
Scenario 13	151 m^2 to 200 m^2	4	Various	Pre-1919	North West
Scenario 14	151 m^2 to 200 m^2	4	Various	1919-44	North West
Scenario 15	151 m^2 to 200 m^2	4	Various	Post 1999	North West
Scenario 16	101 m^2 to 150 m^2	3	Various	Pre-1919	North West
Scenario 17	101 m^2 to 150 m^2	3	Various	1919-44	North West
Scenario 18	101 m^2 to 150 m^2	3	Various	Post 1999	North West
Scenario 19	51 m^2 to 100 m^2	2	Various	Pre-1919	North West
Scenario 20	51 m^2 to 100 m^2	2	Various	1919-44	North West
Scenario 21	51 m^2 to 100 m^2	2	Various	Post 1999	North West
Scenario 22	50 m^2 or less	1	Various	Pre-1919	North West
Scenario 23	50 m^2 or less	1	Various	Post 1999	North West
Scenario 24	151 m^2 to 200 m^2	4	Various	Pre-1919	Yorkshire&Humber
Scenario 25	151 m^2 to 200 m^2	4	Various	1919-44	Yorkshire&Humber
Scenario 26	151 m^2 to 200 m^2	4	Various	Post 1999	Yorkshire&Humber
Scenario 27	101 m^2 to 150 m^2	3	Various	Pre-1919	Yorkshire&Humber
Scenario 28	101 m^2 to 150 m^2	3	Various	1919-44	Yorkshire&Humber
Scenario 29	101 m^2 to 150 m^2	3	Various	Post 1999	Yorkshire&Humber
Scenario 30	51 m^2 to 100 m^2	2	Various	Pre-1919	Yorkshire&Humber
Scenario 31	51 m^2 to 100 m^2	2	Various	1919-44	Yorkshire&Humber
Scenario 32	51 m^2 to 100 m^2	2	Various	Post 1999	Yorkshire&Humber
Scenario 33	50 m^2 or less	1	Various	Pre-1919	Yorkshire&Humber
Scenario 34	50 m^2 or less	1	Various	Post 1999	Yorkshire&Humber
Scenario 35	151 m^2 to 200 m^2	4	Various	Pre-1919	South West
Scenario 36	151 m^2 to 200 m^2	4	Various	Post 1999	South West
Scenario 37	101 m^2 to 150 m^2	3	Various	Pre-1919	South West
Scenario 38	101 m^2 to 150 m^2	3	Various	Post 1999	South West
Scenario 39	51 m^2 to 100 m^2	2	Various	Pre-1919	South West
Scenario 40	51 m^2 to 100 m^2	2	Various	1919-44	South West
Scenario 41	51 m^2 to 100 m^2	2	Various	Post 1999	South West
Scenario 42	50 m^2 or less	1	Various	Pre-1919	South West
Scenario 43	50 m^2 or less	1	Various	Post 1999	South West

Table 6.13 Simulated applications of TE heating system with hybrid energy supply in various domestic scenarios

6.6 Simulation results and discussion

6.6.1 Supply-demand relationships of domestic heating and hot water supply in various simulated scenarios

Property type	**Independent heating period**	**Heating months***	**Potential hot water supply period**	**Hot water months****
Scenario 1				
Mid-terraced	Apr - Oct	4	Apr - Oct	5
End-terraced	Apr - Oct	4	Apr - Sep	5
Semi-detached	Apr - Sep	3	Apr -Sep	5
Detached	Apr - Sep	3	Apr -Sep	5
Bungalow	Mar - Oct	5	Mar- Oct	7
Scenario 2				
Mid-terraced	Apr - Oct	4	Apr - Sep	5
End-terraced	Apr - Sep	3	Apr - Sep	5
Semi-detached	Apr - Sep	3	Apr -Sep	5
Detached	Apr - Sep	3	Apr -Sep	5
Bungalow	Mar - Oct	5	Apr - Oct	7
Scenario 3				
Mid-terraced	Apr - Sep	3	Apr - Sep	5
End-terraced	Apr - Sep	3	Apr - Sep	5
Semi-detached	May - Sep	2	May -Sep	5
Detached	Apr - Sep	3	May -Sep	5
Bungalow	Apr - Oct	4	Apr - Oct	7
Scenario 4				
Mid-terraced	Apr - Oct	4	Apr - Oct	6
End-terraced	Apr - Oct	4	Apr - Oct	5
Semi-detached	Apr - Oct	4	Apr -Oct	5
Detached	Apr - Oct	4	Apr -Oct	5
Bungalow	Mar - Oct	5	Mar - Oct	8
Scenario 5				
Mid-terraced	Apr - Oct	4	Apr - Oct	5
End-terraced	Apr - Oct	4	Apr - Oct	5
Semi-detached	Apr - Oct	4	Apr -Oct	5
Detached	Apr - Oct	4	Apr -Sep	5
Bungalow	Mar - Oct	5	Mar - Oct	7
Scenario 6				
Mid-terraced	Apr - Oct	4	Apr - Oct	5
End-terraced	Apr - Oct	4	Apr - Oct	5
Semi-detached	Apr - Oct	4	Apr -Sep	5
Detached	Apr - Sep	3	Apr -Sep	5
Bungalow	Mar - Oct	5	Mar - Oct	7

Table 6.14 The supply-demand relationship results in various simulated scenarios of North East region (a)
$*$ the valued heating months are counted by all independent heating months without any external gird power supplements. Jun, Jul and Aug are excluded from the count results due to no heating demands in these months.
$**$ the number hot water months only count the months whose the monthly hot water demands can be fully supported by possible excess renewable energy production. Any partly supplement months are not counted into the results.

All the scenario simulation results summarized in Table 6.14 to Table 6.20 reveal that in most common property types contain mid-terraced, end-terraced, semi-detached and detached of

Property type	Independent heating period	Heating months*	Potential hot water supply period	Hot water months**
Scenario 7				
Mid-terraced	Apr - Oct	4	Apr - Oct	6
End-terraced	Apr - Oct	4	Apr - Oct	6
Semi-detached	Apr - Oct	4	Apr -Oct	6
Detached	Apr - Oct	4	Apr -Oct	5
Bungalow	Mar - Oct	5	Mar - Oct	8
Scenario 8				
Mid-terraced	Apr - Oct	4	Apr - Oct	5
End-terraced	Apr - Oct	4	Apr - Sep	5
Semi-detached	Apr - Sep	3	Apr -Sep	5
Detached	Apr - Sep	3	May-Sep	5
Bungalow	Mar - Oct	5	Mar - Oct	7
Scenario 9				
Mid-terraced	Apr - Sep	3	Apr - Sep	5
End-terraced	Apr - Sep	3	Apr - Sep	5
Semi-detached	May - Sep	2	May -Sep	5
Detached	May - Sep	2	May -Sep	5
Bungalow	Apr - Oct	4	Apr - Oct	7
Scenario 10				
Mid-terraced	Apr - Oct	4	Apr - Oct	6
End-terraced	Apr - Oct	4	Apr - Oct	5
Semi-detached	Apr - Oct	4	Apr -Oct	5
Detached	Apr - Oct	4	Apr -Oct	5
Bungalow	Mar - Oct	5	Mar - Oct	8
Scenario 11				
Mid-terraced	Apr - Oct	4	Apr - Oct	5
End-terraced	Apr - Oct	4	Apr - Oct	5
Bungalow	Mar - Oct	5	Mar - Oct	8
Scenario 12				
Mid-terraced	Apr - Oct	4	Apr - Oct	6
End-terraced	Apr - Oct	4	Apr - Oct	6
Bungalow	Feb - Dec	8	Feb - Nov	8

Table 6.15 The supply-demand relationship results in various simulated scenarios of North East region (b)

England northern regions (i.e. North East, North West, and Yorkshire & Humber), the TE heating system powered by local renewable energy (i.e. solar and wind energy) can generally meet the domestic heating demands for 2 to 4 months throughout the year without any energy requirements to the external grid system. Meanwhile in the UK southern region (i.e. South West), the entire system is likely able to fully meet the domestic heating demands for 4 to 6 months due to the lower local heating demands and more available renewable energy resources supply. Moreover, in any same region, the system applied in bungalows can potentially achieve longer independent heating period than in the other property types (i.e. the system can independently support the domestic heating demands for 4 to 5 months per year in most bungalows of the northern regions and up to 8 to 9 months per year in all bungalows of South West region respectively) due to bungalows have larger roof areas and open space where allow setting more PV panels and wind turbines respectively.

In summary of all simulated scenarios, in some semi-detached and detached properties located in the northern regions such as scenario 3, scenario 9, scenario 14, scenario 20, scenario

Property type	**Independent heating period**	**Heating months***	**Potential hot water supply period**	**Hot water months****
Scenario 13				
Mid-terraced	Apr - Sep	3	Apr - Sep	5
End-terraced	Apr - Sep	3	Apr - Sep	5
Semi-detached	Apr - Sep	3	May - Sep	5
Detached	Apr - Sep	3	Apr - Sep	5
Bungalow	Apr - Oct	4	Apr - Oct	7
Scenario 14				
Mid-terraced	Apr - Sep	3	Apr - Sep	5
End-terraced	Apr - Sep	3	May - Sep	5
Semi-detached	May - Sep	2	May - Sep	5
Detached	May - Sep	2	May - Sep	5
Bungalow	Apr - Oct	4	Apr - Oct	6
Scenario 15				
Mid-terraced	Apr - Oct	4	Apr - Oct	5
End-terraced	Apr - Oct	4	Apr - Oct	5
Semi-detached	Apr - Oct	4	Apr - Sep	5
Detached	Apr - Oct	4	Apr - Oct	5
Bungalow	Mar - Oct	5	Mar - Oct	7
Scenario 16				
Mid-terraced	Apr - Oct	4	Apr - Oct	5
End-terraced	Apr - Oct	4	Apr - Oct	5
Semi-detached	Apr - Oct	4	Apr - Sep	5
Detached	Apr - Sep	3	Apr - Sep	5
Bungalow	Mar - Oct	5	Mar - Oct	7
Scenario 17				
Mid-terraced	Apr - Oct	4	Apr - Oct	5
End-terraced	Apr - Oct	4	Apr - Sep	5
Semi-detached	Apr - Sep	3	Apr - Sep	5
Detached	Apr - Sep	3	Apr - Sep	5
Bungalow	Apr - Oct	4	Apr - Oct	7

Table 6.16 The supply-demand relationship results in various simulated scenarios of North West region (a)

25 and scenario 31, the heating effect of TE heating system with renewable energy supply seems very poor (i.e. can merely support the independent heating in May and Sep). On the contrary, when the system services for bungalows in scenario 36, scenario 37, scenario 38, scenario 39, scenario 41, scenario 42, scenario 43, or mid-terraced and end-terraced properties in scenario 43, the optimal heating effect is suggested as long as 9 months independent heating periods which means all monthly heating demands can be fully meet throughout the year whilst off the utility grid supply.

Additionally, during the months of June, July and August, the roof PV panels can always maintain higher solar power output level whilst there are no domestic heating demands. And in some other months, the renewable energy outputs may also have surplus after fully supplying the monthly domestic heating demands. In above cases, the excess renewable energy can be considered using to support the domestic hot water purpose. Relevant simulation results show that the domestic hot water demands can be fully meet by excess renewable energy supply for 5-6 months (i.e. between Apr and Oct) in most scenarios of England northern regions, and 7-8 months (i.e. between Mar and Nov) in most scenarios of South West region. Furthermore, in bungalow scenarios, the fully supply periods of domestic hot water can be extended to 7-8

Property type	Independent heating period	Heating months*	Potential hot water supply period	Hot water months**
Scenario 18				
Mid-terraced	Apr - Oct	4	Apr - Oct	6
End-terraced	Apr - Oct	4	Apr - Oct	6
Semi-detached	Apr - Oct	4	Apr - Oct	5
Detached	Apr - Oct	4	Apr - Oct	5
Bungalow	Mar - Oct	5	Mar - Oct	8
Scenario 19				
Mid-terraced	Apr - Oct	4	Apr - Sep	5
End-terraced	Apr - Sep	3	Apr - Sep	5
Semi-detached	Apr - Sep	3	Apr - Sep	5
Detached	Apr - Sep	3	May - Sep	5
Bungalow	Mar - Oct	5	Mar - Oct	7
Scenario 20				
Mid-terraced	Apr - Sep	3	Apr - Sep	5
End-terraced	Apr - Sep	3	Apr - Sep	5
Semi-detached	May - Sep	2	May - Sep	5
Detached	May - Sep	2	May - Sep	5
Bungalow	Apr - Oct	4	Apr - Oct	7
Scenario 21				
Mid-terraced	Apr - Oct	4	Apr - Oct	6
End-terraced	Apr - Oct	4	Apr - Oct	5
Semi-detached	Apr - Oct	4	Apr - Oct	5
Detached	Apr - Oct	4	Apr - Sep	5
Bungalow	Mar - Oct	5	Mar - Oct	8
Scenario 22				
Mid-terraced	Apr - Oct	4	Apr - Oct	5
End-terraced	Apr - Oct	4	Apr - Oct	5
Bungalow	Mar - Oct	5	Mar - Oct	8
Scenario 23				
Mid-terraced	Apr - Oct	4	Apr - Oct	6
End-terraced	Mar - Oct	5	Apr - Oct	6
Bungalow	Mar - Nov	6	Mar - Nov	8

Table 6.17 The supply-demand relationship results in various simulated scenarios of North West region (b)

months per year in the northern regions and 9-12 months in South West region respectively. Especially in the South West scenarios of pre-1919 bungalow with 101 m^2 to 150 m^2 floor area and 3 occupants, post 1999 bungalow with 101 m^2 to 150 m^2 floor area and 3 occupants, post 1999 bungalow with 51 m^2 to 100 m^2 floor area and 2 occupants, pre-1919 bungalow with 50 m^2 or less floor area and 1 occupant, and post 1999 bungalow with 50 m^2 or less floor area and 1 occupant, the TE heating system merely powered by local renewable energy (i.e. off the utility grid supply) can fully meet both of monthly domestic heating demands and hot water demands throughout the year which are suggested as the best optimal results.

6.6.2 Energy saving efficiency in various simulated scenarios

The energy saving efficiency can potentially be deem as an important indication for evaluating the contributions of TE heating system powered by hybrid energy (i.e. solar/wind renewable energy and utility grid supply) in different domestic scenarios. In general, higher energy saving efficiency result will suggest a better potential of utilizing the system in corresponding scenario.

Property type	Independent heating period	Heating months*	Potential hot water supply period	Hot water months**
Scenario 24				
Mid-terraced	Apr - Oct	4	Apr - Sep	5
End-terraced	Apr - Sep	3	Apr - Sep	5
Semi-detached	Apr - Sep	3	Apr - Sep	5
Detached	Apr - Sep	3	Apr - Sep	5
Bungalow	Mar - Oct	5	Apr - Oct	7
Scenario 25				
Mid-terraced	Apr - Sep	3	Apr - Sep	5
End-terraced	Apr - Sep	3	Apr - Sep	5
Semi-detached	May - Sep	2	May - Sep	5
Detached	Apr - Sep	3	Apr - Sep	5
Bungalow	Apr - Oct	4	Apr - Oct	7
Scenario 26				
Mid-terraced	Apr - Oct	4	Apr - Oct	6
End-terraced	Apr - Oct	4	Apr - Oct	6
Semi-detached	Apr - Oct	4	Apr - Oct	5
Detached	Apr - Oct	4	Apr - Oct	5
Bungalow	Mar - Oct	5	Mar - Oct	8
Scenario 27				
Mid-terraced	Apr - Oct	4	Apr - Oct	5
End-terraced	Apr - Oct	4	Apr - Oct	5
Semi-detached	Apr - Oct	4	Apr - Oct	5
Detached	Apr - Oct	4	Apr - Sep	5
Bungalow	Mar - Oct	5	Mar - Oct	7
Scenario 28				
Mid-terraced	Apr - Oct	4	Apr - Oct	5
End-terraced	Apr - Oct	4	Apr - Oct	5
Semi-detached	Apr - Oct	4	Apr - Sep	5
Detached	Apr - Sep	3	Apr - Sep	5
Bungalow	Mar - Oct	5	Mar - Oct	7

Table 6.18 The supply-demand relationship results in various simulated scenarios of Yorkshire & Humber regions (a)

Table 6.21 has summarized all estimation results regarding the energy saving efficiency of TE heating system applied in various simulated scenarios. These results reveal that under the typical UK climate context (i.e. ambient temperature, irradiance and wind speed levels), in comparison with using generic electric heaters powered by the grid electricity supply to meet the domestic heating demands, the application of TE heating system with hybrid energy supply can save minimum 56.11% grid energy consumption in a 1919-44 detached property with 51 m^2 to 100 m^2 floor area, 2 occupants and located in North West region. Then if employing the heating system in other domestic heating scenarios of England northern regions, it would be able to achieve higher energy saving efficiency around 57.21%-81.57% in mid-terraced, end-terraced, semi-detached and detached properties, and around 71.40%-99.81% in bungalows respectively. Moreover, when employing the heating system in domestic scenarios of South West region, the energy saving efficiency can commonly remain above 74% and especially in some bungalow scenarios the energy saving efficiency is capable of reaching 100% which implies the dwelling heating system can completely off the grid supply.

Furthermore, comparing the energy saving efficiencies of TE heating system applied in different types of properties which have similar floor areas, property ages, equivalent number of

Property type	Independent heating period	Heating months*	Potential hot water supply period	Hot water months**
Scenario 29				
Mid-terraced	Apr - Oct	4	Apr - Oct	6
End-terraced	Apr - Oct	4	Apr - Oct	6
Semi-detached	Apr - Oct	4	Apr - Oct	6
Detached	Apr - Oct	4	Apr - Oct	5
Bungalow	Mar - Oct	5	Mar - Oct	8
Scenario 30				
Mid-terraced	Apr - Oct	4	Apr - Oct	5
End-terraced	Apr - Oct	4	Apr - Sep	5
Semi-detached	Apr - Sep	3	Apr - Sep	5
Detached	Apr - Sep	3	Apr - Sep	5
Bungalow	Mar - Oct	5	Mar - Oct	7
Scenario 31				
Mid-terraced	Apr - Oct	4	Apr - Sep	5
End-terraced	Apr - Sep	3	Apr - Sep	5
Semi-detached	Apr - Sep	3	May - Sep	5
Detached	May - Sep	2	May - Sep	5
Bungalow	Apr - Oct	4	Apr - Oct	7
Scenario 32				
Mid-terraced	Apr - Oct	4	Apr - Oct	6
End-terraced	Apr - Oct	4	Apr - Oct	6
Semi-detached	Apr - Oct	4	Apr - Oct	5
Detached	Apr - Oct	4	Apr - Oct	5
Bungalow	Mar - Oct	5	Mar - Oct	8
Scenario 33				
Mid-terraced	Apr - Oct	4	Apr - Oct	5
End-terraced	Apr - Oct	4	Apr - Oct	5
Bungalow	Mar - Oct	5	Mar - Oct	8
Scenario 34				
Mid-terraced	Mar - Oct	5	Apr - Oct	6
End-terraced	Mar - Oct	5	Mar - Oct	6
Bungalow	Feb - Dec	8	Feb - Dec	8

Table 6.19 The supply-demand relationship results in various simulated scenarios of Yorkshire & Humber regions (b)

occupants, and located in same region, the results show that the heating system can always achieve the highest energy saving efficiency in the property type of bungalow, and mostly followed by the mid-terraced and end-terraced types. It also notes that when the floor areas of dwelling are larger than 150 m^2, the energy saving efficiency of TE heating system applied in detached properties are commonly higher than in semi-detached properties. But in the 51 m^2-150 m^2 floor area band, the trend likely appears to opposite.

Finally, in comparison of different scenario simulation results between northern regions and southern regions, it shows that the change of energy saving efficiency caused by the regional difference in mid-terraced, end-terraced, semi-detached and detached dwellings with similar floor areas, property ages, and equivalent number of occupants is around 17.03%-28.66%. Similarly the regional difference influence to the change of energy saving efficiency in bungalow properties is around 0.19%-25.60%. Additionally, the property age changes from pre-1919 to post 1999 in all same scenarios can commonly cause about 4%-10% increase of the energy saving efficiency. Hereby the TE heating system should be most likely recommended to service for the dwellings

Property type	Independent heating period	Heating months*	Potential hot water supply period	Hot water months**
Scenario 35				
Mid-terraced	Mar - Oct	5	Mar - Oct	7
End-terraced	Mar - Oct	5	Apr - Oct	7
Semi-detached	Apr - Oct	4	Apr - Oct	7
Detached	Apr - Oct	4	Apr - Oct	7
Bungalow	Feb - Dec	8	Feb - Dec	9
Scenario 36				
Mid-terraced	Mar - Nov	6	Mar - Oct	7
End-terraced	Mar - Oct	5	Mar - Oct	7
Semi-detached	Mar - Oct	5	Mar - Oct	7
Detached	Mar - Oct	5	Mar - Oct	7
Bungalow	Jan - Dec	9	Jan - Dec	11
Scenario 37				
Mid-terraced	Mar - Nov	6	Mar - Nov	8
End-terraced	Mar - Nov	6	Mar - Nov	7
Semi-detached	Mar - Oct	5	Mar - Oct	7
Detached	Mar - Oct	5	Mar - Oct	7
Bungalow	Jan - Dec	9	Jan - Dec	12
Scenario 38				
Mid-terraced	Feb - Dec	8	Mar - Dec	8
End-terraced	Mar - Nov	6	Mar - Nov	8
Semi-detached	Mar - Nov	6	Mar - Nov	8
Detached	Mar - Nov	6	Mar - Nov	7
Bungalow	Jan - Dec	9	Jan - Dec	12
Scenario 39				
Mid-terraced	Mar - Oct	5	Mar - Oct	7
End-terraced	Mar - Oct	5	Mar - Oct	7
Semi-detached	Apr - Oct	4	Apr - Oct	7
Detached	Apr - Oct	4	Apr - Oct	7
Bungalow	Jan - Dec	9	Jan - Dec	9
Scenario 40				
Mid-terraced	Mar - Oct	5	Mar - Oct	7
End-terraced	Apr - Oct	4	Apr - Oct	7
Semi-detached	Apr - Oct	4	Apr - Oct	7
Detached	Apr - Oct	4	Apr - Oct	6
Bungalow	Feb - Dec	8	Feb - Dec	9
Scenario 41				
Mid-terraced	Mar - Nov	6	Mar - Nov	8
End-terraced	Mar - Nov	6	Mar - Oct	7
Semi-detached	Mar - Oct	5	Mar - Oct	7
Detached	Mar - Oct	5	Mar - Oct	7
Bungalow	Jan - Dec	9	Jan - Dec	12
Scenario 42				
Mid-terraced	Mar - Dec	7	Mar - Dec	8
End-terraced	Mar - Dec	7	Mar - Dec	8
Bungalow	Jan - Dec	9	Jan - Dec	12
Scenario 43				
Mid-terraced	Jan - Dec	9	Jan - Dec	9
End-terraced	Jan - Dec	9	Jan - Dec	9
Bungalow	Jan - Dec	9	Jan - Dec	12

Table 6.20 The supply-demand relationship results in various simulated scenarios of South West region

newly built with better insulation performance in the UK southern region than the old dwellings with poor insulation performance in England northern regions.

Property type \ Region & Age	North East Pre-1919	North East 1919-44	North East Post 1999	North West Pre-1919	North West 1919-44	North West Post 1999	York-shire Pre-1919	York-shire 1919-44	York-shire Post 1999	South West Pre-1919	South West 1919-44	South West Post 1999
151 m^2 **to** 200 m^2 **floor area and 3 occupants**												
Mid-terraced	64.93											
End-terraced	63.90											
Semi-detached	61.92											
Detached	62.87											
Bungalow	77.96											
151 m^2 **to** 200 m^2 **floor area and 4 occupants**												
Mid-terraced	64.27	62.43	69.67	62.04	60.22	67.09	64.04	62.24	69.38	84.58		92.48
End-terraced	63.24	61.31	68.39	60.94	59.21	65.94	63.04	61.13	68.11	83.06		90.85
Semi-detached	61.22	59.32	66.28	59.13	57.21	64.06	61.04	59.26	66.03	79.72		87.65
Detached	62.13	60.30	67.24	59.95	58.21	64.91	61.95	60.13	66.97	81.28		89.10
Bungalow	77.21	74.50	83.33	73.90	71.40	79.66	76.72	74.15	82.70	99.50		100
101 m^2 **to** 150 m^2 **floor area and 3 occupants**												
Mid-terraced	70.25	68.36	74.92	67.44	65.76	71.58	69.52	67.69	74.05	94.56		99.30
End-terraced	68.69	66.92	73.06	66.05	64.48	69.93	68.00	66.29	72.25	92.66		97.98
Semi-detached	66.89	65.26	70.92	64.46	62.79	68.03	66.26	64.67	70.17	90.12		95.38
Detached	65.23	63.61	68.95	62.76	61.12	66.28	64.65	63.03	68.26	87.47		92.98
Bungalow	81.98	80.00	86.89	78.29	76.57	82.51	80.94	79.03	85.65	100		100
51 m^2 **to** 100 m^2 **floor area and 2 occupants**												
Mid-terraced	65.77	63.33	71.09	64.32	61.80	69.25	65.78	63.36	71.10	87.41	83.65	94.64
End-terraced	63.94	61.34	68.78	62.48	59.95	67.11	63.95	61.41	68.79	84.57	80.53	91.91
Semi-detached	62.17	59.60	66.85	60.72	58.33	65.31	62.25	59.74	66.86	81.98	77.63	89.07
Detached	60.14	57.25	64.77	58.83	56.11	63.39	60.21	57.47	64.78	78.43	74.50	85.85
Bungalow	79.00	75.85	85.05	76.70	73.67	82.14	78.75	75.86	84.73	100	99.15	100
50 m^2 **or less floor area and 1 occupant**												
Mid-terraced	69.85		79.01	69.67		78.77	71.68		81.24	98.33		100
End-terraced	70.17		79.45	69.99		79.08	72.02		81.57	98.63		100
Bungalow	89.29		99.33	87.97		97.59	91.41		99.81	100		100

Table 6.21 The energy saving efficiency caused by applying TE heating system powered by hybrid energy in various domestic heating scenarios

6.7 Summary

In this chapter, for ascertaining the feasibility of universally applying the TE system with renewable energy supply in the UK domestic heating context, relevant baselines and estimation methods regarding the monthly heating demands, solar energy outputs by roof PV panels and wind energy outputs by wind turbines in various domestic scenarios have been defined and studied respectively. The possible heating supply-demand relationships, energy saving efficiencies and hot water supply caused by applying TE heating system with hybrid energy supply (i.e. solar/wind renewable energy and utility grid supply) to service for different UK domestic scenarios across England and Wales were further estimated. The main summaries are listed as follows:

1. Under the typical UK climate context (i.e. ambient temperature, irradiance and wind speed levels), the TE heating system powered by renewable energy generally can independently

meet the domestic heating demands for 2-6 months per year (i.e. exclude June, July and August) in most property types (i.e. involve mid-terraced, end-terraced, semi-detached and detached). Moreover, it seems that this system can better heating the bungalow property without any external grid supply requirements for 4-9 months per year benefited from more allowable renewable energy supply (i.e. larger roof areas and surrounding open space where allow installing more PV panels and wind turbines).

2. Compared with using generic electric heaters powered by the grid electricity supply to meet the domestic heating demands, the application of TE heating system with hybrid energy supply can save more than 56% grid energy consumption when heating COP remains above 1.8. Higher energy saving efficiency is most likely achieved in the property type: bungalow > mid-terrace > end terrace > semi-detached > detached.

3. For supplying the domestic heating demands, the TE heating system with hybrid energy supply can save minimum 56.11% grid energy consumption when servicing for a 1919-44 detached property with 51 m^2 to 100 m^2 floor area, 2 occupants and located in North West region. Meanwhile in some domestic scenarios of South West region, the maximum energy saving efficiency of 100% can be reached (i.e. it means that the dwelling heating system can completely off the grid supply) whilst the annual domestic hot water demands can also be fully meet.

4. Compared with most domestic scenarios of England northern regions, the energy saving efficiency estimated in similar domestic scenarios of the UK southern regions can relatively raise maximum 28.66% because of lower domestic heating demands level and more available renewable energy supply in the local context. And the property age changes from pre-1919 to post 1999 in all same scenarios can cause about 4%-10% increase of the energy saving efficiency benefited from higher thermal insulation standard for newly built buildings.

Finally, when applying TE heating system in the domestic scenarios of England northern regions, for extending as long as possible independent heating periods, it could rationally consider increasing the renewable energy production devices (e.g. building community solar power supply farm or wind farm in suitable open terrain for collecting more renewable energy). In the other side, when applying TE heating system in the domestic scenarios of the UK southern regions, it will obtain more satisfied results such as both of the domestic heating demands and hot water demands can be independently and fully meet without additional grid supply whilst the renewable energy production still has more surplus. In these cases the renewable energy production devices can be rationally reduced for avoiding capital cost waste.

Chapter 7

Carbon Emission/Saving Caused by Applying TE Heating System in Domestic Context

This study in terms of the design and application of TE heating system with hybrid energy supply (i.e. solar/wind renewable energy and utility grid supply) intends to compete with existing domestic heating system in near future for reducing the greenhouse gas emission caused by the UK domestic energy consumption. However, it notes that while solar and wind power are low-carbon but aren't zero-carbon due to carbon will usually be emitted during manufacture, construction, maintenance and decommissioning processes throughout the devices' life cycles [111]. Therefore the potential CO_2 emissions of the entire system will be classified and estimated in this chapter. For further ascertaining the carbon saving contribution of the entire system, more analysis in terms of the CO_2 emission compared with condensing boiler heating by burning natural gas and possible carbon saving caused by rationally using excess renewable energy outputs will also be presented then.

7.1 Carbon dioxide emission factors and basic calculations

Different fuels emit different amounts of CO_2 in relation to the energy (i.e. heat) they produce when burned. For instance, during the process of burning hard coal or burning natural gas to product equivalent 1 kWh heat, it will emit around 0.34 kgCO_2 by hard coal burning or 0.20 kgCO_2 by natural gas burning, respectively [146]. To analyze carbon emissions across fuels, the CO_2 emission factors (in unit of kg CO_2 per kWh) are useful indications to determine the amount of CO_2 emitted per unit of heat output (or heat content) of different fuels (see Table 7.1).

Moreover, if fuels are used for electricity generation, CO_2 emission would increase with the reciprocal of the power plant efficiency [146]. For examples, if a power plant with an efficiency of 33% burns hard coal, it would consume 3.03 kWh hard coal whilst emitting 1.03 kg CO_2 for generating 1 kWh of electricity; if a power plant with a higher efficiency of 50% burns natural gas (i.e. the efficiencies of gas power plants are commonly higher than coal power

Fuel	**CO_2 emission factor** ($kgCO_2$/kWh)
Wood *	0.39
Peat	0.38
Lignite	0.36
Hard coal	0.34
Fuel oil	0.28
Diesel	0.27
Crude oil	0.26
Kerosene	0.26
Gasoline	0.25
Refinery gas	0.24
Liquid petroleum gas	0.23
Natural gas	0.20

Table 7.1 Specific CO_2 emission factors of burning various fuels * not sustainable used without reforestation (sources from [146])

plants [147]), it would consume 2 kWh natural gas whilst emitting 0.40 kg CO_2 for generating 1 kWh of electricity. Hereby, the corresponding CO_2 emission factors of electricity generations by different energy sources are summarized in Table 7.2 (note: the CO_2 emission factors of electricity generations by solar, wind, hydro, and nuclear energy sources are determined by average CO_2 emission levels on full life-cycle basis (i.e. construction, maintenance and decommissioning) of the corresponding power supply devices or power plants). The data results reveal that when generating equivalent electricity, burning coal always cause the most CO_2 emissions than the renewable energy supply (i.e. solar, wind and hydro) or nuclear power supply to deprave the natural environment, and followed by burning oil and gas.

Energy source	**CO_2 emission factor** ($kgCO_2$/kWh)
Lignite	1.20
Hard coal	1.07
Oil	0.90
Natural gas (combined cycle)	0.40
Solar PV	0.060
Wind (offshore)	0.014
Wind (onshore)	0.011
Nuclear	0.008
Hydro	0.005

Table 7.2 Average CO_2 emissions of electricity generation by various energy sources (sources from [148])

Additionally, the national grid power supply profile (see Figure 7.1) shows that the UK grid electricity supply always incorporates multiple energy sources. Thus the determination of the CO_2 emission factor of the grid electricity supply is more complex than determining the CO_2 emission factor of electricity generation by any single energy source. The consumptions of coal, gas and oil occupy Larger proportions in the grid power supply profile (i.e. till 2014 and 2015, there are still more than 50% of grid electricity supply relying on the coal, gas and oil resources) will usually result in higher average CO_2 emission levels per unit of the grid electricity supply. [132], [149], [112], [150] and [151] indicate the CO_2 emission factors of the UK grid electricity supply in recent years are commonly around 0.5 kg CO_2 per kW h. The specific CO_2 emission factors of the grid electricity supply published by various research institutes may have minor differences caused by employing different determinate methodologies or databases of different years.

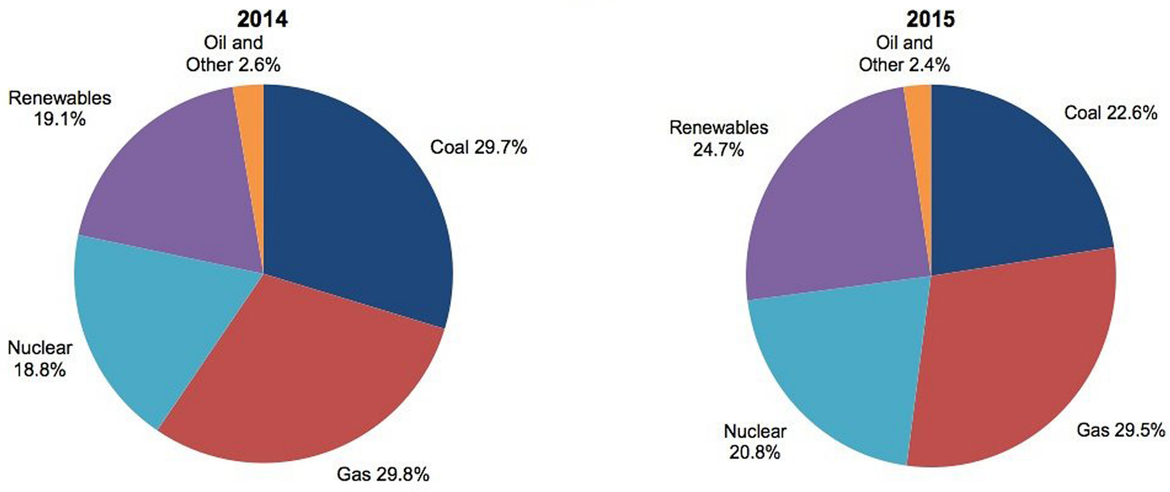


Fig. 7.1 Different sources of electricity generated in UK in 2014 and 2015 (Source from [152])

Finally, various CO_2 emission factors in relation to burning fuels or generating electricity can potentially be used as reference values for estimating possible CO_2 emissions depend on specific fuel consumption/electricity generation.

For calculating the specific CO_2 emission caused by the grid-connected domestic electricity consumption, [153] gives the equation as:

$$\text{monthly } CO_2 \text{ emission by the gird electricity consumption} = (\text{monthly grid electricity bill} \div \text{grid electricity price per unit}) \times CO_2 \text{ emission factor of grid electricity supply}$$
$$= \text{monthly grid electricity consumption} \times CO_2 \text{ emission factor of grid electricity supply} \tag{7.1}$$

Similarly, for domestic heating purpose, the specific CO_2 emission caused by burning natural gas can be calculated as:

$$\text{monthly } CO_2 \text{ emission by gas heating} = (\text{monthly domestic heating demand} \div \text{boiler efficiency}) \times CO_2 \text{ emission factor of burning gas}$$
$$= \text{monthly gas consumption for domestic heating} \times CO_2 \text{ emission factor of burning gas} \tag{7.2}$$

If the dwelling employs the renewable energy (i.e. solar or wind) to supply part of domestic energy demands, the potential CO_2 emission caused by renewable energy supply can be calculated as:

$$\begin{aligned} &\text{monthly } CO_2 \text{ emission by solar output} = \text{monthly electricity generation by wind energy} \\ &\times CO_2 \text{ emission factor of electricity generation by wind energy} \end{aligned} \tag{7.3}$$

$$\begin{aligned} &\text{monthly } CO_2 \text{ emission by wind output} = \text{monthly electricity generation by solar energy} \\ &\times CO_2 \text{ emission factor of electricity generation by solar energy} \end{aligned} \tag{7.4}$$

7.2 Energy output/demand classification in TE domestic heating scenario

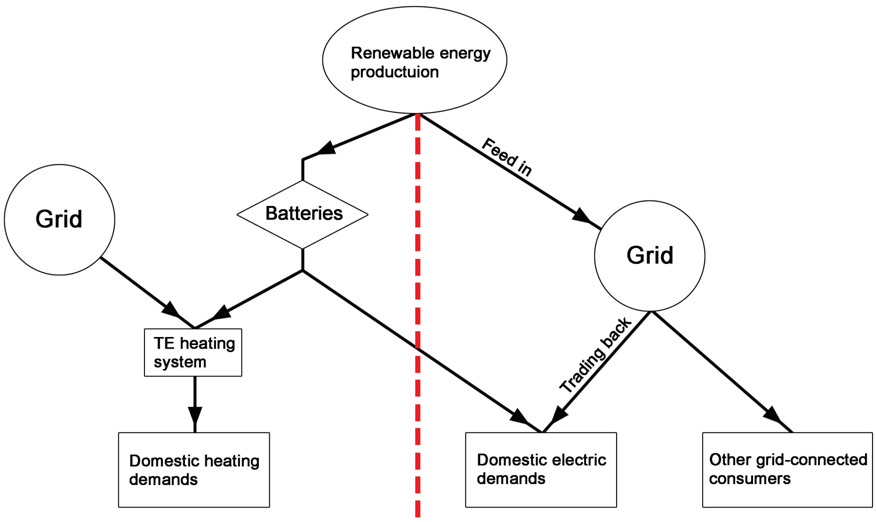


Fig. 7.2 Energy output/demand classification of the entire system

Figure 7.2 shows that the energy output/demand when employing TE heating system with hybrid energy supply in domestic context can be potentially classified by two parts: in one side, part of renewable energy output (i.e. solar and wind energy) can be used to power TE heating system to service for the domestic heating demands. Meanwhile it may also require some additional grid electricity supply due to the shortage of available renewable energy resources and higher domestic heating demand levels in some cold months; in the other side, during some warm months, the renewable energy supply equipment (i.e. solar panels and wind turbines) can usually generate a lot of electricity which is not requested by domestic heating demands due to more available renewable energy resources and less domestic heating demands. In that case the excess renewable energy generation will be self-consumed by domestic electricity demands or feed into grid to supply other grid-connected consumers which can potentially save more grid energy.

Hereby, based on relevant simulation results of Chapter 6 in relation to monthly domestic heating demands, monthly electricity outputs by roof PV panels and wind turbines, and detailed heating supply-demand relationships caused by employing TE heating system and hybrid energy supply in various dwelling scenarios, in this section the study can further categorize and estimate specific solar energy outputs which are used to supply domestic heating demands, specific wind energy outputs which are used to supply domestic heating demands, additional grid electricity requirements during renewable energy supply shortage periods, excess solar energy outputs which are not required by heating demands, and excess wind energy outputs which are not required by heating demands in various scenarios.

Take for example, in a typical scenario of Pre-1919 mid-terraced property with 101 m^2 to 150 m^2 floor area, 3 occupants and located in North East region, initial simulation results are shown in Table 7.3.

	Jan	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	**Total**
Monthly heating demand (kW h/month)	1773.59	1685.99	1433.18	804.65	488.27	0.00	0.00	0.00	171.45	576.82	1164.35	1433.41	9531.71
Roof PV panels outputs (kW h/month)	127.13	247.02	486.39	675.11	915.83	906.09	883.25	817.92	531.88	324.71	154.63	87.04	6157.00
Two wind turbines outputs (kW h/month)	293.88	226.98	254.20	156.10	123.84	96.64	91.38	107.34	156.52	204.90	221.42	267.42	2200.62
Renewable output sum (kW h/month)	421.01	474.00	740.59	831.21	1039.67	1002.73	974.63	925.26	688.40	529.61	376.05	354.46	8357.62
Heat generation * (kW h/month)	606.25	682.57	1066.46	1196.94	1497.12	1443.93	1403.47	1332.37	991.30	762.63	541.52	510.42	12034.97
Excess heat (kW h/month)	-1167.34	-1003.43	-366.72	392.29	1008.85	1443.93	1403.47	1332.37	819.85	185.81	-622.83	-922.99	2503.26

Table 7.3 Simulation of domestic scenario which is Pre-1919 mid-terraced property with 101 m^2 to 150 m^2 floor area, 3 occupants and located in North East region
* monthly maximum heat generation of TE heating system merely powered by renewable energy is calculated by: monthly renewable energy output sum × overall efficiency (80%) of renewable energy storage × TE heating COP (1.8)

Table 7.3 shows that during some cold months, the TE heating system has to request the external grid electricity supply to generate additional heat of 1167.34 kW h in Jan, 1003.43 kW h in Feb, 366.72 kW h in Mar, 622.83 kW h in Nov, and 922.99 kW h in Dec respectively for meeting the monthly domestic heating demands. Hereby the monthly grid electricity requirement can be calculated as: monthly additional TE heating powered by the grid electricity ÷ TE heating COP (1.8) ÷ (1 − 20% of energy loss by the AC/DC conversion).

Meanwhile, during Jan, Feb, Mar, Nov, and Dec, both of the monthly solar energy outputs and monthly wind energy outputs are completely consumed for supplying the domestic heating purpose. Thus the specific solar and wind energy outputs which are used to supply domestic heating demands in these months can be directly determined.

Moreover, during Apr, May, Sep, and Oct, the monthly renewable energy outputs are more than the energy requirements for supplying the domestic heating demands. Hence, in those months, the specific solar energy outputs which are consumed for domestic heating purpose will be estimated by: monthly TE heating powered by renewable energy (i.e. is equal to the monthly heating demands) $\div$ TE heating COP (1.8) $\div$ overall efficiency (80%) of renewable energy storage $\times$ ratio of comparing solar energy output with renewable energy output sum in corresponding month. Similarly, the specific wind energy outputs which are consumed for domestic heating purpose will be estimated by: monthly TE heating powered by renewable energy $\div$ TE heating COP (1.8) $\div$ overall efficiency (80%) of renewable energy storage $\times$ ratio of comparing wind energy output with renewable energy output sum in corresponding month.

Finally, the excess solar/wind energy outputs which are not required by heating demands can be simply calculated by: monthly solar/wind energy outputs $-$ specific solar/wind energy outputs which are consumed for domestic heating purpose. All relevant calculation results regarding the renewable energy output allocations and grid electricity demands in this domestic scenario are summarized in Table 7.4.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Solar output consumed by domestic heating (kW h/month)	127.13	247.02	486.39	453.84	298.69	0.00	0.00	0.00	91.99	245.59	154.63	87.04	2192.33
Wind output consumed by domestic heating (kW h/month)	293.88	226.98	254.20	104.94	40.39	0.00	0.00	0.00	27.07	154.98	221.42	267.42	1591.28
Additional grid supply (kW h/month)	810.65	696.82	254.67	0.00	0.00	0.00	0.00	0.00	0.00	0.00	432.52	640.97	2835.63
Excess solar energy output (kW h/month)	0.00	0.00	0.00	221.26	617.14	906.09	883.25	817.92	439.89	79.11	0.00	0.00	3964.67
Excess wind energy output (kW h/month)	0.00	0.00	0.00	51.16	83.45	96.64	91.38	107.34	129.45	49.92	0.00	0.00	609.34

Table 7.4 Renewable energy output allocations and the grid electricity demands in typical Pre-1919 mid-terraced property with 101 m^2 to 150 m^2 floor area, 3 occupants and located in North East region

Utilizing same calculation methods, it can further calculate the renewable energy output allocations and additional grid electricity demands in more various domestic scenarios as shown in Table 7.5, Table 7.6, Table 7.7, and Table 7.8. All the calculation results regarding different energy outputs/demands will be used as important reference data to combine with suitable CO_2 emission factors (i.e. studied in section 7.1) for estimating possible carbon emission/saving caused by applying TE heating system with hybrid energy supply in various domestic scenarios in next sections.

		Solar output consumed by domestic heating (kWh/year)	**Wind output consumed by domestic heating** (kWh/year)	**Additional grid supply for domestic heating** (kWh/year)	**Excess solar power** (kWh/year)	**Excess wind power** (kWh/year)
scenario1	Mid-terraced	3165.42	1652.03	4913.86	5043.91	548.59
	End-terraced	3270.97	1678.86	5324.50	4949.28	526.93
	Semi-detached	3409.13	1700.07	6202.49	4800.20	500.55
	Detached	3343.42	1689.98	5784.91	4865.92	510.64
	Bungalow	4891.04	2965.75	3652.45	11527.63	1435.49
scenario2	Mid-terraced	3224.95	1665.66	5182.28	4984.38	534.96
	End-terraced	3319.00	1686.23	5629.73	4890.34	514.39
	Semi-detached	3462.01	1708.18	6538.53	4747.32	492.44
	Detached	3393.99	1697.74	6106.30	4815.34	502.88
	Bungalow	5015.27	3002.96	3894.98	11413.59	1402.28
scenario3	Mid-terraced	3373.06	1694.53	5973.30	4836.27	506.09
	End-terraced	3455.12	1707.13	6494.73	4754.22	493.49
	Semi-detached	3588.71	1727.17	7518.05	4620.62	473.45
	Detached	3537.32	1719.74	7017.10	4672.01	480.88
	Bungalow	5214.77	3048.62	4794.67	11203.89	1352.62
scenario4	Mid-terraced	2834.04	1576.19	3419.43	5375.30	624.43
	End-terraced	2910.17	1593.61	3762.77	5299.16	607.01
	Semi-detached	3055.62	1626.90	4418.67	5153.71	573.72
	Detached	2986.44	1611.07	4106.72	5222.89	589.55
	Bungalow	4256.16	2780.81	2223.16	12162.51	1620.43
scenario5	Mid-terraced	2192.33	1591.28	2835.63	3964.67	609.34
	End-terraced	2265.59	1613.28	3185.19	3891.41	587.34
	Semi-detached	2363.16	1642.58	3650.75	3793.84	558.04
	Detached	2468.90	1674.33	4155.32	3688.10	526.29
	Bungalow	3509.01	2893.10	2242.63	8804.99	1508.14
scenario6	Mid-terraced	2282.05	1618.22	3263.74	3874.95	582.40
	End-terraced	2361.34	1642.03	3642.06	3795.66	558.59
	Semi-detached	2466.93	1673.74	4145.93	3690.07	526.88
	Detached	2572.84	1702.73	4705.95	3584.16	497.89
	Bungalow	3696.43	2965.00	2694.75	8617.56	1436.24
scenario7	Mid-terraced	2019.88	1539.49	2012.72	4137.12	661.13
	End-terraced	2081.54	1558.00	2306.97	4075.45	642.62
	Semi-detached	2163.68	1582.67	2698.88	3993.32	617.95
	Detached	2252.69	1609.40	3123.63	3904.31	591.22
	Bungalow	3148.73	2754.88	1373.53	9165.27	1646.36
scenario8	Mid-terraced	1547.74	818.01	2299.20	2556.93	282.30
	End-terraced	1634.10	839.22	2653.46	2476.45	263.88
	Semi-detached	1695.61	848.66	3044.34	2409.06	251.65
	Detached	1780.39	861.77	3546.82	2329.09	239.38
	Bungalow	2372.58	1461.63	1662.03	5836.75	738.99
scenario9	Mid-terraced	1656.53	842.66	2795.99	2448.14	257.65
	End-terraced	1726.35	853.38	3239.68	2378.32	246.93
	Semi-detached	1789.86	863.00	3690.76	2314.80	237.31
	Detached	1831.60	868.43	4325.08	2273.06	231.88
	Bungalow	2556.81	1512.73	2169.24	5652.53	687.89
scenario10	Mid-terraced	1379.30	779.46	1539.61	2725.37	320.85
	End-terraced	1443.10	794.06	1827.34	2661.56	306.25
	Semi-detached	1506.91	808.67	2115.07	2597.76	291.64
	Detached	1589.85	827.65	2489.12	2514.81	272.66
	Bungalow	2051.12	1367.99	938.31	6158.22	832.63
scenario11	Mid-terraced	790.29	817.52	1233.50	1262.04	282.79
	End-terraced	784.88	815.15	1204.92	1267.45	285.16
	Bungalow	1098.42	1397.38	454.91	3006.25	803.24
scenario12	Mid-terraced	674.97	766.92	624.60	1377.36	333.39
	End-terraced	671.03	765.19	603.81	1381.30	335.12
	Bungalow	891.02	1249.11	5.91	3219.20	960.73

Table 7.5 Renewable energy output allocations and the grid electricity demands in various simulated scenarios of North East region

∗ all the data were counted depend on initialenergy outputs/consumptions and didn't exclude the possible energy loss caused by energy storage, inverter, converter and rectifier.

		Solar output consumed by domestic heating (kWh/year)	**Wind output consumed by domestic heating** (kWh/year)	**Additional grid supply for domestic heating** (kWh/year)	**Excess solar power** (kWh/year)	**Excess wind power** (kWh/year)
scenario13	Mid-terraced	3113.17	1314.29	5337.20	4648.76	436.89
	End-terraced	3186.50	1324.66	5798.36	4575.42	426.52
	Semi-detached	3326.61	1344.47	6679.36	4435.32	406.71
	Detached	3259.97	1335.05	6260.35	4501.95	416.13
	Bungalow	4844.25	2363.28	4341.13	10679.59	1139.08
scenario14	Mid-terraced	3239.47	1332.15	6131.42	4522.45	419.03
	End-terraced	3319.86	1343.52	6636.90	4442.07	407.66
	Semi-detached	3419.50	1356.58	7665.14	4342.43	394.60
	Detached	3385.93	1352.58	7160.05	4375.99	398.60
	Bungalow	5042.72	2402.48	5213.29	10481.13	1099.88
scenario15	Mid-terraced	2746.83	1245.77	3597.47	5015.10	505.41
	End-terraced	2822.56	1260.73	3930.30	4939.36	490.45
	Semi-detached	2967.25	1289.31	4566.13	4794.67	461.87
	Detached	2898.44	1275.72	4263.72	4863.49	475.46
	Bungalow	4155.91	2191.91	2628.95	11367.93	1310.45
scenario16	Mid-terraced	2124.69	1259.76	2987.90	3696.76	491.42
	End-terraced	2197.43	1278.72	3324.42	3624.01	472.46
	Semi-detached	2302.16	1307.81	3760.91	3527.12	447.22
	Detached	2382.08	1322.86	4284.07	3439.36	428.32
	Bungalow	3429.55	2291.54	2601.20	8213.34	1210.82
scenario17	Mid-terraced	2213.78	1282.97	3400.03	3607.66	468.21
	End-terraced	2300.79	1307.55	3751.91	3528.93	447.69
	Semi-detached	2380.60	1322.58	4274.34	3440.85	428.60
	Detached	2467.09	1338.86	4840.55	3354.35	412.32
	Bungalow	3614.45	2354.08	3038.69	8028.44	1148.28
scenario18	Mid-terraced	1953.43	1215.13	2195.68	3868.01	536.05
	End-terraced	2014.67	1231.09	2478.96	3806.78	520.09
	Semi-detached	2096.23	1252.34	2856.25	3725.22	498.84
	Detached	2184.62	1275.38	3265.15	3636.82	475.80
	Bungalow	3071.22	2169.96	1764.51	8571.67	1332.40
scenario19	Mid-terraced	1472.92	642.54	2236.00	2408.04	233.05
	End-terraced	1543.11	655.24	2583.90	2337.85	220.35
	Semi-detached	1601.10	663.44	2948.51	2279.86	212.15
	Detached	1682.07	675.00	3416.02	2204.49	201.49
	Bungalow	2263.12	1143.53	1720.24	5498.80	607.65
scenario20	Mid-terraced	1564.26	658.23	2716.86	2316.70	217.36
	End-terraced	1630.07	667.54	3130.73	2250.89	208.05
	Semi-detached	1690.99	676.06	3550.29	2189.97	199.53
	Detached	1730.31	680.74	4141.98	2150.65	194.85
	Bungalow	2430.21	1183.24	2206.09	5331.71	567.94
scenario21	Mid-terraced	1311.68	610.69	1527.46	2569.28	264.90
	End-terraced	1372.76	622.76	1795.86	2508.20	252.83
	Semi-detached	1433.83	634.82	2064.25	2447.13	240.77
	Detached	1515.47	651.33	2410.10	2367.73	225.09
	Bungalow	1955.06	1064.38	1045.16	5806.86	686.80
scenario22	Mid-terraced	717.96	631.13	1045.85	1222.52	244.46
	End-terraced	713.22	629.31	1021.76	1227.26	246.28
	Bungalow	992.35	1063.93	430.87	2888.61	687.25
scenario23	Mid-terraced	616.91	592.33	532.61	1323.58	283.26
	End-terraced	613.46	591.00	515.09	1328.68	285.76
	Bungalow	805.98	940.13	62.80	3074.98	811.05

Table 7.6 Renewable energy output allocations and the grid electricity demands in various simulated scenarios of North West region

∗ all the data were counted depend on initial energy outputs/consumptions and didn't exclude the possible energy loss caused by energy storage, inverter, converter and rectifier.

		Solar output consumed by domestic heating (kWh/year)	**Wind output consumed by domestic heating** (kWh/year)	**Additional grid supply for domestic heating** (kWh/year)	**Excess solar power** (kWh/year)	**Excess wind power** (kWh/year)
scenario24	Mid-terraced	3284.23	1551.72	5192.61	5149.21	509.18
	End-terraced	3381.46	1571.76	5634.94	5051.99	489.14
	Semi-detached	3525.53	1591.93	6539.75	4907.92	468.97
	Detached	3457.01	1582.34	6109.41	4976.44	478.56
	Bungalow	5118.17	2798.51	3944.10	11771.98	1331.72
scenario25	Mid-terraced	3435.92	1579.39	5977.00	4997.52	481.51
	End-terraced	3518.59	1590.96	6496.14	4914.86	469.94
	Semi-detached	3669.95	1612.02	7495.49	4763.50	448.88
	Detached	3601.40	1602.55	7016.21	4832.05	458.35
	Bungalow	5319.86	2840.91	4839.84	11547.04	1280.89
scenario26	Mid-terraced	2889.05	1468.63	3437.52	5544.39	592.27
	End-terraced	2966.02	1484.82	3779.34	5467.43	576.08
	Semi-detached	3113.05	1515.73	4432.36	5320.39	545.17
	Detached	3043.12	1501.03	4121.78	5390.32	559.87
	Bungalow	4335.98	2586.22	2297.20	12530.92	1535.58
scenario27	Mid-terraced	2250.07	1487.13	2923.07	4075.01	573.77
	End-terraced	2325.19	1507.87	3274.80	3999.90	553.03
	Semi-detached	2425.23	1535.48	3743.24	3899.86	525.42
	Detached	2533.65	1565.41	4250.94	3791.43	495.49
	Bungalow	3607.03	2703.47	2387.82	9043.14	1418.33
scenario28	Mid-terraced	2342.07	1512.53	3353.83	3983.02	548.37
	End-terraced	2423.36	1534.96	3734.50	3901.72	525.94
	Semi-detached	2531.64	1564.85	4241.50	3793.45	496.05
	Detached	2636.38	1589.93	4810.88	3688.70	470.97
	Bungalow	3799.76	2771.69	2842.75	8850.41	1350.11
scenario29	Mid-terraced	2073.24	1438.33	2095.05	4251.84	622.57
	End-terraced	2136.47	1455.78	2391.14	4188.61	605.12
	Semi-detached	2220.69	1479.02	2785.47	4104.40	581.88
	Detached	2311.96	1504.22	3212.85	4013.13	556.68
	Bungalow	3236.57	2572.35	1513.34	9413.60	1549.45
scenario30	Mid-terraced	1566.44	759.95	2260.19	2650.29	270.50
	End-terraced	1646.78	776.84	2617.02	2569.94	253.61
	Semi-detached	1717.77	789.67	2987.28	2498.96	240.78
	Detached	1797.32	800.80	3486.89	2419.40	229.65
	Bungalow	2396.18	1354.41	1653.31	6037.26	706.49
scenario31	Mid-terraced	1678.89	784.22	2743.11	2540.65	247.45
	End-terraced	1748.35	793.95	3179.34	2468.37	236.50
	Semi-detached	1817.81	803.67	3615.57	2398.91	226.78
	Detached	1867.05	809.81	4230.23	2349.67	220.64
	Bungalow	2595.11	1406.83	2132.03	5838.34	654.07
scenario32	Mid-terraced	1398.28	724.59	1513.36	2818.44	305.86
	End-terraced	1461.98	737.99	1796.26	2754.75	292.46
	Semi-detached	1525.67	751.38	2079.16	2691.05	279.07
	Detached	1608.48	768.79	2446.92	2608.24	261.66
	Bungalow	2074.47	1267.99	941.76	6358.98	792.91
scenario33	Mid-terraced	767.61	746.75	1042.82	1340.75	283.70
	End-terraced	762.62	744.73	1017.10	1345.74	285.72
	Bungalow	1058.52	1268.56	328.56	3158.21	792.34
scenario34	Mid-terraced	661.21	703.81	494.81	1451.54	329.81
	End-terraced	657.58	702.35	476.11	1457.25	332.78
	Bungalow	842.89	1106.75	18.19	3378.27	973.07

Table 7.7 Renewable energy output allocations and the grid electricity demands in various simulated scenarios of Yorkshire & Humber region

∗ all the data were counted depend on initial energy outputs/consumptions and didn't exclude the possible energy loss caused by energy storage, inverter, converter and rectifier.

		Solar output consumed by domestic heating (kWh/year)	**Wind output consumed by domestic heating** (kWh/year)	**Additional grid supply for domestic heating** (kWh/year)	**Excess solar power** (kWh/year)	**Excess wind power** (kWh/year)
scenario35	Mid-terraced	2836.01	3528.64	1816.55	6724.58	1894.62
	End-terraced	2949.48	3596.50	2091.73	6619.69	1833.10
	Semi-detached	3074.47	3658.27	2777.08	6486.11	1764.99
	Detached	3015.03	3628.89	2451.12	6545.56	1794.37
	Bungalow	3939.91	5755.79	19.80	15196.90	5164.43
scenario36	Mid-terraced	2417.38	3283.15	658.71	7152.16	2161.24
	End-terraced	2498.92	3330.96	884.21	7061.67	2092.30
	Semi-detached	2654.67	3422.31	1315.01	6905.92	2000.95
	Detached	2580.59	3378.86	1110.12	6980.00	2044.40
	Bungalow	3062.67	4458.41	0.00	16058.51	6388.11
scenario37	Mid-terraced	1832.86	3244.87	431.46	5337.58	2178.39
	End-terraced	1926.85	3359.72	592.84	5250.50	2085.29
	Semi-detached	2028.30	3438.00	906.19	5142.14	1985.26
	Detached	2138.25	3522.84	1245.79	5032.20	1900.42
	Bungalow	2518.45	4676.56	0.00	11822.43	6169.96
scenario38	Mid-terraced	1627.87	3025.71	15.94	5555.64	2447.27
	End-terraced	1701.17	3104.08	144.04	5469.27	2319.18
	Semi-detached	1798.80	3208.45	357.11	5371.64	2214.81
	Detached	1913.43	3349.37	551.41	5265.84	2101.69
	Bungalow	2120.03	3936.73	0.00	12220.85	6909.79
scenario39	Mid-terraced	1333.78	1714.93	675.32	3446.52	996.70
	End-terraced	1418.49	1764.61	909.61	3361.81	947.02
	Semi-detached	1495.17	1808.35	1157.87	3285.13	903.28
	Detached	1563.86	1842.29	1534.51	3216.44	869.34
	Bungalow	1797.88	2638.79	49.02	7773.89	2822.31
scenario40	Mid-terraced	1461.60	1791.76	973.79	3330.92	928.91
	End-terraced	1521.57	1821.40	1302.66	3258.72	890.23
	Semi-detached	1581.55	1851.04	1631.53	3198.74	860.59
	Detached	1659.52	1889.57	2059.06	3120.77	822.06
	Bungalow	2018.17	2924.21	38.04	7546.48	2518.22
scenario41	Mid-terraced	1143.75	1580.90	227.76	3636.54	1130.73
	End-terraced	1223.64	1650.34	370.71	3558.76	1066.27
	Semi-detached	1290.80	1689.73	556.46	3489.49	1021.90
	Detached	1378.11	1740.93	797.93	3402.19	970.70
	Bungalow	1416.50	2062.03	0.00	8144.09	3361.23
scenario42	Mid-terraced	607.92	1587.31	37.19	1783.82	1139.33
	End-terraced	602.43	1578.89	22.52	1789.72	1151.63
	Bungalow	639.77	1678.60	0.00	4140.53	3744.66
scenario43	Mid-terraced	448.05	1175.59	0.00	1942.10	1536.04
	End-terraced	442.32	1160.54	0.00	1947.83	1551.09
	Bungalow	465.30	1220.85	0.00	4314.99	4202.41

Table 7.8 Renewable energy output allocations and the grid electricity demands in various simulated scenarios of South West region
∗ all the data were counted depend on initial energy outputs/consumptions and didn't exclude the possible energy loss caused by energy storage, inverter, converter and rectifier.

7.3 Carbon saving contribution of applying TE heating system with hybrid energy supply in domestic scenario

Based on the energy output/demand classification in section 7.2, this section will be able to estimate possible CO_2 emissions caused by applying TE heating system with hybrid energy supply for domestic heating purpose and possible CO_2 emissions caused by excess renewable energy outputs, respectively. For further ascertaining the carbon saving contribution of the entire system, it can compare these CO_2 emission estimation results with the CO_2 emissions caused by applying condensing boilers to service for same domestic heating scenarios and the CO_2 emissions caused by generating equivalent grid electricity with the excess renewable energy outputs, correspondingly.

7.3.1 Carbon emission in comparison with natural gas heating

Till 2015, there are 88% of UK domestic space and hot water supply relying on boilers burn natural gas [154]. Hence estimating and comparing the CO_2 emissions when applying condensing boiler and TE heating system to service for same domestic heating scenario will be helpful to evaluate the application potential of TE heating system to compete with existing domestic heating system.

Before the start of calculating relevant CO_2 emissions, the following assumptions have been adopted:

- the CO_2 emission factor of burning natural gas will utilize the value of 0.20 kgCO$_2$/kWh suggested by [146];
- before connect into batteries or the grid, the CO_2 emission factor of electricity generation by roof PV panels is assumed as 0.058 kgCO$_2$/kWh [113] and the CO_2 emission factor of electricity generation by micro wind turbines is assumed as 0.045 kgCO$_2$/kWh [111]. It notes above carbon footprint values are most likely the maximum values determined by the power farms in the UK context but these values may still be disputed when use to support the small-scale power estimations in domestic scenario.
- the average CO_2 emission factor of the UK grid electricity supply will utilize the value of 0.46 kgCO$_2$/kWh (involves imported electricity and grid transmission/distribution losses) which was calculated based on the data year of 2014 and newly updated by UK government in 2016 [112];

Hereby for firstly estimating the annual CO_2 emission (in unit of kgCO$_2$/year) caused by employing condensing boiler to service for the domestic heating demands, it can simply calculate as: annual grid gas consumption for supplying domestic heating demands $\times$ CO_2 emission factor of burning gas $=$ annual domestic heating demands $\div$ boiler efficiency (90%) $\times$ CO_2 emission factor of burning gas.

Then for calculating the specific annual CO_2 emission (in unit of $kgCO_2$/year) caused by applying TE heating system with hybrid energy supply to meet the domestic heating demands, the calculation can utilize: solar energy output which is consumed for the domestic heating purpose $\times$ CO_2 emission factor of electricity generation by PV panels + wind energy output which is consumed for the domestic heating purpose $\times$ CO_2 emission factor of electricity generation by wind turbines + additional grid electricity consumed for the domestic heating purpose during the renewable energy shortage periods $\times$ average CO_2 emission factor of grid electricity supply.

Finally importing relevant scenario simulation results in relation to annual domestic heating demands, specific renewable energy output allocations and additional grid electricity demands studied in Chapter 6 and section 7.2 into above calculations, corresponding CO_2 emission estimation results in various domestic heating scenarios will be demonstrated as shown in Figure 7.3, Figure 7.4, Figure 7.5, and Figure 7.6.

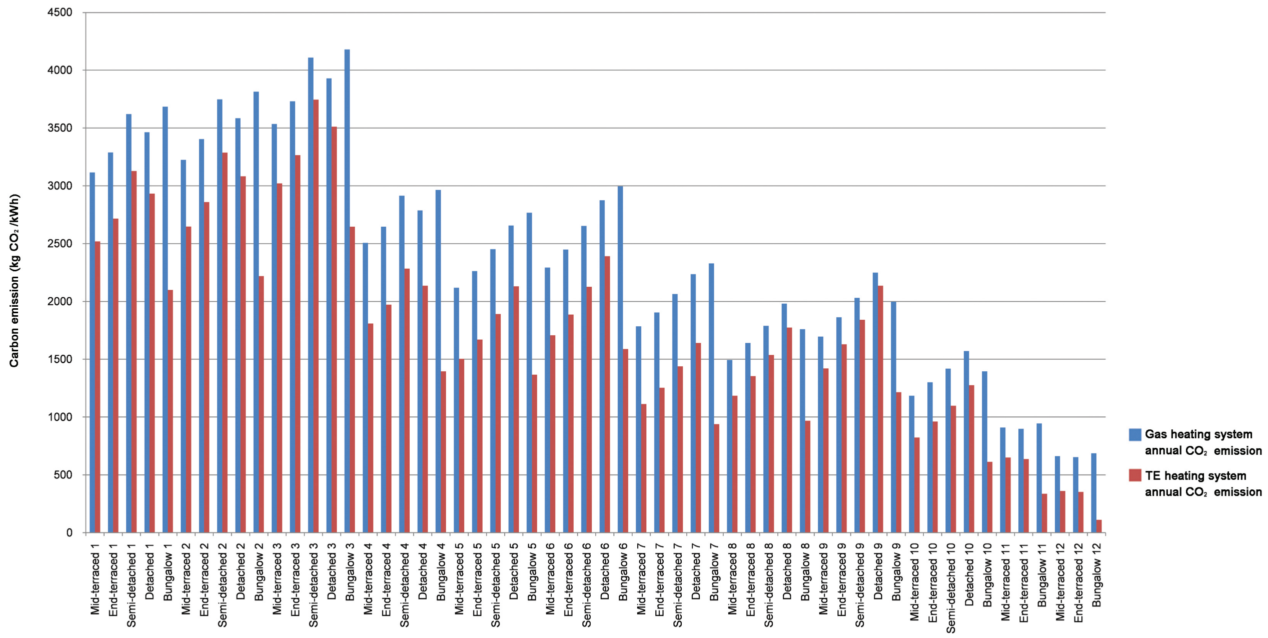


Fig. 7.3 Comparison of the carbon emissions between condensing boiler and TE heating system for domestic heating in various scenarios of North East

Figure 7.3, Figure 7.4, Figure 7.5, and Figure 7.6 show that when meeting the domestic heating demands in each same scenario, applying TE heating system with hybrid power supply can commonly cause less CO_2 emissions than employing condensing boiler.

Additionally, the comparison results also reveal that the CO_2 emission levels in the dwellings of the England northern regions are always higher than the UK southern regions due to more heating demands of northern families. The highest CO_2 emission level is estimated as 4178.58 $kgCO_2$/year if employing condensing boiler to service for the heating demand in 1919-44 bungalow with 151 m^2 to 200 m^2 floor area, 4 occupants and located in North East region. But the carbon emission would decline to 2645.19 $kgCO_2$/year if employing TE heating system powered by hybrid energy to service for same heating scenario. The corresponding

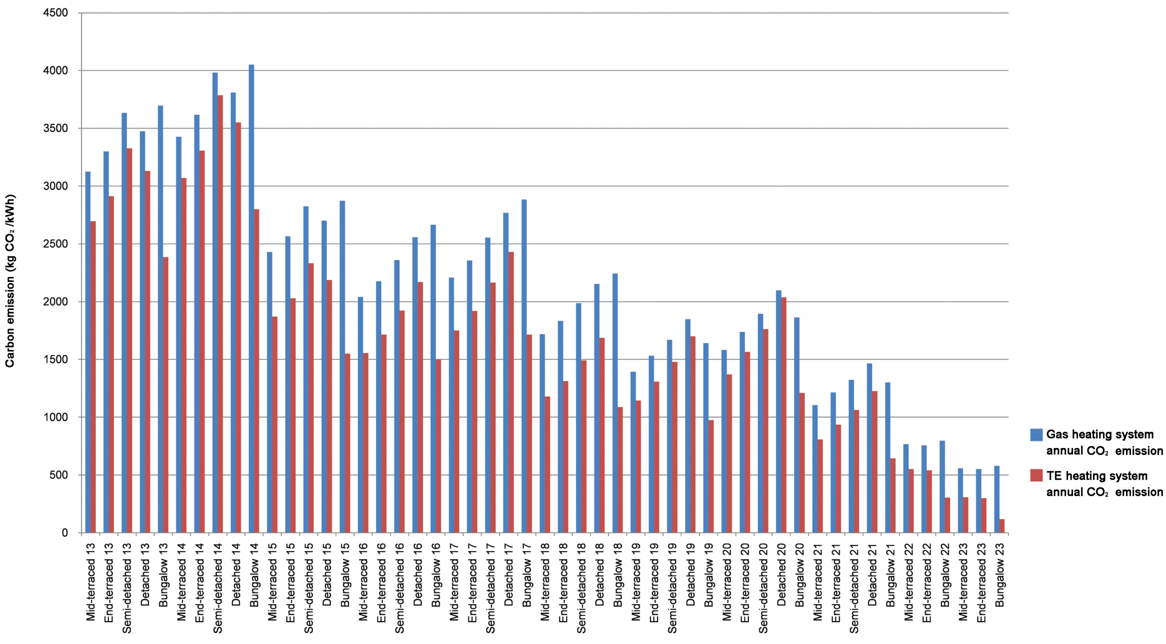


Fig. 7.4 Comparison of the carbon emissions between condensing boiler and TE heating system for domestic heating in various scenarios of North West

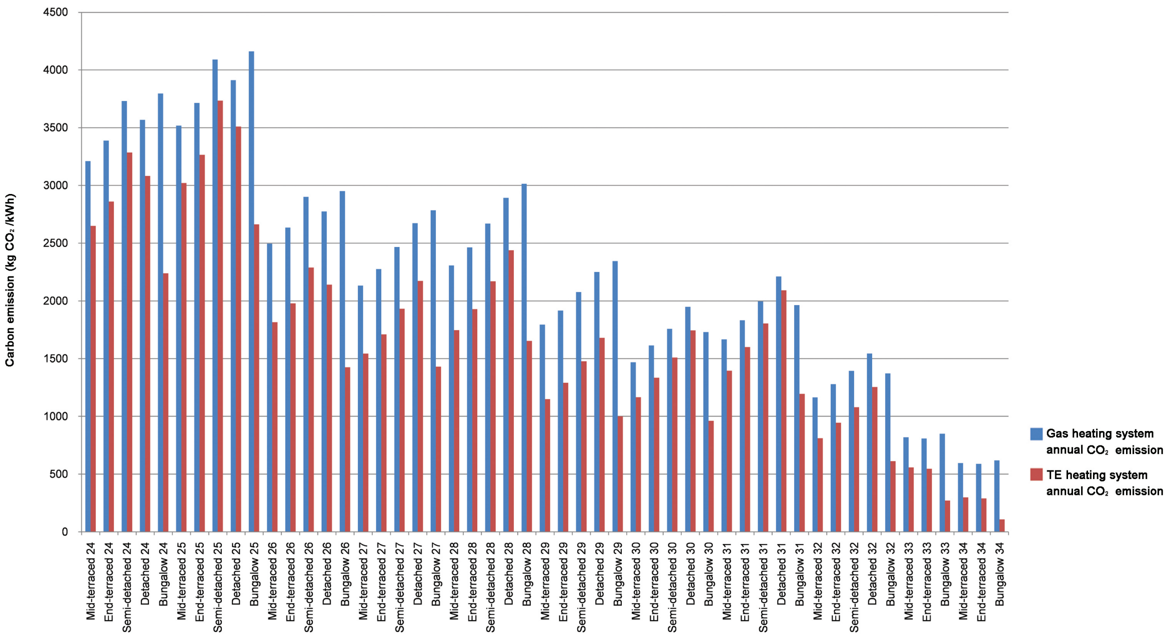


Fig. 7.5 Comparison of the carbon emissions between condensing boiler and TE heating system for domestic heating in various scenarios of Yorkshire & Humber

carbon saving efficiency can be calculated by: (4178.58 $kgCO_2$/year − 2645.19 $kgCO_2$/year) ÷ 4178.58 $kgCO_2$/year ≈ 36.70%.

Meanwhile the lowest CO_2 emission level by employing condensing boiler is 512.91 $kgCO_2$/year in post 1999 end-terraced property with 50 m^2 or less floor area, 1 occupant and located in South West region whilst it would be reduced to only 77.88 $kgCO_2$/year if replacing the condensing

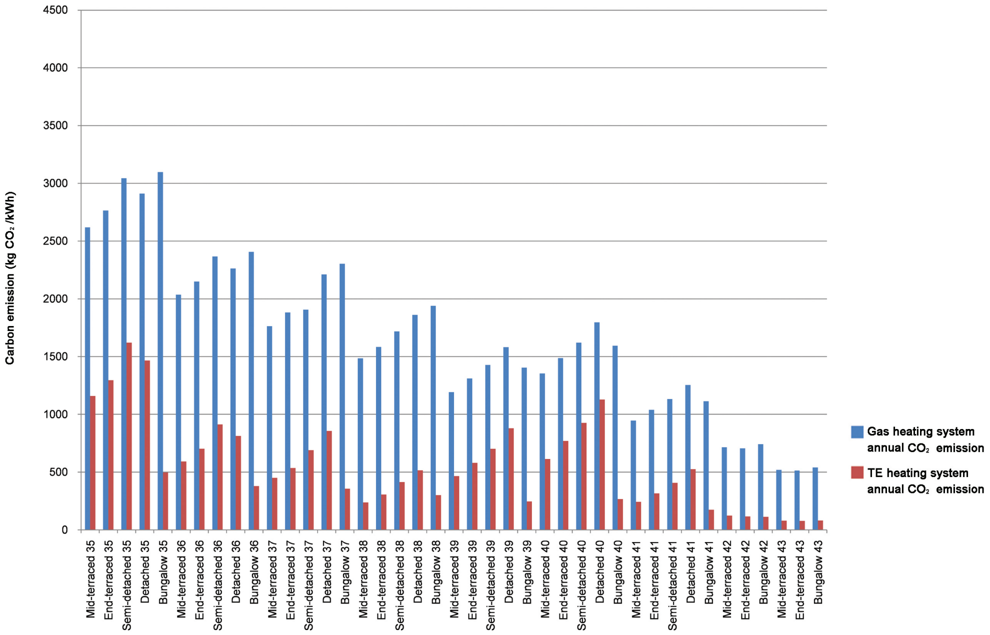


Fig. 7.6 Comparison of the carbon emissions between condensing boiler and TE heating system for domestic heating in various scenarios of South West

boiler to TE heating system and the corresponding carbon saving efficiency is calculated as (512.91 $kgCO_2$/year − 77.88 $kgCO_2$/year) ÷ 512.91 $kgCO_2$/year ≈ 84.82%.

Table 7.9 has summarized all calculation results regarding the carbon saving efficiency of comparing TE heating system with condensing boilers in various domestic heating scenarios. These results reveal that in England northern regions (i.e. North East, North West, and Yorkshire & Humber), when applying TE heating system in most property types (i.e. mid-terraced, end-terraced, semi-detached and detached dwellings) built before 1944, the reachable carbon saving efficiency are very limited (i.e. commonly lower than 33%). The minimum carbon saving efficiency is estimated at only 2.89% in the scenario which is a 1919-44 detached property with 51 m^2 to 100 m^2 floor area, 2 occupants and located in North West region. But if applying TE heating system in the properties built post 1999, the carbon saving efficiency could relatively increase about 6%-14%. Additionally, in bungalow properties, the achievable carbon efficiencies can be commonly remained above 30% till maximum 83.89% benefited from bungalows have larger roof areas and open space where allow setting more PV panels and wind turbines respectively.

Furthermore, in the UK southern region (i.e. South West), due to more available renewable energy resources and lower domestic heating demand levels in the local context, employing TE heating system in most domestic scenarios can easily achieve carbon saving efficiency above 40%. Especially in the specific scenarios involve post 1999 mid-terraced, end-terraced properties with 101 m^2 to 150 m^2 floor area and 3 occupants, all mid-terraced, end-terraced properties with less than 50 m^2 floor area and 1 occupant, and all bungalows, the carbon saving efficiency can commonly remain above 80% which suggest the best optimal results to promote government' carbon plan.

Region & Age / Property type	North East Pre-1919	North East 1919-44	North East Post 1999	North West Pre-1919	North West 1919-44	North West Post 1999	York-shire Pre-1919	York-shire 1919-44	York-shire Post 1999	South West Pre-1919	South West 1919-44	South West Post 1999
$151\,m^2$ **to** $200\,m^2$ **floor area and 3 occupants**												
Mid-terraced	19.13											
End-terraced	17.44											
Semi-detached	13.60											
Detached	15.33											
Bungalow	43.05											
$151\,m^2$ **to** $200\,m^2$ **floor area and 4 occupants**												
Mid-terraced	17.92	14.53	27.83	13.76	10.41	23.00	17.46	14.15	27.24	55.73		70.96
End-terraced	16.02	12.48	25.48	11.74	8.58	20.90	15.62	12.11	24.92	53.14		67.35
Semi-detached	12.31	8.83	21.61	8.43	4.92	17.45	11.95	8.69	21.10	46.75		61.41
Detached	13.99	10.62	23.36	9.93	6.74	19.01	13.61	10.28	22.83	49.64		64.09
Bungalow	41.83	36.70	52.94	35.48	30.91	46.08	41.06	36.00	51.71	83.96		84.28
$101\,m^2$ **to** $150\,m^2$ **floor area and 3 occupants**												
Mid-terraced	29.03	25.56	37.62	23.77	20.70	31.37	27.65	24.28	35.97	74.43		83.97
End-terraced	26.16	22.90	34.20	21.23	18.56	28.35	24.86	21.70	32.66	71.53		80.77
Semi-detached	22.85	19.84	30.27	18.50	15.24	24.87	21.65	18.73	28.84	63.84		75.94
Detached	19.79	16.82	26.64	15.18	12.18	21.65	18.68	15.71	25.32	61.29		72.30
Bungalow	50.64	46.98	59.70	43.73	40.56	51.49	48.65	45.14	57.34	84.52		84.52
$51\,m^2$ **to** $100\,m^2$ **floor area and 2 occupants**												
Mid-terraced	20.67	16.19	30.43	17.92	13.32	26.97	20.64	16.30	30.40	60.96	54.66	74.36
End-terraced	17.52	12.53	26.19	14.56	9.92	23.04	17.28	12.63	26.16	55.71	48.24	69.59
Semi-detached	14.06	9.34	22.65	11.34	6.97	19.75	14.16	9.57	22.62	50.92	42.89	64.05
Detached	10.45	5.03	18.83	8.02	2.89	16.30	10.42	5.41	18.80	44.37	37.12	58.09
Bungalow	44.97	39.18	56.10	40.63	35.08	50.64	44.46	39.14	55.46	82.51	83.30	84.28
$50\,m^2$ **or less floor area and 1 occupant**												
Mid-terraced	28.51		45.41	28.09		44.84	31.83		49.99	82.67		84.82
End-terraced	29.09		46.22	28.67		45.64	32.46		50.85	83.50		84.82
Bungalow	64.43		83.89	61.85		79.63	68.27		82.68	84.82		84.82

Table 7.9 The carbon saving efficiency of comparing TE heating system with condensing boiler in various domestic heating scenarios

7.3.2 Potential carbon saving caused by excess renewable energy output

During some warm months, excess renewable energy outputs which are not requested by domestic heating demands can be optionally self-consumed for supplying domestic electric demands or feed in the utility grid to supply other grid-connected consumers. Hence more grid electricity will be saved which is helpful to reduce more carbon emissions caused by burning fossil fuels during the grid electricity supply process.

For calculating the annual CO_2 emission ($kgCO_2$/year) caused by the excess renewable energy outputs, it can simply calculate by: the excess solar energy output which isn't consumed by the domestic heating $\times$ CO_2 emission factor of electricity generation by PV panel + the excess wind energy output which isn't consumed by the domestic heating $\times$ CO_2 emission factor of electricity generation by wind turbine.

Additionally, if the excess renewable energy outputs can be fully consumed by the domestic electric demands and other grid-connected consumers, and assuming the average energy loss of the excess renewable energy caused by energy conversion, storage and grid transmission is 15%, then the CO_2 emission ($kgCO_2$/year) caused by consuming equivalent grid electricity would be estimated by: (excess solar energy output + excess wind energy output) $\times$ (1 $-$ energy loss of 15%) $\times$ average CO_2 emission factor of grid electricity supply.

Hereby all the estimation results regarding the CO_2 emission caused by excess renewable energy outputs and the possible CO_2 emission caused by equivalent grid electricity supply are shown as in Figure 7.7, Figure 7.8, Figure 7.9, and Figure 7.10.

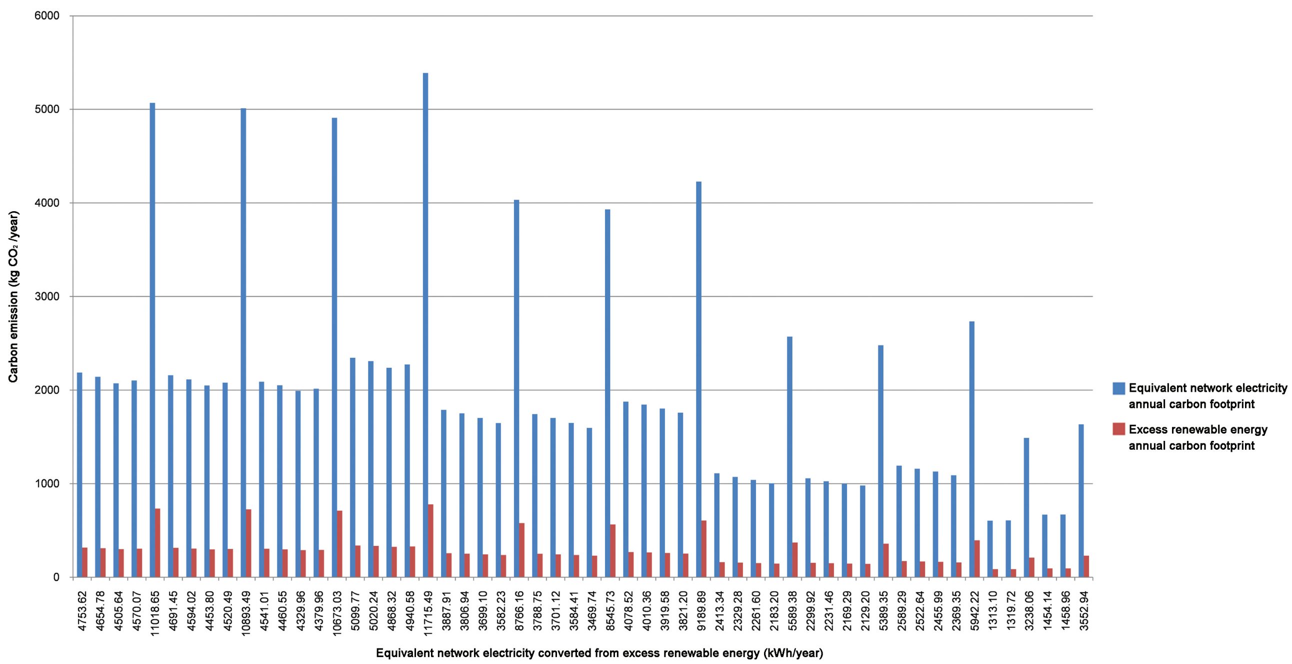


Fig. 7.7 Comparison of the carbon emissions between excess renewable energy outputs and equivalent grid electricity supply in various scenarios of North East

The results show that the CO_2 emissions caused by excess renewable energy outputs in domestic scenarios of South West region are always more than in similar domestic scenarios of England northern regions mainly because of more available renewable energy resources supply in the UK southern regions. The maximum excess renewable energy output is 22 446.62 kW h/year in the scenario of post 1999 bungalow with 151 m^2 to 200 m^2 floor area, 4 occupants and located in South West region whilst it can save the most carbon emissions of 7557.77 $kgCO_2$/year in comparison with consuming equivalent grid electricity of 19 079.62 kW h/year (i.e. equivalent grid electricity is calculated by: excess renewable energy output of 22 446.62 kW h/year $\times$ (1 $-$ energy loss of 15%)) in all scenarios. Relatively the minimum excess renewable energy output is 1466.98 kW h/year in the scenario of pre-1919 mid-terraced property with 50 m^2 or less floor area, 1 occupant and located in North West region and the corresponding lowest carbon saving is 491.68 $kgCO_2$/year.

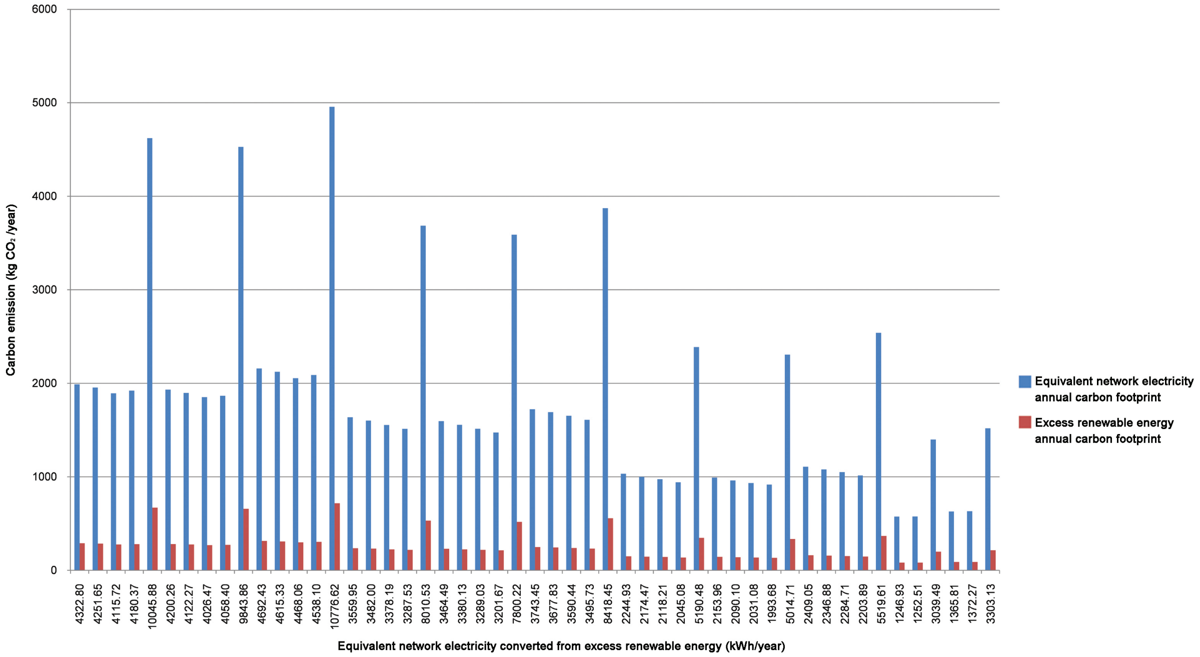


Fig. 7.8 Comparison of the carbon emissions between excess renewable energy outputs and equivalent grid electricity supply in various scenarios of North West

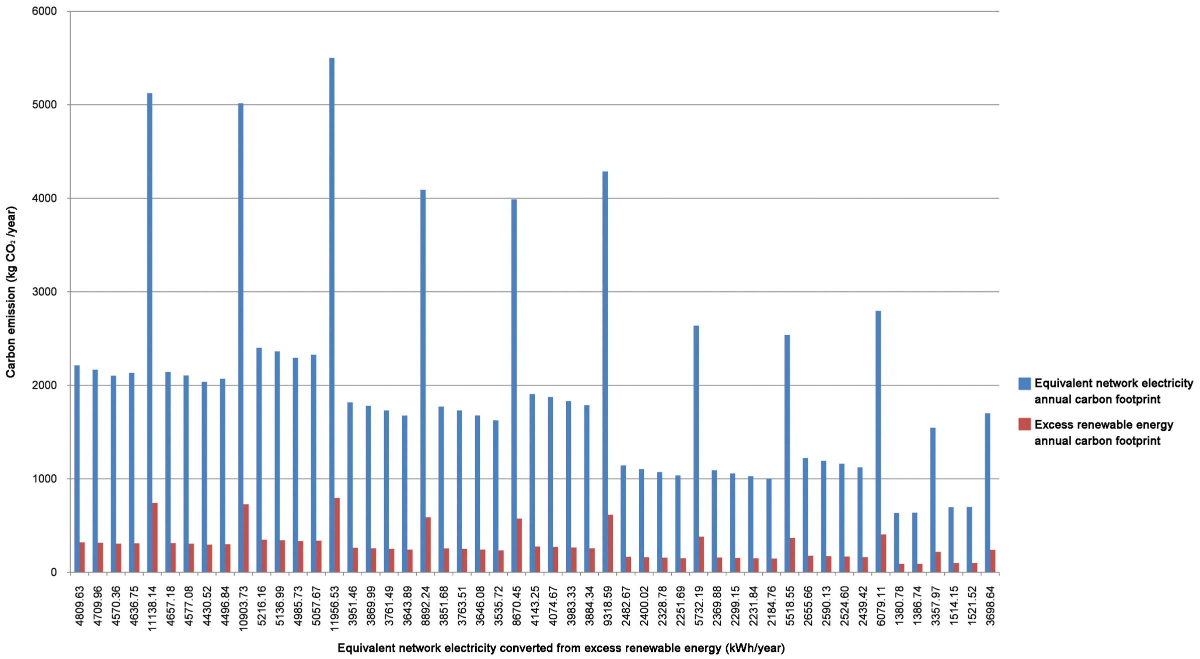


Fig. 7.9 Comparison of the carbon emissions between excess renewable energy outputs and equivalent grid electricity supply in various scenarios of Yorkshire & Humber

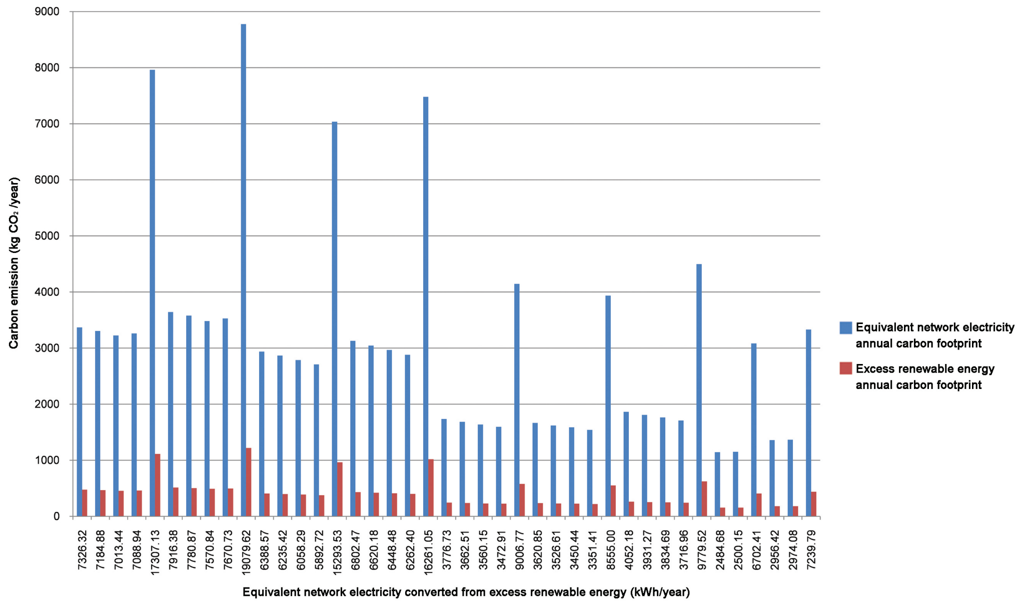


Fig. 7.10 Comparison of the carbon emissions between excess renewable energy outputs and equivalent grid electricity supply in various scenarios of South West

7.3.3 Total carbon saving contribution of TE heating system combined with renewable energy supply

Although in most properties of England northern regions, applying TE heating system with hybrid energy supply to meet the domestic heating demands can merely achieve limited carbon saving efficiencies in comparison with employing common condensing boilers, utilizing the excess renewable energy outputs during warm months to supply part of the domestic grid electric demands can further promote the total carbon saving contribution of the entire system to some extents.

The total carbon saving efficiency caused by employing TE heating system and hybrid energy supply in the domestic scenario is suggested calculating by: (CO_2 emission reduction of comparing TE heating system with condensing boiler + CO_2 emission reduction of comparing excess renewable energy outputs with equivalent grid electricity supply) ÷ (CO_2 emission of heating by condensing boiler + CO_2 emission caused by equivalent grid electricity supply). All the relevant results have been summarized in Table 7.10, Table 7.11, Table 7.12, and Table 7.13.

The estimation results suggest that it can potentially save maximum 9586.25 kgCO_2/year and minimum 706.93 kgCO_2/year by employing TE heating system and hybrid energy supply to service for all domestic heating demands and part of grid-connected electric demands in most domestic scenarios across England and Wales. Finally, in the scenario of 1919-44 detached property with 51 m^2 to 100 m^2 floor area, 2 occupants and located in North West region, although the carbon saving efficiency in comparison with common condensing boilers is very limited (i.e. 2.89%), after adding the additional carbon saving contribution caused by rationally using the excess renewable energy outputs (i.e. replacing part of the grid electricity supply to meet domestic electric demands), the total carbon saving efficiency of the entire system can be raised

		Carbon saving by TE heating (kgCO$_2$/year)	**Carbon saving by excess renewable energy outputs** (kgCO$_2$/year)	**Carbon emission of heating by condensing boiler** (kgCO$_2$/year)	**Carbon emission by equivalent grid ele supply** (kgCO$_2$/year)	**Total carbon saving efficiency** (%)
scenario1	Mid-terraced	595.71	1869.43	3114.02	2186.66	46.51
	End-terraced	573.25	1830.43	3287.78	2141.20	44.27
	Semi-detached	492.36	1771.66	3619.74	2072.60	39.77
	Detached	530.83	1797.03	3461.86	2102.23	41.84
	Bungalow	1585.69	4335.38	3682.95	5068.58	67.66
scenario2	Mid-terraced	577.47	1844.90	3223.32	2158.06	45.01
	End-terraced	545.13	1806.46	3403.19	2113.25	42.63
	Semi-detached	461.40	1751.24	3746.79	2048.75	38.18
	Detached	501.22	1777.50	3583.37	2079.42	40.24
	Bungalow	1594.52	4285.91	3812.23	5011.01	66.65
scenario3	Mid-terraced	513.48	1785.58	3533.09	2088.86	40.89
	End-terraced	465.44	1753.90	3730.23	2051.85	38.38
	Semi-detached	362.69	1702.48	4106.86	1991.78	33.86
	Detached	417.31	1722.16	3927.73	2014.78	36.00
	Bungalow	1533.39	4198.90	4178.58	4909.60	63.07
scenario4	Mid-terraced	697.25	2006.03	2505.49	2345.89	55.72
	End-terraced	673.92	1974.65	2645.30	2309.31	53.46
	Semi-detached	629.36	1914.69	2912.38	2239.43	49.38
	Detached	650.55	1943.21	2785.35	2272.66	51.28
	Bungalow	1568.59	4610.78	2963.24	5389.13	73.98
scenario5	Mid-terraced	615.00	1531.07	2118.16	1788.44	54.93
	End-terraced	591.31	1499.06	2260.50	1751.19	52.11
	Semi-detached	559.75	1456.43	2450.07	1701.59	48.56
	Detached	525.55	1410.23	2655.53	1647.83	44.98
	Bungalow	1400.99	3453.88	2766.31	4032.43	71.41
scenario6	Mid-terraced	585.98	1491.87	2292.48	1742.82	51.49
	End-terraced	560.34	1457.23	2446.54	1702.51	48.63
	Semi-detached	526.18	1411.09	2651.71	1648.83	45.05
	Detached	483.50	1365.80	2874.08	1596.08	41.37
	Bungalow	1406.58	3366.59	2993.98	3931.04	68.93
scenario7	Mid-terraced	670.79	1606.41	1783.07	1876.12	62.23
	End-terraced	650.84	1579.47	1902.89	1844.77	59.51
	Semi-detached	624.27	1543.59	2062.47	1803.01	56.08
	Detached	595.48	1504.70	2235.43	1757.75	52.59
	Bungalow	1390.27	3621.68	2328.68	4227.35	76.45
scenario8	Mid-terraced	308.57	949.13	1492.78	1110.14	48.32
	End-terraced	287.43	915.96	1640.57	1071.47	44.37
	Semi-detached	251.42	889.29	1788.35	1040.34	40.33
	Detached	206.89	858.41	1980.47	1004.27	35.69
	Bungalow	790.88	2199.33	1758.80	2571.11	69.06
scenario9	Mid-terraced	274.30	904.38	1694.46	1057.96	42.82
	End-terraced	233.43	877.42	1862.21	1026.47	38.46
	Semi-detached	189.56	852.94	2029.96	997.88	34.43
	Detached	113.19	837.16	2248.04	979.43	29.45
	Bungalow	782.19	2120.30	1996.41	2479.10	64.85
scenario10	Mid-terraced	360.18	1018.56	1183.48	1191.07	58.06
	End-terraced	340.63	992.26	1300.64	1160.41	54.16
	Semi-detached	321.08	965.96	1417.81	1129.76	50.52
	Detached	295.67	931.77	1570.12	1089.90	46.14
	Bungalow	782.23	2338.78	1394.37	2733.42	75.61
scenario11	Mid-terraced	259.19	518.10	909.22	604.03	51.37
	End-terraced	261.12	520.73	897.58	607.07	51.96
	Bungalow	608.38	1279.00	944.23	1489.51	77.55
scenario12	Mid-terraced	300.30	574.02	661.28	668.91	65.73
	End-terraced	301.70	575.92	652.81	671.12	66.29
	Bungalow	576.13	1404.41	686.74	1634.35	85.33

Table 7.10 Carbon saving by employing TE heating system and hybrid renewable energy in various simulated scenarios of North East region

to 28.01%. Similarly, in the other domestic scenarios, the total carbon saving efficiency can reach maximum 86.53%.

		Carbon saving by TE heating (kgCO$_2$/year)	**Carbon saving by excess renewable energy outputs** (kgCO$_2$/year)	**Carbon emission of heating by condensing boiler** (kgCO$_2$/year)	**Carbon emission by equivalent grid ele supply** (kgCO$_2$/year)	**Total carbon saving efficiency** (%)
scenario13	Mid-terraced	429.87	1699.20	3124.69	1988.49	41.64
	End-terraced	387.37	1671.19	3299.05	1955.76	39.17
	Semi-detached	306.19	1617.68	3632.14	1893.23	34.82
	Detached	344.80	1643.13	3473.72	1922.97	36.84
	Bungalow	1311.34	3950.43	3695.57	4621.10	63.27
scenario14	Mid-terraced	356.68	1650.96	3424.97	1932.12	37.48
	End-terraced	310.10	1620.26	3616.09	1896.25	35.02
	Semi-detached	195.85	1582.56	3981.19	1852.18	30.49
	Detached	256.67	1595.12	3807.54	1866.86	32.63
	Bungalow	1252.01	3870.77	4050.72	4528.17	59.71
scenario15	Mid-terraced	558.61	1844.90	2428.82	2158.52	52.39
	End-terraced	535.97	1814.50	2564.35	2123.05	50.14
	Semi-detached	492.72	1756.43	2823.26	2055.31	46.10
	Detached	513.29	1784.05	2700.12	2087.53	47.98
	Bungalow	1323.57	4238.94	2872.57	4957.25	71.04
scenario16	Mid-terraced	484.80	1401.05	2039.15	1637.58	51.29
	End-terraced	461.96	1370.27	2176.18	1601.72	48.50
	Semi-detached	436.29	1329.27	2358.69	1553.97	45.12
	Detached	388.12	1293.51	2556.48	1512.26	41.33
	Bungalow	1164.55	3153.99	2663.13	3684.85	68.03
scenario17	Mid-terraced	456.82	1363.35	2206.97	1593.66	47.89
	End-terraced	437.12	1330.03	2355.28	1554.86	45.19
	Semi-detached	389.02	1294.10	2552.81	1512.95	41.40
	Detached	336.89	1259.66	2766.88	1472.77	37.66
	Bungalow	1168.94	3070.78	2882.31	3588.10	65.52
scenario18	Mid-terraced	538.57	1473.52	1716.56	1721.99	58.52
	End-terraced	519.34	1447.61	1831.91	1691.80	55.82
	Semi-detached	493.73	1413.09	1985.54	1651.60	52.43
	Detached	465.98	1375.69	2152.05	1608.04	48.98
	Bungalow	1154.37	3315.37	2241.82	3872.49	73.10
scenario19	Mid-terraced	249.56	882.51	1392.47	1032.67	46.68
	End-terraced	222.74	854.74	1530.32	1000.26	42.58
	Semi-detached	189.14	832.60	1668.18	974.38	38.66
	Detached	148.08	803.81	1847.39	940.74	34.14
	Bungalow	666.58	2041.35	1640.61	2387.62	67.22
scenario20	Mid-terraced	210.49	846.67	1580.59	990.82	41.11
	End-terraced	172.35	821.53	1737.07	961.45	36.83
	Semi-detached	131.91	798.30	1893.55	934.30	32.89
	Detached	60.67	783.59	2096.97	917.09	28.01
	Bungalow	653.25	1971.97	1862.25	2306.77	62.97
scenario21	Mid-terraced	297.76	947.22	1103.95	1108.16	56.28
	End-terraced	279.50	922.71	1213.24	1079.56	52.43
	Semi-detached	261.25	898.20	1322.53	1050.97	48.85
	Detached	238.76	866.33	1464.61	1013.79	44.59
	Bungalow	658.61	2171.32	1300.67	2539.02	73.70
scenario22	Mid-terraced	215.25	491.68	766.38	573.59	52.76
	End-terraced	216.88	493.89	756.57	576.16	53.33
	Bungalow	492.25	1199.70	795.89	1398.16	77.12
scenario23	Mid-terraced	249.95	538.76	557.39	628.27	66.52
	End-terraced	251.14	541.32	550.25	631.25	67.07
	Bungalow	460.91	1304.59	578.85	1519.44	84.14

Table 7.11 Carbon saving by employing TE heating system and hybrid renewable energy in various simulated scenarios of North West region

		Carbon saving by TE heating (kgCO_2/year)	**Carbon saving by excess renewable energy outputs** (kgCO_2/year)	**Carbon emission of heating by condensing boiler** (kgCO_2/year)	**Carbon emission by equivalent grid ele supply** (kgCO_2/year)	**Total carbon saving efficiency** (%)
scenario24	Mid-terraced	560.23	1890.86	3209.14	2212.43	45.21
	End-terraced	529.28	1851.55	3388.21	2166.58	42.86
	Semi-detached	445.90	1796.60	3730.31	2102.36	38.45
	Detached	485.56	1822.74	3567.60	2132.91	40.49
	Bungalow	1558.38	4380.84	3795.45	5123.54	66.59
scenario25	Mid-terraced	497.76	1830.78	3517.54	2142.30	41.14
	End-terraced	449.92	1799.25	3713.82	2105.46	38.65
	Semi-detached	355.46	1741.56	4088.79	2038.04	34.23
	Detached	402.00	1767.66	3910.45	2068.55	36.29
	Bungalow	1497.48	4288.35	4160.19	5015.72	63.05
scenario26	Mid-terraced	679.55	2051.21	2494.47	2399.43	55.80
	End-terraced	656.31	2019.98	2633.66	2363.01	53.56
	Semi-detached	611.92	1960.32	2899.57	2293.44	49.53
	Detached	633.03	1988.69	2773.10	2326.53	51.41
	Bungalow	1525.63	4704.11	2950.20	5500.00	73.72
scenario27	Mid-terraced	589.25	1555.50	2131.29	1817.67	54.31
	End-terraced	565.39	1523.32	2274.51	1780.20	51.51
	Semi-detached	533.61	1480.45	2465.26	1730.28	48.00
	Detached	499.17	1433.99	2672.00	1676.19	44.46
	Bungalow	1354.20	3502.11	2783.47	4090.43	70.65
scenario28	Mid-terraced	560.03	1516.08	2306.70	1771.77	50.90
	End-terraced	534.21	1481.25	2461.71	1731.21	48.07
	Semi-detached	499.81	1434.85	2668.15	1677.19	44.52
	Detached	454.44	1391.29	2891.90	1626.43	40.85
	Bungalow	1359.77	3414.33	3012.54	3988.40	68.19
scenario29	Mid-terraced	645.42	1631.27	1794.12	1905.90	61.53
	End-terraced	625.34	1604.18	1914.69	1874.35	58.84
	Semi-detached	598.59	1568.09	2075.26	1832.33	55.45
	Detached	569.59	1528.98	2249.29	1786.80	52.00
	Bungalow	1343.51	3670.84	2343.12	4286.55	75.63
scenario30	Mid-terraced	302.97	976.14	1467.70	1142.03	49.01
	End-terraced	278.70	943.54	1613.01	1104.01	44.98
	Semi-detached	248.99	915.46	1758.31	1071.24	41.15
	Detached	202.95	885.12	1947.20	1035.78	36.48
	Bungalow	768.80	2254.86	1729.25	2636.81	69.25
scenario31	Mid-terraced	271.49	931.65	1665.99	1090.14	43.65
	End-terraced	231.30	903.80	1830.92	1057.61	39.30
	Semi-detached	191.10	877.30	1995.86	1026.65	35.35
	Detached	119.63	858.78	2210.27	1004.99	30.43
	Bungalow	768.31	2170.48	1962.87	2538.53	65.29
scenario32	Mid-terraced	353.74	1044.37	1163.60	1221.60	58.62
	End-terraced	334.51	1018.52	1278.79	1191.46	54.77
	Semi-detached	315.27	992.68	1393.99	1161.32	51.19
	Detached	290.27	959.08	1543.74	1122.13	46.86
	Bungalow	760.36	2391.89	1370.95	2796.39	75.64
scenario33	Mid-terraced	260.47	544.63	818.30	635.16	55.39
	End-terraced	262.21	546.99	807.82	637.90	55.97
	Bungalow	580.19	1325.83	849.80	1544.67	79.60
scenario34	Mid-terraced	297.51	597.48	595.15	696.51	69.29
	End-terraced	298.78	600.41	587.53	699.90	69.84
	Bungalow	511.00	1461.65	618.06	1701.38	85.05

Table 7.12 Carbon saving by employing TE heating system and hybrid renewable energy in various simulated scenarios of Yorkshire & Humber region

		Carbon saving by TE heating (kgCO$_2$/year)	Carbon saving by excess renewable energy outputs (kgCO$_2$/year)	Carbon emission of heating by condensing boiler (kgCO$_2$/year)	Carbon emission by equivalent grid ele supply (kgCO$_2$/year)	Total carbon saving efficiency (%)
scenario35	Mid-terraced	1459.09	2894.82	2617.98	3370.11	72.71
	End-terraced	1468.96	2838.61	2764.07	3305.04	70.98
	Semi-detached	1422.75	2770.56	3043.14	3226.18	66.89
	Detached	1444.73	2800.52	2910.41	3260.91	68.79
	Bungalow	2599.66	6847.46	3096.29	7961.28	85.44
scenario36	Mid-terraced	1444.00	3129.46	2034.96	3641.54	80.57
	End-terraced	1446.94	3075.47	2148.51	3579.20	78.96
	Semi-detached	1452.56	2992.00	2365.44	3482.59	76.00
	Detached	1449.89	3031.70	2262.26	3528.54	77.39
	Bungalow	2028.48	7557.77	2406.75	8776.63	85.72
scenario37	Mid-terraced	1312.15	2531.14	1762.94	2938.74	81.74
	End-terraced	1345.76	2469.93	1881.41	2868.30	80.34
	Semi-detached	1217.01	2399.23	1906.20	2786.81	77.06
	Detached	1354.59	2333.26	2210.20	2710.65	74.94
	Bungalow	1945.89	6071.68	2302.40	7035.03	85.86
scenario38	Mid-terraced	1246.14	2696.78	1484.05	3129.14	85.47
	End-terraced	1279.16	2623.70	1583.77	3045.28	84.31
	Semi-detached	1303.61	2555.08	1716.60	2966.30	82.40
	Detached	1345.20	2480.71	1860.55	2880.70	80.69
	Bungalow	1638.05	6460.33	1938.16	7480.08	85.99
scenario39	Mid-terraced	726.51	1492.55	1191.69	1737.30	75.76
	End-terraced	729.56	1447.15	1309.67	1684.75	72.69
	Semi-detached	726.93	1406.48	1427.64	1637.67	69.60
	Detached	701.53	1371.86	1581.01	1597.54	65.23
	Bungalow	1158.47	3565.22	1404.05	4143.11	85.16
scenario40	Mid-terraced	739.34	1430.60	1352.69	1665.59	71.89
	End-terraced	717.16	1393.17	1486.60	1622.24	67.88
	Semi-detached	694.99	1362.95	1620.52	1587.20	64.16
	Detached	666.16	1323.65	1794.61	1541.65	59.64
	Bungalow	1327.59	3384.28	1593.73	3935.30	85.22
scenario41	Mid-terraced	702.52	1602.20	944.77	1864.00	82.05
	End-terraced	722.54	1554.00	1038.30	1808.39	79.97
	Semi-detached	724.96	1515.58	1131.84	1763.96	77.37
	Detached	728.11	1468.79	1253.43	1709.80	74.14
	Bungalow	938.18	3874.97	1113.13	4498.58	85.77
scenario42	Mid-terraced	590.58	988.22	714.37	1142.95	85.00
	End-terraced	588.88	994.44	705.23	1150.07	85.34
	Bungalow	629.23	2674.45	741.88	3083.11	86.37
scenario43	Mid-terraced	440.68	1178.19	519.56	1359.95	86.13
	End-terraced	435.04	1185.30	512.91	1368.08	86.14
	Bungalow	457.64	2890.93	539.57	3330.31	86.53

Table 7.13 Carbon saving by employing TE heating system and hybrid renewable energy in various simulated scenarios of South West region

7.4 Summary

For ascertaining the carbon saving potential caused by applying TE heating system with hybrid energy supply in the domestic context, the CO_2 emission factors of various energy sources have been studied and the potential CO_2 emission reductions caused by the entire system application were further classified and estimated. The main summaries are listed as follows:

1. in comparison with condensing boiler heating by burning natural gas, applying the TE heating system powered by hybrid energy supply to service for domestic heating demands can potentially save 60.67 kgCO_2/year-2599.66 kgCO_2/year in various scenarios. And the reachable carbon saving efficiency is estimated between 2.89% and 84.82%.

2. By rationally using the excess renewable energy outputs which are not requested by the domestic heating demands to replace equivalent grid electricity supply in the domestic context, it can further save more additional CO_2 emissions between 491.68 kgCO_2/year and 7557.77 kgCO_2/year in various scenarios.

3. When using the entire system to service for the domestic heating demands and part of domestic electricity demands, it can potentially save maximum 9586.25 kgCO_2/year in a pre-1919 bungalow with 101 m^2 to 150 m^2 floor area of South West region, and minimum 706.93 kgCO_2/year in a post 1999 end-terraced property with 50 m^2 or less floor area of the North West region. The correspondingly total carbon saving efficiency can be achieved between 28.01% and 86.53%.

Chapter 8

Conclusions

This thesis presents both of experimental studies of the heating exchange performance of TE modules for supporting large-scale space heating application and simulation analysis regarding the energy saving efficiency, and possible carbon saving when employing TE heating system powered by hybrid energy (i.e. solar/wind renewable energy and utility grid supply) in various domestic scenarios across England and Wales. Detailed study findings have been summarized at the end of each corresponding chapter which are helpful to fairly assess the potentiality/contribution if applying the TE heating system with hybrid energy supply in typical UK domestic context and to further ascertain the feasibility of universally applying the entire system to service for more UK dwellings. Study limitations and recommendations for further study works will be presented at the end of this chapter.

8.1 Study summary

Chapter 2 presents a comprehensive literature review in relation to the working principle of thermoelectric heat exchange module, the thermoelectric material figure-of-merit, relevant calculations of thermoelectric material performance and development status in terms of existing TE researches and applications. The review results prove that the heating COP of common commercial TE modules can achieve higher than 2.0 which is always better than its cooling COP. Relevant background studies suggest a potential application of TE modules powered by renewable low-voltage DC for supporting the UK domestic heating demands which may be able to compete with the traditional heating system in near future for reducing the greenhouse gas emission caused by UK domestic heating and contribute to government's Carbon Plan.

For further ascertaining actual space heating performance of TE modules in the UK context, an experimental study which utilizing three pieces of TEC1-12706 modules to heating a 1 m^3 enclosed space are presented in Chapter 3. The tests monitor and record all the temperature changes of TE hot surface, TE cold surface, internal heating test space and external ambient. Relevant test results reveal that TE modules could produce enough temperature difference to meet the UK domestic thermal comfort level (i.e. 18 °C-24 °C). Moreover, the experimental study also calculates and analyzes achievable heating COP and heat transfer power of TE module change with different working voltages. The calculation results determine that during the whole space heating period, the heating COP values of tested TE modules can always remain above 1.8 with all voltage input tests (i.e. 4 V to 9 V) in both lab and low-temperature courtyard environments whilst the minimum average heat transfer power is estimated at64.41 $W m^{-2}$ which suggest a acceptable heat pump efficiency and heating power for the domestic heating application.

Then for determining the potential application of TE heating system if being powered by renewable energy to support the domestic heating, a realistic case study in typical pre-1900s mid-terraced property with 180 m^2 floor area located in Newcastle upon Tyne is proposed in Chapter 4. Based on investigations in relation to the heating demands and available renewable energy supply (i.e. solar and wind energy supply) in the case studied dwelling scenario, detailed heating supply-demand relationship when employing TE heating system with minimum heating COP of 1.8 to service for the domestic heating demands can be simulated. The simulation results reveal that TE heating system merely powered by local renewable energy cannot fully meet the monthly heating demands in some cold months (i.e. Jan, Feb, Mar, Nov and Dec) due to the poor renewable energy supply and higher heating demand levels. Thus additional grid electricity supply is suggested as the energy complement during any renewable energy shortage periods. Furthermore, in comparison with employing generic electric heaters powered by the grid electricity to meet same domestic heating demands, relevant estimation results reveal that the application of TE system with hybrid energy supply would be able to achieve a minimum energy saving efficiency of 64.93% whilst reducing 3927.72 kg CO_2 emission per year.

In Chapter 5, the specific application design of TE heating system combined with hybrid energy supply are demonstrated in the typical mid-terraced property scenario. All the main system components contain PV panels, micro wind turbines, batteries, hybrid inverter/chargers and TE heating equipment have been identified. Relevant performance studies (e.g. the power output efficiencies of solar cells and wind turbine, the lead-acid battery efficiency and depth of discharge, and generic conversion loss of the converter and inverter, etc) and capital cost investigations associate with these components are also presented. Moreover, in a typical mid-terraced property with 180 m^2 floor area, the total system cost during the minimum system lifecycle of 15 years is simply estimated as $60,418.54. Meanwhile in comparison with using general electric heaters, it can estimate 136 488.60 kW h grid electricity saving and 58 915.80 kg CO_2 emission reduction caused by the entire system application for meeting the domestic heating loads during the minimum system lifecycle.

In Chapter 6, the study intends to explore specific heating supply-demand relationships when employing TE heating system with hybrid energy supply in more domestic scenarios across England and Wales for evaluating the feasibility of universally applying the entire system in the UK domestic context. Relevant baselines and estimation methods regarding the monthly heating demands, solar energy outputs by roof PV panels and wind energy outputs by wind turbines in various domestic scenarios have been defined and studied respectively. Hereby the study can simulate more different heating scenarios. The simulation results in relation to the heating supply-demand relationships, energy saving efficiencies and possible domestic hot water supply shows that the entire system generally can independently meet the domestic heating demands for 2-6 months per year (exclude June, July and August) in most common property types (mid-terraced, end-terraced, semi-detached and detached) and 4-9 months per year in bungalows. The simulated minimum energy saving efficiency of the heating system in comparison with generic electric heater is 56.11% in the domestic scenarios of England northern regions. Meanwhile both of the domestic heating demands and hot water demands can be potentially meet without extra grid-supply throughout the year in some domestic scenarios of the UK southern regions.

Finally, in Chapter 7, for ascertaining the carbon saving potential caused by applying TE heating system with hybrid energy supply in the UK domestic context, the CO_2 emission factors of various energy sources have been studied and the potential CO_2 emission reductions caused by the entire system application are further classified and estimated. Relevant estimation results suggest that in comparison with employing condensing boiler for supporting the domestic heating demands and consuming grid electricity for meeting all domestic electric demands, appropriate applications of the entire system in various domestic scenarios across England and Wales can potentially save 706.93 kgCO_2/year-9586.25 kgCO_2/year whilst the final carbon saving efficiency can reach between 28.01% and 86.53%.

8.2 Feasibility of applying TE heating system combined with hybrid renewable energy for UK domestic heating

Firstly the potential advantages of TE heating system in comparison with other common types of heat pumps can be briefly summarized as:

- In comparison to the structures of conventional vapor compression (VC) and absorption refrigeration (AR) heat pumps, the solid-state TE heat pump doesn't require any fluid refrigerants or moving parts. These lead to TE heat pump can easily achieve zero ODP (Ozone Depletion Potential), low GWP (Global Warming Potential), higher levels of reliability, lower working noisy, lower maintenance costs and longer lifecycle.

- The experimental study proves the average heating COP of TE air-source heat pump generally can reach near 2.0 or higher during the space heating process which is competitive to the generic energy efficiency around 1.4 of the gas absorption heat pumps.

- The COP changes of TE modules are much sensitive with the input power (i.e. voltage/current) changes. Thus in comparison with both of VC and AR heat pumps design, the TE heat pump will more easily achieve the smart control by monitoring temperature and adjusting power for optimizing the energy efficiency in time.

- Limited by the bulky equipment volume, the VC heat pumps can only extract heat from outdoor air via the heat exchange devices fixed on the building outer wall and heating the whole building interior or some specific rooms. But the TE heat pumps can be rationally distributed on both building exterior walls and interior walls benefited from their small equipment volumes. Hereby it both can extract outdoor heat and can transfer useless indoor heat (e.g. waste heat from kitchen and bathroom) to any occupied rooms where request heating demands. These applications are helpful to prevent more available indoor heat loss and to further promote the energy using efficiency.

Then when further combining TE heating system with renewable energy supply system (i.e. PV panels and wind turbines) to service for the UK domestic heating demands, various scenario simulation results reveal that TE heating system merely powered by renewable energy usually cannot meet all the domestic heating demands throughout the year in most England northern regions. Thus it has to require additional grid electricity supply during any renewable energy shortage periods. However, in some scenarios of the UK southern regions, benefited from more available renewable energy resources and lower domestic heating demand levels, the entire system is most likely able to fully meet the domestic heating demands whilst off the grid supply. Relevant estimation results in this study also show that for supporting the domestic heating purpose, the application of TE heating system with hybrid energy supply in various scenarios can save minimum 56.11% annual grid electricity consumption compared with employing generic electric heaters powered by the grid electricity, and can save 2.89%-84.82% CO_2 emission in comparison with condensing boiler heating by burning natural gas, respectively. Meanwhile, during some warm months, the excess renewable energy outputs which are not requested by the domestic heating demands can potentially be used to supply the domestic hot water and electric demands which will further save more grid energy consumptions and CO_2 emissions.

Additionally, the performance improvements of the VC heat pumps are mostly relied on the engineering technical innovation. But the performance improvements of TE heat pumps are most likely related to the thermoelectric material development. The experimental results have shown that when testing TEC1-12706 module in a lower outdoor temperature of 3 °C, the minimum heating COP is detected as 1.8 which cannot be comparable with the typical heating COP around 3.0 of the VC heat pumps. The relatively poor heat pump performance of TE module is mostly limited by common thermoelectric material figure-of-merit which are determined by ZT varies between 0.8-1.1 in the near room temperature application. However, the Lincoln labs reports that $ZT \geq 2.0$ has become achievable as the new thermoelectric material development. Based on the Equation 2.7 and Equation 2.16 of Chapter 2, it can theoretically estimate the heating COP value of TE module would increase to around 1.65 times of the original value if the ZT is improved to 2.0 from 0.8 in general indoor heating application (i.e. the hot temperature gets 30 °C whilst the cold side temperature keeps at 0 °C). This implies the TE heat pumps will have more development potential in near future to compete with the VC heat pumps. Meanwhile the application of TE domestic heating system powered by hybrid energy in domestic context can make more grid energy saving and carbon saving contributions with less economic costs benefited from the thermoelectric material performance development.

8.3 Study limitations

limited by scheduled experiment time and available experiment apparatus support in lab, the experimental study can only test the actual heating performance of TEC1-12706 module which is the most common commercial module with cheap costs. However, there exist many other types of TE modules utilize new thermoelectric materials can potentially compete with TEC1-12706 module. The optimal selection of TE module with higher performance (i.e. heating COP) can further promote the energy using efficiency of the entire heating system and correspondingly extend independent heating periods. This will be helpful to relief the dispute regarding the feasibility of employing TE heating system powered by renewable energy to service for the domestic heating demands in the UK northern regions (i.e. the entire system off the gird energy supply can only meet the domestic heating demands for 2-4 months throughout the year in most properties of England northern regions).

Additionally, in Chapter 4, Chapter 6 and Chapter 7, the studies have investigated and imported as more as possible variable parameters into the scenario simulations for calculating relatively realistic results. However, the actual contexts are always complicated with more uncertainty factors. For instances, the regional average irradiance investigation results cannot detect special terrain influence factors which may further affect the estimation results of the roof PV output power in some specific scenarios; the regional average wind speed investigation results cannot detect the significant differences in urban areas and rural areas (i.e. wind speed will be typically weakened by numerous buildings, woods, or high hedgerows, etc) which will affect the accuracy of specific wind energy output estimation; there also exist some deviations between the estimated domestic heating demands and the real demands due to uncertain behaviors of the occupants and actual weather change conditions in each specific year. Hence, although these simulation study results have contributed with fundamental reference data regarding possible heating supply-demand relationship, grid energy saving efficiency, carbon saving contribution when applying TE domestic heating system with hybrid energy supply in various domestic scenarios across England and Wales, there is still a large simulation correction spaces supported by more detailed investigations and statistics for further promoting the simulation accuracy and providing more reliable results.

8.4 Future works

In future works, the study regarding further reseach of the TE domestic heating system can continue to test and compare more different TE modules for exploring higher efficiency of the TE heating system. Meanwhile it will require a detailed design of the smart control system which can automatically adjust the working voltage levels for optimizing the heat exchange efficiency of TE modules depends on ambient temperature monitoring results and can flexibly change the heat transfer direction in indoor space according actual demands (i.e. the heat transfer direction can be easily reversed by reversing the circuit current direction).

Additionally, the future study can also make more investigations regarding detailed renewable energy output profile and energy consumption profile throughout the day in each specific domestic context. The comparison results between energy supply and demand will be helpful to correct simulation deviations, and to optimize system battery size which can relief the higher cost concern of batteries to some extents. Further economic estimates are also appreciative for better evaluating the application values of the entire system in future UK domestic context.

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Appendix A

TE module performance calculations

Ambient	Voltage (V)	Current (A)	Resistance (Ω)	T_h (K)	T_c (K)	ΔT (K)	Q_h (W)	W (W)	ε_h (COP)
Laboratory	4	1.35	2.22	297.87	293.20	4.67	19.74	4.37	4.52
	5	1.68	2.22	298.35	292.15	6.20	24.99	6.80	3.68
	6	1.97	2.22	301.18	292.41	8.77	29.36	9.49	3.09
	7	2.25	2.22	303.52	294.02	9.50	34.79	12.33	2.82
	8	2.56	2.22	303.47	292.92	10.55	40.61	15.92	2.55
	9	2.82	2.22	306.43	293.70	12.73	45.33	19.48	2.33
Courtyard	6	2.15	2.22	284.72	274.10	10.62	30.06	11.42	2.63
	7	2.51	2.22	283.22	273.72	9.50	37.59	15.20	2.47
	8	2.75	2.22	289.83	276.19	13.64	40.96	18.69	2.19
	9	3.18	2.22	286.53	275.08	11.45	50.86	24.30	2.09

Table A.1 The related data records at 10 minutes after the start of each heating test

Ambient	Voltage (V)	Current (A)	Resistance (Ω)	T_h (K)	T_c (K)	ΔT (K)	Q_h (W)	W (W)	ε_h (COP)
Laboratory	4	1.28	2.22	303.06	294.34	8.72	16.46	4.20	3.92
	5	1.56	2.22	306.32	293.58	12.74	19.58	6.41	3.06
	6	1.85	2.22	309.04	294.46	14.58	24.38	8.97	2.72
	7	2.13	2.22	311.78	295.33	16.45	29.22	11.85	2.47
	8	2.41	2.22	312.70	294.22	18.48	34.00	15.16	2.24
	9	2.63	2.22	317.96	295.17	22.79	36.92	18.40	2.01
Courtyard	6	2.00	2.22	293.28	275.20	18.08	23.74	10.72	2.22
	7	2.32	2.22	294.90	274.80	20.10	29.06	14.32	2.03
	8	2.57	2.22	299.98	276.69	23.29	32.97	17.70	1.86
	9	2.88	2.22	300.31	276.51	23.80	39.32	21.90	1.80

Table A.2 The heating COP calculation at the end of each heating test

Time	Current (A)	Resistance (Ω)	T_h (K)	T_c (K)	ΔT (K)	Q_h (W)	W (W)	ε_h (COP)
00:10:20	2.73	2.22	296.55	292.76	3.79	47.20	17.07	2.77
00:13:20	2.62	2.22	300.01	292.48	7.53	43.18	16.24	2.66
00:16:45	2.57	2.22	302.43	292.80	9.63	41.22	15.92	2.59
00:24:25	2.52	2.22	305.97	293.31	12.66	38.87	15.72	2.47
00:37:50	2.46	2.22	309.70	293.86	15.84	36.22	15.41	2.35
00:43:35	2.44	2.22	310.85	294.09	16.76	35.41	15.29	2.32
00:51:45	2.42	2.22	312.15	294.11	18.04	34.40	15.22	2.26
00:54:35	2.41	2.22	312.70	294.22	18.48	34.00	15.16	2.24

Table A.3 The changes of heat generation and COP of 8 V heating test in lab ambient

Time	Current (A)	Resistance (Ω)	T_h (K)	T_c (K)	ΔT (K)	Q_h (W)	W (W)	ε_h (COP)
00:21:50	2.89	2.22	283.93	276.02	7.91	46.36	19.70	2.35
00:28:55	2.75	2.22	289.54	276.19	13.35	41.09	18.65	2.20
00:37:20	2.69	2.22	292.75	276.44	16.31	38.56	18.29	2.11
00:47:45	2.65	2.22	295.35	276.76	18.59	36.76	18.09	2.03
00:55:15	2.63	2.22	296.59	276.77	19.82	35.79	18.00	1.99
01:04:05	2.60	2.22	297.97	276.78	21.19	34.55	17.81	1.94
01:15:55	2.58	2.22	299.26	276.98	22.28	33.67	17.70	1.90
01:25:35	2.57	2.22	299.97	276.68	23.29	32.97	17.70	1.86

Table A.4 The changes of heat generation and COP of 8 V heating test in courtyard ambient

Heat dissipation method at the TE hot side	Voltage (V)	Current (A)	Resistance (Ω)	T_h (K)	T_c (K)	ΔT (K)	Q_h (W)	W (W)	ε_c (COP)
Forced air	3	1.03	2.22	292.82	287.32	5.50	10.66	2.64	4.04
	4	1.36	2.22	294.28	286.47	7.81	13.20	4.65	2.84
	5	1.71	2.22	293.66	284.83	8.83	16.37	7.26	2.25
	6	1.99	2.22	298.95	287.81	11.14	18.23	9.92	1.84
	7	2.33	2.22	298.38	287.24	11.14	21.50	13.37	1.61
	8	2.65	2.22	297.65	284.62	13.03	22.95	17.34	1.32
	9	2.93	2.22	298.59	284.76	13.83	24.82	21.12	1.18
	10	3.21	2.22	300.42	285.65	14.77	26.56	25.28	1.05
Forced air & assisted water	7	2.37	2.22	295.07	283.88	11.19	21.44	13.82	1.55
	8	2.76	2.22	292.45	282.70	9.75	25.52	18.28	1.40
	9	3.09	2.22	293.55	282.98	10.57	27.68	22.86	1.21
	10	3.34	2.22	294.86	283.72	11.14	29.29	26.66	1.10

Table A.5 The Cooling COP calculation at the end of each cooling test

Appendix B

Weather data collection from NASA

Location	North East		**Typical city**	Newcastle	
Latitude (°N)	54.97				
Longitude (°E)	-1.61				
Elevation (m)	90				
Month	**Air temperature** (°C)	**Relative humidity** (%)	**Daily solar radiation horizontal** (kWh/(m^2day))	**Atmospheric pressure** (kPa)	**Wind speed** (m/s)
Jan	4.5	79.40	0.63	100.1	5.8
Feb	4.5	77.00	1.31	100.3	5.5
Mar	5.7	76.00	2.32	100.2	5.5
Apr	7.2	74.10	3.53	100.2	4.7
May	10.2	70.80	4.67	100.5	4.3
Jun	13.3	68.20	4.73	100.4	4.0
Jul	15.8	68.00	4.62	100.4	3.9
Aug	16.0	68.50	3.92	100.4	4.1
Sep	13.7	70.20	2.72	100.3	4.7
Oct	10.7	74.90	1.57	100.0	5.1
Nov	7.3	80.30	0.77	100.0	5.3
Dec	5.4	80.50	0.47	100.2	5.6
Annual	9.5	74.00	2.60	100.3	4.9
Measured at (m)					10

Table B.1 Weather data of the North East

Location	North West		**Typical city**	Greater Manchester	
Latitude (°N)	53.48				
Longitude (°E)	-2.23				
Elevation (m)	123				
Month	**Air temperature** (°C)	**Relative humidity** (%)	**Daily solar radiation horizontal** (kWh/(m^2day))	**Atmospheric pressure** (kPa)	**Wind speed** (m/s)
Jan	3.5	84.00	0.67	99.8	5.2
Feb	3.7	81.00	1.33	100.0	4.8
Mar	5.4	78.40	2.32	99.9	5.2
Apr	7.3	73.20	3.65	99.8	4.5
May	10.9	67.50	4.90	100.1	4.2
Jun	14.0	65.10	4.99	100.1	4.0
Jul	16.5	64.50	4.86	100.1	3.7
Aug	16.3	66.40	4.01	100.0	3.7
Sep	13.6	69.50	2.78	100.0	4.3
Oct	10.1	77.00	1.56	99.7	4.6
Nov	6.4	84.50	0.81	99.7	5.0
Dec	4.3	85.30	0.50	99.8	5.1
Annual	9.3	74.70	2.70	99.9	4.5
Measured at (m)					10

Table B.2 Weather data of the North West

Location	Yorkshire & Humber		**Typical city**	York	
Latitude (°N)	53.96				
Longitude (°E)	-1.08				
Elevation (m)	94				
Month	**Air temperature** (°C)	**Relative humidity** (%)	**Daily solar radiation horizontal** (kWh/(m^{2}day))	**Atmospheric pressure** (kPa)	**Wind speed** (m/s)
Jan	3.6	83.50	0.65	100.2	5.6
Feb	3.9	80.00	1.32	100.4	5.3
Mar	5.7	76.80	2.22	100.3	5.4
Apr	7.6	71.80	3.39	100.2	4.6
May	11.2	66.30	4.42	100.5	4.2
Jun	14.5	63.00	4.50	100.4	4.0
Jul	17.0	62.20	4.48	100.4	3.8
Aug	16.9	63.60	3.85	100.4	4.0
Sep	14.1	67.50	2.64	100.3	4.6
Oct	10.5	75.30	1.57	100.1	5.0
Nov	6.5	83.80	0.82	100.1	5.2
Dec	4.4	84.80	0.51	100.2	5.5
Annual	9.7	73.20	2.53	100.3	4.8
Measured at (m)					10

Table B.3 Weather data of the Yorkshire & Humber

Location	East Midlands		**Typical city**	Lincoln	
Latitude (°N)	53.22				
Longitude (°E)	-0.53				
Elevation (m)	57				
Month	**Air temperature** (°C)	**Relative humidity** (%)	**Daily solar radiation horizontal** (kWh/(m^{2}day))	**Atmospheric pressure** (kPa)	**Wind speed** (m/s)
Jan	4.5	80.40	0.65	100.7	6.1
Feb	4.6	77.30	1.32	100.8	5.8
Mar	6.1	75.30	2.22	100.7	5.6
Apr	7.9	72.00	3.39	100.7	4.8
May	11.1	68.20	4.42	100.9	4.3
Jun	14.4	65.50	4.50	100.9	4.0
Jul	16.9	64.90	4.48	100.9	4.0
Aug	17.1	65.30	3.85	100.8	4.2
Sep	14.6	67.90	2.64	100.8	4.8
Oct	11.3	73.40	1.57	100.5	5.3
Nov	7.5	80.60	0.82	100.5	5.5
Dec	5.5	81.30	0.51	100.7	5.8
Annual	10.1	72.70	2.53	100.7	5.0
Measured at (m)					10

Table B.4 Weather data of the East Midlands

Location	West Midlands		**Typical city**	Birmingham	
Latitude (°N)	52.48				
Longitude (°E)	-1.89				
Elevation (m)	93				
Month	**Air temperature** (°C)	**Relative humidity** (%)	**Daily solar radiation horizontal** (kW h/(m^{2}day))	**Atmospheric pressure** (kPa)	**Wind speed** (m/s)
Jan	3.6	84.50	0.72	100.3	6.3
Feb	3.9	80.80	1.37	100.5	5.8
Mar	5.9	77.40	2.30	100.4	6.1
Apr	8.0	71.10	3.49	100.2	5.1
May	11.8	65.10	4.49	100.5	4.7
Jun	15.2	61.60	4.67	100.5	4.5
Jul	17.7	60.90	4.67	100.5	4.3
Aug	17.6	62.40	4.07	100.4	4.4
Sep	14.6	66.90	2.75	100.4	5.1
Oct	10.8	75.30	1.69	100.2	5.5
Nov	6.6	84.40	0.93	100.2	6.0
Dec	4.4	85.70	0.57	100.3	6.2
Annual	10.0	73.00	2.64	100.4	5.3
Measured at (m)					10

Table B.5 Weather data of the West Midlands

Location	East of England		**Typical city**	Great Yarmouth	
Latitude (°N)	52.59				
Longitude (°E)	1.73				
Elevation (m)	16				
Month	**Air temperature** (°C)	**Relative humidity** (%)	**Daily solar radiation horizontal** (kW h/(m^{2}day))	**Atmospheric pressure** (kPa)	**Wind speed** (m/s)
Jan	5.4	77.90	0.73	101.3	7.1
Feb	5.2	75.40	1.36	101.4	6.8
Mar	6.7	75.00	2.40	101.3	6.5
Apr	8.5	72.10	3.62	101.2	5.7
May	11.7	70.40	4.66	101.4	5.2
Jun	14.7	69.00	4.88	101.4	4.8
Jul	17.4	68.00	4.84	101.4	4.9
Aug	18.1	67.00	4.23	101.4	5.0
Sep	15.9	67.70	2.87	101.3	5.6
Oct	12.8	70.80	1.68	101.1	6.4
Nov	8.9	76.50	0.94	101.1	6.5
Dec	6.6	78.20	0.57	101.3	6.8
Annual	11.0	72.30	2.73	101.3	5.9
Measured at (m)					10

Table B.6 Weather data of the East of England

Location	London		**Typical city**	London	
Latitude (°N)	51.50				
Longitude (°E)	-0.12				
Elevation (m)	58				
Month	**Air temperature** (°C)	**Relative humidity** (%)	**Daily solar radiation horizontal** (kW h/(m^2day))	**Atmospheric pressure** (kPa)	**Wind speed** (m/s)
Jan	4.2	83.90	0.77	100.8	6.3
Feb	4.3	80.20	1.39	101.0	5.8
Mar	6.4	76.80	2.34	100.9	6.0
Apr	8.6	69.80	3.59	100.7	5.1
May	12.7	64.00	4.57	100.9	4.7
Jun	16.1	60.80	4.84	100.9	4.4
Jul	18.6	60.20	4.80	100.9	4.4
Aug	18.6	61.20	4.23	100.9	4.3
Sep	15.5	66.30	2.86	100.9	5.0
Oct	11.7	74.10	1.73	100.7	5.5
Nov	7.3	83.20	0.96	100.7	5.9
Dec	4.9	85.00	0.60	100.8	6.1
Annual	10.7	72.10	2.72	100.8	5.3
Measured at (m)					10

Table B.7 Weather data of the London

Location	Wales		**Typical city**	Cardiff	
Latitude (°N)	51.50				
Longitude (°E)	-3.18				
Elevation (m)	99				
Month	**Air temperature** (°C)	**Relative humidity** (%)	**Daily solar radiation horizontal** (kW h/(m^2day))	**Atmospheric pressure** (kPa)	**Wind speed** (m/s)
Jan	4.7	84.00	0.74	100.3	8.2
Feb	4.6	81.10	1.35	100.5	7.6
Mar	6.3	79.30	2.23	100.4	7.4
Apr	8.0	73.60	3.54	100.2	6.4
May	11.7	68.10	4.55	100.4	5.8
Jun	14.8	65.80	4.73	100.5	5.4
Jul	17.1	65.80	4.69	100.5	5.3
Aug	16.8	67.70	4.00	100.4	5.5
Sep	14.4	70.40	2.76	100.4	6.1
Oct	11.0	77.20	1.59	100.1	7.0
Nov	7.4	84.30	0.92	100.2	7.5
Dec	5.4	85.00	0.59	100.3	7.9
Annual	10.2	75.20	2.64	100.3	6.7
Measured at (m)					10

Table B.8 Weather data of the Wales

Location	South East		**Typical city**	Southampton	
Latitude (°N)	50.91				
Longitude (°E)	-1.40				
Elevation (m)	45				
Month	**Air temperature** (°C)	**Relative humidity** (%)	**Daily solar radiation horizontal** (kWh/(m^{2}day))	**Atmospheric pressure** (kPa)	**Wind speed** (m/s)
Jan	6.3	79.00	0.90	101.1	6.5
Feb	5.9	77.20	1.64	101.2	6.2
Mar	7.2	77.40	2.70	101.1	6.0
Apr	8.9	72.90	4.21	100.9	5.3
May	12.2	69.80	5.36	101.1	4.8
Jun	15.2	68.20	5.64	101.2	4.5
Jul	17.4	68.80	5.55	101.2	4.4
Aug	17.8	68.80	4.79	101.1	4.4
Sep	15.9	69.40	3.30	101.1	4.9
Oct	13.0	72.90	1.95	100.8	5.7
Nov	9.5	77.30	1.08	100.9	5.9
Dec	7.3	79.20	0.68	101.1	6.2
Annual	11.4	73.40	3.15	101.1	5.4
Measured at (m)					10

Table B.9 Weather data of the South East

Location	South West		**Typical city**	Plymouth	
Latitude (°N)	50.37				
Longitude (°E)	-4.16				
Elevation (m)	35				
Month	**Air temperature** (°C)	**Relative humidity** (%)	**Daily solar radiation horizontal** (kWh/(m^{2}day))	**Atmospheric pressure** (kPa)	**Wind speed** (m/s)
Jan	8.1	75.30	0.84	101.1	8.7
Feb	7.4	75.00	1.52	101.3	8.2
Mar	8.1	77.20	2.62	101.2	7.7
Apr	9.1	75.70	4.28	101.0	6.9
May	11.7	74.70	5.44	101.2	6.2
Jun	14.0	75.60	5.61	101.3	5.6
Jul	16.1	76.00	5.46	101.3	5.5
Aug	16.7	75.20	4.67	101.2	5.7
Sep	15.5	73.40	3.33	101.2	6.2
Oct	13.3	73.90	1.83	100.9	7.4
Nov	10.8	74.70	1.05	101.0	7.9
Dec	9.2	75.50	0.66	101.1	8.4
Annual	11.7	75.20	3.11	101.2	7.0
Measured at (m)					10

Table B.10 Weather data of the South West

Appendix C

Scenario simulation results in North East region

Scenario 1 simulation in different property types with $151\,m^2$ to $200\,m^2$ floor area, 3 occupants and built pre-1919 in North East region

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total	Energy saving
Monthly heating demand (kWh/month)	3030.90	2881.21	2449.18	1375.07	834.42	0.00	0.00	0.00	292.99	985.73	1989.76	2449.56	16288.83	61.92%
Roof PV panels outputs (kWh/month)	169.50	329.37	648.53	900.14	1221.10	1208.12	1177.67	1090.56	709.18	432.94	206.18	116.05	8209.33	
Two wind turbines outputs (kWh/month)	293.88	226.98	254.20	156.10	123.84	96.64	91.38	107.34	156.52	204.90	221.42	267.42	2200.62	
Renewable final output (kWh/month)	370.71	445.08	722.18	844.99	1075.95	1043.81	1015.24	958.32	692.56	510.27	342.08	306.77	8327.96	
Heat generation (**COP**=1.8)	667.27	801.14	1299.93	1520.99	1936.72	1878.85	1827.43	1724.98	1246.60	918.49	615.74	552.19	14990.33	
Excess heat (kWh/month)	-2363.63	-2080.07	-1149.25	145.91	1102.30	1878.85	1827.43	1724.98	953.61	-67.24	-1374.03	-1897.37	-1298.50	
Feasibility of monthly self-heating	×	×	×	✓	✓	✓	✓	✓	✓	×	×	×	×	
Hot water supply				★	★	★	★	★	★					

Table C.1 Scenario 1 simulation in semi-detached property

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total	Energy saving
Monthly heating demand (kWh/month)	2898.71	2755.54	2342.35	1315.10	798.02	0.00	0.00	0.00	280.21	942.74	1902.98	2342.72	15578.36	62.87%
Roof PV panels outputs (kWh/month)	169.50	329.37	648.53	900.14	1221.10	1208.12	1177.67	1090.56	709.18	432.94	206.18	116.05	8209.33	
Two wind turbines outputs (kWh/month)	293.88	226.98	254.20	156.10	123.84	96.64	91.38	107.34	156.52	204.90	221.42	267.42	2200.62	
Renewable final output (kWh/month)	370.71	445.08	722.18	844.99	1075.95	1043.81	1015.24	958.32	692.56	510.27	342.08	306.77	8327.96	
Heat generation (COP=1.8)	667.27	801.14	1299.93	1520.99	1936.72	1878.85	1827.43	1724.98	1246.60	918.49	615.74	552.19	14990.33	
Excess heat (kWh/month)	-2231.43	-1954.40	-1042.43	205.89	1138.70	1878.85	1827.43	1724.98	966.39	-24.25	-1287.24	-1790.53	-588.03	
Feasibility of monthly self-heating	×	×	×	✓	✓	✓	✓	✓	✓	×	×	×	×	
Hot water supply				★	★	★	★	★	★					

Table C.2 Scenario 1 simulation in detached property

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total	Energy saving
Monthly heating demand (kWh/month)	3083.83	2931.53	2491.95	1399.09	848.99	0.00	0.00	0.00	298.10	1002.95	2024.51	2492.34	16573.29	77.96%
Roof PV panels outputs (kWh/month)	339.01	658.73	1297.05	1800.28	2442.21	2416.24	2355.34	2181.12	1418.35	865.88	412.35	232.10	16418.66	
Four wind turbines outputs (kWh/month)	587.76	453.96	508.40	312.20	247.68	193.28	182.76	214.68	313.04	409.80	442.84	534.84	4401.24	
Renewable final output (kWh/month)	741.41	890.15	1444.36	1689.98	2151.91	2087.62	2030.48	1916.64	1385.11	1020.55	684.15	613.55	16655.92	
Heat generation (COP=1.8)	1334.54	1602.28	2599.85	3041.97	3873.44	3757.71	3654.86	3449.95	2493.20	1836.99	1231.48	1104.39	29980.66	
Excess heat (kWh/month)	-1749.29	-1329.25	107.90	1642.89	3024.45	3757.71	3654.86	3449.95	2195.10	834.04	-793.04	-1387.95	13407.37	
Feasibility of monthly self-heating	×	×	✓	✓	✓	✓	✓	✓	✓	✓	×	×	✓	
Hot water supply			★	★	★	★	★	★	★	★				

Table C.3 Scenario 1 simulation in bungalow property

Scenario 2 simulation in different property types with $151\,m^2$ to $200\,m^2$ floor area, 4 occupants and built pre-1919 in North East region

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total	Energy saving
Monthly heating demand (kW h/month)	2698.97	2565.67	2180.95	1224.48	743.04	0.00	0.00	0.00	260.90	877.78	1771.86	2181.30	14504.96	64.27%
Roof PV panels outputs (kW h/month)	169.50	329.37	648.53	900.14	1221.10	1208.12	1177.67	1090.56	709.18	432.94	206.18	116.05	8209.33	
Two wind turbines outputs (kW h/month)	293.88	226.98	254.20	156.10	123.84	96.64	91.38	107.34	156.52	204.90	221.42	267.42	2200.62	
Renewable final output (kW h/month)	370.71	445.08	722.18	844.99	1075.95	1043.81	1015.24	958.32	692.56	510.27	342.08	306.77	8327.96	
Heat generation (**COP**=1.8)	667.27	801.14	1299.93	1520.99	1936.72	1878.85	1827.43	1724.98	1246.60	918.49	615.74	552.19	14990.33	
Excess heat (kW h/month)	-2031.70	-1764.53	-881.03	296.50	1193.68	1878.85	1827.43	1724.98	985.70	40.71	-1156.12	-1629.10	485.37	
Feasibility of monthly self-heating	×	×	×	✓	✓	✓	✓	✓	✓	✓	×	×	✓	
Hot water supply				★	★	★	★	★	★					

Table C.4 Scenario 2 simulation in mid-terraced property

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total	Energy saving
Monthly heating demand (kW h/month)	2849.58	2708.84	2302.65	1292.81	784.50	0.00	0.00	0.00	275.46	926.76	1870.73	2303.02	15314.34	63.24%
Roof PV panels outputs (kW h/month)	169.50	329.37	648.53	900.14	1221.10	1208.12	1177.67	1090.56	709.18	432.94	206.18	116.05	8209.33	
Two wind turbines outputs (kW h/month)	293.88	226.98	254.20	156.10	123.84	96.64	91.38	107.34	156.52	204.90	221.42	267.42	2200.62	
Renewable final output (kW h/month)	370.71	445.08	722.18	844.99	1075.95	1043.81	1015.24	958.32	692.56	510.27	342.08	306.77	8327.96	
Heat generation (**COP**=1.8)	667.27	801.14	1299.93	1520.99	1936.72	1878.85	1827.43	1724.98	1246.60	918.49	615.74	552.19	14990.33	
Excess heat (kW h/month)	-2182.30	-1907.70	-1002.73	228.18	1152.22	1878.85	1827.43	1724.98	971.14	-8.27	-1254.99	-1750.82	-324.00	
Feasibility of monthly self-heating	×	×	×	✓	✓	✓	✓	✓	✓	×	×	×	×	
Hot water supply				★	★	★	★	★	★					

Table C.5 Scenario 2 simulation in end-terraced property

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total	Energy saving
Monthly heating demand (kWh/month)	3137.29	2982.34	2535.14	1423.34	863.71	0.00	0.00	0.00	303.27	1020.33	2059.61	2535.54	16860.56	61.22%
Roof PV panels outputs (kWh/month)	169.50	329.37	648.53	900.14	1221.10	1208.12	1177.67	1090.56	709.18	432.94	206.18	116.05	8209.33	
Two wind turbines outputs (kWh/month)	293.88	226.98	254.20	156.10	123.84	96.64	91.38	107.34	156.52	204.90	221.42	267.42	2200.62	
Renewable final output (kWh/month)	370.71	445.08	722.18	844.99	1075.95	1043.81	1015.24	958.32	692.56	510.27	342.08	306.77	8327.96	
Heat generation (COP=1.8)	667.27	801.14	1299.93	1520.99	1936.72	1878.85	1827.43	1724.98	1246.60	918.49	615.74	552.19	14990.33	
Excess heat (kWh/month)	-2470.02	-2181.20	-1235.22	97.65	1073.01	1878.85	1827.43	1724.98	943.33	-101.84	-1443.87	-1983.35	-1870.23	
Feasibility of monthly self-heating	×	×	×	✓	✓	✓	✓	✓	✓	×	×	×	×	
Hot water supply				★	★	★	★	★	★					

Table C.6 Scenario 2 simulation in semi-detached property

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total	Energy saving
Monthly heating demand (kWh/month)	3000.45	2852.26	2424.57	1361.26	826.03	0.00	0.00	0.00	290.04	975.83	1969.77	2424.95	16125.16	62.13%
Roof PV panels outputs (kWh/month)	169.50	329.37	648.53	900.14	1221.10	1208.12	1177.67	1090.56	709.18	432.94	206.18	116.05	8209.33	
Two wind turbines outputs (kWh/month)	293.88	226.98	254.20	156.10	123.84	96.64	91.38	107.34	156.52	204.90	221.42	267.42	2200.62	
Renewable final output (kWh/month)	370.71	445.08	722.18	844.99	1075.95	1043.81	1015.24	958.32	692.56	510.27	342.08	306.77	8327.96	
Heat generation (COP=1.8)	667.27	801.14	1299.93	1520.99	1936.72	1878.85	1827.43	1724.98	1246.60	918.49	615.74	552.19	14990.33	
Excess heat (kWh/month)	-2333.18	-2051.12	-1124.64	159.73	1110.69	1878.85	1827.43	1724.98	956.56	-57.34	-1354.03	-1872.76	-1134.83	
Feasibility of monthly self-heating	×	×	×	✓	✓	✓	✓	✓	✓	×	×	×	×	
Hot water supply				★	★	★	★	★	★					

Table C.7 Scenario 2 simulation in detached property

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total	Energy saving
Monthly heating demand (kWh/month)	3192.08	3034.42	2579.42	1448.19	878.79	0.00	0.00	0.00	308.57	1038.15	2095.57	2579.82	17155.01	77.21%
Roof PV panels outputs (kWh/month)	339.01	658.73	1297.05	1800.28	2442.21	2416.24	2355.34	2181.12	1418.35	865.88	412.35	232.10	16418.66	
Four wind turbines outputs (kWh/month)	587.76	453.96	508.40	312.20	247.68	193.28	182.76	214.68	313.04	409.80	442.84	534.84	4401.24	
Renewable final output (kWh/month)	741.41	890.15	1444.36	1689.98	2151.91	2087.62	2030.48	1916.64	1385.11	1020.55	684.15	613.55	16655.92	
Heat generation (COP=1.8)	1334.54	1602.28	2599.85	3041.97	3873.44	3757.71	3654.86	3449.95	2493.20	1836.99	1231.48	1104.39	29980.66	
Excess heat (kWh/month)	-1857.53	-1432.14	20.44	1593.78	2994.65	3757.71	3654.86	3449.95	2184.64	798.83	-864.10	-1475.43	12825.65	
Feasibility of monthly self-heating	×	×	✓	✓	✓	✓	✓	✓	✓	✓	×	×	✓	
Hot water supply				★	★	★	★	★	★	★				

Table C.8 Scenario 2 simulation in bungalow property

Scenario 3 simulation in different property types with $151\,\mathrm{m}^2$ to $200\,\mathrm{m}^2$ floor area, 4 occupants and built 1919-44 in North East region

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total	Energy saving
Monthly heating demand (kWh/month)	2958.35	2812.23	2390.54	1342.15	814.44	0.00	0.00	0.00	285.97	962.14	1942.13	2390.92	15898.89	62.43%
Roof PV panels outputs (kWh/month)	169.50	329.37	648.53	900.14	1221.10	1208.12	1177.67	1090.56	709.18	432.94	206.18	116.05	8209.33	
Two wind turbines outputs (kWh/month)	293.88	226.98	254.20	156.10	123.84	96.64	91.38	107.34	156.52	204.90	221.42	267.42	2200.62	
Renewable final output (kWh/month)	370.71	445.08	722.18	844.99	1075.95	1043.81	1015.24	958.32	692.56	510.27	342.08	306.77	8327.96	
Heat generation (**COP**=1.8)	667.27	801.14	1299.93	1520.99	1936.72	1878.85	1827.43	1724.98	1246.60	918.49	615.74	552.19	14990.33	
Excess heat (kWh/month)	-2291.07	-2011.10	-1090.62	178.83	1122.28	1878.85	1827.43	1724.98	960.63	-43.64	-1326.39	-1838.73	-908.55	
Feasibility of monthly self-heating	×	×	×	✓	✓	✓	✓	✓	✓	×	×	×	×	
Hot water supply				★	★	★	★	★	★					

Table C.9 Scenario 3 simulation in mid-terraced property

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total	Energy saving
Monthly heating demand (kWh/month)	3123.42	2969.16	2523.94	1417.05	859.89	0.00	0.00	0.00	301.93	1015.82	2050.50	2524.34	16786.04	61.31%
Roof PV panels outputs (kWh/month)	169.50	329.37	648.53	900.14	1221.10	1208.12	1177.67	1090.56	709.18	432.94	206.18	116.05	8209.33	
Two wind turbines outputs (kWh/month)	293.88	226.98	254.20	156.10	123.84	96.64	91.38	107.34	156.52	204.90	221.42	267.42	2200.62	
Renewable final output (kWh/month)	370.71	445.08	722.18	844.99	1075.95	1043.81	1015.24	958.32	692.56	510.27	342.08	306.77	8327.96	
Heat generation (**COP**=1.8)	667.27	801.14	1299.93	1520.99	1936.72	1878.85	1827.43	1724.98	1246.60	918.49	615.74	552.19	14990.33	
Excess heat (kWh/month)	-2456.15	-2168.02	-1224.01	103.94	1076.83	1878.85	1827.43	1724.98	944.67	-97.33	-1434.76	-1972.14	-1795.71	
Feasibility of monthly self-heating	×	×	×	✓	✓	✓	✓	✓	✓	×	×	×	×	
Hot water supply				★	★	★	★	★	★					

Table C.10 Scenario 3 simulation in end-terraced property

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total	Energy saving
Monthly heating demand (kWh/month)	3438.78	3268.94	2778.77	1560.12	946.71	0.00	0.00	0.00	332.42	1118.39	2257.53	2779.21	18480.86	59.32%
Roof PV panels outputs (kWh/month)	169.50	329.37	648.53	900.14	1221.10	1208.12	1177.67	1090.56	709.18	432.94	206.18	116.05	8209.33	
Two wind turbines outputs (kWh/month)	293.88	226.98	254.20	156.10	123.84	96.64	91.38	107.34	156.52	204.90	221.42	267.42	2200.62	
Renewable final output (kWh/month)	370.71	445.08	722.18	844.99	1075.95	1043.81	1015.24	958.32	692.56	510.27	342.08	306.77	8327.96	
Heat generation (COP=1.8)	667.27	801.14	1299.93	1520.99	1936.72	1878.85	1827.43	1724.98	1246.60	918.49	615.74	552.19	14990.33	
Excess heat (kWh/month)	-2771.51	-2467.80	-1478.84	-39.13	990.01	1878.85	1827.43	1724.98	914.19	-199.89	-1641.79	-2227.01	-3490.53	
Feasibility of monthly self-heating	×	×	×	×	✓	✓	✓	✓	✓	×	×	×	×	
Hot water supply					★	★	★	★	★					

Table C.11 Scenario 3 simulation in semi-detached property

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total	Energy saving
Monthly heating demand (kWh/month)	3288.79	3126.36	2657.57	1492.07	905.42	0.00	0.00	0.00	317.92	1069.61	2159.07	2657.99	17674.79	60.30%
Roof PV panels outputs (kWh/month)	169.50	329.37	648.53	900.14	1221.10	1208.12	1177.67	1090.56	709.18	432.94	206.18	116.05	8209.33	
Two wind turbines outputs (kWh/month)	293.88	226.98	254.20	156.10	123.84	96.64	91.38	107.34	156.52	204.90	221.42	267.42	2200.62	
Renewable final output (kWh/month)	370.71	445.08	722.18	844.99	1075.95	1043.81	1015.24	958.32	692.56	510.27	342.08	306.77	8327.96	
Heat generation (COP=1.8)	667.27	801.14	1299.93	1520.99	1936.72	1878.85	1827.43	1724.98	1246.60	918.49	615.74	552.19	14990.33	
Excess heat (kWh/month)	-2621.52	-2325.22	-1357.64	28.91	1031.30	1878.85	1827.43	1724.98	928.69	-151.11	-1543.33	-2105.79	-2684.46	
Feasibility of monthly self-heating	×	×	×	✓	✓	✓	✓	✓	✓	×	×	×	×	
Hot water supply					★	★	★	★	★					

Table C.12 Scenario 3 simulation in detached property

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total	Energy saving
Monthly heating demand (kWh/month)	3498.84	3326.03	2827.30	1587.37	963.24	0.00	0.00	0.00	338.22	1137.92	2296.96	2827.74	18803.61	74.50%
Roof PV panels outputs (kWh/month)	339.01	658.73	1297.05	1800.28	2442.21	2416.24	2355.34	2181.12	1418.35	865.88	412.35	232.10	16418.66	
Four wind turbines outputs (kWh/month)	587.76	453.96	508.40	312.20	247.68	193.28	182.76	214.68	313.04	409.80	442.84	534.84	4401.24	
Renewable final output (kWh/month)	741.41	890.15	1444.36	1689.98	2151.91	2087.62	2030.48	1916.64	1385.11	1020.55	684.15	613.55	16655.92	
Heat generation (COP=1.8)	1334.54	1602.28	2599.85	3041.97	3873.44	3757.71	3654.86	3449.95	2493.20	1836.99	1231.48	1104.39	29980.66	
Excess heat (kWh/month)	-2164.29	-1723.75	-227.45	1454.61	2910.20	3757.71	3654.86	3449.95	2154.98	699.07	-1065.48	-1723.35	11177.05	
Feasibility of monthly self-heating	×	×	×	✓	✓	✓	✓	✓	✓	✓	×	×	✓	
Hot water supply				★	★	★	★	★	★	★				

Table C.13 Scenario 3 simulation in bungalow property

Scenario 4 simulation in different property types with $151\,m^2$ to $200\,m^2$ floor area, 4 occupants and built post 1999 in North East region

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total	Energy saving
Monthly heating demand (kW h/month)	2097.91	1994.30	1695.26	951.79	577.56	0.00	0.00	0.00	202.80	682.30	1377.26	1695.52	11274.70	69.67%
Roof PV panels outputs (kW h/month)	169.50	329.37	648.53	900.14	1221.10	1208.12	1177.67	1090.56	709.18	432.94	206.18	116.05	8209.33	
Two wind turbines outputs (kW h/month)	293.88	226.98	254.20	156.10	123.84	96.64	91.38	107.34	156.52	204.90	221.42	267.42	2200.62	
Renewable final output (kW h/month)	370.71	445.08	722.18	844.99	1075.95	1043.81	1015.24	958.32	692.56	510.27	342.08	306.77	8327.96	
Heat generation (COP=1.8)	667.27	801.14	1299.93	1520.99	1936.72	1878.85	1827.43	1724.98	1246.60	918.49	615.74	552.19	14990.33	
Excess heat (kW h/month)	-1430.64	-1193.16	-395.33	569.20	1359.16	1878.85	1827.43	1724.98	1043.80	236.19	-761.52	-1143.33	3715.63	
Feasibility of monthly self-heating	×	×	×	✓	✓	✓	✓	✓	✓	✓	×	×	✓	
Hot water supply				★	★	★	★	★	★	★				

Table C.14 Scenario 4 simulation in mid-terraced property

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total	Energy saving
Monthly heating demand (kW h/month)	2214.98	2105.58	1789.85	1004.90	609.79	0.00	0.00	0.00	214.11	720.37	1454.12	1790.13	11903.83	68.39%
Roof PV panels outputs (kW h/month)	169.50	329.37	648.53	900.14	1221.10	1208.12	1177.67	1090.56	709.18	432.94	206.18	116.05	8209.33	
Two wind turbines outputs (kW h/month)	293.88	226.98	254.20	156.10	123.84	96.64	91.38	107.34	156.52	204.90	221.42	267.42	2200.62	
Renewable final output (kW h/month)	370.71	445.08	722.18	844.99	1075.95	1043.81	1015.24	958.32	692.56	510.27	342.08	306.77	8327.96	
Heat generation (COP=1.8)	667.27	801.14	1299.93	1520.99	1936.72	1878.85	1827.43	1724.98	1246.60	918.49	615.74	552.19	14990.33	
Excess heat (kW h/month)	-1547.70	-1304.44	-489.93	516.09	1326.93	1878.85	1827.43	1724.98	1032.49	198.12	-838.38	-1237.94	3086.50	
Feasibility of monthly self-heating	×	×	×	✓	✓	✓	✓	✓	✓	✓	×	×	✓	
Hot water supply				★	★	★	★	★	★	★				

Table C.15 Scenario 4 simulation in end-terraced property

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total	Energy saving
Monthly heating demand (kW h/month)	2438.61	2318.17	1970.57	1106.36	671.36	0.00	0.00	0.00	235.73	793.10	1600.93	1970.88	13105.72	66.28%
Roof PV panels outputs (kW h/month)	169.50	329.37	648.53	900.14	1221.10	1208.12	1177.67	1090.56	709.18	432.94	206.18	116.05	8209.33	
Two wind turbines outputs (kW h/month)	293.88	226.98	254.20	156.10	123.84	96.64	91.38	107.34	156.52	204.90	221.42	267.42	2200.62	
Renewable final output (kW h/month)	370.71	445.08	722.18	844.99	1075.95	1043.81	1015.24	958.32	692.56	510.27	342.08	306.77	8327.96	
Heat generation (COP=1.8)	667.27	801.14	1299.93	1520.99	1936.72	1878.85	1827.43	1724.98	1246.60	918.49	615.74	552.19	14990.33	
Excess heat (kW h/month)	-1771.34	-1517.03	-670.64	414.63	1265.36	1878.85	1827.43	1724.98	1010.87	125.39	-985.19	-1418.68	1884.61	
Feasibility of monthly self-heating	×	×	×	✓	✓	✓	✓	✓	✓	✓	×	×	✓	
Hot water supply				★	★	★	★	★	★	★				

Table C.16 Scenario 4 simulation in semi-detached property

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total	Energy saving
Monthly heating demand (kW h/month)	2332.25	2217.06	1884.62	1058.10	642.08	0.00	0.00	0.00	225.45	758.51	1531.10	1884.91	12534.09	67.24%
Roof PV panels outputs (kW h/month)	169.50	329.37	648.53	900.14	1221.10	1208.12	1177.67	1090.56	709.18	432.94	206.18	116.05	8209.33	
Two wind turbines outputs (kW h/month)	293.88	226.98	254.20	156.10	123.84	96.64	91.38	107.34	156.52	204.90	221.42	267.42	2200.62	
Renewable final output (kW h/month)	370.71	445.08	722.18	844.99	1075.95	1043.81	1015.24	958.32	692.56	510.27	342.08	306.77	8327.96	
Heat generation (COP=1.8)	667.27	801.14	1299.93	1520.99	1936.72	1878.85	1827.43	1724.98	1246.60	918.49	615.74	552.19	14990.33	
Excess heat (kW h/month)	-1664.98	-1415.92	-584.69	462.88	1294.64	1878.85	1827.43	1724.98	1021.15	159.98	-915.36	-1332.72	2456.24	
Feasibility of monthly self-heating	×	×	×	✓	✓	✓	✓	✓	✓	✓	×	×	✓	
Hot water supply				★	★	★	★	★	★	★				

Table C.17 Scenario 4 simulation in detached property

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total	Energy saving
Monthly heating demand (kW h/month)	2481.20	2358.66	2004.98	1125.68	683.08	0.00	0.00	0.00	239.85	806.96	1628.89	2005.30	13334.59	83.33%
Roof PV panels outputs (kW h/month)	339.01	658.73	1297.05	1800.28	2442.21	2416.24	2355.34	2181.12	1418.35	865.88	412.35	232.10	16418.66	
Four wind turbines outputs (kW h/month)	587.76	453.96	508.40	312.20	247.68	193.28	182.76	214.68	313.04	409.80	442.84	534.84	4401.24	
Renewable final output (kW h/month)	741.41	890.15	1444.36	1689.98	2151.91	2087.62	2030.48	1916.64	1385.11	1020.55	684.15	613.55	16655.92	
Heat generation (COP=1.8)	1334.54	1602.28	2599.85	3041.97	3873.44	3757.71	3654.86	3449.95	2493.20	1836.99	1231.48	1104.39	29980.66	
Excess heat (kW h/month)	-1146.66	-756.38	594.87	1916.29	3190.35	3757.71	3654.86	3449.95	2253.36	1030.03	-397.41	-900.91	16646.07	
Feasibility of monthly self-heating	×	×	✓	✓	✓	✓	✓	✓	✓	✓	×	×	✓	
Hot water supply			★	★	★	★	★	★	★	★				

Table C.18 Scenario 4 simulation in bungalow property

Scenario 5 simulation in different property types with $101\,m^2$ to $150\,m^2$ floor area, 3 occupants and built pre-1919 in North East region

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total	Energy saving
Monthly heating demand (kW h/month)	1773.59	1685.99	1433.18	804.65	488.27	0.00	0.00	0.00	171.45	576.82	1164.35	1433.41	9531.71	70.25%
Roof PV panels outputs (kW h/month)	127.13	247.02	486.39	675.11	915.83	906.09	883.25	817.92	531.88	324.71	154.63	87.04	6157.00	
Two wind turbines outputs (kW h/month)	293.88	226.98	254.20	156.10	123.84	96.64	91.38	107.34	156.52	204.90	221.42	267.42	2200.62	
Renewable final output (kW h/month)	336.81	379.20	592.48	664.96	831.73	802.18	779.71	740.21	550.72	423.69	300.84	283.57	6686.10	
Heat generation (**COP**=1.8)	606.25	682.57	1066.46	1196.94	1497.12	1443.93	1403.47	1332.37	991.30	762.63	541.52	510.42	12034.97	
Excess heat (kW h/month)	-1167.34	-1003.43	-366.72	392.29	1008.85	1443.93	1403.47	1332.37	819.85	185.81	-622.83	-922.99	2503.26	
Feasibility of monthly self-heating	×	×	×	✓	✓	✓	✓	✓	✓	✓	×	×	✓	
Hot water supply				★	★	★	★	★	★	★				

Table C.19 Scenario 5 simulation in mid-terraced property

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total	Energy saving
Monthly heating demand (kW h/month)	1892.77	1799.29	1529.49	858.72	521.09	0.00	0.00	0.00	182.97	615.58	1242.59	1529.73	10172.24	68.69%
Roof PV panels outputs (kW h/month)	127.13	247.02	486.39	675.11	915.83	906.09	883.25	817.92	531.88	324.71	154.63	87.04	6157.00	
Two wind turbines outputs (kW h/month)	293.88	226.98	254.20	156.10	123.84	96.64	91.38	107.34	156.52	204.90	221.42	267.42	2200.62	
Renewable final output (kW h/month)	336.81	379.20	592.48	664.96	831.73	802.18	779.71	740.21	550.72	423.69	300.84	283.57	6686.10	
Heat generation (**COP**=1.8)	606.25	682.57	1066.46	1196.94	1497.12	1443.93	1403.47	1332.37	991.30	762.63	541.52	510.42	12034.97	
Excess heat (kW h/month)	-1286.52	-1116.72	-463.03	338.21	976.03	1443.93	1403.47	1332.37	808.33	147.05	-701.08	-1019.31	1862.73	
Feasibility of monthly self-heating	×	×	×	✓	✓	✓	✓	✓	✓	✓	×	×	✓	
Hot water supply				★	★	★	★	★	★	★				

Table C.20 Scenario 5 simulation in end-terraced property

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total	Energy saving
Monthly heating demand (kW h/month)	2051.51	1950.19	1657.76	930.74	564.79	0.00	0.00	0.00	198.31	667.21	1346.80	1658.02	11025.33	66.89%
Roof PV panels outputs (kW h/month)	127.13	247.02	486.39	675.11	915.83	906.09	883.25	817.92	531.88	324.71	154.63	87.04	6157.00	
Two wind turbines outputs (kW h/month)	293.88	226.98	254.20	156.10	123.84	96.64	91.38	107.34	156.52	204.90	221.42	267.42	2200.62	
Renewable final output (kW h/month)	336.81	379.20	592.48	664.96	831.73	802.18	779.71	740.21	550.72	423.69	300.84	283.57	6686.10	
Heat generation (COP=1.8)	606.25	682.57	1066.46	1196.94	1497.12	1443.93	1403.47	1332.37	991.30	762.63	541.52	510.42	12034.97	
Excess heat (kW h/month)	-1445.26	-1267.62	-591.30	266.20	932.33	1443.93	1403.47	1332.37	792.99	95.43	-805.29	-1147.60	1009.64	
Feasibility of monthly self-heating	×	×	×	✓	✓	✓	✓	✓	✓	✓	×	×	✓	
Hot water supply				★	★	★	★	★	★	★				

Table C.21 Scenario 5 simulation in semi-detached property

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total	Energy saving
Monthly heating demand (kW h/month)	2223.55	2113.73	1796.78	1008.79	612.15	0.00	0.00	0.00	214.94	723.16	1459.74	1797.06	11949.90	65.23%
Roof PV panels outputs (kW h/month)	127.13	247.02	486.39	675.11	915.83	906.09	883.25	817.92	531.88	324.71	154.63	87.04	6157.00	
Two wind turbines outputs (kW h/month)	293.88	226.98	254.20	156.10	123.84	96.64	91.38	107.34	156.52	204.90	221.42	267.42	2200.62	
Renewable final output (kW h/month)	336.81	379.20	592.48	664.96	831.73	802.18	779.71	740.21	550.72	423.69	300.84	283.57	6686.10	
Heat generation (COP=1.8)	606.25	682.57	1066.46	1196.94	1497.12	1443.93	1403.47	1332.37	991.30	762.63	541.52	510.42	12034.97	
Excess heat (kW h/month)	-1617.30	-1431.16	-730.32	188.15	884.97	1443.93	1403.47	1332.37	776.36	39.47	-918.23	-1286.65	85.07	
Feasibility of monthly self-heating	×	×	×	✓	✓	✓	✓	✓	✓	✓	×	×	✓	
Hot water supply				★	★	★	★	★	★					

Table C.22 Scenario 5 simulation in detached property

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total	Energy saving
Monthly heating demand (kW h/month)	2316.31	2201.91	1871.73	1050.87	637.69	0.00	0.00	0.00	223.91	753.33	1520.64	1872.03	12448.41	81.98%
Roof PV panels outputs (kW h/month)	254.26	494.05	972.79	1350.21	1831.66	1812.18	1766.50	1635.84	1063.76	649.41	309.27	174.07	12314.00	
Four wind turbines outputs (kW h/month)	587.76	453.96	508.40	312.20	247.68	193.28	182.76	214.68	313.04	409.80	442.84	534.84	4401.24	
Renewable final output (kW h/month)	673.61	758.41	1184.95	1329.93	1663.47	1604.37	1559.41	1480.42	1101.44	847.37	601.68	567.13	13372.19	
Heat generation (COP=1.8)	1212.50	1365.13	2132.91	2393.87	2994.24	2887.86	2806.94	2664.75	1982.60	1525.27	1083.03	1020.83	24069.94	
Excess heat (kW h/month)	-1103.81	-836.77	261.18	1343.00	2356.56	2887.86	2806.94	2664.75	1758.69	771.94	-437.61	-851.20	11621.53	
Feasibility of monthly self-heating	×	×	✓	✓	✓	✓	✓	✓	✓	✓	×	×	✓	
Hot water supply			★	★	★	★	★	★	★	★				

Table C.23 Scenario 5 simulation in bungalow property

Scenario 6 simulation in different property types with $101\,m^2$ to $150\,m^2$ floor area, 3 occupants and built 1919-44 in North East region

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total	Energy saving
Monthly heating demand (kW h/month)	1919.56	1824.75	1551.13	870.87	528.46	0.00	0.00	0.00	185.56	624.29	1260.17	1551.38	10316.17	68.36%
Roof PV panels outputs (kW h/month)	127.13	247.02	486.39	675.11	915.83	906.09	883.25	817.92	531.88	324.71	154.63	87.04	6157.00	
Two wind turbines outputs (kW h/month)	293.88	226.98	254.20	156.10	123.84	96.64	91.38	107.34	156.52	204.90	221.42	267.42	2200.62	
Renewable final output (kW h/month)	336.81	379.20	592.48	664.96	831.73	802.18	779.71	740.21	550.72	423.69	300.84	283.57	6686.10	
Heat generation (**COP**=1.8)	606.25	682.57	1066.46	1196.94	1497.12	1443.93	1403.47	1332.37	991.30	762.63	541.52	510.42	12034.97	
Excess heat (kW h/month)	-1313.30	-1142.18	-484.68	326.06	968.66	1443.93	1403.47	1332.37	805.74	138.34	-718.66	-1040.96	1718.80	
Feasibility of monthly self-heating	×	×	×	✓	✓	✓	✓	✓	✓	✓	×	×	✓	
Hot water supply				★	★	★	★	★	★	★				

Table C.24 Scenario 6 simulation in mid-terraced property

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total	Energy saving
Monthly heating demand (kW h/month)	2048.55	1947.37	1655.37	929.39	563.97	0.00	0.00	0.00	198.03	666.25	1344.86	1655.63	11009.42	66.92%
Roof PV panels outputs (kW h/month)	127.13	247.02	486.39	675.11	915.83	906.09	883.25	817.92	531.88	324.71	154.63	87.04	6157.00	
Two wind turbines outputs (kW h/month)	293.88	226.98	254.20	156.10	123.84	96.64	91.38	107.34	156.52	204.90	221.42	267.42	2200.62	
Renewable final output (kW h/month)	336.81	379.20	592.48	664.96	831.73	802.18	779.71	740.21	550.72	423.69	300.84	283.57	6686.10	
Heat generation (**COP**=1.8)	606.25	682.57	1066.46	1196.94	1497.12	1443.93	1403.47	1332.37	991.30	762.63	541.52	510.42	12034.97	
Excess heat (kW h/month)	-1442.30	-1264.81	-588.91	267.54	933.15	1443.93	1403.47	1332.37	793.27	96.39	-803.34	-1145.21	1025.56	
Feasibility of monthly self-heating	×	×	×	✓	✓	✓	✓	✓	✓	✓	×	×	✓	
Hot water supply				★	★	★	★	★	★	★				

Table C.25 Scenario 6 simulation in end-terraced property

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total	Energy saving
Monthly heating demand (kW h/month)	2220.35	2110.69	1794.19	1007.34	611.27	0.00	0.00	0.00	214.63	722.12	1457.64	1794.48	11932.71	65.26%
Roof PV panels outputs (kW h/month)	127.13	247.02	486.39	675.11	915.83	906.09	883.25	817.92	531.88	324.71	154.63	87.04	6157.00	
Two wind turbines outputs (kW h/month)	293.88	226.98	254.20	156.10	123.84	96.64	91.38	107.34	156.52	204.90	221.42	267.42	2200.62	
Renewable final output (kW h/month)	336.81	379.20	592.48	664.96	831.73	802.18	779.71	740.21	550.72	423.69	300.84	283.57	6686.10	
Heat generation (COP=1.8)	606.25	682.57	1066.46	1196.94	1497.12	1443.93	1403.47	1332.37	991.30	762.63	541.52	510.42	12034.97	
Excess heat (kW h/month)	-1614.10	-1428.12	-727.74	189.60	885.85	1443.93	1403.47	1332.37	776.66	40.51	-916.13	-1284.06	102.26	
Feasibility of monthly self-heating	×	×	×	✓	✓	✓	✓	✓	✓	✓	×	×	✓	
Hot water supply				★	★	★	★	★	★					

Table C.26 Scenario 6 simulation in semi-detached property

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total	Energy saving
Monthly heating demand (kW h/month)	2406.55	2287.69	1944.65	1091.81	662.53	0.00	0.00	0.00	232.63	782.68	1579.88	1944.96	12933.38	63.61%
Roof PV panels outputs (kW h/month)	127.13	247.02	486.39	675.11	915.83	906.09	883.25	817.92	531.88	324.71	154.63	87.04	6157.00	
Two wind turbines outputs (kW h/month)	293.88	226.98	254.20	156.10	123.84	96.64	91.38	107.34	156.52	204.90	221.42	267.42	2200.62	
Renewable final output (kW h/month)	336.81	379.20	592.48	664.96	831.73	802.18	779.71	740.21	550.72	423.69	300.84	283.57	6686.10	
Heat generation (COP=1.8)	606.25	682.57	1066.46	1196.94	1497.12	1443.93	1403.47	1332.37	991.30	762.63	541.52	510.42	12034.97	
Excess heat (kW h/month)	-1800.30	-1605.12	-878.20	105.12	834.59	1443.93	1403.47	1332.37	758.67	-20.04	-1038.36	-1434.54	-898.41	
Feasibility of monthly self-heating	×	×	×	✓	✓	✓	✓	✓	✓	×	×	×	×	
Hot water supply				★	★	★	★	★	★					

Table C.27 Scenario 6 simulation in detached property

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total	Energy saving
Monthly heating demand (kW h/month)	2506.94	2383.12	2025.78	1137.36	690.17	0.00	0.00	0.00	242.34	815.33	1645.79	2026.10	13472.92	80.00%
Roof PV panels outputs (kW h/month)	254.26	494.05	972.79	1350.21	1831.66	1812.18	1766.50	1635.84	1063.76	649.41	309.27	174.07	12314.00	
Four wind turbines outputs (kW h/month)	587.76	453.96	508.40	312.20	247.68	193.28	182.76	214.68	313.04	409.80	442.84	534.84	4401.24	
Renewable final output (kW h/month)	673.61	758.41	1184.95	1329.93	1663.47	1604.37	1559.41	1480.42	1101.44	847.37	601.68	567.13	13372.19	
Heat generation (COP=1.8)	1212.50	1365.13	2132.91	2393.87	2994.24	2887.86	2806.94	2664.75	1982.60	1525.27	1083.03	1020.83	24069.94	
Excess heat (kW h/month)	-1294.44	-1017.99	107.13	1256.51	2304.07	2887.86	2806.94	2664.75	1740.26	709.94	-562.76	-1005.26	10597.03	
Feasibility of monthly self-heating	×	×	✓	✓	✓	✓	✓	✓	✓	✓	×	×	✓	
Hot water supply			★	★	★	★	★	★	★	★				

Table C.28 Scenario 6 simulation in bungalow property

Scenario 7 simulation in different property types with $101\,m^2$ to $150\,m^2$ floor area, 3 occupants and built post 1999 in North East region

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total	Energy saving
Monthly heating demand (kW h/month)	1493.01	1419.27	1206.45	677.35	411.03	0.00	0.00	0.00	144.32	485.57	980.15	1206.64	8023.79	74.92%
Roof PV panels outputs (kW h/month)	127.13	247.02	486.39	675.11	915.83	906.09	883.25	817.92	531.88	324.71	154.63	87.04	6157.00	
Two wind turbines outputs (kW h/month)	293.88	226.98	254.20	156.10	123.84	96.64	91.38	107.34	156.52	204.90	221.42	267.42	2200.62	
Renewable final output (kW h/month)	336.81	379.20	592.48	664.96	831.73	802.18	779.71	740.21	550.72	423.69	300.84	283.57	6686.10	
Heat generation (**COP**=1.8)	606.25	682.57	1066.46	1196.94	1497.12	1443.93	1403.47	1332.37	991.30	762.63	541.52	510.42	12034.97	
Excess heat (kW h/month)	-886.76	-736.70	-140.00	519.58	1086.09	1443.93	1403.47	1332.37	846.97	277.07	-438.63	-696.22	4011.18	
Feasibility of monthly self-heating	×	×	×	✓	✓	✓	✓	✓	✓	✓	×	×	✓	
Hot water supply				★	★	★	★	★	★	★				

Table C.29 Scenario 7 simulation in mid-terraced property

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total	Energy saving
Monthly heating demand (kW h/month)	1593.34	1514.64	1287.53	722.87	438.65	0.00	0.00	0.00	154.02	518.20	1046.01	1287.73	8562.99	73.06%
Roof PV panels outputs (kW h/month)	127.13	247.02	486.39	675.11	915.83	906.09	883.25	817.92	531.88	324.71	154.63	87.04	6157.00	
Two wind turbines outputs (kW h/month)	293.88	226.98	254.20	156.10	123.84	96.64	91.38	107.34	156.52	204.90	221.42	267.42	2200.62	
Renewable final output (kW h/month)	336.81	379.20	592.48	664.96	831.73	802.18	779.71	740.21	550.72	423.69	300.84	283.57	6686.10	
Heat generation (**COP**=1.8)	606.25	682.57	1066.46	1196.94	1497.12	1443.93	1403.47	1332.37	991.30	762.63	541.52	510.42	12034.97	
Excess heat (kW h/month)	-987.09	-832.08	-221.07	474.06	1058.47	1443.93	1403.47	1332.37	837.28	244.44	-504.50	-777.31	3471.98	
Feasibility of monthly self-heating	×	×	×	✓	✓	✓	✓	✓	✓	✓	×	×	✓	
Hot water supply				★	★	★	★	★	★	★				

Table C.30 Scenario 7 simulation in end-terraced property

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total	Energy saving
Monthly heating demand (kW h/month)	1726.96	1641.67	1395.50	783.50	475.44	0.00	0.00	0.00	166.94	561.66	1133.74	1395.72	9281.12	70.92%
Roof PV panels outputs (kW h/month)	127.13	247.02	486.39	675.11	915.83	906.09	883.25	817.92	531.88	324.71	154.63	87.04	6157.00	
Two wind turbines outputs (kW h/month)	293.88	226.98	254.20	156.10	123.84	96.64	91.38	107.34	156.52	204.90	221.42	267.42	2200.62	
Renewable final output (kW h/month)	336.81	379.20	592.48	664.96	831.73	802.18	779.71	740.21	550.72	423.69	300.84	283.57	6686.10	
Heat generation (COP=1.8)	606.25	682.57	1066.46	1196.94	1497.12	1443.93	1403.47	1332.37	991.30	762.63	541.52	510.42	12034.97	
Excess heat (kW h/month)	-1120.71	-959.10	-329.05	413.44	1021.68	1443.93	1403.47	1332.37	824.36	200.98	-592.22	-885.31	2753.85	
Feasibility of monthly self-heating	×	×	×	✓	✓	✓	✓	✓	✓	✓	×	×	✓	
Hot water supply				★	★	★	★	★	★	★				

Table C.31 Scenario 7 simulation in semi-detached property

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total	Energy saving
Monthly heating demand (kW h/month)	1871.78	1779.34	1512.53	849.20	515.31	0.00	0.00	0.00	180.94	608.76	1228.81	1512.77	10059.43	68.95%
Roof PV panels outputs (kW h/month)	127.13	247.02	486.39	675.11	915.83	906.09	883.25	817.92	531.88	324.71	154.63	87.04	6157.00	
Two wind turbines outputs (kW h/month)	293.88	226.98	254.20	156.10	123.84	96.64	91.38	107.34	156.52	204.90	221.42	267.42	2200.62	
Renewable final output (kW h/month)	336.81	379.20	592.48	664.96	831.73	802.18	779.71	740.21	550.72	423.69	300.84	283.57	6686.10	
Heat generation (COP=1.8)	606.25	682.57	1066.46	1196.94	1497.12	1443.93	1403.47	1332.37	991.30	762.63	541.52	510.42	12034.97	
Excess heat (kW h/month)	-1265.53	-1096.77	-446.07	347.74	981.81	1443.93	1403.47	1332.37	810.36	153.88	-687.30	-1002.35	1975.54	
Feasibility of monthly self-heating	×	×	×	✓	✓	✓	✓	✓	✓	✓	×	×	✓	
Hot water supply				★	★	★	★	★	★	★				

Table C.32 Scenario 7 simulation in detached property

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total	Energy saving
Monthly heating demand (kW h/month)	1949.87	1853.56	1575.63	884.62	536.80	0.00	0.00	0.00	188.49	634.15	1280.07	1575.87	10479.07	86.89%
Roof PV panels outputs (kW h/month)	254.26	494.05	972.79	1350.21	1831.66	1812.18	1766.50	1635.84	1063.76	649.41	309.27	174.07	12314.00	
Four wind turbines outputs (kW h/month)	587.76	453.96	508.40	312.20	247.68	193.28	182.76	214.68	313.04	409.80	442.84	534.84	4401.24	
Renewable final output (kW h/month)	673.61	758.41	1184.95	1329.93	1663.47	1604.37	1559.41	1480.42	1101.44	847.37	601.68	567.13	13372.19	
Heat generation (COP=1.8)	1212.50	1365.13	2132.91	2393.87	2994.24	2887.86	2806.94	2664.75	1982.60	1525.27	1083.03	1020.83	24069.94	
Excess heat (kW h/month)	-737.37	-488.43	557.29	1509.25	2457.44	2887.86	2806.94	2664.75	1794.11	891.12	-197.04	-555.04	13590.87	
Feasibility of monthly self-heating	×	×	✓	✓	✓	✓	✓	✓	✓	✓	×	×	✓	
Hot water supply			★	★	★	★	★	★	★	★				

Table C.33 Scenario 7 simulation in bungalow property

Scenario 8 simulation in different property types with 51 m^2 to 100 m^2 floor area, 2 occupants and built pre-1919 in North East region

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total	Energy saving
Monthly heating demand (kWh/month)	1249.95	1188.21	1010.04	567.08	344.11	0.00	0.00	0.00	120.83	406.52	820.58	1010.20	6717.52	65.77%
Roof PV panels outputs (kWh/month)	84.75	164.68	324.26	450.07	610.55	604.06	588.83	545.28	354.59	216.47	103.09	58.02	4104.67	
One wind turbine output (kWh/month)	146.94	113.49	127.10	78.05	61.92	48.32	45.69	53.67	78.26	102.45	110.71	133.71	1100.31	
Renewable final output (kWh/month)	185.35	222.54	361.09	422.50	537.98	521.90	507.62	479.16	346.28	255.14	171.04	153.39	4163.98	
Heat generation (COP=1.8)	333.64	400.57	649.96	760.49	968.36	939.43	913.72	862.49	623.30	459.25	307.87	276.10	7495.17	
Excess heat (kWh/month)	-916.31	-787.64	-360.08	193.41	624.25	939.43	913.72	862.49	502.47	52.73	-512.71	-734.10	777.64	
Feasibility of monthly self-heating	×	×	×	✓	✓	✓	✓	✓	✓	✓	×	×	✓	
Hot water supply				★	★	★	★	★	★	★				

Table C.34 Scenario 8 simulation in mid-terraced property

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total	Energy saving
Monthly heating demand (kWh/month)	1373.69	1305.85	1110.04	623.22	378.18	0.00	0.00	0.00	132.79	446.76	901.82	1110.21	7382.56	63.94%
Roof PV panels outputs (kWh/month)	84.75	164.68	324.26	450.07	610.55	604.06	588.83	545.28	354.59	216.47	103.09	58.02	4104.67	
One wind turbine output (kWh/month)	146.94	113.49	127.10	78.05	61.92	48.32	45.69	53.67	78.26	102.45	110.71	133.71	1100.31	
Renewable final output (kWh/month)	185.35	222.54	361.09	422.50	537.98	521.90	507.62	479.16	346.28	255.14	171.04	153.39	4163.98	
Heat generation (COP=1.8)	333.64	400.57	649.96	760.49	968.36	939.43	913.72	862.49	623.30	459.25	307.87	276.10	7495.17	
Excess heat (kWh/month)	-1040.05	-905.28	-460.07	137.27	590.18	939.43	913.72	862.49	490.51	12.48	-593.95	-834.11	112.61	
Feasibility of monthly self-heating	×	×	×	✓	✓	✓	✓	✓	✓	✓	×	×	✓	
Hot water supply				★	★	★	★	★	★					

Table C.35 Scenario 8 simulation in end-terraced property

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total	Energy saving
Monthly heating demand (kW h/month)	1497.44	1423.48	1210.03	679.36	412.25	0.00	0.00	0.00	144.75	487.01	983.06	1210.22	8047.59	62.17%
Roof PV panels outputs (kW h/month)	84.75	164.68	324.26	450.07	610.55	604.06	588.83	545.28	354.59	216.47	103.09	58.02	4104.67	
One wind turbine output (kW h/month)	146.94	113.49	127.10	78.05	61.92	48.32	45.69	53.67	78.26	102.45	110.71	133.71	1100.31	
Renewable final output (kW h/month)	185.35	222.54	361.09	422.50	537.98	521.90	507.62	479.16	346.28	255.14	171.04	153.39	4163.98	
Heat generation (COP=1.8)	333.64	400.57	649.96	760.49	968.36	939.43	913.72	862.49	623.30	459.25	307.87	276.10	7495.17	
Excess heat (kW h/month)	-1163.80	-1022.91	-560.07	81.13	556.11	939.43	913.72	862.49	478.55	-27.76	-675.19	-934.12	-552.43	
Feasibility of monthly self-heating	×	×	×	✓	✓	✓	✓	✓	✓	×	×	×	×	
Hot water supply				★	★	★	★	★	★					

Table C.36 Scenario 8 simulation in semi-detached property

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total	Energy saving
Monthly heating demand (kW h/month)	1658.30	1576.40	1340.02	752.35	456.54	0.00	0.00	0.00	160.30	539.33	1088.66	1340.23	8912.14	60.14%
Roof PV panels outputs (kW h/month)	84.75	164.68	324.26	450.07	610.55	604.06	588.83	545.28	354.59	216.47	103.09	58.02	4104.67	
One wind turbine output (kW h/month)	146.94	113.49	127.10	78.05	61.92	48.32	45.69	53.67	78.26	102.45	110.71	133.71	1100.31	
Renewable final output (kW h/month)	185.35	222.54	361.09	422.50	537.98	521.90	507.62	479.16	346.28	255.14	171.04	153.39	4163.98	
Heat generation (COP=1.8)	333.64	400.57	649.96	760.49	968.36	939.43	913.72	862.49	623.30	459.25	307.87	276.10	7495.17	
Excess heat (kW h/month)	-1324.67	-1175.83	-690.06	8.15	511.82	939.43	913.72	862.49	463.00	-80.08	-780.79	-1064.14	-1416.97	
Feasibility of monthly self-heating	×	×	×	✓	✓	✓	✓	✓	✓	×	×	×	×	
Hot water supply					★	★	★	★	★					

Table C.37 Scenario 8 simulation in detached property

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total	Energy saving
Monthly heating demand (kW h/month)	1472.69	1399.95	1190.03	668.13	405.44	0.00	0.00	0.00	142.36	478.96	966.81	1190.22	7914.58	79.00%
Roof PV panels outputs (kW h/month)	169.50	329.37	648.53	900.14	1221.10	1208.12	1177.67	1090.56	709.18	432.94	206.18	116.05	8209.33	
Two wind turbines outputs (kW h/month)	293.88	226.98	254.20	156.10	123.84	96.64	91.38	107.34	156.52	204.90	221.42	267.42	2200.62	
Renewable final output (kW h/month)	370.71	445.08	722.18	844.99	1075.95	1043.81	1015.24	958.32	692.56	510.27	342.08	306.77	8327.96	
Heat generation (COP=1.8)	667.27	801.14	1299.93	1520.99	1936.72	1878.85	1827.43	1724.98	1246.60	918.49	615.74	552.19	14990.33	
Excess heat (kW h/month)	-805.41	-598.81	109.89	852.85	1531.28	1878.85	1827.43	1724.98	1104.24	439.53	-351.07	-638.02	7075.75	
Feasibility of monthly self-heating	×	×	✓	✓	✓	✓	✓	✓	✓	✓	×	×	✓	
Hot water supply			★	★	★	★	★	★	★	★				

Table C.38 Scenario 8 simulation in bungalow property

Scenario 9 simulation in different property types with $51\,m^2$ to $100\,m^2$ floor area, 2 occupants and built 1919-44 in North East region

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total	Energy saving
Monthly heating demand (kWh/month)	1418.81	1348.74	1146.50	643.69	390.60	0.00	0.00	0.00	137.15	461.44	931.44	1146.68	7625.06	63.33%
Roof PV panels outputs (kWh/month)	84.75	164.68	324.26	450.07	610.55	604.06	588.83	545.28	354.59	216.47	103.09	58.02	4104.67	
One wind turbine output (kWh/month)	146.94	113.49	127.10	78.05	61.92	48.32	45.69	53.67	78.26	102.45	110.71	133.71	1100.31	
Renewable final output (kWh/month)	185.35	222.54	361.09	422.50	537.98	521.90	507.62	479.16	346.28	255.14	171.04	153.39	4163.98	
Heat generation (COP=1.8)	333.64	400.57	649.96	760.49	968.36	939.43	913.72	862.49	623.30	459.25	307.87	276.10	7495.17	
Excess heat (kWh/month)	-1085.18	-948.17	-496.54	116.80	577.76	939.43	913.72	862.49	486.15	-2.19	-623.57	-870.58	-129.89	
Feasibility of monthly self-heating	×	×	×	✓	✓	✓	✓	✓	✓	×	×	×	×	
Hot water supply				★	★	★	★	★	★					

Table C.39 Scenario 9 simulation in mid-terraced property

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total	Energy saving
Monthly heating demand (kWh/month)	1559.28	1482.26	1260.00	707.42	429.27	0.00	0.00	0.00	150.73	507.12	1023.65	1260.20	8379.94	61.34%
Roof PV panels outputs (kWh/month)	84.75	164.68	324.26	450.07	610.55	604.06	588.83	545.28	354.59	216.47	103.09	58.02	4104.67	
One wind turbine output (kWh/month)	146.94	113.49	127.10	78.05	61.92	48.32	45.69	53.67	78.26	102.45	110.71	133.71	1100.31	
Renewable final output (kWh/month)	185.35	222.54	361.09	422.50	537.98	521.90	507.62	479.16	346.28	255.14	171.04	153.39	4163.98	
Heat generation (COP=1.8)	333.64	400.57	649.96	760.49	968.36	939.43	913.72	862.49	623.30	459.25	307.87	276.10	7495.17	
Excess heat (kWh/month)	-1225.64	-1081.70	-610.04	53.07	539.09	939.43	913.72	862.49	472.57	-47.87	-715.78	-984.10	-884.77	
Feasibility of monthly self-heating	×	×	×	✓	✓	✓	✓	✓	✓	×	×	×	×	
Hot water supply				★	★	★	★	★	★					

Table C.40 Scenario 9 simulation in end-terraced property

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total	Energy saving
Monthly heating demand (kW h/month)	1699.74	1615.79	1373.50	771.14	467.94	0.00	0.00	0.00	164.31	552.80	1115.87	1373.72	9134.82	59.60%
Roof PV panels outputs (kW h/month)	84.75	164.68	324.26	450.07	610.55	604.06	588.83	545.28	354.59	216.47	103.09	58.02	4104.67	
One wind turbine output (kW h/month)	146.94	113.49	127.10	78.05	61.92	48.32	45.69	53.67	78.26	102.45	110.71	133.71	1100.31	
Renewable final output (kW h/month)	185.35	222.54	361.09	422.50	537.98	521.90	507.62	479.16	346.28	255.14	171.04	153.39	4163.98	
Heat generation (COP=1.8)	333.64	400.57	649.96	760.49	968.36	939.43	913.72	862.49	623.30	459.25	307.87	276.10	7495.17	
Excess heat (kW h/month)	-1366.10	-1215.22	-723.54	-10.65	500.42	939.43	913.72	862.49	458.99	-93.56	-808.00	-1097.62	-1639.66	
Feasibility of monthly self-heating	×	×	×	×	✓	✓	✓	✓	✓	×	×	×	×	
Hot water supply					★	★	★	★	★					

Table C.41 Scenario 9 simulation in semi-detached property

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total	Energy saving
Monthly heating demand (kW h/month)	1882.34	1789.37	1521.06	853.99	518.21	0.00	0.00	0.00	181.96	612.19	1235.74	1521.30	10116.17	57.25%
Roof PV panels outputs (kW h/month)	84.75	164.68	324.26	450.07	610.55	604.06	588.83	545.28	354.59	216.47	103.09	58.02	4104.67	
One wind turbine output (kW h/month)	146.94	113.49	127.10	78.05	61.92	48.32	45.69	53.67	78.26	102.45	110.71	133.71	1100.31	
Renewable final output (kW h/month)	185.35	222.54	361.09	422.50	537.98	521.90	507.62	479.16	346.28	255.14	171.04	153.39	4163.98	
Heat generation (COP=1.8)	333.64	400.57	649.96	760.49	968.36	939.43	913.72	862.49	623.30	459.25	307.87	276.10	7495.17	
Excess heat (kW h/month)	-1548.70	-1388.80	-871.10	-93.49	450.14	939.43	913.72	862.49	441.34	-152.94	-927.87	-1245.20	-2621.00	
Feasibility of monthly self-heating	×	×	×	×	✓	✓	✓	✓	✓	×	×	×	×	
Hot water supply					★	★	★	★	★					

Table C.42 Scenario 9 simulation in detached property

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total	Energy saving
Monthly heating demand (kW h/month)	1671.65	1589.09	1350.80	758.40	460.21	0.00	0.00	0.00	161.59	543.67	1097.42	1351.02	8983.85	75.85%
Roof PV panels outputs (kW h/month)	169.50	329.37	648.53	900.14	1221.10	1208.12	1177.67	1090.56	709.18	432.94	206.18	116.05	8209.33	
Two wind turbines outputs (kW h/month)	293.88	226.98	254.20	156.10	123.84	96.64	91.38	107.34	156.52	204.90	221.42	267.42	2200.62	
Renewable final output (kW h/month)	370.71	445.08	722.18	844.99	1075.95	1043.81	1015.24	958.32	692.56	510.27	342.08	306.77	8327.96	
Heat generation (COP=1.8)	667.27	801.14	1299.93	1520.99	1936.72	1878.85	1827.43	1724.98	1246.60	918.49	615.74	552.19	14990.33	
Excess heat (kW h/month)	-1004.37	-787.95	-50.88	762.59	1476.51	1878.85	1827.43	1724.98	1085.01	374.83	-481.68	-798.82	6006.49	
Feasibility of monthly self-heating	×	×	×	✓	✓	✓	✓	✓	✓	✓	×	×	✓	
Hot water supply				★	★	★	★	★	★	★				

Table C.43 Scenario 9 simulation in bungalow property

Scenario 10 simulation in different property types with 51 m^2 to 100 m^2 floor area, 2 occupants and built post 1999 in North East region

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total	Energy saving
Monthly heating demand (kW h/month)	990.96	942.01	800.76	449.58	272.81	0.00	0.00	0.00	95.79	322.29	650.56	800.89	5325.65	71.09%
Roof PV panels outputs (kW h/month)	84.75	164.68	324.26	450.07	610.55	604.06	588.83	545.28	354.59	216.47	103.09	58.02	4104.67	
One wind turbine output (kW h/month)	146.94	113.49	127.10	78.05	61.92	48.32	45.69	53.67	78.26	102.45	110.71	133.71	1100.31	
Renewable final output (kW h/month)	185.35	222.54	361.09	422.50	537.98	521.90	507.62	479.16	346.28	255.14	171.04	153.39	4163.98	
Heat generation (COP=1.8)	333.64	400.57	649.96	760.49	968.36	939.43	913.72	862.49	623.30	459.25	307.87	276.10	7495.17	
Excess heat (kW h/month)	-657.32	-541.45	-150.80	310.91	695.55	939.43	913.72	862.49	527.51	136.96	-342.69	-524.79	2169.51	
Feasibility of monthly self-heating	×	×	×	✓	✓	✓	✓	✓	✓	✓	×	×	✓	
Hot water supply				★	★	★	★	★	★	★				

Table C.44 Scenario 10 simulation in mid-terraced property

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total	Energy saving
Monthly heating demand (kW h/month)	1089.06	1035.27	880.04	494.09	299.82	0.00	0.00	0.00	105.28	354.19	714.96	880.18	5852.89	68.78%
Roof PV panels outputs (kW h/month)	84.75	164.68	324.26	450.07	610.55	604.06	588.83	545.28	354.59	216.47	103.09	58.02	4104.67	
One wind turbine output (kW h/month)	146.94	113.49	127.10	78.05	61.92	48.32	45.69	53.67	78.26	102.45	110.71	133.71	1100.31	
Renewable final output (kW h/month)	185.35	222.54	361.09	422.50	537.98	521.90	507.62	479.16	346.28	255.14	171.04	153.39	4163.98	
Heat generation (COP=1.8)	333.64	400.57	649.96	760.49	968.36	939.43	913.72	862.49	623.30	459.25	307.87	276.10	7495.17	
Excess heat (kW h/month)	-755.43	-634.70	-230.07	266.40	668.54	939.43	913.72	862.49	518.03	105.05	-407.09	-604.08	1642.27	
Feasibility of monthly self-heating	×	×	×	✓	✓	✓	✓	✓	✓	✓	×	×	✓	
Hot water supply				★	★	★	★	★	★	★				

Table C.45 Scenario 10 simulation in end-terraced property

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total	Energy saving
Monthly heating demand (kW h/month)	1187.17	1128.53	959.31	538.60	326.83	0.00	0.00	0.00	114.76	386.10	779.37	959.46	6380.13	66.85%
Roof PV panels outputs (kW h/month)	84.75	164.68	324.26	450.07	610.55	604.06	588.83	545.28	354.59	216.47	103.09	58.02	4104.67	
One wind turbine output (kW h/month)	146.94	113.49	127.10	78.05	61.92	48.32	45.69	53.67	78.26	102.45	110.71	133.71	1100.31	
Renewable final output (kW h/month)	185.35	222.54	361.09	422.50	537.98	521.90	507.62	479.16	346.28	255.14	171.04	153.39	4163.98	
Heat generation (COP=1.8)	333.64	400.57	649.96	760.49	968.36	939.43	913.72	862.49	623.30	459.25	307.87	276.10	7495.17	
Excess heat (kW h/month)	-853.53	-727.96	-309.35	221.89	641.53	939.43	913.72	862.49	508.54	73.15	-471.50	-683.37	1115.03	
Feasibility of monthly self-heating	×	×	×	✓	✓	✓	✓	✓	✓	✓	×	×	✓	
Hot water supply				★	★	★	★	★	★	★				

Table C.46 Scenario 10 simulation in semi-detached property

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total	Energy saving
Monthly heating demand (kW h/month)	1314.70	1249.77	1062.37	596.46	361.94	0.00	0.00	0.00	127.09	427.58	863.09	1062.54	7065.54	64.77%
Roof PV panels outputs (kW h/month)	84.75	164.68	324.26	450.07	610.55	604.06	588.83	545.28	354.59	216.47	103.09	58.02	4104.67	
One wind turbine output (kW h/month)	146.94	113.49	127.10	78.05	61.92	48.32	45.69	53.67	78.26	102.45	110.71	133.71	1100.31	
Renewable final output (kW h/month)	185.35	222.54	361.09	422.50	537.98	521.90	507.62	479.16	346.28	255.14	171.04	153.39	4163.98	
Heat generation (COP=1.8)	333.64	400.57	649.96	760.49	968.36	939.43	913.72	862.49	623.30	459.25	307.87	276.10	7495.17	
Excess heat (kW h/month)	-981.07	-849.20	-412.41	164.03	606.42	939.43	913.72	862.49	496.21	31.67	-555.22	-786.44	429.62	
Feasibility of monthly self-heating	×	×	×	✓	✓	✓	✓	✓	✓	✓	×	×	✓	
Hot water supply				★	★	★	★	★	★	★				

Table C.47 Scenario 10 simulation in detached property

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total	Energy saving
Monthly heating demand (kW h/month)	1167.55	1109.88	943.46	529.70	321.43	0.00	0.00	0.00	112.86	379.72	766.49	943.61	6274.68	85.05%
Roof PV panels outputs (kW h/month)	169.50	329.37	648.53	900.14	1221.10	1208.12	1177.67	1090.56	709.18	432.94	206.18	116.05	8209.33	
Two wind turbines outputs (kW h/month)	293.88	226.98	254.20	156.10	123.84	96.64	91.38	107.34	156.52	204.90	221.42	267.42	2200.62	
Renewable final output (kW h/month)	370.71	445.08	722.18	844.99	1075.95	1043.81	1015.24	958.32	692.56	510.27	342.08	306.77	8327.96	
Heat generation (COP=1.8)	667.27	801.14	1299.93	1520.99	1936.72	1878.85	1827.43	1724.98	1246.60	918.49	615.74	552.19	14990.33	
Excess heat (kW h/month)	-500.27	-308.74	356.47	991.29	1615.29	1878.85	1827.43	1724.98	1133.74	538.77	-150.75	-391.41	8715.65	
Feasibility of monthly self-heating	×	×	✓	✓	✓	✓	✓	✓	✓	✓	×	×	✓	
Hot water supply			★	★	★	★	★	★	★	★				

Table C.48 Scenario 10 simulation in bungalow property

Scenario 11 simulation in different property types with 50 m^2 or less floor area, 1 occupant and built pre-1919 in North East region

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total	Energy saving
Monthly heating demand (kW h/month)	761.31	723.71	615.19	345.40	209.59	0.00	0.00	0.00	73.59	247.60	499.80	615.29	4091.49	69.85%
Roof PV panels outputs (kW h/month)	42.38	82.34	162.13	225.04	305.28	302.03	294.42	272.64	177.29	108.24	51.54	29.01	2052.33	
One wind turbine output (kW h/month)	146.94	113.49	127.10	78.05	61.92	48.32	45.69	53.67	78.26	102.45	110.71	133.71	1100.31	
Renewable final output (kW h/month)	151.45	156.67	231.39	242.47	293.76	280.28	272.09	261.05	204.44	168.55	129.80	130.18	2522.11	
Heat generation (COP=1.8)	272.61	282.00	416.49	436.44	528.76	504.50	489.75	469.89	368.00	303.39	233.65	234.32	4539.81	
Excess heat (kW h/month)	-488.70	-441.72	-198.70	91.05	319.17	504.50	489.75	469.89	294.40	55.79	-266.15	-380.97	448.31	
Feasibility of monthly self-heating	×	×	×	✓	✓	✓	✓	✓	✓	✓	×	×	✓	
Hot water supply				★	★	★	★	★	★	★				

Table C.49 Scenario 11 simulation in mid-terraced property

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total	Energy saving
Monthly heating demand (kW h/month)	751.57	714.45	607.32	340.98	206.91	0.00	0.00	0.00	72.65	244.43	493.40	607.42	4039.12	70.17%
Roof PV panels outputs (kW h/month)	42.38	82.34	162.13	225.04	305.28	302.03	294.42	272.64	177.29	108.24	51.54	29.01	2052.33	
One wind turbine output (kW h/month)	146.94	113.49	127.10	78.05	61.92	48.32	45.69	53.67	78.26	102.45	110.71	133.71	1100.31	
Renewable final output (kW h/month)	151.45	156.67	231.39	242.47	293.76	280.28	272.09	261.05	204.44	168.55	129.80	130.18	2522.11	
Heat generation (COP=1.8)	272.61	282.00	416.49	436.44	528.76	504.50	489.75	469.89	368.00	303.39	233.65	234.32	4539.81	
Excess heat (kW h/month)	-478.95	-432.45	-190.83	95.47	321.85	504.50	489.75	469.89	295.35	58.96	-259.75	-373.10	500.69	
Feasibility of monthly self-heating	×	×	×	✓	✓	✓	✓	✓	✓	✓	×	×	✓	
Hot water supply				★	★	★	★	★	★	★				

Table C.50 Scenario 11 simulation in end-terraced property

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total	Energy saving
Monthly heating demand (kW h/month)	790.62	751.58	638.88	358.69	217.66	0.00	0.00	0.00	76.43	257.13	519.04	638.98	4249.01	89.29%
Roof PV panels outputs (kW h/month)	84.75	164.68	324.26	450.07	610.55	604.06	588.83	545.28	354.59	216.47	103.09	58.02	4104.67	
Two wind turbines outputs (kW h/month)	293.88	226.98	254.20	156.10	123.84	96.64	91.38	107.34	156.52	204.90	221.42	267.42	2200.62	
Renewable final output (kW h/month)	302.91	313.33	462.77	484.94	587.51	560.56	544.17	522.10	408.89	337.10	259.61	260.36	5044.23	
Heat generation (COP=1.8)	545.23	564.00	832.99	872.89	1057.52	1009.01	979.51	939.77	736.00	606.77	467.29	468.64	9079.61	
Excess heat (kW h/month)	-245.40	-187.58	194.11	514.19	839.86	1009.01	979.51	939.77	659.57	349.64	-51.75	-170.34	4830.60	
Feasibility of monthly self-heating	×	×	✓	✓	✓	✓	✓	✓	✓	✓	×	×	✓	
Hot water supply			★	★	★	★	★	★	★	★				

Table C.51 Scenario 11 simulation in bungalow property

Scenario 12 simulation in different property types with $50\,\mathrm{m}^2$ or less floor area, 1 occupant and built post 1999 in North East region

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total	Energy saving
Monthly heating demand (kW h/month)	553.70	526.36	447.43	251.21	152.44	0.00	0.00	0.00	53.52	180.08	363.50	447.50	2975.74	79.01%
Roof PV panels outputs (kW h/month)	42.38	82.34	162.13	225.04	305.28	302.03	294.42	272.64	177.29	108.24	51.54	29.01	2052.33	
One wind turbine output (kW h/month)	146.94	113.49	127.10	78.05	61.92	48.32	45.69	53.67	78.26	102.45	110.71	133.71	1100.31	
Renewable final output (kW h/month)	151.45	156.67	231.39	242.47	293.76	280.28	272.09	261.05	204.44	168.55	129.80	130.18	2522.11	
Heat generation (COP=1.8)	272.61	282.00	416.49	436.44	528.76	504.50	489.75	469.89	368.00	303.39	233.65	234.32	4539.81	
Excess heat (kW h/month)	-281.09	-244.36	-30.94	185.24	376.33	504.50	489.75	469.89	314.47	123.31	-129.86	-213.18	1564.06	
Feasibility of monthly self-heating	×	×	×	✓	✓	✓	✓	✓	✓	✓	×	×	✓	
Hot water supply				★	★	★	★	★	★	★				

Table C.52 Scenario 12 simulation in mid-terraced property

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total	Energy saving
Monthly heating demand (kW h/month)	546.62	519.62	441.70	247.99	150.49	0.00	0.00	0.00	52.84	177.77	358.85	441.77	2937.65	79.45%
Roof PV panels outputs (kW h/month)	42.38	82.34	162.13	225.04	305.28	302.03	294.42	272.64	177.29	108.24	51.54	29.01	2052.33	
One wind turbine output (kW h/month)	146.94	113.49	127.10	78.05	61.92	48.32	45.69	53.67	78.26	102.45	110.71	133.71	1100.31	
Renewable final output (kW h/month)	151.45	156.67	231.39	242.47	293.76	280.28	272.09	261.05	204.44	168.55	129.80	130.18	2522.11	
Heat generation (COP=1.8)	272.61	282.00	416.49	436.44	528.76	504.50	489.75	469.89	368.00	303.39	233.65	234.32	4539.81	
Excess heat (kW h/month)	-274.00	-237.62	-25.21	188.45	378.28	504.50	489.75	469.89	315.16	125.61	-125.20	-207.45	1602.15	
Feasibility of monthly self-heating	×	×	×	✓	✓	✓	✓	✓	✓	✓	×	×	✓	
Hot water supply				★	★	★	★	★	★	★				

Table C.53 Scenario 12 simulation in end-terraced property

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total	Energy saving
Monthly heating demand (kW h/month)	575.02	546.62	464.66	260.88	158.31	0.00	0.00	0.00	55.59	187.01	377.50	464.73	3090.31	99.33%
Roof PV panels outputs (kW h/month)	84.75	164.68	324.26	450.07	610.55	604.06	588.83	545.28	354.59	216.47	103.09	58.02	4104.67	
Two wind turbines outputs (kW h/month)	293.88	226.98	254.20	156.10	123.84	96.64	91.38	107.34	156.52	204.90	221.42	267.42	2200.62	
Renewable final output (kW h/month)	302.91	313.33	462.77	484.94	587.51	560.56	544.17	522.10	408.89	337.10	259.61	260.36	5044.23	
Heat generation (COP=1.8)	545.23	564.00	832.99	872.89	1057.52	1009.01	979.51	939.77	736.00	606.77	467.29	468.64	9079.61	
Excess heat (kW h/month)	-29.79	17.37	368.33	612.01	899.22	1009.01	979.51	939.77	680.41	419.76	89.79	3.91	5989.30	
Feasibility of monthly self-heating	×	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	
Hot water supply		★	★	★	★	★	★	★	★	★	★			

Table C.54 Scenario 12 simulation in bungalow property

Appendix D

Scenario simulation results in North West region

Scenario 13 simulation in different property types with 151 m^2 to 200 m^2 floor area, 4 occupants and built pre-1919 in North West region

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total	Energy saving
Monthly heating demand (kWh/month)	2616.39	2487.16	2114.22	1187.01	720.30	0.00	0.00	0.00	252.92	850.92	1717.64	2114.55	14061.11	62.04%
Roof PV panels outputs (kWh/month)	160.27	311.42	613.18	851.08	1154.55	1142.28	1113.49	1031.12	670.53	409.35	194.94	109.72	7761.92	
Two wind turbines outputs (kWh/month)	216.22	154.42	216.16	136.60	114.88	96.24	77.40	78.00	119.64	150.74	186.44	204.44	1751.18	
Renewable final output (kWh/month)	301.19	372.67	663.47	790.15	1015.55	990.81	952.71	887.30	632.13	448.07	305.10	251.33	7610.48	
Heat generation (COP=1.8)	542.14	670.80	1194.25	1422.26	1827.98	1783.47	1714.88	1597.14	1137.84	806.53	549.19	452.40	13698.87	
Excess heat (kWh/month)	-2074.25	-1816.36	-919.97	235.25	1107.68	1783.47	1714.88	1597.14	884.92	-44.40	-1168.45	-1662.16	-362.24	
Feasibility of monthly self-heating	×	×	×	✓	✓	✓	✓	✓	✓	×	×	×	×	
Hot water supply				★	★	★	★	★	★					

Table D.1 Scenario 13 simulation in mid-terraced property

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total	Energy saving
Monthly heating demand (kWh/month)	2762.38	2625.95	2232.19	1253.25	760.49	0.00	0.00	0.00	267.03	898.40	1813.48	2232.54	14845.72	60.94%
Roof PV panels outputs (kWh/month)	160.27	311.42	613.18	851.08	1154.55	1142.28	1113.49	1031.12	670.53	409.35	194.94	109.72	7761.92	
Two wind turbines outputs (kWh/month)	216.22	154.42	216.16	136.60	114.88	96.24	77.40	78.00	119.64	150.74	186.44	204.44	1751.18	
Renewable final output (kWh/month)	301.19	372.67	663.47	790.15	1015.55	990.81	952.71	887.30	632.13	448.07	305.10	251.33	7610.48	
Heat generation (COP=1.8)	542.14	670.80	1194.25	1422.26	1827.98	1783.47	1714.88	1597.14	1137.84	806.53	549.19	452.40	13698.87	
Excess heat (kWh/month)	-2220.24	-1955.14	-1037.94	169.02	1067.49	1783.47	1714.88	1597.14	870.81	-91.88	-1264.29	-1780.15	-1146.85	
Feasibility of monthly self-heating	×	×	×	✓	✓	✓	✓	✓	✓	×	×	×	×	
Hot water supply				★	★	★	★	★	★					

Table D.2 Scenario 13 simulation in end-terraced property

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total	Energy saving
Monthly heating demand (kW h/month)	3041.29	2891.08	2457.57	1379.78	837.28	0.00	0.00	0.00	293.99	989.11	1996.58	2457.95	16344.63	59.13%
Roof PV panels outputs (kW h/month)	160.27	311.42	613.18	851.08	1154.55	1142.28	1113.49	1031.12	670.53	409.35	194.94	109.72	7761.92	
Two wind turbines outputs (kW h/month)	216.22	154.42	216.16	136.60	114.88	96.24	77.40	78.00	119.64	150.74	186.44	204.44	1751.18	
Renewable final output (kW h/month)	301.19	372.67	663.47	790.15	1015.55	990.81	952.71	887.30	632.13	448.07	305.10	251.33	7610.48	
Heat generation (COP=1.8)	542.14	670.80	1194.25	1422.26	1827.98	1783.47	1714.88	1597.14	1137.84	806.53	549.19	452.40	13698.87	
Excess heat (kW h/month)	-2499.15	-2220.28	-1263.32	42.48	990.71	1783.47	1714.88	1597.14	843.85	-182.59	-1447.39	-2005.56	-2645.76	
Feasibility of monthly self-heating	×	×	×	✓	✓	✓	✓	✓	✓	×	×	×	×	
Hot water supply					★	★	★	★	★					

Table D.3 Scenario 13 simulation in semi-detached property

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total	Energy saving
Monthly heating demand (kW h/month)	2908.64	2764.98	2350.38	1319.60	800.76	0.00	0.00	0.00	281.17	945.97	1909.50	2350.75	15631.73	59.95%
Roof PV panels outputs (kW h/month)	160.27	311.42	613.18	851.08	1154.55	1142.28	1113.49	1031.12	670.53	409.35	194.94	109.72	7761.92	
Two wind turbines outputs (kW h/month)	216.22	154.42	216.16	136.60	114.88	96.24	77.40	78.00	119.64	150.74	186.44	204.44	1751.18	
Renewable final output (kW h/month)	301.19	372.67	663.47	790.15	1015.55	990.81	952.71	887.30	632.13	448.07	305.10	251.33	7610.48	
Heat generation (COP=1.8)	542.14	670.80	1194.25	1422.26	1827.98	1783.47	1714.88	1597.14	1137.84	806.53	549.19	452.40	13698.87	
Excess heat (kW h/month)	-2366.50	-2094.18	-1156.12	102.66	1027.23	1783.47	1714.88	1597.14	856.67	-139.44	-1360.31	-1898.35	-1932.86	
Feasibility of monthly self-heating	×	×	×	✓	✓	✓	✓	✓	✓	×	×	×	×	
Hot water supply				★	★	★	★	★	★					

Table D.4 Scenario 13 simulation in detached property

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total	Energy saving
Monthly heating demand (kW h/month)	3094.40	2941.57	2500.48	1403.88	851.90	0.00	0.00	0.00	299.13	1006.38	2031.45	2500.88	16630.07	73.90%
Roof PV panels outputs (kW h/month)	320.53	622.83	1226.36	1702.17	2309.11	2284.56	2226.97	2062.25	1341.05	818.69	389.88	219.45	15523.85	
Four wind turbines outputs (kW h/month)	432.44	308.84	432.32	273.20	229.76	192.48	154.80	156.00	239.28	301.48	372.88	408.88	3502.36	
Renewable final output (kW h/month)	602.38	745.34	1326.95	1580.29	2031.09	1981.63	1905.42	1774.60	1264.27	896.14	610.21	502.66	15220.97	
Heat generation (COP=1.8)	1084.28	1341.61	2388.50	2844.53	3655.97	3566.93	3429.75	3194.28	2275.68	1613.05	1098.37	904.79	27397.74	
Excess heat (kW h/month)	-2010.12	-1599.96	-111.98	1440.65	2804.07	3566.93	3429.75	3194.28	1976.55	606.67	-933.07	-1596.09	10767.67	
Feasibility of monthly self-heating	×	×	×	✓	✓	✓	✓	✓	✓	✓	×	×	✓	
Hot water supply				★	★	★	★	★	★	★				

Table D.5 Scenario 13 simulation in bungalow property

Scenario 14 simulation in different property types with 151 m^2 to 200 m^2 floor area, 4 occupants and built 1919-44 in North West region

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total	Energy saving
Monthly heating demand (kWh/month)	2867.82	2726.18	2317.39	1301.08	789.52	0.00	0.00	0.00	277.22	932.69	1882.70	2317.76	15412.38	60.22%
Roof PV panels outputs (kWh/month)	160.27	311.42	613.18	851.08	1154.55	1142.28	1113.49	1031.12	670.53	409.35	194.94	109.72	7761.92	
Two wind turbines outputs (kWh/month)	216.22	154.42	216.16	136.60	114.88	96.24	77.40	78.00	119.64	150.74	186.44	204.44	1751.18	
Renewable final output (kWh/month)	301.19	372.67	663.47	790.15	1015.55	990.81	952.71	887.30	632.13	448.07	305.10	251.33	7610.48	
Heat generation (COP=1.8)	542.14	670.80	1194.25	1422.26	1827.98	1783.47	1714.88	1597.14	1137.84	806.53	549.19	452.40	13698.87	
Excess heat (kWh/month)	-2325.68	-2055.38	-1123.14	121.18	1038.46	1783.47	1714.88	1597.14	860.62	-126.17	-1333.51	-1865.36	-1713.51	
Feasibility of monthly self-heating	×	×	×	✓	✓	✓	✓	✓	✓	×	×	×	×	
Hot water supply				★	★	★	★	★	★					

Table D.6 Scenario 14 simulation in mid-terraced property

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total	Energy saving
Monthly heating demand (kWh/month)	3027.85	2878.30	2446.70	1373.69	833.58	0.00	0.00	0.00	292.69	984.74	1987.76	2447.09	16272.39	59.21%
Roof PV panels outputs (kWh/month)	160.27	311.42	613.18	851.08	1154.55	1142.28	1113.49	1031.12	670.53	409.35	194.94	109.72	7761.92	
Two wind turbines outputs (kWh/month)	216.22	154.42	216.16	136.60	114.88	96.24	77.40	78.00	119.64	150.74	186.44	204.44	1751.18	
Renewable final output (kWh/month)	301.19	372.67	663.47	790.15	1015.55	990.81	952.71	887.30	632.13	448.07	305.10	251.33	7610.48	
Heat generation (COP=1.8)	542.14	670.80	1194.25	1422.26	1827.98	1783.47	1714.88	1597.14	1137.84	806.53	549.19	452.40	13698.87	
Excess heat (kWh/month)	-2485.71	-2207.50	-1252.45	48.58	994.41	1783.47	1714.88	1597.14	845.15	-178.21	-1438.57	-1994.69	-2573.52	
Feasibility of monthly self-heating	×	×	×	✓	✓	✓	✓	✓	✓	×	×	×	×	
Hot water supply					★	★	★	★	★					

Table D.7 Scenario 14 simulation in end-terraced property

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total	Energy saving
Monthly heating demand (kWh/month)	3333.55	3168.91	2693.74	1512.38	917.74	0.00	0.00	0.00	322.24	1084.16	2188.45	2694.16	17915.35	57.21%
Roof PV panels outputs (kWh/month)	160.27	311.42	613.18	851.08	1154.55	1142.28	1113.49	1031.12	670.53	409.35	194.94	109.72	7761.92	
Two wind turbines outputs (kWh/month)	216.22	154.42	216.16	136.60	114.88	96.24	77.40	78.00	119.64	150.74	186.44	204.44	1751.18	
Renewable final output (kWh/month)	301.19	372.67	663.47	790.15	1015.55	990.81	952.71	887.30	632.13	448.07	305.10	251.33	7610.48	
Heat generation (COP=1.8)	542.14	670.80	1194.25	1422.26	1827.98	1783.47	1714.88	1597.14	1137.84	806.53	549.19	452.40	13698.87	
Excess heat (kWh/month)	-2791.42	-2498.11	-1499.49	-90.12	910.25	1783.47	1714.88	1597.14	815.60	-277.64	-1639.27	-2241.77	-4216.48	
Feasibility of monthly self-heating	×	×	×	×	✓	✓	✓	✓	✓	×	×	×	×	
Hot water supply					★	★	★	★	★					

Table D.8 Scenario 14 simulation in semi-detached property

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total	Energy saving
Monthly heating demand (kWh/month)	3188.16	3030.69	2576.25	1446.42	877.71	0.00	0.00	0.00	308.19	1036.88	2093.00	2576.65	17133.94	58.21%
Roof PV panels outputs (kWh/month)	160.27	311.42	613.18	851.08	1154.55	1142.28	1113.49	1031.12	670.53	409.35	194.94	109.72	7761.92	
Two wind turbines outputs (kWh/month)	216.22	154.42	216.16	136.60	114.88	96.24	77.40	78.00	119.64	150.74	186.44	204.44	1751.18	
Renewable final output (kWh/month)	301.19	372.67	663.47	790.15	1015.55	990.81	952.71	887.30	632.13	448.07	305.10	251.33	7610.48	
Heat generation (COP=1.8)	542.14	670.80	1194.25	1422.26	1827.98	1783.47	1714.88	1597.14	1137.84	806.53	549.19	452.40	13698.87	
Excess heat (kWh/month)	-2646.02	-2359.89	-1382.00	-24.15	950.27	1783.47	1714.88	1597.14	829.65	-230.35	-1543.81	-2124.26	-3435.07	
Feasibility of monthly self-heating	×	×	×	×	✓	✓	✓	✓	✓	×	×	×	×	
Hot water supply					★	★	★	★	★					

Table D.9 Scenario 14 simulation in detached property

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total	Energy saving
Monthly heating demand (kWh/month)	3391.77	3224.25	2740.78	1538.79	933.77	0.00	0.00	0.00	327.87	1103.10	2226.67	2741.21	18228.22	71.40%
Roof PV panels outputs (kWh/month)	320.53	622.83	1226.36	1702.17	2309.11	2284.56	2226.97	2062.25	1341.05	818.69	389.88	219.45	15523.85	
Four wind turbines outputs (kWh/month)	432.44	308.84	432.32	273.20	229.76	192.48	154.80	156.00	239.28	301.48	372.88	408.88	3502.36	
Renewable final output (kWh/month)	602.38	745.34	1326.95	1580.29	2031.09	1981.63	1905.42	1774.60	1264.27	896.14	610.21	502.66	15220.97	
Heat generation (COP=1.8)	1084.28	1341.61	2388.50	2844.53	3655.97	3566.93	3429.75	3194.28	2275.68	1613.05	1098.37	904.79	27397.74	
Excess heat (kWh/month)	-2307.49	-1882.65	-352.28	1305.73	2722.20	3566.93	3429.75	3194.28	1947.81	509.95	-1128.30	-1836.42	9169.52	
Feasibility of monthly self-heating	×	×	×	✓	✓	✓	✓	✓	✓	✓	×	×	✓	
Hot water supply				★	★	★	★	★	★	★				

Table D.10 Scenario 14 simulation in bungalow property

Scenario 15 simulation in different property types with 151 m^2 to 200 m^2 floor area, 4 occupants and built post 1999 in North West region

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total	Energy saving
Monthly heating demand (kWh/month)	2033.72	1933.27	1643.38	922.67	559.89	0.00	0.00	0.00	196.59	661.42	1335.12	1643.64	10929.70	67.09%
Roof PV panels outputs (kWh/month)	160.27	311.42	613.18	851.08	1154.55	1142.28	1113.49	1031.12	670.53	409.35	194.94	109.72	7761.92	
Two wind turbines outputs (kWh/month)	216.22	154.42	216.16	136.60	114.88	96.24	77.40	78.00	119.64	150.74	186.44	204.44	1751.18	
Renewable final output (kWh/month)	301.19	372.67	663.47	790.15	1015.55	990.81	952.71	887.30	632.13	448.07	305.10	251.33	7610.48	
Heat generation (COP=1.8)	542.14	670.80	1194.25	1422.26	1827.98	1783.47	1714.88	1597.14	1137.84	806.53	549.19	452.40	13698.87	
Excess heat (kWh/month)	-1491.58	-1262.47	-449.13	499.60	1268.10	1783.47	1714.88	1597.14	941.25	145.10	-785.93	-1191.24	2769.17	
Feasibility of monthly self-heating	×	×	×	✓	✓	✓	✓	✓	✓	✓	×	×	✓	
Hot water supply				★	★	★	★	★	★	★				

Table D.11 Scenario 15 simulation in mid-terraced property

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total	Energy saving
Monthly heating demand (kWh/month)	2147.20	2041.15	1735.08	974.15	591.13	0.00	0.00	0.00	207.56	698.33	1409.62	1735.36	11539.58	65.94%
Roof PV panels outputs (kWh/month)	160.27	311.42	613.18	851.08	1154.55	1142.28	1113.49	1031.12	670.53	409.35	194.94	109.72	7761.92	
Two wind turbines outputs (kWh/month)	216.22	154.42	216.16	136.60	114.88	96.24	77.40	78.00	119.64	150.74	186.44	204.44	1751.18	
Renewable final output (kWh/month)	301.19	372.67	663.47	790.15	1015.55	990.81	952.71	887.30	632.13	448.07	305.10	251.33	7610.48	
Heat generation (COP=1.8)	542.14	670.80	1194.25	1422.26	1827.98	1783.47	1714.88	1597.14	1137.84	806.53	549.19	452.40	13698.87	
Excess heat (kWh/month)	-1605.06	-1370.35	-540.83	448.11	1236.85	1783.47	1714.88	1597.14	930.28	108.20	-860.43	-1282.96	2159.29	
Feasibility of monthly self-heating	×	×	×	✓	✓	✓	✓	✓	✓	✓	×	×	✓	
Hot water supply				★	★	★	★	★	★	★				

Table D.12 Scenario 15 simulation in end-terraced property

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total	Energy saving
Monthly heating demand (kW h/month)	2363.99	2247.24	1910.27	1072.51	650.81	0.00	0.00	0.00	228.52	768.84	1551.94	1910.57	12704.68	64.06%
Roof PV panels outputs (kW h/month)	160.27	311.42	613.18	851.08	1154.55	1142.28	1113.49	1031.12	670.53	409.35	194.94	109.72	7761.92	
Two wind turbines outputs (kW h/month)	216.22	154.42	216.16	136.60	114.88	96.24	77.40	78.00	119.64	150.74	186.44	204.44	1751.18	
Renewable final output (kW h/month)	301.19	372.67	663.47	790.15	1015.55	990.81	952.71	887.30	632.13	448.07	305.10	251.33	7610.48	
Heat generation (COP=1.8)	542.14	670.80	1194.25	1422.26	1827.98	1783.47	1714.88	1597.14	1137.84	806.53	549.19	452.40	13698.87	
Excess heat (kW h/month)	-1821.85	-1576.43	-716.02	349.76	1177.17	1783.47	1714.88	1597.14	909.32	37.69	-1002.76	-1458.17	994.19	
Feasibility of monthly self-heating	×	×	×	✓	✓	✓	✓	✓	✓	✓	×	×	✓	
Hot water supply				★	★	★	★	★	★					

Table D.13 Scenario 15 simulation in semi-detached property

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total	Energy saving
Monthly heating demand (kW h/month)	2260.88	2149.22	1826.95	1025.73	622.43	0.00	0.00	0.00	218.55	735.30	1484.25	1827.24	12150.55	64.91%
Roof PV panels outputs (kW h/month)	160.27	311.42	613.18	851.08	1154.55	1142.28	1113.49	1031.12	670.53	409.35	194.94	109.72	7761.92	
Two wind turbines outputs (kW h/month)	216.22	154.42	216.16	136.60	114.88	96.24	77.40	78.00	119.64	150.74	186.44	204.44	1751.18	
Renewable final output (kW h/month)	301.19	372.67	663.47	790.15	1015.55	990.81	952.71	887.30	632.13	448.07	305.10	251.33	7610.48	
Heat generation (COP=1.8)	542.14	670.80	1194.25	1422.26	1827.98	1783.47	1714.88	1597.14	1137.84	806.53	549.19	452.40	13698.87	
Excess heat (kW h/month)	-1718.74	-1478.42	-632.70	396.54	1205.56	1783.47	1714.88	1597.14	919.29	71.22	-935.06	-1374.84	1548.32	
Feasibility of monthly self-heating	×	×	×	✓	✓	✓	✓	✓	✓	✓	×	×	✓	
Hot water supply				★	★	★	★	★	★	★				

Table D.14 Scenario 15 simulation in detached property

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total	Energy saving
Monthly heating demand (kW h/month)	2405.28	2286.48	1943.63	1091.24	662.18	0.00	0.00	0.00	232.51	782.26	1579.05	1943.93	12926.55	79.66%
Roof PV panels outputs (kW h/month)	320.53	622.83	1226.36	1702.17	2309.11	2284.56	2226.97	2062.25	1341.05	818.69	389.88	219.45	15523.85	
Four wind turbines outputs (kW h/month)	432.44	308.84	432.32	273.20	229.76	192.48	154.80	156.00	239.28	301.48	372.88	408.88	3502.36	
Renewable final output (kW h/month)	602.38	745.34	1326.95	1580.29	2031.09	1981.63	1905.42	1774.60	1264.27	896.14	610.21	502.66	15220.97	
Heat generation (COP=1.8)	1084.28	1341.61	2388.50	2844.53	3655.97	3566.93	3429.75	3194.28	2275.68	1613.05	1098.37	904.79	27397.74	
Excess heat (kW h/month)	-1321.00	-944.87	444.88	1753.29	2993.79	3566.93	3429.75	3194.28	2043.17	830.79	-480.67	-1039.14	14471.18	
Feasibility of monthly self-heating	×	×	✓	✓	✓	✓	✓	✓	✓	✓	×	×	✓	
Hot water supply			★	★	★	★	★	★	★	★				

Table D.15 Scenario 15 simulation in bungalow property

Scenario 16 simulation in different property types with 101 m^2 to 150 m^2 floor area, 3 occupants and built pre-1919 in North West region

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total	Energy saving
Monthly heating demand (kWh/month)	1707.43	1623.11	1379.72	774.64	470.06	0.00	0.00	0.00	165.05	555.31	1120.92	1379.94	9176.18	67.44%
Roof PV panels outputs (kWh/month)	120.20	233.56	459.89	638.31	865.92	856.71	835.11	773.34	502.89	307.01	146.21	82.29	5821.44	
Two wind turbines outputs (kWh/month)	216.22	154.42	216.16	136.60	114.88	96.24	77.40	78.00	119.64	150.74	186.44	204.44	1751.18	
Renewable final output (kWh/month)	269.14	310.39	540.84	619.93	784.64	762.36	730.01	681.07	498.03	366.20	266.12	229.39	6058.10	
Heat generation (COP=1.8)	484.44	558.69	973.51	1115.87	1412.34	1372.25	1314.02	1225.93	896.45	659.16	479.01	412.90	10904.58	
Excess heat (kWh/month)	-1222.99	-1064.41	-406.22	341.24	942.28	1372.25	1314.02	1225.93	731.40	103.86	-641.91	-967.05	1728.40	
Feasibility of monthly self-heating	×	×	×	✓	✓	✓	✓	✓	✓	✓	×	×	✓	
Hot water supply				★	★	★	★	★	★	★				

Table D.16 Scenario 16 simulation in mid-terraced property

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total	Energy saving
Monthly heating demand (kWh/month)	1822.17	1732.18	1472.44	826.69	501.65	0.00	0.00	0.00	176.14	592.62	1196.24	1472.67	9792.82	66.05%
Roof PV panels outputs (kWh/month)	120.20	233.56	459.89	638.31	865.92	856.71	835.11	773.34	502.89	307.01	146.21	82.29	5821.44	
Two wind turbines outputs (kWh/month)	216.22	154.42	216.16	136.60	114.88	96.24	77.40	78.00	119.64	150.74	186.44	204.44	1751.18	
Renewable final output (kWh/month)	269.14	310.39	540.84	619.93	784.64	762.36	730.01	681.07	498.03	366.20	266.12	229.39	6058.10	
Heat generation (COP=1.8)	484.44	558.69	973.51	1115.87	1412.34	1372.25	1314.02	1225.93	896.45	659.16	479.01	412.90	10904.58	
Excess heat (kWh/month)	-1337.73	-1173.48	-498.93	289.18	910.69	1372.25	1314.02	1225.93	720.31	66.54	-717.23	-1059.78	1111.76	
Feasibility of monthly self-heating	×	×	×	✓	✓	✓	✓	✓	✓	✓	×	×	✓	
Hot water supply				★	★	★	★	★	★	★				

Table D.17 Scenario 16 simulation in end-terraced property

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total	Energy saving
Monthly heating demand (kW h/month)	1974.99	1877.45	1595.93	896.02	543.72	0.00	0.00	0.00	190.92	642.32	1296.57	1596.18	10614.08	64.46%
Roof PV panels outputs (kW h/month)	120.20	233.56	459.89	638.31	865.92	856.71	835.11	773.34	502.89	307.01	146.21	82.29	5821.44	
Two wind turbines outputs (kW h/month)	216.22	154.42	216.16	136.60	114.88	96.24	77.40	78.00	119.64	150.74	186.44	204.44	1751.18	
Renewable final output (kW h/month)	269.14	310.39	540.84	619.93	784.64	762.36	730.01	681.07	498.03	366.20	266.12	229.39	6058.10	
Heat generation (COP=1.8)	484.44	558.69	973.51	1115.87	1412.34	1372.25	1314.02	1225.93	896.45	659.16	479.01	412.90	10904.58	
Excess heat (kW h/month)	-1490.55	-1318.75	-622.42	219.85	868.62	1372.25	1314.02	1225.93	705.53	16.84	-817.56	-1183.28	290.49	
Feasibility of monthly self-heating	×	×	×	✓	✓	✓	✓	✓	✓	✓	×	×	✓	
Hot water supply				★	★	★	★	★	★					

Table D.18 Scenario 16 simulation in semi-detached property

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total	Energy saving
Monthly heating demand (kW h/month)	2140.61	2034.89	1729.76	971.16	589.32	0.00	0.00	0.00	206.93	696.19	1405.29	1730.03	11504.17	62.76%
Roof PV panels outputs (kW h/month)	120.20	233.56	459.89	638.31	865.92	856.71	835.11	773.34	502.89	307.01	146.21	82.29	5821.44	
Two wind turbines outputs (kW h/month)	216.22	154.42	216.16	136.60	114.88	96.24	77.40	78.00	119.64	150.74	186.44	204.44	1751.18	
Renewable final output (kW h/month)	269.14	310.39	540.84	619.93	784.64	762.36	730.01	681.07	498.03	366.20	266.12	229.39	6058.10	
Heat generation (COP=1.8)	484.44	558.69	973.51	1115.87	1412.34	1372.25	1314.02	1225.93	896.45	659.16	479.01	412.90	10904.58	
Excess heat (kW h/month)	-1656.17	-1476.19	-756.25	144.71	823.03	1372.25	1314.02	1225.93	689.52	-37.03	-926.29	-1317.14	-599.60	
Feasibility of monthly self-heating	×	×	×	✓	✓	✓	✓	✓	✓	×	×	×	×	
Hot water supply				★	★	★	★	★	★					

Table D.19 Scenario 16 simulation in detached property

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total	Energy saving
Monthly heating demand (kW h/month)	2229.91	2119.78	1801.92	1011.67	613.90	0.00	0.00	0.00	215.56	725.23	1463.92	1802.20	11984.09	78.29%
Roof PV panels outputs (kW h/month)	240.40	467.12	919.77	1276.62	1731.83	1713.42	1670.23	1546.69	1005.79	614.02	292.41	164.59	11642.89	
Four wind turbines outputs (kW h/month)	432.44	308.84	432.32	273.20	229.76	192.48	154.80	156.00	239.28	301.48	372.88	408.88	3502.36	
Renewable final output (kW h/month)	538.27	620.77	1081.67	1239.86	1569.27	1524.72	1460.02	1362.15	996.06	732.40	532.23	458.77	12116.20	
Heat generation (COP=1.8)	968.89	1117.39	1947.01	2231.75	2824.69	2744.49	2628.04	2451.87	1792.90	1318.32	958.02	825.79	21809.15	
Excess heat (kW h/month)	-1261.02	-1002.39	145.09	1220.07	2210.79	2744.49	2628.04	2451.87	1577.34	593.09	-505.90	-976.41	9825.07	
Feasibility of monthly self-heating	×	×	✓	✓	✓	✓	✓	✓	✓	✓	×	×	✓	
Hot water supply			★	★	★	★	★	★	★	★				

Table D.20 Scenario 16 simulation in bungalow property

Scenario 17 simulation in different property types with 101 m^2 to 150 m^2 floor area, 3 occupants and built 1919-44 in North West region

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total	Energy saving
Monthly heating demand (kWh/month)	1847.96	1756.69	1493.27	838.39	508.75	0.00	0.00	0.00	178.64	601.01	1213.17	1493.51	9931.38	65.76%
Roof PV panels outputs (kWh/month)	120.20	233.56	459.89	638.31	865.92	856.71	835.11	773.34	502.89	307.01	146.21	82.29	5821.44	
Two wind turbines outputs (kWh/month)	216.22	154.42	216.16	136.60	114.88	96.24	77.40	78.00	119.64	150.74	186.44	204.44	1751.18	
Renewable final output (kWh/month)	269.14	310.39	540.84	619.93	784.64	762.36	730.01	681.07	498.03	366.20	266.12	229.39	6058.10	
Heat generation (**COP**=1.8)	484.44	558.69	973.51	1115.87	1412.34	1372.25	1314.02	1225.93	896.45	659.16	479.01	412.90	10904.58	
Excess heat (kWh/month)	-1363.51	-1197.99	-519.77	277.48	903.60	1372.25	1314.02	1225.93	717.81	58.15	-734.16	-1080.61	973.20	
Feasibility of monthly self-heating	×	×	×	✓	✓	✓	✓	✓	✓	✓	×	×	✓	
Hot water supply				★	★	★	★	★	★	★				

Table D.21 Scenario 17 simulation in mid-terraced property

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total	Energy saving
Monthly heating demand (kWh/month)	1972.14	1874.74	1593.62	894.73	542.94	0.00	0.00	0.00	190.64	641.39	1294.69	1593.87	10598.77	64.48%
Roof PV panels outputs (kWh/month)	120.20	233.56	459.89	638.31	865.92	856.71	835.11	773.34	502.89	307.01	146.21	82.29	5821.44	
Two wind turbines outputs (kWh/month)	216.22	154.42	216.16	136.60	114.88	96.24	77.40	78.00	119.64	150.74	186.44	204.44	1751.18	
Renewable final output (kWh/month)	269.14	310.39	540.84	619.93	784.64	762.36	730.01	681.07	498.03	366.20	266.12	229.39	6058.10	
Heat generation (**COP**=1.8)	484.44	558.69	973.51	1115.87	1412.34	1372.25	1314.02	1225.93	896.45	659.16	479.01	412.90	10904.58	
Excess heat (kWh/month)	-1487.70	-1316.04	-620.12	221.15	869.41	1372.25	1314.02	1225.93	705.81	17.77	-815.69	-1180.98	305.81	
Feasibility of monthly self-heating	×	×	×	✓	✓	✓	✓	✓	✓	✓	×	×	✓	
Hot water supply				★	★	★	★	★	★					

Table D.22 Scenario 17 simulation in end-terraced property

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total	Energy saving
Monthly heating demand (kW h/month)	2137.53	2031.96	1727.27	969.76	588.47	0.00	0.00	0.00	206.63	695.18	1403.27	1727.54	11487.62	62.79%
Roof PV panels outputs (kW h/month)	120.20	233.56	459.89	638.31	865.92	856.71	835.11	773.34	502.89	307.01	146.21	82.29	5821.44	
Two wind turbines outputs (kW h/month)	216.22	154.42	216.16	136.60	114.88	96.24	77.40	78.00	119.64	150.74	186.44	204.44	1751.18	
Renewable final output (kW h/month)	269.14	310.39	540.84	619.93	784.64	762.36	730.01	681.07	498.03	366.20	266.12	229.39	6058.10	
Heat generation (COP=1.8)	484.44	558.69	973.51	1115.87	1412.34	1372.25	1314.02	1225.93	896.45	659.16	479.01	412.90	10904.58	
Excess heat (kW h/month)	-1653.09	-1473.27	-753.76	146.11	823.88	1372.25	1314.02	1225.93	689.82	-36.02	-924.26	-1314.65	-583.05	
Feasibility of monthly self-heating	×	×	×	✓	✓	✓	✓	✓	✓	×	×	×	×	
Hot water supply				★	★	★	★	★	★					

Table D.23 Scenario 17 simulation in semi-detached property

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total	Energy saving
Monthly heating demand (kW h/month)	2316.78	2202.36	1872.12	1051.09	637.82	0.00	0.00	0.00	223.96	753.48	1520.95	1872.41	12450.97	61.12%
Roof PV panels outputs (kW h/month)	120.20	233.56	459.89	638.31	865.92	856.71	835.11	773.34	502.89	307.01	146.21	82.29	5821.44	
Two wind turbines outputs (kW h/month)	216.22	154.42	216.16	136.60	114.88	96.24	77.40	78.00	119.64	150.74	186.44	204.44	1751.18	
Renewable final output (kW h/month)	269.14	310.39	540.84	619.93	784.64	762.36	730.01	681.07	498.03	366.20	266.12	229.39	6058.10	
Heat generation (COP=1.8)	484.44	558.69	973.51	1115.87	1412.34	1372.25	1314.02	1225.93	896.45	659.16	479.01	412.90	10904.58	
Excess heat (kW h/month)	-1832.34	-1643.66	-898.61	64.79	774.53	1372.25	1314.02	1225.93	672.49	-94.32	-1041.94	-1459.52	-1546.39	
Feasibility of monthly self-heating	×	×	×	✓	✓	✓	✓	✓	✓	×	×	×	×	
Hot water supply				★	★	★	★	★	★					

Table D.24 Scenario 17 simulation in detached property

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total	Energy saving
Monthly heating demand (kW h/month)	2413.43	2294.23	1950.22	1094.94	664.43	0.00	0.00	0.00	233.30	784.91	1584.40	1950.52	12970.38	76.57%
Roof PV panels outputs (kW h/month)	240.40	467.12	919.77	1276.62	1731.83	1713.42	1670.23	1546.69	1005.79	614.02	292.41	164.59	11642.89	
Four wind turbines outputs (kW h/month)	432.44	308.84	432.32	273.20	229.76	192.48	154.80	156.00	239.28	301.48	372.88	408.88	3502.36	
Renewable final output (kW h/month)	538.27	620.77	1081.67	1239.86	1569.27	1524.72	1460.02	1362.15	996.06	732.40	532.23	458.77	12116.20	
Heat generation (COP=1.8)	968.89	1117.39	1947.01	2231.75	2824.69	2744.49	2628.04	2451.87	1792.90	1318.32	958.02	825.79	21809.15	
Excess heat (kW h/month)	-1444.54	-1176.84	-3.20	1136.81	2160.26	2744.49	2628.04	2451.87	1559.60	533.41	-626.38	-1124.73	8838.78	
Feasibility of monthly self-heating	×	×	×	✓	✓	✓	✓	✓	✓	✓	×	×	✓	
Hot water supply				★	★	★	★	★	★	★				

Table D.25 Scenario 17 simulation in bungalow property

Scenario 18 simulation in different property types with 101 m^2 to 150 m^2 floor area, 3 occupants and built post 1999 in North West region

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total	Energy saving
Monthly heating demand (kW h/month)	1437.32	1366.33	1161.45	652.09	395.70	0.00	0.00	0.00	138.94	467.46	943.59	1161.63	7724.51	71.58%
Roof PV panels outputs (kW h/month)	120.20	233.56	459.89	638.31	865.92	856.71	835.11	773.34	502.89	307.01	146.21	82.29	5821.44	
Two wind turbines outputs (kW h/month)	216.22	154.42	216.16	136.60	114.88	96.24	77.40	78.00	119.64	150.74	186.44	204.44	1751.18	
Renewable final output (kW h/month)	269.14	310.39	540.84	619.93	784.64	762.36	730.01	681.07	498.03	366.20	266.12	229.39	6058.10	
Heat generation (**COP**=1.8)	484.44	558.69	973.51	1115.87	1412.34	1372.25	1314.02	1225.93	896.45	659.16	479.01	412.90	10904.58	
Excess heat (kW h/month)	-952.87	-807.64	-187.94	463.78	1016.65	1372.25	1314.02	1225.93	757.51	191.70	-464.58	-748.74	3180.07	
Feasibility of monthly self-heating	×	×	×	✓	✓	✓	✓	✓	✓	✓	×	×	✓	
Hot water supply				★	★	★	★	★	★	★				

Table D.26 Scenario 18 simulation in mid-terraced property

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total	Energy saving
Monthly heating demand (kW h/month)	1533.91	1458.15	1239.50	695.91	422.29	0.00	0.00	0.00	148.28	498.87	1007.00	1239.70	8243.59	69.93%
Roof PV panels outputs (kW h/month)	120.20	233.56	459.89	638.31	865.92	856.71	835.11	773.34	502.89	307.01	146.21	82.29	5821.44	
Two wind turbines outputs (kW h/month)	216.22	154.42	216.16	136.60	114.88	96.24	77.40	78.00	119.64	150.74	186.44	204.44	1751.18	
Renewable final output (kW h/month)	269.14	310.39	540.84	619.93	784.64	762.36	730.01	681.07	498.03	366.20	266.12	229.39	6058.10	
Heat generation (**COP**=1.8)	484.44	558.69	973.51	1115.87	1412.34	1372.25	1314.02	1225.93	896.45	659.16	479.01	412.90	10904.58	
Excess heat (kW h/month)	-1049.46	-899.45	-265.99	419.96	990.06	1372.25	1314.02	1225.93	748.17	160.29	-527.99	-826.80	2660.98	
Feasibility of monthly self-heating	×	×	×	✓	✓	✓	✓	✓	✓	✓	×	×	✓	
Hot water supply				★	★	★	★	★	★	★				

Table D.27 Scenario 18 simulation in end-terraced property

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total	Energy saving
Monthly heating demand (kW h/month)	1662.55	1580.43	1343.45	754.27	457.70	0.00	0.00	0.00	160.71	540.71	1091.45	1343.66	8934.94	68.03%
Roof PV panels outputs (kW h/month)	120.20	233.56	459.89	638.31	865.92	856.71	835.11	773.34	502.89	307.01	146.21	82.29	5821.44	
Two wind turbines outputs (kW h/month)	216.22	154.42	216.16	136.60	114.88	96.24	77.40	78.00	119.64	150.74	186.44	204.44	1751.18	
Renewable final output (kW h/month)	269.14	310.39	540.84	619.93	784.64	762.36	730.01	681.07	498.03	366.20	266.12	229.39	6058.10	
Heat generation (**COP**=1.8)	484.44	558.69	973.51	1115.87	1412.34	1372.25	1314.02	1225.93	896.45	659.16	479.01	412.90	10904.58	
Excess heat (kW h/month)	-1178.10	-1021.74	-369.94	361.60	954.64	1372.25	1314.02	1225.93	735.74	118.45	-612.44	-930.77	1969.64	
Feasibility of monthly self-heating	×	×	×	✓	✓	✓	✓	✓	✓	✓	×	×	✓	
Hot water supply				★	★	★	★	★	★	★				

Table D.28 Scenario 18 simulation in semi-detached property

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total	Energy saving
Monthly heating demand (kW h/month)	1801.97	1712.97	1456.11	817.52	496.09	0.00	0.00	0.00	174.19	586.05	1182.98	1456.34	9684.21	66.28%
Roof PV panels outputs (kW h/month)	120.20	233.56	459.89	638.31	865.92	856.71	835.11	773.34	502.89	307.01	146.21	82.29	5821.44	
Two wind turbines outputs (kW h/month)	216.22	154.42	216.16	136.60	114.88	96.24	77.40	78.00	119.64	150.74	186.44	204.44	1751.18	
Renewable final output (kW h/month)	269.14	310.39	540.84	619.93	784.64	762.36	730.01	681.07	498.03	366.20	266.12	229.39	6058.10	
Heat generation (**COP**=1.8)	484.44	558.69	973.51	1115.87	1412.34	1372.25	1314.02	1225.93	896.45	659.16	479.01	412.90	10904.58	
Excess heat (kW h/month)	-1317.52	-1154.27	-482.61	298.35	916.26	1372.25	1314.02	1225.93	722.26	73.11	-703.97	-1043.45	1220.36	
Feasibility of monthly self-heating	×	×	×	✓	✓	✓	✓	✓	✓	✓	×	×	✓	
Hot water supply				★	★	★	★	★	★	★				

Table D.29 Scenario 18 simulation in detached property

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total	Energy saving
Monthly heating demand (kW h/month)	1877.14	1784.43	1516.85	851.63	516.78	0.00	0.00	0.00	181.46	610.50	1232.33	1517.09	10088.20	82.51%
Roof PV panels outputs (kW h/month)	240.40	467.12	919.77	1276.62	1731.83	1713.42	1670.23	1546.69	1005.79	614.02	292.41	164.59	11642.89	
Four wind turbines outputs (kW h/month)	432.44	308.84	432.32	273.20	229.76	192.48	154.80	156.00	239.28	301.48	372.88	408.88	3502.36	
Renewable final output (kW h/month)	538.27	620.77	1081.67	1239.86	1569.27	1524.72	1460.02	1362.15	996.06	732.40	532.23	458.77	12116.20	
Heat generation (**COP**=1.8)	968.89	1117.39	1947.01	2231.75	2824.69	2744.49	2628.04	2451.87	1792.90	1318.32	958.02	825.79	21809.15	
Excess heat (kW h/month)	-908.25	-667.04	430.16	1380.12	2307.91	2744.49	2628.04	2451.87	1611.44	707.82	-274.31	-691.30	11720.95	
Feasibility of monthly self-heating	×	×	✓	✓	✓	✓	✓	✓	✓	✓	×	×	✓	
Hot water supply			★	★	★	★	★	★	★	★				

Table D.30 Scenario 18 simulation in bungalow property

Scenario 19 simulation in different property types with $51\,m^2$ to $100\,m^2$ floor area, 2 occupants and built pre-1919 in North West region

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total	Energy saving
Monthly heating demand (kW h/month)	1165.95	1108.36	942.17	528.97	320.99	0.00	0.00	0.00	112.71	379.20	765.44	942.32	6266.10	64.32%
Roof PV panels outputs (kW h/month)	80.13	155.71	306.59	425.54	577.28	571.14	556.74	515.56	335.26	204.67	97.47	54.86	3880.96	
One wind turbine output (kW h/month)	108.11	77.21	108.08	68.30	57.44	48.12	38.70	39.00	59.82	75.37	93.22	102.22	875.59	
Renewable final output (kW h/month)	150.59	186.33	331.74	395.07	507.77	495.41	476.35	443.65	316.07	224.03	152.55	125.67	3805.24	
Heat generation (COP=1.8)	271.07	335.40	597.13	711.13	913.99	891.73	857.44	798.57	568.92	403.26	274.59	226.20	6849.43	
Excess heat (kW h/month)	-894.88	-772.96	-345.04	182.16	593.00	891.73	857.44	798.57	456.21	24.06	-490.84	-716.12	583.33	
Feasibility of monthly self-heating	×	×	×	✓	✓	✓	✓	✓	✓	✓	×	×	✓	
Hot water supply				★	★	★	★	★	★					

Table D.31 Scenario 19 simulation in mid-terraced property

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total	Energy saving
Monthly heating demand (kW h/month)	1281.38	1218.09	1035.44	581.34	352.77	0.00	0.00	0.00	123.87	416.74	841.22	1035.60	6886.45	62.48%
Roof PV panels outputs (kW h/month)	80.13	155.71	306.59	425.54	577.28	571.14	556.74	515.56	335.26	204.67	97.47	54.86	3880.96	
One wind turbine output (kW h/month)	108.11	77.21	108.08	68.30	57.44	48.12	38.70	39.00	59.82	75.37	93.22	102.22	875.59	
Renewable final output (kW h/month)	150.59	186.33	331.74	395.07	507.77	495.41	476.35	443.65	316.07	224.03	152.55	125.67	3805.24	
Heat generation (COP=1.8)	271.07	335.40	597.13	711.13	913.99	891.73	857.44	798.57	568.92	403.26	274.59	226.20	6849.43	
Excess heat (kW h/month)	-1010.31	-882.69	-438.32	129.79	561.22	891.73	857.44	798.57	445.05	-13.48	-566.62	-809.41	-37.01	
Feasibility of monthly self-heating	×	×	×	✓	✓	✓	✓	✓	✓	×	×	×	×	
Hot water supply				★	★	★	★	★	★					

Table D.32 Scenario 19 simulation in end-terraced property

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total	Energy saving
Monthly heating demand (kW h/month)	1396.81	1327.82	1128.72	633.71	384.55	0.00	0.00	0.00	135.02	454.28	916.99	1128.89	7506.79	60.72%
Roof PV panels outputs (kW h/month)	80.13	155.71	306.59	425.54	577.28	571.14	556.74	515.56	335.26	204.67	97.47	54.86	3880.96	
One wind turbine output (kW h/month)	108.11	77.21	108.08	68.30	57.44	48.12	38.70	39.00	59.82	75.37	93.22	102.22	875.59	
Renewable final output (kW h/month)	150.59	186.33	331.74	395.07	507.77	495.41	476.35	443.65	316.07	224.03	152.55	125.67	3805.24	
Heat generation (COP=1.8)	271.07	335.40	597.13	711.13	913.99	891.73	857.44	798.57	568.92	403.26	274.59	226.20	6849.43	
Excess heat (kW h/month)	-1125.74	-992.42	-531.59	77.42	529.45	891.73	857.44	798.57	433.89	-51.02	-642.40	-902.70	-657.36	
Feasibility of monthly self-heating	×	×	×	✓	✓	✓	✓	✓	✓	×	×	×	×	
Hot water supply				★	★	★	★	★	★					

Table D.33 Scenario 19 simulation in semi-detached property

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total	Energy saving
Monthly heating demand (kW h/month)	1546.87	1470.47	1249.97	701.79	425.86	0.00	0.00	0.00	149.53	503.08	1015.51	1250.17	8313.24	58.83%
Roof PV panels outputs (kW h/month)	80.13	155.71	306.59	425.54	577.28	571.14	556.74	515.56	335.26	204.67	97.47	54.86	3880.96	
One wind turbine output (kW h/month)	108.11	77.21	108.08	68.30	57.44	48.12	38.70	39.00	59.82	75.37	93.22	102.22	875.59	
Renewable final output (kW h/month)	150.59	186.33	331.74	395.07	507.77	495.41	476.35	443.65	316.07	224.03	152.55	125.67	3805.24	
Heat generation (COP=1.8)	271.07	335.40	597.13	711.13	913.99	891.73	857.44	798.57	568.92	403.26	274.59	226.20	6849.43	
Excess heat (kW h/month)	-1275.80	-1135.06	-652.85	9.34	488.13	891.73	857.44	798.57	419.39	-99.82	-740.91	-1023.97	-1463.81	
Feasibility of monthly self-heating	×	×	×	✓	✓	✓	✓	✓	✓	×	×	×	×	
Hot water supply					★	★	★	★	★					

Table D.34 Scenario 19 simulation in detached property

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total	Energy saving
Monthly heating demand (kW h/month)	1373.72	1305.87	1110.06	623.24	378.19	0.00	0.00	0.00	132.79	446.77	901.84	1110.24	7382.72	76.70%
Roof PV panels outputs (kW h/month)	160.27	311.42	613.18	851.08	1154.55	1142.28	1113.49	1031.12	670.53	409.35	194.94	109.72	7761.92	
Two wind turbines outputs (kW h/month)	216.22	154.42	216.16	136.60	114.88	96.24	77.40	78.00	119.64	150.74	186.44	204.44	1751.18	
Renewable final output (kW h/month)	301.19	372.67	663.47	790.15	1015.55	990.81	952.71	887.30	632.13	448.07	305.10	251.33	7610.48	
Heat generation (COP=1.8)	542.14	670.80	1194.25	1422.26	1827.98	1783.47	1714.88	1597.14	1137.84	806.53	549.19	452.40	13698.87	
Excess heat (kW h/month)	-831.58	-635.07	84.19	799.03	1449.79	1783.47	1714.88	1597.14	1005.05	359.75	-352.65	-657.84	6316.14	
Feasibility of monthly self-heating	×	×	✓	✓	✓	✓	✓	✓	✓	✓	×	×	✓	
Hot water supply			★	★	★	★	★	★	★	★				

Table D.35 Scenario 19 simulation in bungalow property

Scenario 20 simulation in different property types with 51 m^2 to 100 m^2 floor area, 2 occupants and built 1919-44 in North West region

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total	Energy saving
Monthly heating demand (kW h/month)	1323.47	1258.10	1069.45	600.44	364.36	0.00	0.00	0.00	127.94	430.43	868.85	1069.62	7112.66	61.80%
Roof PV panels outputs (kW h/month)	80.13	155.71	306.59	425.54	577.28	571.14	556.74	515.56	335.26	204.67	97.47	54.86	3880.96	
One wind turbine output (kW h/month)	108.11	77.21	108.08	68.30	57.44	48.12	38.70	39.00	59.82	75.37	93.22	102.22	875.59	
Renewable final output (kW h/month)	150.59	186.33	331.74	395.07	507.77	495.41	476.35	443.65	316.07	224.03	152.55	125.67	3805.24	
Heat generation (COP=1.8)	271.07	335.40	597.13	711.13	913.99	891.73	857.44	798.57	568.92	403.26	274.59	226.20	6849.43	
Excess heat (kW h/month)	-1052.40	-922.70	-472.33	110.69	549.64	891.73	857.44	798.57	440.98	-27.17	-594.25	-843.42	-263.22	
Feasibility of monthly self-heating	×	×	×	✓	✓	✓	✓	✓	✓	×	×	×	×	
Hot water supply				★	★	★	★	★	★					

Table D.36 Scenario 20 simulation in mid-terraced property

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total	Energy saving
Monthly heating demand (kW h/month)	1454.49	1382.66	1175.33	659.88	400.43	0.00	0.00	0.00	140.60	473.04	954.86	1175.52	7816.81	59.95%
Roof PV panels outputs (kW h/month)	80.13	155.71	306.59	425.54	577.28	571.14	556.74	515.56	335.26	204.67	97.47	54.86	3880.96	
One wind turbine output (kW h/month)	108.11	77.21	108.08	68.30	57.44	48.12	38.70	39.00	59.82	75.37	93.22	102.22	875.59	
Renewable final output (kW h/month)	150.59	186.33	331.74	395.07	507.77	495.41	476.35	443.65	316.07	224.03	152.55	125.67	3805.24	
Heat generation (COP=1.8)	271.07	335.40	597.13	711.13	913.99	891.73	857.44	798.57	568.92	403.26	274.59	226.20	6849.43	
Excess heat (kW h/month)	-1183.42	-1047.25	-578.20	51.25	513.57	891.73	857.44	798.57	428.32	-69.78	-680.27	-949.32	-967.37	
Feasibility of monthly self-heating	×	×	×	✓	✓	✓	✓	✓	✓	×	×	×	×	
Hot water supply				★	★	★	★	★	★					

Table D.37 Scenario 20 simulation in end-terraced property

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total	Energy saving
Monthly heating demand (kWh/month)	1585.52	1507.21	1281.21	719.32	436.50	0.00	0.00	0.00	153.27	515.65	1040.88	1281.41	8520.96	58.33%
Roof PV panels outputs (kWh/month)	80.13	155.71	306.59	425.54	577.28	571.14	556.74	515.56	335.26	204.67	97.47	54.86	3880.96	
One wind turbine output (kWh/month)	108.11	77.21	108.08	68.30	57.44	48.12	38.70	39.00	59.82	75.37	93.22	102.22	875.59	
Renewable final output (kWh/month)	150.59	186.33	331.74	395.07	507.77	495.41	476.35	443.65	316.07	224.03	152.55	125.67	3805.24	
Heat generation (**COP**=1.8)	271.07	335.40	597.13	711.13	913.99	891.73	857.44	798.57	568.92	403.26	274.59	226.20	6849.43	
Excess heat (kWh/month)	-1314.45	-1171.81	-684.08	-8.19	477.49	891.73	857.44	798.57	415.65	-112.39	-766.29	-1055.21	-1671.53	
Feasibility of monthly self-heating	×	×	×	×	✓	✓	✓	✓	✓	×	×	×	×	
Hot water supply					★	★	★	★	★					

Table D.38 Scenario 20 simulation in semi-detached property

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total	Energy saving
Monthly heating demand (kWh/month)	1755.85	1669.13	1418.84	796.60	483.39	0.00	0.00	0.00	169.73	571.05	1152.70	1419.07	9436.36	56.11%
Roof PV panels outputs (kWh/month)	80.13	155.71	306.59	425.54	577.28	571.14	556.74	515.56	335.26	204.67	97.47	54.86	3880.96	
One wind turbine output (kWh/month)	108.11	77.21	108.08	68.30	57.44	48.12	38.70	39.00	59.82	75.37	93.22	102.22	875.59	
Renewable final output (kWh/month)	150.59	186.33	331.74	395.07	507.77	495.41	476.35	443.65	316.07	224.03	152.55	125.67	3805.24	
Heat generation (**COP**=1.8)	271.07	335.40	597.13	711.13	913.99	891.73	857.44	798.57	568.92	403.26	274.59	226.20	6849.43	
Excess heat (kWh/month)	-1484.78	-1333.73	-821.72	-85.47	430.60	891.73	857.44	798.57	399.19	-167.79	-878.11	-1192.87	-2586.93	
Feasibility of monthly self-heating	×	×	×	×	✓	✓	✓	✓	✓	×	×	×	×	
Hot water supply					★	★	★	★	★					

Table D.39 Scenario 20 simulation in detached property

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total	Energy saving
Monthly heating demand (kWh/month)	1559.31	1482.30	1260.03	707.44	429.28	0.00	0.00	0.00	150.73	507.13	1023.68	1260.23	8380.13	73.67%
Roof PV panels outputs (kWh/month)	160.27	311.42	613.18	851.08	1154.55	1142.28	1113.49	1031.12	670.53	409.35	194.94	109.72	7761.92	
Two wind turbines outputs (kWh/month)	216.22	154.42	216.16	136.60	114.88	96.24	77.40	78.00	119.64	150.74	186.44	204.44	1751.18	
Renewable final output (kWh/month)	301.19	372.67	663.47	790.15	1015.55	990.81	952.71	887.30	632.13	448.07	305.10	251.33	7610.48	
Heat generation (**COP**=1.8)	542.14	670.80	1194.25	1422.26	1827.98	1783.47	1714.88	1597.14	1137.84	806.53	549.19	452.40	13698.87	
Excess heat (kWh/month)	-1017.17	-811.49	-65.78	714.83	1398.70	1783.47	1714.88	1597.14	987.11	299.39	-474.49	-807.83	5318.74	
Feasibility of monthly self-heating	×	×	×	✓	✓	✓	✓	✓	✓	✓	×	×	✓	
Hot water supply				★	★	★	★	★	★	★				

Table D.40 Scenario 20 simulation in bungalow property

Scenario 21 simulation in different property types with $51\,\mathrm{m}^2$ to $100\,\mathrm{m}^2$ floor area, 2 occupants and built post 1999 in North West region

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total	Energy saving
Monthly heating demand (kW h/month)	924.37	878.71	746.95	419.37	254.48	0.00	0.00	0.00	89.36	300.63	606.84	747.07	4967.77	69.25%
Roof PV panels outputs (kW h/month)	80.13	155.71	306.59	425.54	577.28	571.14	556.74	515.56	335.26	204.67	97.47	54.86	3880.96	
One wind turbine output (kW h/month)	108.11	77.21	108.08	68.30	57.44	48.12	38.70	39.00	59.82	75.37	93.22	102.22	875.59	
Renewable final output (kW h/month)	150.59	186.33	331.74	395.07	507.77	495.41	476.35	443.65	316.07	224.03	152.55	125.67	3805.24	
Heat generation (**COP**=1.8)	271.07	335.40	597.13	711.13	913.99	891.73	857.44	798.57	568.92	403.26	274.59	226.20	6849.43	
Excess heat (kW h/month)	-653.30	-543.31	-149.82	291.76	659.51	891.73	857.44	798.57	479.56	102.63	-332.24	-520.87	1881.67	
Feasibility of monthly self-heating	×	×	×	✓	✓	✓	✓	✓	✓	✓	×	×	✓	
Hot water supply				★	★	★	★	★	★	★				

Table D.41 Scenario 21 simulation in mid-terraced property

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total	Energy saving
Monthly heating demand (kW h/month)	1015.88	965.70	820.90	460.89	279.67	0.00	0.00	0.00	98.20	330.39	666.92	821.03	5459.58	67.11%
Roof PV panels outputs (kW h/month)	80.13	155.71	306.59	425.54	577.28	571.14	556.74	515.56	335.26	204.67	97.47	54.86	3880.96	
One wind turbine output (kW h/month)	108.11	77.21	108.08	68.30	57.44	48.12	38.70	39.00	59.82	75.37	93.22	102.22	875.59	
Renewable final output (kW h/month)	150.59	186.33	331.74	395.07	507.77	495.41	476.35	443.65	316.07	224.03	152.55	125.67	3805.24	
Heat generation (**COP**=1.8)	271.07	335.40	597.13	711.13	913.99	891.73	857.44	798.57	568.92	403.26	274.59	226.20	6849.43	
Excess heat (kW h/month)	-744.81	-630.30	-223.77	250.24	634.32	891.73	857.44	798.57	470.72	72.87	-392.32	-594.83	1389.86	
Feasibility of monthly self-heating	×	×	×	✓	✓	✓	✓	✓	✓	✓	×	×	✓	
Hot water supply				★	★	★	★	★	★	★				

Table D.42 Scenario 21 simulation in end-terraced property

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total	Energy saving
Monthly heating demand (kW h/month)	1107.39	1052.70	894.85	502.41	304.87	0.00	0.00	0.00	107.05	360.15	726.99	894.99	5951.39	65.31%
Roof PV panels outputs (kW h/month)	80.13	155.71	306.59	425.54	577.28	571.14	556.74	515.56	335.26	204.67	97.47	54.86	3880.96	
One wind turbine output (kW h/month)	108.11	77.21	108.08	68.30	57.44	48.12	38.70	39.00	59.82	75.37	93.22	102.22	875.59	
Renewable final output (kW h/month)	150.59	186.33	331.74	395.07	507.77	495.41	476.35	443.65	316.07	224.03	152.55	125.67	3805.24	
Heat generation (COP=1.8)	271.07	335.40	597.13	711.13	913.99	891.73	857.44	798.57	568.92	403.26	274.59	226.20	6849.43	
Excess heat (kW h/month)	-836.32	-717.29	-297.72	208.73	609.12	891.73	857.44	798.57	461.87	43.11	-452.40	-668.79	898.05	
Feasibility of monthly self-heating	×	×	×	✓	✓	✓	✓	✓	✓	✓	×	×	✓	
Hot water supply				★	★	★	★	★	★	★				

Table D.43 Scenario 21 simulation in semi-detached property

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total	Energy saving
Monthly heating demand (kW h/month)	1226.36	1165.79	990.98	556.38	337.62	0.00	0.00	0.00	118.55	398.84	805.09	991.13	6590.74	63.39%
Roof PV panels outputs (kW h/month)	80.13	155.71	306.59	425.54	577.28	571.14	556.74	515.56	335.26	204.67	97.47	54.86	3880.96	
One wind turbine output (kW h/month)	108.11	77.21	108.08	68.30	57.44	48.12	38.70	39.00	59.82	75.37	93.22	102.22	875.59	
Renewable final output (kW h/month)	150.59	186.33	331.74	395.07	507.77	495.41	476.35	443.65	316.07	224.03	152.55	125.67	3805.24	
Heat generation (COP=1.8)	271.07	335.40	597.13	711.13	913.99	891.73	857.44	798.57	568.92	403.26	274.59	226.20	6849.43	
Excess heat (kW h/month)	-955.29	-830.38	-393.85	154.75	576.37	891.73	857.44	798.57	450.37	4.42	-530.50	-764.94	258.70	
Feasibility of monthly self-heating	×	×	×	✓	✓	✓	✓	✓	✓	✓	×	×	✓	
Hot water supply				★	★	★	★	★	★					

Table D.44 Scenario 21 simulation in detached property

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total	Energy saving
Monthly heating demand (kW h/month)	1089.09	1035.30	880.06	494.10	299.83	0.00	0.00	0.00	105.28	354.20	714.98	880.20	5853.02	82.14%
Roof PV panels outputs (kW h/month)	160.27	311.42	613.18	851.08	1154.55	1142.28	1113.49	1031.12	670.53	409.35	194.94	109.72	7761.92	
Two wind turbines outputs (kW h/month)	216.22	154.42	216.16	136.60	114.88	96.24	77.40	78.00	119.64	150.74	186.44	204.44	1751.18	
Renewable final output (kW h/month)	301.19	372.67	663.47	790.15	1015.55	990.81	952.71	887.30	632.13	448.07	305.10	251.33	7610.48	
Heat generation (COP=1.8)	542.14	670.80	1194.25	1422.26	1827.98	1783.47	1714.88	1597.14	1137.84	806.53	549.19	452.40	13698.87	
Excess heat (kW h/month)	-546.95	-364.49	314.19	928.16	1528.15	1783.47	1714.88	1597.14	1032.56	452.32	-165.79	-427.80	7845.85	
Feasibility of monthly self-heating	×	×	✓	✓	✓	✓	✓	✓	✓	✓	×	×	✓	
Hot water supply			★	★	★	★	★	★	★	★				

Table D.45 Scenario 21 simulation in bungalow property

Scenario 22 simulation in different property types with $50\,\mathrm{m}^2$ or less floor area, 1 occupant and built pre-1919 in North West region

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total	Energy saving
Monthly heating demand (kW h/month)	641.71	610.02	518.55	291.13	176.67	0.00	0.00	0.00	62.03	208.70	421.28	518.63	3448.72	69.67%
Roof PV panels outputs (kW h/month)	40.07	77.85	153.30	212.77	288.64	285.57	278.37	257.78	167.63	102.34	48.74	27.43	1940.48	
One wind turbine output (kW h/month)	108.11	77.21	108.08	68.30	57.44	48.12	38.70	39.00	59.82	75.37	93.22	102.22	875.59	
Renewable final output (kW h/month)	118.54	124.05	209.10	224.86	276.86	266.95	253.66	237.42	181.96	142.17	113.56	103.72	2252.86	
Heat generation (COP=1.8)	213.37	223.29	376.38	404.74	498.35	480.51	456.58	427.36	327.53	255.90	204.42	186.70	4055.14	
Excess heat (kW h/month)	-428.34	-386.73	-142.17	113.61	321.69	480.51	456.58	427.36	265.50	47.20	-216.86	-331.93	606.42	
Feasibility of monthly self-heating	×	×	×	✓	✓	✓	✓	✓	✓	✓	×	×	✓	
Hot water supply				★	★	★	★	★	★	★				

Table D.46 Scenario 22 simulation in mid-terraced property

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total	Energy saving
Monthly heating demand (kW h/month)	633.50	602.21	511.91	287.41	174.40	0.00	0.00	0.00	61.24	206.03	415.89	511.99	3404.58	69.99%
Roof PV panels outputs (kW h/month)	40.07	77.85	153.30	212.77	288.64	285.57	278.37	257.78	167.63	102.34	48.74	27.43	1940.48	
One wind turbine output (kW h/month)	108.11	77.21	108.08	68.30	57.44	48.12	38.70	39.00	59.82	75.37	93.22	102.22	875.59	
Renewable final output (kW h/month)	118.54	124.05	209.10	224.86	276.86	266.95	253.66	237.42	181.96	142.17	113.56	103.72	2252.86	
Heat generation (COP=1.8)	213.37	223.29	376.38	404.74	498.35	480.51	456.58	427.36	327.53	255.90	204.42	186.70	4055.14	
Excess heat (kW h/month)	-420.12	-378.92	-135.53	117.33	323.95	480.51	456.58	427.36	266.29	49.87	-211.47	-325.29	650.57	
Feasibility of monthly self-heating	×	×	×	✓	✓	✓	✓	✓	✓	✓	×	×	✓	
Hot water supply				★	★	★	★	★	★	★				

Table D.47 Scenario 22 simulation in end-terraced property

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total	Energy saving
Monthly heating demand (kW h/month)	666.42	633.50	538.51	302.34	183.47	0.00	0.00	0.00	64.42	216.74	437.50	538.60	3581.49	87.97%
Roof PV panels outputs (kW h/month)	80.13	155.71	306.59	425.54	577.28	571.14	556.74	515.56	335.26	204.67	97.47	54.86	3880.96	
Two wind turbines outputs (kW h/month)	216.22	154.42	216.16	136.60	114.88	96.24	77.40	78.00	119.64	150.74	186.44	204.44	1751.18	
Renewable final output (kW h/month)	237.08	248.10	418.20	449.71	553.73	533.90	507.31	474.85	363.92	284.33	227.13	207.44	4505.71	
Heat generation (COP=1.8)	426.75	446.58	752.76	809.48	996.71	961.03	913.17	854.73	655.06	511.80	408.83	373.39	8110.28	
Excess heat (kW h/month)	-239.67	-186.92	214.25	507.14	813.24	961.03	913.17	854.73	590.64	295.06	-28.67	-165.20	4528.79	
Feasibility of monthly self-heating	×	×	✓	✓	✓	✓	✓	✓	✓	✓	×	×	✓	
Hot water supply			★	★	★	★	★	★	★	★				

Table D.48 Scenario 22 simulation in bungalow property

Scenario 23 simulation in different property types with 50 m^2 or less floor area, 1 occupant and built post 1999 in North West region

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total	Energy saving
Monthly heating demand (kW h/month)	466.72	443.67	377.14	211.74	128.49	0.00	0.00	0.00	45.12	151.79	306.40	377.20	2508.25	78.77%
Roof PV panels outputs (kW h/month)	40.07	77.85	153.30	212.77	288.64	285.57	278.37	257.78	167.63	102.34	48.74	27.43	1940.48	
One wind turbine output (kW h/month)	108.11	77.21	108.08	68.30	57.44	48.12	38.70	39.00	59.82	75.37	93.22	102.22	875.59	
Renewable final output (kW h/month)	118.54	124.05	209.10	224.86	276.86	266.95	253.66	237.42	181.96	142.17	113.56	103.72	2252.86	
Heat generation (COP=1.8)	213.37	223.29	376.38	404.74	498.35	480.51	456.58	427.36	327.53	255.90	204.42	186.70	4055.14	
Excess heat (kW h/month)	-253.34	-220.37	-0.76	193.00	369.86	480.51	456.58	427.36	282.41	104.11	-101.98	-190.50	1546.89	
Feasibility of monthly self-heating	×	×	×	✓	✓	✓	✓	✓	✓	✓	×	×	✓	
Hot water supply				★	★	★	★	★	★	★				

Table D.49 Scenario 23 simulation in mid-terraced property

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total	Energy saving
Monthly heating demand (kWh/month)	460.74	437.99	372.31	209.03	126.84	0.00	0.00	0.00	44.54	149.85	302.47	372.37	2476.15	79.08%
Roof PV panels outputs (kWh/month)	40.07	77.85	153.30	212.77	288.64	285.57	278.37	257.78	167.63	102.34	48.74	27.43	1940.48	
One wind turbine output (kWh/month)	108.11	77.21	108.08	68.30	57.44	48.12	38.70	39.00	59.82	75.37	93.22	102.22	875.59	
Renewable final output (kWh/month)	118.54	124.05	209.10	224.86	276.86	266.95	253.66	237.42	181.96	142.17	113.56	103.72	2252.86	
Heat generation (COP=1.8)	213.37	223.29	376.38	404.74	498.35	480.51	456.58	427.36	327.53	255.90	204.42	186.70	4055.14	
Excess heat (kWh/month)	-247.37	-214.69	4.07	195.71	371.51	480.51	456.58	427.36	282.99	106.05	-98.06	-185.67	1578.99	
Feasibility of monthly self-heating	×	×	✓	✓	✓	✓	✓	✓	✓	✓	×	×	✓	
Hot water supply				★	★	★	★	★	★	★				

Table D.50 Scenario 23 simulation in end-terraced property

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total	Energy saving
Monthly heating demand (kWh/month)	484.69	460.75	391.66	219.89	133.44	0.00	0.00	0.00	46.85	157.63	318.19	391.72	2604.82	97.59%
Roof PV panels outputs (kWh/month)	80.13	155.71	306.59	425.54	577.28	571.14	556.74	515.56	335.26	204.67	97.47	54.86	3880.96	
Two wind turbines outputs (kWh/month)	216.22	154.42	216.16	136.60	114.88	96.24	77.40	78.00	119.64	150.74	186.44	204.44	1751.18	
Renewable final output (kWh/month)	237.08	248.10	418.20	449.71	553.73	533.90	507.31	474.85	363.92	284.33	227.13	207.44	4505.71	
Heat generation (COP=1.8)	426.75	446.58	752.76	809.48	996.71	961.03	913.17	854.73	655.06	511.80	408.83	373.39	8110.28	
Excess heat (kWh/month)	-57.94	-14.16	361.10	589.59	863.27	961.03	913.17	854.73	608.21	354.16	90.64	-18.33	5505.46	
Feasibility of monthly self-heating	×	×	✓	✓	✓	✓	✓	✓	✓	✓	✓	×	✓	
Hot water supply			★	★	★	★	★	★	★	★	★			

Table D.51 Scenario 23 simulation in bungalow property

Appendix E

Scenario simulation results in Yorkshire & Humber regions

Scenario 24 simulation in different property types with 151 m^2 to 200 m^2 floor area, 4 occupants and built pre-1919 in Yorkshire & Humber regions

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total	Energy saving
Monthly heating demand (kWh/month)	2687.10	2554.38	2171.36	1219.09	739.77	0.00	0.00	0.00	259.75	873.92	1764.06	2171.70	14441.14	64.04%
Roof PV panels outputs (kWh/month)	174.13	338.36	666.23	924.71	1254.44	1241.10	1209.82	1120.33	728.54	444.76	211.81	119.22	8433.45	
Two wind turbines outputs (kWh/month)	267.16	206.40	241.30	146.34	115.28	96.58	84.34	99.48	146.84	193.42	209.56	254.20	2060.90	
Renewable final output (kWh/month)	353.03	435.81	726.02	856.84	1095.78	1070.15	1035.33	975.85	700.30	510.55	337.09	298.73	8395.48	
Heat generation (COP=1.8)	635.46	784.45	1306.84	1542.32	1972.40	1926.26	1863.59	1756.53	1260.54	918.98	606.77	537.72	15111.86	
Excess heat (kWh/month)	-2051.64	-1769.93	-864.51	323.22	1232.63	1926.26	1863.59	1756.53	1000.79	45.06	-1157.29	-1633.98	670.72	
Feasibility of monthly self-heating	×	×	×	✓	✓	✓	✓	✓	✓	✓	×	×	✓	
Hot water supply				★	★	★	★	★	★					

Table E.1 Scenario 24 simulation in mid-terraced property

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total	Energy saving
Monthly heating demand (kWh/month)	2837.04	2696.92	2292.52	1287.12	781.05	0.00	0.00	0.00	274.25	922.68	1862.49	2292.88	15246.95	63.04%
Roof PV panels outputs (kWh/month)	174.13	338.36	666.23	924.71	1254.44	1241.10	1209.82	1120.33	728.54	444.76	211.81	119.22	8433.45	
Two wind turbines outputs (kWh/month)	267.16	206.40	241.30	146.34	115.28	96.58	84.34	99.48	146.84	193.42	209.56	254.20	2060.90	
Renewable final output (kWh/month)	353.03	435.81	726.02	856.84	1095.78	1070.15	1035.33	975.85	700.30	510.55	337.09	298.73	8395.48	
Heat generation (COP=1.8)	635.46	784.45	1306.84	1542.32	1972.40	1926.26	1863.59	1756.53	1260.54	918.98	606.77	537.72	15111.86	
Excess heat (kWh/month)	-2201.58	-1912.47	-985.68	255.20	1191.35	1926.26	1863.59	1756.53	986.30	-3.70	-1255.73	-1755.16	-135.09	
Feasibility of monthly self-heating	×	×	×	✓	✓	✓	✓	✓	✓	×	×	×	×	
Hot water supply				★	★	★	★	★	★					

Table E.2 Scenario 24 simulation in end-terraced property

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total	Energy saving
Monthly heating demand (kW h/month)	3123.48	2969.22	2523.99	1417.08	859.90	0.00	0.00	0.00	301.94	1015.84	2050.54	2524.39	16786.38	61.04%
Roof PV panels outputs (kW h/month)	174.13	338.36	666.23	924.71	1254.44	1241.10	1209.82	1120.33	728.54	444.76	211.81	119.22	8433.45	
Two wind turbines outputs (kW h/month)	267.16	206.40	241.30	146.34	115.28	96.58	84.34	99.48	146.84	193.42	209.56	254.20	2060.90	
Renewable final output (kW h/month)	353.03	435.81	726.02	856.84	1095.78	1070.15	1035.33	975.85	700.30	510.55	337.09	298.73	8395.48	
Heat generation (COP=1.8)	635.46	784.45	1306.84	1542.32	1972.40	1926.26	1863.59	1756.53	1260.54	918.98	606.77	537.72	15111.86	
Excess heat (kW h/month)	-2488.02	-2184.76	-1217.14	125.24	1112.49	1926.26	1863.59	1756.53	958.61	-96.86	-1443.78	-1986.67	-1674.52	
Feasibility of monthly self-heating	×	×	×	✓	✓	✓	✓	✓	✓	×	×	×	×	
Hot water supply				★	★	★	★	★	★					

Table E.3 Scenario 24 simulation in semi-detached property

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total	Energy saving
Monthly heating demand (kW h/month)	2987.25	2839.71	2413.90	1355.27	822.40	0.00	0.00	0.00	288.77	971.54	1961.11	2414.28	16054.21	61.95%
Roof PV panels outputs (kW h/month)	174.13	338.36	666.23	924.71	1254.44	1241.10	1209.82	1120.33	728.54	444.76	211.81	119.22	8433.45	
Two wind turbines outputs (kW h/month)	267.16	206.40	241.30	146.34	115.28	96.58	84.34	99.48	146.84	193.42	209.56	254.20	2060.90	
Renewable final output (kW h/month)	353.03	435.81	726.02	856.84	1095.78	1070.15	1035.33	975.85	700.30	510.55	337.09	298.73	8395.48	
Heat generation (COP=1.8)	635.46	784.45	1306.84	1542.32	1972.40	1926.26	1863.59	1756.53	1260.54	918.98	606.77	537.72	15111.86	
Excess heat (kW h/month)	-2351.79	-2055.26	-1107.06	187.05	1150.00	1926.26	1863.59	1756.53	971.77	-52.55	-1354.34	-1876.56	-942.35	
Feasibility of monthly self-heating	×	×	×	✓	✓	✓	✓	✓	✓	×	×	×	×	
Hot water supply				★	★	★	★	★	★					

Table E.4 Scenario 24 simulation in detached property

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total	Energy saving
Monthly heating demand (kW h/month)	3178.03	3021.07	2568.07	1441.82	874.92	0.00	0.00	0.00	307.21	1033.58	2086.35	2568.47	17079.53	76.72%
Roof PV panels outputs (kW h/month)	348.26	676.72	1332.46	1849.43	2508.88	2482.20	2419.64	2240.66	1457.07	889.52	423.61	238.43	16866.89	
Four wind turbines outputs (kW h/month)	534.32	412.80	482.60	292.68	230.56	193.16	168.68	198.96	293.68	386.84	419.12	508.40	4121.80	
Renewable final output (kW h/month)	706.07	871.61	1452.05	1713.69	2191.55	2140.29	2070.65	1951.70	1400.60	1021.09	674.18	597.47	16790.96	
Heat generation (COP=1.8)	1270.92	1568.90	2613.69	3084.64	3944.79	3852.52	3727.18	3513.06	2521.08	1837.96	1213.53	1075.44	30223.72	
Excess heat (kW h/month)	-1907.11	-1452.17	45.62	1642.81	3069.87	3852.52	3727.18	3513.06	2213.87	804.38	-872.82	-1493.03	13144.19	
Feasibility of monthly self-heating	×	×	✓	✓	✓	✓	✓	✓	✓	✓	×	×	✓	
Hot water supply				★	★	★	★	★	★	★				

Table E.5 Scenario 24 simulation in bungalow property

Scenario 25 simulation in different property types with $151\,\mathrm{m}^2$ to $200\,\mathrm{m}^2$ floor area, 4 occupants and built 1919-44 in Yorkshire & Humber regions

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total	Energy saving
Monthly heating demand (kWh/month)	2945.33	2799.86	2380.03	1336.25	810.86	0.00	0.00	0.00	284.72	957.90	1933.59	2380.40	15828.93	62.24%
Roof PV panels outputs (kWh/month)	174.13	338.36	666.23	924.71	1254.44	1241.10	1209.82	1120.33	728.54	444.76	211.81	119.22	8433.45	
Two wind turbines outputs (kWh/month)	267.16	206.40	241.30	146.34	115.28	96.58	84.34	99.48	146.84	193.42	209.56	254.20	2060.90	
Renewable final output (kWh/month)	353.03	435.81	726.02	856.84	1095.78	1070.15	1035.33	975.85	700.30	510.55	337.09	298.73	8395.48	
Heat generation (COP=1.8)	635.46	784.45	1306.84	1542.32	1972.40	1926.26	1863.59	1756.53	1260.54	918.98	606.77	537.72	15111.86	
Excess heat (kWh/month)	-2309.87	-2015.41	-1073.18	206.07	1161.54	1926.26	1863.59	1756.53	975.83	-38.92	-1326.82	-1842.68	-717.07	
Feasibility of monthly self-heating	×	×	×	✓	✓	✓	✓	✓	✓	×	×	×	×	
Hot water supply				★	★	★	★	★	★					

Table E.6 Scenario 25 simulation in mid-terraced property

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total	Energy saving
Monthly heating demand (kWh/month)	3109.68	2956.09	2512.83	1410.81	856.10	0.00	0.00	0.00	300.60	1011.35	2041.48	2513.23	16712.18	61.13%
Roof PV panels outputs (kWh/month)	174.13	338.36	666.23	924.71	1254.44	1241.10	1209.82	1120.33	728.54	444.76	211.81	119.22	8433.45	
Two wind turbines outputs (kWh/month)	267.16	206.40	241.30	146.34	115.28	96.58	84.34	99.48	146.84	193.42	209.56	254.20	2060.90	
Renewable final output (kWh/month)	353.03	435.81	726.02	856.84	1095.78	1070.15	1035.33	975.85	700.30	510.55	337.09	298.73	8395.48	
Heat generation (COP=1.8)	635.46	784.45	1306.84	1542.32	1972.40	1926.26	1863.59	1756.53	1260.54	918.98	606.77	537.72	15111.86	
Excess heat (kWh/month)	-2474.22	-2171.64	-1205.99	131.51	1116.29	1926.26	1863.59	1756.53	959.94	-92.37	-1434.71	-1975.51	-1600.32	
Feasibility of monthly self-heating	×	×	×	✓	✓	✓	✓	✓	✓	×	×	×	×	
Hot water supply				★	★	★	★	★	★					

Table E.7 Scenario 25 simulation in end-terraced property

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total	Energy saving
Monthly heating demand (kW h/month)	3423.65	3254.56	2766.54	1553.26	942.54	0.00	0.00	0.00	330.95	1113.47	2247.60	2766.98	18399.55	59.26%
Roof PV panels outputs (kW h/month)	174.13	338.36	666.23	924.71	1254.44	1241.10	1209.82	1120.33	728.54	444.76	211.81	119.22	8433.45	
Two wind turbines outputs (kW h/month)	267.16	206.40	241.30	146.34	115.28	96.58	84.34	99.48	146.84	193.42	209.56	254.20	2060.90	
Renewable final output (kW h/month)	353.03	435.81	726.02	856.84	1095.78	1070.15	1035.33	975.85	700.30	510.55	337.09	298.73	8395.48	
Heat generation (COP=1.8)	635.46	784.45	1306.84	1542.32	1972.40	1926.26	1863.59	1756.53	1260.54	918.98	606.77	537.72	15111.86	
Excess heat (kW h/month)	-2788.19	-2470.11	-1459.70	-10.94	1029.85	1926.26	1863.59	1756.53	929.59	-194.48	-1640.83	-2229.26	-3287.69	
Feasibility of monthly self-heating	×	×	×	×	✓	✓	✓	✓	✓	×	×	×	×	
Hot water supply					★	★	★	★	★					

Table E.8 Scenario 25 simulation in semi-detached property

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total	Energy saving
Monthly heating demand (kW h/month)	3274.32	3112.61	2645.87	1485.51	901.43	0.00	0.00	0.00	316.52	1064.90	2149.57	2646.29	17597.02	60.13%
Roof PV panels outputs (kW h/month)	174.13	338.36	666.23	924.71	1254.44	1241.10	1209.82	1120.33	728.54	444.76	211.81	119.22	8433.45	
Two wind turbines outputs (kW h/month)	267.16	206.40	241.30	146.34	115.28	96.58	84.34	99.48	146.84	193.42	209.56	254.20	2060.90	
Renewable final output (kW h/month)	353.03	435.81	726.02	856.84	1095.78	1070.15	1035.33	975.85	700.30	510.55	337.09	298.73	8395.48	
Heat generation (COP=1.8)	635.46	784.45	1306.84	1542.32	1972.40	1926.26	1863.59	1756.53	1260.54	918.98	606.77	537.72	15111.86	
Excess heat (kW h/month)	-2638.86	-2328.15	-1339.03	56.81	1070.96	1926.26	1863.59	1756.53	944.02	-145.92	-1542.80	-2108.57	-2485.16	
Feasibility of monthly self-heating	×	×	×	✓	✓	✓	✓	✓	✓	×	×	×	×	
Hot water supply				★	★	★	★	★	★					

Table E.9 Scenario 25 simulation in detached property

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total	Energy saving
Monthly heating demand (kW h/month)	3483.44	3311.40	2814.86	1580.38	959.00	0.00	0.00	0.00	336.73	1132.91	2286.85	2815.30	18720.88	74.15%
Roof PV panels outputs (kW h/month)	348.26	676.72	1332.46	1849.43	2508.88	2482.20	2419.64	2240.66	1457.07	889.52	423.61	238.43	16866.89	
Four wind turbines outputs (kW h/month)	534.32	412.80	482.60	292.68	230.56	193.16	168.68	198.96	293.68	386.84	419.12	508.40	4121.80	
Renewable final output (kW h/month)	706.07	871.61	1452.05	1713.69	2191.55	2140.29	2070.65	1951.70	1400.60	1021.09	674.18	597.47	16790.96	
Heat generation (COP=1.8)	1270.92	1568.90	2613.69	3084.64	3944.79	3852.52	3727.18	3513.06	2521.08	1837.96	1213.53	1075.44	30223.72	
Excess heat (kW h/month)	-2212.52	-1742.49	-201.17	1504.25	2985.79	3852.52	3727.18	3513.06	2184.35	705.05	-1073.32	-1739.86	11502.84	
Feasibility of monthly self-heating	×	×	×	✓	✓	✓	✓	✓	✓	✓	×	×	✓	
Hot water supply				★	★	★	★	★	★	★				

Table E.10 Scenario 25 simulation in bungalow property

Scenario 26 simulation in different property types with $151\,m^2$ to $200\,m^2$ floor area, 4 occupants and built post 1999 in Yorkshire & Humber regions

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total	Energy saving
Monthly heating demand (kWh/month)	2088.68	1985.52	1687.80	947.60	575.02	0.00	0.00	0.00	201.91	679.30	1371.20	1688.06	11225.10	69.38%
Roof PV panels outputs (kWh/month)	174.13	338.36	666.23	924.71	1254.44	1241.10	1209.82	1120.33	728.54	444.76	211.81	119.22	8433.45	
Two wind turbines outputs (kWh/month)	267.16	206.40	241.30	146.34	115.28	96.58	84.34	99.48	146.84	193.42	209.56	254.20	2060.90	
Renewable final output (kWh/month)	353.03	435.81	726.02	856.84	1095.78	1070.15	1035.33	975.85	700.30	510.55	337.09	298.73	8395.48	
Heat generation (COP=1.8)	635.46	784.45	1306.84	1542.32	1972.40	1926.26	1863.59	1756.53	1260.54	918.98	606.77	537.72	15111.86	
Excess heat (kWh/month)	-1453.22	-1201.07	-380.95	594.72	1397.38	1926.26	1863.59	1756.53	1058.64	239.68	-764.44	-1150.34	3886.76	
Feasibility of monthly self-heating	×	×	×	✓	✓	✓	✓	✓	✓	✓	×	×	✓	
Hot water supply				★	★	★	★	★	★	★				

Table E.11 Scenario 26 simulation in mid-terraced property

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total	Energy saving
Monthly heating demand (kWh/month)	2205.23	2096.32	1781.98	1000.48	607.11	0.00	0.00	0.00	213.17	717.20	1447.72	1782.26	11851.46	68.11%
Roof PV panels outputs (kWh/month)	174.13	338.36	666.23	924.71	1254.44	1241.10	1209.82	1120.33	728.54	444.76	211.81	119.22	8433.45	
Two wind turbines outputs (kWh/month)	267.16	206.40	241.30	146.34	115.28	96.58	84.34	99.48	146.84	193.42	209.56	254.20	2060.90	
Renewable final output (kWh/month)	353.03	435.81	726.02	856.84	1095.78	1070.15	1035.33	975.85	700.30	510.55	337.09	298.73	8395.48	
Heat generation (COP=1.8)	635.46	784.45	1306.84	1542.32	1972.40	1926.26	1863.59	1756.53	1260.54	918.98	606.77	537.72	15111.86	
Excess heat (kWh/month)	-1569.77	-1311.86	-475.13	541.84	1365.29	1926.26	1863.59	1756.53	1047.37	201.78	-840.95	-1244.54	3260.40	
Feasibility of monthly self-heating	×	×	×	✓	✓	✓	✓	✓	✓	✓	×	×	✓	
Hot water supply				★	★	★	★	★	★	★				

Table E.12 Scenario 26 simulation in end-terraced property

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total	Energy saving
Monthly heating demand (kW h/month)	2427.88	2307.97	1961.90	1101.49	668.40	0.00	0.00	0.00	234.70	789.62	1593.89	1962.21	13048.05	66.03%
Roof PV panels outputs (kW h/month)	174.13	338.36	666.23	924.71	1254.44	1241.10	1209.82	1120.33	728.54	444.76	211.81	119.22	8433.45	
Two wind turbines outputs (kW h/month)	267.16	206.40	241.30	146.34	115.28	96.58	84.34	99.48	146.84	193.42	209.56	254.20	2060.90	
Renewable final output (kW h/month)	353.03	435.81	726.02	856.84	1095.78	1070.15	1035.33	975.85	700.30	510.55	337.09	298.73	8395.48	
Heat generation (COP=1.8)	635.46	784.45	1306.84	1542.32	1972.40	1926.26	1863.59	1756.53	1260.54	918.98	606.77	537.72	15111.86	
Excess heat (kW h/month)	-1792.42	-1523.52	-655.05	440.83	1303.99	1926.26	1863.59	1756.53	1025.85	129.37	-987.12	-1424.49	2063.81	
Feasibility of monthly self-heating	×	×	×	✓	✓	✓	✓	✓	✓	✓	×	×	✓	
Hot water supply				★	★	★	★	★	★	★				

Table E.13 Scenario 26 simulation in semi-detached property

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total	Energy saving
Monthly heating demand (kW h/month)	2321.99	2207.31	1876.32	1053.45	639.25	0.00	0.00	0.00	224.46	755.17	1524.37	1876.62	12478.94	66.97%
Roof PV panels outputs (kW h/month)	174.13	338.36	666.23	924.71	1254.44	1241.10	1209.82	1120.33	728.54	444.76	211.81	119.22	8433.45	
Two wind turbines outputs (kW h/month)	267.16	206.40	241.30	146.34	115.28	96.58	84.34	99.48	146.84	193.42	209.56	254.20	2060.90	
Renewable final output (kW h/month)	353.03	435.81	726.02	856.84	1095.78	1070.15	1035.33	975.85	700.30	510.55	337.09	298.73	8395.48	
Heat generation (COP=1.8)	635.46	784.45	1306.84	1542.32	1972.40	1926.26	1863.59	1756.53	1260.54	918.98	606.77	537.72	15111.86	
Excess heat (kW h/month)	-1686.53	-1422.85	-569.48	488.87	1333.15	1926.26	1863.59	1756.53	1036.08	163.81	-917.60	-1338.90	2632.92	
Feasibility of monthly self-heating	×	×	×	✓	✓	✓	✓	✓	✓	✓	×	×	✓	
Hot water supply				★	★	★	★	★	★	★				

Table E.14 Scenario 26 simulation in detached property

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total	Energy saving
Monthly heating demand (kW h/month)	2470.28	2348.28	1996.16	1120.73	680.08	0.00	0.00	0.00	238.79	803.40	1621.72	1996.47	13275.92	82.70%
Roof PV panels outputs (kW h/month)	348.26	676.72	1332.46	1849.43	2508.88	2482.20	2419.64	2240.66	1457.07	889.52	423.61	238.43	16866.89	
Four wind turbines outputs (kW h/month)	534.32	412.80	482.60	292.68	230.56	193.16	168.68	198.96	293.68	386.84	419.12	508.40	4121.80	
Renewable final output (kW h/month)	706.07	871.61	1452.05	1713.69	2191.55	2140.29	2070.65	1951.70	1400.60	1021.09	674.18	597.47	16790.96	
Heat generation (COP=1.8)	1270.92	1568.90	2613.69	3084.64	3944.79	3852.52	3727.18	3513.06	2521.08	1837.96	1213.53	1075.44	30223.72	
Excess heat (kW h/month)	-1199.37	-779.37	617.53	1963.91	3264.72	3852.52	3727.18	3513.06	2282.29	1034.56	-408.19	-921.03	16947.80	
Feasibility of monthly self-heating	×	×	✓	✓	✓	✓	✓	✓	✓	✓	×	×	✓	
Hot water supply			★	★	★	★	★	★	★	★				

Table E.15 Scenario 26 simulation in bungalow property

Scenario 27 simulation in different property types with $101\,m^2$ to $150\,m^2$ floor area, 3 occupants and built pre-1919 in Yorkshire & Humber regions

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total	Energy saving
Monthly heating demand (kWh/month)	1784.59	1696.45	1442.07	809.64	491.30	0.00	0.00	0.00	172.51	580.40	1171.57	1442.29	9590.81	69.52%
Roof PV panels outputs (kWh/month)	130.60	253.77	499.67	693.54	940.83	930.83	907.36	840.25	546.40	333.57	158.85	89.41	6325.09	
Two wind turbines outputs (kWh/month)	267.16	206.40	241.30	146.34	115.28	96.58	84.34	99.48	146.84	193.42	209.56	254.20	2060.90	
Renewable final output (kWh/month)	318.21	368.13	592.78	671.90	844.89	821.93	793.36	751.78	554.59	421.59	294.73	274.89	6708.79	
Heat generation (COP=1.8)	572.77	662.64	1067.00	1209.42	1520.80	1479.47	1428.05	1353.21	998.27	758.87	530.52	494.80	12075.82	
Excess heat (kWh/month)	-1211.81	-1033.80	-375.07	399.78	1029.50	1479.47	1428.05	1353.21	825.76	178.47	-641.05	-947.49	2485.01	
Feasibility of monthly self-heating	×	×	×	✓	✓	✓	✓	✓	✓	✓	×	×	✓	
Hot water supply				★	★	★	★	★	★	★				

Table E.16 Scenario 27 simulation in mid-terraced property

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total	Energy saving
Monthly heating demand (kWh/month)	1904.51	1810.45	1538.97	864.05	524.32	0.00	0.00	0.00	184.10	619.40	1250.30	1539.22	10235.31	68.00%
Roof PV panels outputs (kWh/month)	130.60	253.77	499.67	693.54	940.83	930.83	907.36	840.25	546.40	333.57	158.85	89.41	6325.09	
Two wind turbines outputs (kWh/month)	267.16	206.40	241.30	146.34	115.28	96.58	84.34	99.48	146.84	193.42	209.56	254.20	2060.90	
Renewable final output (kWh/month)	318.21	368.13	592.78	671.90	844.89	821.93	793.36	751.78	554.59	421.59	294.73	274.89	6708.79	
Heat generation (COP=1.8)	572.77	662.64	1067.00	1209.42	1520.80	1479.47	1428.05	1353.21	998.27	758.87	530.52	494.80	12075.82	
Excess heat (kWh/month)	-1331.74	-1147.80	-471.97	345.38	996.48	1479.47	1428.05	1353.21	814.17	139.47	-719.78	-1044.41	1840.51	
Feasibility of monthly self-heating	×	×	×	✓	✓	✓	✓	✓	✓	✓	×	×	✓	
Hot water supply				★	★	★	★	★	★	★				

Table E.17 Scenario 27 simulation in end-terraced property

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total	Energy saving
Monthly heating demand (kW h/month)	2064.23	1962.28	1668.04	936.51	568.29	0.00	0.00	0.00	199.54	671.34	1355.15	1668.30	11093.69	66.26%
Roof PV panels outputs (kW h/month)	130.60	253.77	499.67	693.54	940.83	930.83	907.36	840.25	546.40	333.57	158.85	89.41	6325.09	
Two wind turbines outputs (kW h/month)	267.16	206.40	241.30	146.34	115.28	96.58	84.34	99.48	146.84	193.42	209.56	254.20	2060.90	
Renewable final output (kW h/month)	318.21	368.13	592.78	671.90	844.89	821.93	793.36	751.78	554.59	421.59	294.73	274.89	6708.79	
Heat generation (**COP**=1.8)	572.77	662.64	1067.00	1209.42	1520.80	1479.47	1428.05	1353.21	998.27	758.87	530.52	494.80	12075.82	
Excess heat (kW h/month)	-1491.46	-1299.64	-601.04	272.91	952.51	1479.47	1428.05	1353.21	798.73	87.52	-824.64	-1173.50	982.13	
Feasibility of monthly self-heating	×	×	×	✓	✓	✓	✓	✓	✓	✓	×	×	✓	
Hot water supply				★	★	★	★	★	★	★				

Table E.18 Scenario 27 simulation in semi-detached property

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total	Energy saving
Monthly heating demand (kW h/month)	2237.34	2126.83	1807.92	1015.04	615.95	0.00	0.00	0.00	216.28	727.64	1468.79	1808.20	12023.99	64.65%
Roof PV panels outputs (kW h/month)	130.60	253.77	499.67	693.54	940.83	930.83	907.36	840.25	546.40	333.57	158.85	89.41	6325.09	
Two wind turbines outputs (kW h/month)	267.16	206.40	241.30	146.34	115.28	96.58	84.34	99.48	146.84	193.42	209.56	254.20	2060.90	
Renewable final output (kW h/month)	318.21	368.13	592.78	671.90	844.89	821.93	793.36	751.78	554.59	421.59	294.73	274.89	6708.79	
Heat generation (**COP**=1.8)	572.77	662.64	1067.00	1209.42	1520.80	1479.47	1428.05	1353.21	998.27	758.87	530.52	494.80	12075.82	
Excess heat (kW h/month)	-1664.56	-1464.19	-740.92	194.38	904.85	1479.47	1428.05	1353.21	781.99	31.22	-938.28	-1313.40	51.82	
Feasibility of monthly self-heating	×	×	×	✓	✓	✓	✓	✓	✓	✓	×	×	✓	
Hot water supply				★	★	★	★	★	★					

Table E.19 Scenario 27 simulation in detached property

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total	Energy saving
Monthly heating demand (kW h/month)	2330.67	2215.56	1883.34	1057.39	641.64	0.00	0.00	0.00	225.30	758.00	1530.07	1883.64	12525.59	80.94%
Roof PV panels outputs (kW h/month)	261.20	507.54	999.35	1387.07	1881.66	1861.65	1814.73	1680.50	1092.80	667.14	317.71	178.83	12650.17	
Four wind turbines outputs (kW h/month)	534.32	412.80	482.60	292.68	230.56	193.16	168.68	198.96	293.68	386.84	419.12	508.40	4121.80	
Renewable final output (kW h/month)	636.41	736.27	1185.56	1343.80	1689.78	1643.85	1586.73	1503.57	1109.19	843.19	589.46	549.78	13417.58	
Heat generation (**COP**=1.8)	1145.54	1325.29	2134.00	2418.84	3041.60	2958.93	2856.11	2706.42	1996.54	1517.74	1061.03	989.60	24151.64	
Excess heat (kW h/month)	-1185.13	-890.27	250.66	1361.45	2399.96	2958.93	2856.11	2706.42	1771.24	759.74	-469.03	-894.03	11626.04	
Feasibility of monthly self-heating	×	×	✓	✓	✓	✓	✓	✓	✓	✓	×	×	✓	
Hot water supply			★	★	★	★	★	★	★	★				

Table E.20 Scenario 27 simulation in bungalow property

Scenario 28 simulation in different property types with 101 m^2 to 150 m^2 floor area, 3 occupants and built 1919-44 in Yorkshire & Humber regions

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total	Energy saving
Monthly heating demand (kWh/month)	1931.46	1836.06	1560.75	876.27	531.74	0.00	0.00	0.00	186.71	628.16	1267.99	1561.00	10380.13	67.69%
Roof PV panels outputs (kWh/month)	130.60	253.77	499.67	693.54	940.83	930.83	907.36	840.25	546.40	333.57	158.85	89.41	6325.09	
Two wind turbines outputs (kWh/month)	267.16	206.40	241.30	146.34	115.28	96.58	84.34	99.48	146.84	193.42	209.56	254.20	2060.90	
Renewable final output (kWh/month)	318.21	368.13	592.78	671.90	844.89	821.93	793.36	751.78	554.59	421.59	294.73	274.89	6708.79	
Heat generation (COP=1.8)	572.77	662.64	1067.00	1209.42	1520.80	1479.47	1428.05	1353.21	998.27	758.87	530.52	494.80	12075.82	
Excess heat (kWh/month)	-1358.69	-1173.42	-493.75	333.15	989.06	1479.47	1428.05	1353.21	811.56	130.70	-737.47	-1066.19	1695.69	
Feasibility of monthly self-heating	×	×	×	✓	✓	✓	✓	✓	✓	✓	×	×	✓	
Hot water supply				★	★	★	★	★	★	★				

Table E.21 Scenario 28 simulation in mid-terraced property

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total	Energy saving
Monthly heating demand (kWh/month)	2061.25	1959.45	1665.63	935.16	567.47	0.00	0.00	0.00	199.25	670.38	1353.20	1665.89	11077.67	66.29%
Roof PV panels outputs (kWh/month)	130.60	253.77	499.67	693.54	940.83	930.83	907.36	840.25	546.40	333.57	158.85	89.41	6325.09	
Two wind turbines outputs (kWh/month)	267.16	206.40	241.30	146.34	115.28	96.58	84.34	99.48	146.84	193.42	209.56	254.20	2060.90	
Renewable final output (kWh/month)	318.21	368.13	592.78	671.90	844.89	821.93	793.36	751.78	554.59	421.59	294.73	274.89	6708.79	
Heat generation (COP=1.8)	572.77	662.64	1067.00	1209.42	1520.80	1479.47	1428.05	1353.21	998.27	758.87	530.52	494.80	12075.82	
Excess heat (kWh/month)	-1488.48	-1296.80	-598.63	274.26	953.33	1479.47	1428.05	1353.21	799.01	88.49	-822.68	-1171.09	998.14	
Feasibility of monthly self-heating	×	×	×	✓	✓	✓	✓	✓	✓	✓	×	×	✓	
Hot water supply				★	★	★	★	★	★	★				

Table E.22 Scenario 28 simulation in end-terraced property

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total	Energy saving
Monthly heating demand (kW h/month)	2234.12	2123.77	1805.32	1013.58	615.06	0.00	0.00	0.00	215.96	726.60	1466.68	1805.60	12006.70	64.67%
Roof PV panels outputs (kW h/month)	130.60	253.77	499.67	693.54	940.83	930.83	907.36	840.25	546.40	333.57	158.85	89.41	6325.09	
Two wind turbines outputs (kW h/month)	267.16	206.40	241.30	146.34	115.28	96.58	84.34	99.48	146.84	193.42	209.56	254.20	2060.90	
Renewable final output (kW h/month)	318.21	368.13	592.78	671.90	844.89	821.93	793.36	751.78	554.59	421.59	294.73	274.89	6708.79	
Heat generation (COP=1.8)	572.77	662.64	1067.00	1209.42	1520.80	1479.47	1428.05	1353.21	998.27	758.87	530.52	494.80	12075.82	
Excess heat (kW h/month)	-1661.34	-1461.13	-738.32	195.84	905.74	1479.47	1428.05	1353.21	782.30	32.27	-936.16	-1310.80	69.12	
Feasibility of monthly self-heating	×	×	×	✓	✓	✓	✓	✓	✓	✓	×	×	✓	
Hot water supply				★	★	★	★	★	★					

Table E.23 Scenario 28 simulation in semi-detached property

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total	Energy saving
Monthly heating demand (kW h/month)	2421.47	2301.87	1956.71	1098.58	666.64	0.00	0.00	0.00	234.08	787.53	1589.68	1957.02	13013.57	63.03%
Roof PV panels outputs (kW h/month)	130.60	253.77	499.67	693.54	940.83	930.83	907.36	840.25	546.40	333.57	158.85	89.41	6325.09	
Two wind turbines outputs (kW h/month)	267.16	206.40	241.30	146.34	115.28	96.58	84.34	99.48	146.84	193.42	209.56	254.20	2060.90	
Renewable final output (kW h/month)	318.21	368.13	592.78	671.90	844.89	821.93	793.36	751.78	554.59	421.59	294.73	274.89	6708.79	
Heat generation (COP=1.8)	572.77	662.64	1067.00	1209.42	1520.80	1479.47	1428.05	1353.21	998.27	758.87	530.52	494.80	12075.82	
Excess heat (kW h/month)	-1848.70	-1639.23	-889.71	110.84	854.16	1479.47	1428.05	1353.21	764.19	-28.66	-1059.16	-1462.22	-937.75	
Feasibility of monthly self-heating	×	×	×	✓	✓	✓	✓	✓	✓	×	×	×	×	
Hot water supply				★	★	★	★	★	★					

Table E.24 Scenario 28 simulation in detached property

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total	Energy saving
Monthly heating demand (kW h/month)	2522.48	2397.90	2038.34	1144.41	694.45	0.00	0.00	0.00	243.84	820.38	1655.99	2038.66	13556.45	79.03%
Roof PV panels outputs (kW h/month)	261.20	507.54	999.35	1387.07	1881.66	1861.65	1814.73	1680.50	1092.80	667.14	317.71	178.83	12650.17	
Four wind turbines outputs (kW h/month)	534.32	412.80	482.60	292.68	230.56	193.16	168.68	198.96	293.68	386.84	419.12	508.40	4121.80	
Renewable final output (kW h/month)	636.41	736.27	1185.56	1343.80	1689.78	1643.85	1586.73	1503.57	1109.19	843.19	589.46	549.78	13417.58	
Heat generation (COP=1.8)	1145.54	1325.29	2134.00	2418.84	3041.60	2958.93	2856.11	2706.42	1996.54	1517.74	1061.03	989.60	24151.64	
Excess heat (kW h/month)	-1376.94	-1072.61	95.66	1274.43	2347.15	2958.93	2856.11	2706.42	1752.70	697.35	-594.96	-1049.06	10595.19	
Feasibility of monthly self-heating	×	×	✓	✓	✓	✓	✓	✓	✓	✓	×	×	✓	
Hot water supply			★	★	★	★	★	★	★	★				

Table E.25 Scenario 28 simulation in bungalow property

Scenario 29 simulation in different property types with 101 m^2 to 150 m^2 floor area, 3 occupants and built post 1999 in Yorkshire & Humber regions

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total	Energy saving
Monthly heating demand (kW h/month)	1502.26	1428.07	1213.93	681.55	413.58	0.00	0.00	0.00	145.22	488.58	986.23	1214.12	8073.54	74.05%
Roof PV panels outputs (kW h/month)	130.60	253.77	499.67	693.54	940.83	930.83	907.36	840.25	546.40	333.57	158.85	89.41	6325.09	
Two wind turbines outputs (kW h/month)	267.16	206.40	241.30	146.34	115.28	96.58	84.34	99.48	146.84	193.42	209.56	254.20	2060.90	
Renewable final output (kW h/month)	318.21	368.13	592.78	671.90	844.89	821.93	793.36	751.78	554.59	421.59	294.73	274.89	6708.79	
Heat generation (COP=1.8)	572.77	662.64	1067.00	1209.42	1520.80	1479.47	1428.05	1353.21	998.27	758.87	530.52	494.80	12075.82	
Excess heat (kW h/month)	-929.49	-765.43	-146.93	527.87	1107.22	1479.47	1428.05	1353.21	853.05	270.29	-455.71	-719.32	4002.28	
Feasibility of monthly self-heating	×	×	×	✓	✓	✓	✓	✓	✓	✓	×	×	✓	
Hot water supply				★	★	★	★	★	★	★				

Table E.26 Scenario 29 simulation in mid-terraced property

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total	Energy saving
Monthly heating demand (kW h/month)	1603.22	1524.03	1295.51	727.35	441.37	0.00	0.00	0.00	154.98	521.41	1052.50	1295.71	8616.08	72.25%
Roof PV panels outputs (kW h/month)	130.60	253.77	499.67	693.54	940.83	930.83	907.36	840.25	546.40	333.57	158.85	89.41	6325.09	
Two wind turbines outputs (kW h/month)	267.16	206.40	241.30	146.34	115.28	96.58	84.34	99.48	146.84	193.42	209.56	254.20	2060.90	
Renewable final output (kW h/month)	318.21	368.13	592.78	671.90	844.89	821.93	793.36	751.78	554.59	421.59	294.73	274.89	6708.79	
Heat generation (COP=1.8)	572.77	662.64	1067.00	1209.42	1520.80	1479.47	1428.05	1353.21	998.27	758.87	530.52	494.80	12075.82	
Excess heat (kW h/month)	-1030.44	-861.39	-228.51	482.07	1079.43	1479.47	1428.05	1353.21	843.29	237.46	-521.98	-800.91	3459.74	
Feasibility of monthly self-heating	×	×	×	✓	✓	✓	✓	✓	✓	✓	×	×	✓	
Hot water supply				★	★	★	★	★	★	★				

Table E.27 Scenario 29 simulation in end-terraced property

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total	Energy saving
Monthly heating demand (kW h/month)	1737.67	1651.85	1404.15	788.35	478.39	0.00	0.00	0.00	167.97	565.14	1140.77	1404.38	9338.66	70.17%
Roof PV panels outputs (kW h/month)	130.60	253.77	499.67	693.54	940.83	930.83	907.36	840.25	546.40	333.57	158.85	89.41	6325.09	
Two wind turbines outputs (kW h/month)	267.16	206.40	241.30	146.34	115.28	96.58	84.34	99.48	146.84	193.42	209.56	254.20	2060.90	
Renewable final output (kW h/month)	318.21	368.13	592.78	671.90	844.89	821.93	793.36	751.78	554.59	421.59	294.73	274.89	6708.79	
Heat generation (**COP**=1.8)	572.77	662.64	1067.00	1209.42	1520.80	1479.47	1428.05	1353.21	998.27	758.87	530.52	494.80	12075.82	
Excess heat (kW h/month)	-1164.90	-989.20	-337.15	421.07	1042.41	1479.47	1428.05	1353.21	830.29	193.73	-610.25	-909.57	2737.15	
Feasibility of monthly self-heating	×	×	×	✓	✓	✓	✓	✓	✓	✓	×	×	✓	
Hot water supply				★	★	★	★	★	★	★				

Table E.28 Scenario 29 simulation in semi-detached property

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total	Energy saving
Monthly heating demand (kW h/month)	1883.39	1790.37	1521.91	854.46	518.50	0.00	0.00	0.00	182.06	612.53	1236.43	1522.15	10121.80	68.26%
Roof PV panels outputs (kW h/month)	130.60	253.77	499.67	693.54	940.83	930.83	907.36	840.25	546.40	333.57	158.85	89.41	6325.09	
Two wind turbines outputs (kW h/month)	267.16	206.40	241.30	146.34	115.28	96.58	84.34	99.48	146.84	193.42	209.56	254.20	2060.90	
Renewable final output (kW h/month)	318.21	368.13	592.78	671.90	844.89	821.93	793.36	751.78	554.59	421.59	294.73	274.89	6708.79	
Heat generation (**COP**=1.8)	572.77	662.64	1067.00	1209.42	1520.80	1479.47	1428.05	1353.21	998.27	758.87	530.52	494.80	12075.82	
Excess heat (kW h/month)	-1310.62	-1127.73	-454.91	354.96	1002.30	1479.47	1428.05	1353.21	816.21	146.34	-705.91	-1027.34	1954.02	
Feasibility of monthly self-heating	×	×	×	✓	✓	✓	✓	✓	✓	✓	×	×	✓	
Hot water supply				★	★	★	★	★	★	★				

Table E.29 Scenario 29 simulation in detached property

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total	Energy saving
Monthly heating demand (kW h/month)	1961.96	1865.06	1585.39	890.11	540.13	0.00	0.00	0.00	189.66	638.08	1288.01	1585.65	10544.04	85.65%
Roof PV panels outputs (kW h/month)	261.20	507.54	999.35	1387.07	1881.66	1861.65	1814.73	1680.50	1092.80	667.14	317.71	178.83	12650.17	
Four wind turbines outputs (kW h/month)	534.32	412.80	482.60	292.68	230.56	193.16	168.68	198.96	293.68	386.84	419.12	508.40	4121.80	
Renewable final output (kW h/month)	636.41	736.27	1185.56	1343.80	1689.78	1643.85	1586.73	1503.57	1109.19	843.19	589.46	549.78	13417.58	
Heat generation (**COP**=1.8)	1145.54	1325.29	2134.00	2418.84	3041.60	2958.93	2856.11	2706.42	1996.54	1517.74	1061.03	989.60	24151.64	
Excess heat (kW h/month)	-816.41	-539.77	548.61	1528.73	2501.46	2958.93	2856.11	2706.42	1806.88	879.65	-226.98	-596.04	13607.59	
Feasibility of monthly self-heating	×	×	✓	✓	✓	✓	✓	✓	✓	✓	×	×	✓	
Hot water supply			★	★	★	★	★	★	★	★				

Table E.30 Scenario 29 simulation in bungalow property

Scenario 30 simulation in different property types with $51\,m^2$ to $100\,m^2$ floor area, 2 occupants and built pre-1919 in Yorkshire & Humber regions

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total	Energy saving
Monthly heating demand (kW h/month)	1228.95	1168.25	993.07	557.55	338.33	0.00	0.00	0.00	118.80	399.69	806.79	993.23	6604.67	65.78%
Roof PV panels outputs (kW h/month)	87.07	169.18	333.12	462.36	627.22	620.55	604.91	560.17	364.27	222.38	105.90	59.61	4216.72	
One wind turbine output (kW h/month)	133.58	103.20	120.65	73.17	57.64	48.29	42.17	49.74	73.42	96.71	104.78	127.10	1030.45	
Renewable final output (kW h/month)	176.52	217.90	363.01	428.42	547.89	535.07	517.66	487.92	350.15	255.27	168.55	149.37	4197.74	
Heat generation (COP=1.8)	317.73	392.23	653.42	771.16	986.20	963.13	931.79	878.26	630.27	459.49	303.38	268.86	7555.93	
Excess heat (kW h/month)	-911.22	-776.02	-339.65	213.61	647.87	963.13	931.79	878.26	511.47	59.80	-503.41	-724.37	951.26	
Feasibility of monthly self-heating	×	×	×	✓	✓	✓	✓	✓	✓	✓	×	×	✓	
Hot water supply				★ (blue)	★ (red)	★ (red)	★ (red)	★ (red)	★ (red)	★ (blue)				

Table E.31 Scenario 30 simulation in mid-terraced property

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total	Energy saving
Monthly heating demand (kW h/month)	1350.61	1283.91	1091.39	612.75	371.83	0.00	0.00	0.00	130.56	439.26	886.67	1091.56	7258.53	63.95%
Roof PV panels outputs (kW h/month)	87.07	169.18	333.12	462.36	627.22	620.55	604.91	560.17	364.27	222.38	105.90	59.61	4216.72	
One wind turbine output (kW h/month)	133.58	103.20	120.65	73.17	57.64	48.29	42.17	49.74	73.42	96.71	104.78	127.10	1030.45	
Renewable final output (kW h/month)	176.52	217.90	363.01	428.42	547.89	535.07	517.66	487.92	350.15	255.27	168.55	149.37	4197.74	
Heat generation (COP=1.8)	317.73	392.23	653.42	771.16	986.20	963.13	931.79	878.26	630.27	459.49	303.38	268.86	7555.93	
Excess heat (kW h/month)	-1032.88	-891.68	-437.97	158.41	614.37	963.13	931.79	878.26	499.71	20.23	-583.28	-822.70	297.40	
Feasibility of monthly self-heating	×	×	×	✓	✓	✓	✓	✓	✓	✓	×	×	✓	
Hot water supply				★ (blue)	★ (red)	★ (red)	★ (red)	★ (red)	★ (red)					

Table E.32 Scenario 30 simulation in end-terraced property

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total	Energy saving
Monthly heating demand (kW h/month)	1472.28	1399.56	1189.70	667.95	405.32	0.00	0.00	0.00	142.32	478.83	966.54	1189.89	7912.39	62.25%
Roof PV panels outputs (kW h/month)	87.07	169.18	333.12	462.36	627.22	620.55	604.91	560.17	364.27	222.38	105.90	59.61	4216.72	
One wind turbine output (kW h/month)	133.58	103.20	120.65	73.17	57.64	48.29	42.17	49.74	73.42	96.71	104.78	127.10	1030.45	
Renewable final output (kW h/month)	176.52	217.90	363.01	428.42	547.89	535.07	517.66	487.92	350.15	255.27	168.55	149.37	4197.74	
Heat generation (COP=1.8)	317.73	392.23	653.42	771.16	986.20	963.13	931.79	878.26	630.27	459.49	303.38	268.86	7555.93	
Excess heat (kW h/month)	-1154.55	-1007.34	-536.28	103.21	580.88	963.13	931.79	878.26	487.95	-19.34	-663.16	-921.03	-356.46	
Feasibility of monthly self-heating	×	×	×	✓	✓	✓	✓	✓	✓	×	×	×	×	
Hot water supply				★	★	★	★	★	★					

Table E.33 Scenario 30 simulation in semi-detached property

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total	Energy saving
Monthly heating demand (kW h/month)	1630.44	1549.92	1317.51	739.71	448.87	0.00	0.00	0.00	157.61	530.27	1070.37	1317.72	8762.41	60.21%
Roof PV panels outputs (kW h/month)	87.07	169.18	333.12	462.36	627.22	620.55	604.91	560.17	364.27	222.38	105.90	59.61	4216.72	
One wind turbine output (kW h/month)	133.58	103.20	120.65	73.17	57.64	48.29	42.17	49.74	73.42	96.71	104.78	127.10	1030.45	
Renewable final output (kW h/month)	176.52	217.90	363.01	428.42	547.89	535.07	517.66	487.92	350.15	255.27	168.55	149.37	4197.74	
Heat generation (COP=1.8)	317.73	392.23	653.42	771.16	986.20	963.13	931.79	878.26	630.27	459.49	303.38	268.86	7555.93	
Excess heat (kW h/month)	-1312.71	-1157.69	-664.09	31.45	537.33	963.13	931.79	878.26	472.66	-70.77	-766.99	-1048.86	-1206.48	
Feasibility of monthly self-heating	×	×	×	✓	✓	✓	✓	✓	✓	×	×	×	×	
Hot water supply				★	★	★	★	★	★					

Table E.34 Scenario 30 simulation in detached property

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total	Energy saving
Monthly heating demand (kW h/month)	1447.95	1376.43	1170.04	656.91	398.62	0.00	0.00	0.00	139.97	470.91	950.57	1170.22	7781.62	78.75%
Roof PV panels outputs (kW h/month)	174.13	338.36	666.23	924.71	1254.44	1241.10	1209.82	1120.33	728.54	444.76	211.81	119.22	8433.45	
Two wind turbines outputs (kW h/month)	267.16	206.40	241.30	146.34	115.28	96.58	84.34	99.48	146.84	193.42	209.56	254.20	2060.90	
Renewable final output (kW h/month)	353.03	435.81	726.02	856.84	1095.78	1070.15	1035.33	975.85	700.30	510.55	337.09	298.73	8395.48	
Heat generation (COP=1.8)	635.46	784.45	1306.84	1542.32	1972.40	1926.26	1863.59	1756.53	1260.54	918.98	606.77	537.72	15111.86	
Excess heat (kW h/month)	-812.49	-591.98	136.81	885.41	1573.77	1926.26	1863.59	1756.53	1120.57	448.07	-343.80	-632.50	7330.24	
Feasibility of monthly self-heating	×	×	✓	✓	✓	✓	✓	✓	✓	✓	×	×	✓	
Hot water supply			★	★	★	★	★	★	★	★				

Table E.35 Scenario 30 simulation in bungalow property

Scenario 31 simulation in different property types with 51 m^2 to 100 m^2 floor area, 2 occupants and built 1919-44 in Yorkshire & Humber regions

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total	Energy saving
Monthly heating demand (kW h/month)	1394.98	1326.08	1127.24	632.88	384.04	0.00	0.00	0.00	134.85	453.69	915.79	1127.42	7496.96	63.36%
Roof PV panels outputs (kW h/month)	87.07	169.18	333.12	462.36	627.22	620.55	604.91	560.17	364.27	222.38	105.90	59.61	4216.72	
One wind turbine output (kW h/month)	133.58	103.20	120.65	73.17	57.64	48.29	42.17	49.74	73.42	96.71	104.78	127.10	1030.45	
Renewable final output (kW h/month)	176.52	217.90	363.01	428.42	547.89	535.07	517.66	487.92	350.15	255.27	168.55	149.37	4197.74	
Heat generation (COP=1.8)	317.73	392.23	653.42	771.16	986.20	963.13	931.79	878.26	630.27	459.49	303.38	268.86	7555.93	
Excess heat (kW h/month)	-1077.25	-933.85	-473.82	138.28	602.16	963.13	931.79	878.26	495.42	5.81	-612.41	-858.56	58.97	
Feasibility of monthly self-heating	×	×	×	✓	✓	✓	✓	✓	✓	✓	×	×	✓	
Hot water supply				★	★	★	★	★	★					

Table E.36 Scenario 31 simulation in mid-terraced property

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total	Energy saving
Monthly heating demand (kW h/month)	1533.08	1457.36	1238.83	695.53	422.06	0.00	0.00	0.00	148.20	498.60	1006.46	1239.03	8239.16	61.41%
Roof PV panels outputs (kW h/month)	87.07	169.18	333.12	462.36	627.22	620.55	604.91	560.17	364.27	222.38	105.90	59.61	4216.72	
One wind turbine output (kW h/month)	133.58	103.20	120.65	73.17	57.64	48.29	42.17	49.74	73.42	96.71	104.78	127.10	1030.45	
Renewable final output (kW h/month)	176.52	217.90	363.01	428.42	547.89	535.07	517.66	487.92	350.15	255.27	168.55	149.37	4197.74	
Heat generation (COP=1.8)	317.73	392.23	653.42	771.16	986.20	963.13	931.79	878.26	630.27	459.49	303.38	268.86	7555.93	
Excess heat (kW h/month)	-1215.35	-1065.14	-585.41	75.62	564.14	963.13	931.79	878.26	482.07	-39.11	-703.07	-970.17	-683.23	
Feasibility of monthly self-heating	×	×	×	✓	✓	✓	✓	✓	✓	×	×	×	×	
Hot water supply				★	★	★	★	★	★					

Table E.37 Scenario 31 simulation in end-terraced property

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total	Energy saving
Monthly heating demand (kW h/month)	1671.18	1588.64	1350.43	758.19	460.08	0.00	0.00	0.00	161.55	543.52	1097.12	1350.64	8981.36	59.74%
Roof PV panels outputs (kW h/month)	87.07	169.18	333.12	462.36	627.22	620.55	604.91	560.17	364.27	222.38	105.90	59.61	4216.72	
One wind turbine output (kW h/month)	133.58	103.20	120.65	73.17	57.64	48.29	42.17	49.74	73.42	96.71	104.78	127.10	1030.45	
Renewable final output (kW h/month)	176.52	217.90	363.01	428.42	547.89	535.07	517.66	487.92	350.15	255.27	168.55	149.37	4197.74	
Heat generation (**COP**=1.8)	317.73	392.23	653.42	771.16	986.20	963.13	931.79	878.26	630.27	459.49	303.38	268.86	7555.93	
Excess heat (kW h/month)	-1353.45	-1196.42	-697.01	12.97	526.12	963.13	931.79	878.26	468.72	-84.02	-793.74	-1081.78	-1425.43	
Feasibility of monthly self-heating	×	×	×	✓	✓	✓	✓	✓	✓	×	×	×	×	
Hot water supply					★	★	★	★	★					

Table E.38 Scenario 31 simulation in semi-detached property

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total	Energy saving
Monthly heating demand (kW h/month)	1850.72	1759.31	1495.51	839.64	509.51	0.00	0.00	0.00	178.90	601.90	1214.98	1495.74	9946.21	57.47%
Roof PV panels outputs (kW h/month)	87.07	169.18	333.12	462.36	627.22	620.55	604.91	560.17	364.27	222.38	105.90	59.61	4216.72	
One wind turbine output (kW h/month)	133.58	103.20	120.65	73.17	57.64	48.29	42.17	49.74	73.42	96.71	104.78	127.10	1030.45	
Renewable final output (kW h/month)	176.52	217.90	363.01	428.42	547.89	535.07	517.66	487.92	350.15	255.27	168.55	149.37	4197.74	
Heat generation (**COP**=1.8)	317.73	392.23	653.42	771.16	986.20	963.13	931.79	878.26	630.27	459.49	303.38	268.86	7555.93	
Excess heat (kW h/month)	-1532.99	-1367.09	-842.08	-68.48	476.69	963.13	931.79	878.26	451.37	-142.41	-911.60	-1226.88	-2390.29	
Feasibility of monthly self-heating	×	×	×	×	✓	✓	✓	✓	✓	×	×	×	×	
Hot water supply					★	★	★	★	★					

Table E.39 Scenario 31 simulation in detached property

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total	Energy saving
Monthly heating demand (kW h/month)	1643.56	1562.39	1328.11	745.66	452.48	0.00	0.00	0.00	158.88	534.53	1078.99	1328.32	8832.92	75.86%
Roof PV panels outputs (kW h/month)	174.13	338.36	666.23	924.71	1254.44	1241.10	1209.82	1120.33	728.54	444.76	211.81	119.22	8433.45	
Two wind turbines outputs (kW h/month)	267.16	206.40	241.30	146.34	115.28	96.58	84.34	99.48	146.84	193.42	209.56	254.20	2060.90	
Renewable final output (kW h/month)	353.03	435.81	726.02	856.84	1095.78	1070.15	1035.33	975.85	700.30	510.55	337.09	298.73	8395.48	
Heat generation (**COP**=1.8)	635.46	784.45	1306.84	1542.32	1972.40	1926.26	1863.59	1756.53	1260.54	918.98	606.77	537.72	15111.86	
Excess heat (kW h/month)	-1008.10	-777.94	-21.27	796.66	1519.92	1926.26	1863.59	1756.53	1101.66	384.45	-472.22	-790.60	6278.94	
Feasibility of monthly self-heating	×	×	×	✓	✓	✓	✓	✓	✓	✓	×	×	✓	
Hot water supply				★	★	★	★	★	★	★				

Table E.40 Scenario 31 simulation in bungalow property

Scenario 32 simulation in different property types with 51 m^2 to 100 m^2 floor area, 2 occupants and built post 1999 in Yorkshire & Humber regions

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total	Energy saving
Monthly heating demand (kW h/month)	974.31	926.19	787.31	442.03	268.23	0.00	0.00	0.00	94.18	316.87	639.63	787.43	5236.18	71.10%
Roof PV panels outputs (kW h/month)	87.07	169.18	333.12	462.36	627.22	620.55	604.91	560.17	364.27	222.38	105.90	59.61	4216.72	
One wind turbine output (kW h/month)	133.58	103.20	120.65	73.17	57.64	48.29	42.17	49.74	73.42	96.71	104.78	127.10	1030.45	
Renewable final output (kW h/month)	176.52	217.90	363.01	428.42	547.89	535.07	517.66	487.92	350.15	255.27	168.55	149.37	4197.74	
Heat generation (COP=1.8)	317.73	392.23	653.42	771.16	986.20	963.13	931.79	878.26	630.27	459.49	303.38	268.86	7555.93	
Excess heat (kW h/month)	-656.58	-533.96	-133.89	329.13	717.97	963.13	931.79	878.26	536.09	142.62	-336.24	-518.57	2319.75	
Feasibility of monthly self-heating	×	×	×	✓	✓	✓	✓	✓	✓	✓	×	×	✓	
Hot water supply				★	★	★	★	★	★	★				

Table E.41 Scenario 32 simulation in mid-terraced property

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total	Energy saving
Monthly heating demand (kW h/month)	1070.77	1017.88	865.25	485.79	294.79	0.00	0.00	0.00	103.51	348.24	702.95	865.39	5754.56	68.79%
Roof PV panels outputs (kW h/month)	87.07	169.18	333.12	462.36	627.22	620.55	604.91	560.17	364.27	222.38	105.90	59.61	4216.72	
One wind turbine output (kW h/month)	133.58	103.20	120.65	73.17	57.64	48.29	42.17	49.74	73.42	96.71	104.78	127.10	1030.45	
Renewable final output (kW h/month)	176.52	217.90	363.01	428.42	547.89	535.07	517.66	487.92	350.15	255.27	168.55	149.37	4197.74	
Heat generation (COP=1.8)	317.73	392.23	653.42	771.16	986.20	963.13	931.79	878.26	630.27	459.49	303.38	268.86	7555.93	
Excess heat (kW h/month)	-753.04	-625.66	-211.83	285.37	691.41	963.13	931.79	878.26	526.76	111.25	-399.57	-596.53	1801.37	
Feasibility of monthly self-heating	×	×	×	✓	✓	✓	✓	✓	✓	✓	×	×	✓	
Hot water supply				★	★	★	★	★	★	★				

Table E.42 Scenario 32 simulation in end-terraced property

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total	Energy saving
Monthly heating demand (kW h/month)	1167.22	1109.57	943.20	529.55	321.34	0.00	0.00	0.00	112.83	379.61	766.27	943.34	6272.94	66.86%
Roof PV panels outputs (kW h/month)	87.07	169.18	333.12	462.36	627.22	620.55	604.91	560.17	364.27	222.38	105.90	59.61	4216.72	
One wind turbine output (kW h/month)	133.58	103.20	120.65	73.17	57.64	48.29	42.17	49.74	73.42	96.71	104.78	127.10	1030.45	
Renewable final output (kW h/month)	176.52	217.90	363.01	428.42	547.89	535.07	517.66	487.92	350.15	255.27	168.55	149.37	4197.74	
Heat generation (COP=1.8)	317.73	392.23	653.42	771.16	986.20	963.13	931.79	878.26	630.27	459.49	303.38	268.86	7555.93	
Excess heat (kW h/month)	-849.49	-717.35	-289.77	241.61	664.86	963.13	931.79	878.26	517.44	79.88	-462.89	-674.48	1282.99	
Feasibility of monthly self-heating	×	×	×	✓	✓	✓	✓	✓	✓	✓	×	×	✓	
Hot water supply				★	★	★	★	★	★	★				

Table E.43 Scenario 32 simulation in semi-detached property

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total	Energy saving
Monthly heating demand (kW h/month)	1292.62	1228.77	1044.52	586.44	355.86	0.00	0.00	0.00	124.95	420.39	848.59	1044.69	6946.84	64.78%
Roof PV panels outputs (kW h/month)	87.07	169.18	333.12	462.36	627.22	620.55	604.91	560.17	364.27	222.38	105.90	59.61	4216.72	
One wind turbine output (kW h/month)	133.58	103.20	120.65	73.17	57.64	48.29	42.17	49.74	73.42	96.71	104.78	127.10	1030.45	
Renewable final output (kW h/month)	176.52	217.90	363.01	428.42	547.89	535.07	517.66	487.92	350.15	255.27	168.55	149.37	4197.74	
Heat generation (COP=1.8)	317.73	392.23	653.42	771.16	986.20	963.13	931.79	878.26	630.27	459.49	303.38	268.86	7555.93	
Excess heat (kW h/month)	-974.89	-836.55	-391.10	184.72	630.34	963.13	931.79	878.26	505.32	39.10	-545.21	-775.83	609.09	
Feasibility of monthly self-heating	×	×	×	✓	✓	✓	✓	✓	✓	✓	×	×	✓	
Hot water supply				★	★	★	★	★	★	★				

Table E.44 Scenario 32 simulation in detached property

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total	Energy saving
Monthly heating demand (kW h/month)	1147.93	1091.24	927.61	520.80	316.03	0.00	0.00	0.00	110.97	373.34	753.61	927.75	6169.27	84.73%
Roof PV panels outputs (kW h/month)	174.13	338.36	666.23	924.71	1254.44	1241.10	1209.82	1120.33	728.54	444.76	211.81	119.22	8433.45	
Two wind turbines outputs (kW h/month)	267.16	206.40	241.30	146.34	115.28	96.58	84.34	99.48	146.84	193.42	209.56	254.20	2060.90	
Renewable final output (kW h/month)	353.03	435.81	726.02	856.84	1095.78	1070.15	1035.33	975.85	700.30	510.55	337.09	298.73	8395.48	
Heat generation (COP=1.8)	635.46	784.45	1306.84	1542.32	1972.40	1926.26	1863.59	1756.53	1260.54	918.98	606.77	537.72	15111.86	
Excess heat (kW h/month)	-512.47	-306.78	379.24	1021.52	1656.37	1926.26	1863.59	1756.53	1149.58	545.64	-146.84	-390.03	8942.59	
Feasibility of monthly self-heating	×	×	✓	✓	✓	✓	✓	✓	✓	✓	×	×	✓	
Hot water supply			★	★	★	★	★	★	★	★				

Table E.45 Scenario 32 simulation in bungalow property

Scenario 33 simulation in different property types with $50\,\mathrm{m}^2$ or less floor area, 1 occupant and built pre-1919 in Yorkshire & Humber regions

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total	Energy saving
Monthly heating demand (kWh/month)	685.18	651.34	553.67	310.86	188.63	0.00	0.00	0.00	66.23	222.84	449.82	553.76	3682.34	71.68%
Roof PV panels outputs (kWh/month)	43.53	84.59	166.56	231.18	313.61	310.28	302.45	280.08	182.13	111.19	52.95	29.80	2108.36	
One wind turbine output (kWh/month)	133.58	103.20	120.65	73.17	57.64	48.29	42.17	49.74	73.42	96.71	104.78	127.10	1030.45	
Renewable final output (kWh/month)	141.69	150.23	229.77	243.48	297.00	286.85	275.70	263.86	204.44	166.32	126.19	125.52	2511.05	
Heat generation (**COP**=1.8)	255.04	270.42	413.58	438.26	534.60	516.33	496.26	474.94	368.00	299.38	227.13	225.94	4519.89	
Excess heat (kWh/month)	-430.14	-380.93	-140.10	127.41	345.97	516.33	496.26	474.94	301.76	76.54	-222.68	-327.82	837.55	
Feasibility of monthly self-heating	×	×	×	✓	✓	✓	✓	✓	✓	✓	×	×	✓	
Hot water supply				★	★	★	★	★	★	★				

Table E.46 Scenario 33 simulation in mid-terraced property

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total	Energy saving
Monthly heating demand (kWh/month)	676.41	643.00	546.59	306.88	186.22	0.00	0.00	0.00	65.39	219.99	444.06	546.67	3635.21	72.02%
Roof PV panels outputs (kWh/month)	43.53	84.59	166.56	231.18	313.61	310.28	302.45	280.08	182.13	111.19	52.95	29.80	2108.36	
One wind turbine output (kWh/month)	133.58	103.20	120.65	73.17	57.64	48.29	42.17	49.74	73.42	96.71	104.78	127.10	1030.45	
Renewable final output (kWh/month)	141.69	150.23	229.77	243.48	297.00	286.85	275.70	263.86	204.44	166.32	126.19	125.52	2511.05	
Heat generation (**COP**=1.8)	255.04	270.42	413.58	438.26	534.60	516.33	496.26	474.94	368.00	299.38	227.13	225.94	4519.89	
Excess heat (kWh/month)	-421.37	-372.59	-133.01	131.38	348.38	516.33	496.26	474.94	302.61	79.39	-216.93	-320.73	884.68	
Feasibility of monthly self-heating	×	×	×	✓	✓	✓	✓	✓	✓	✓	×	×	✓	
Hot water supply				★	★	★	★	★	★	★				

Table E.47 Scenario 33 simulation in end-terraced property

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total	Energy saving
Monthly heating demand (kW h/month)	711.56	676.42	574.99	322.82	195.90	0.00	0.00	0.00	68.78	231.42	467.14	575.08	3824.11	91.41%
Roof PV panels outputs (kW h/month)	87.07	169.18	333.12	462.36	627.22	620.55	604.91	560.17	364.27	222.38	105.90	59.61	4216.72	
Two wind turbines outputs (kW h/month)	267.16	206.40	241.30	146.34	115.28	96.58	84.34	99.48	146.84	193.42	209.56	254.20	2060.90	
Renewable final output (kW h/month)	283.38	300.46	459.53	486.96	594.00	573.70	551.40	527.72	408.89	332.64	252.37	251.05	5022.10	
Heat generation (COP=1.8)	510.08	540.83	827.16	876.52	1069.20	1032.67	992.52	949.89	736.00	598.75	454.27	451.88	9039.78	
Excess heat (kW h/month)	-201.48	-135.58	252.17	553.70	873.30	1032.67	992.52	949.89	667.21	367.33	-12.87	-123.20	5215.66	
Feasibility of monthly self-heating	×	×	✓	✓	✓	✓	✓	✓	✓	✓	×	×	✓	
Hot water supply			★	★	★	★	★	★	★	★				

Table E.48 Scenario 33 simulation in bungalow property

Scenario 34 simulation in different property types with 50 m^2 or less floor area, 1 occupant and built post 1999 in Yorkshire & Humber regions

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total	Energy saving
Monthly heating demand (kW h/month)	498.33	473.72	402.69	226.09	137.19	0.00	0.00	0.00	48.17	162.07	327.15	402.75	2678.17	81.24%
Roof PV panels outputs (kW h/month)	43.53	84.59	166.56	231.18	313.61	310.28	302.45	280.08	182.13	111.19	52.95	29.80	2108.36	
One wind turbine output (kW h/month)	133.58	103.20	120.65	73.17	57.64	48.29	42.17	49.74	73.42	96.71	104.78	127.10	1030.45	
Renewable final output (kW h/month)	141.69	150.23	229.77	243.48	297.00	286.85	275.70	263.86	204.44	166.32	126.19	125.52	2511.05	
Heat generation (COP=1.8)	255.04	270.42	413.58	438.26	534.60	516.33	496.26	474.94	368.00	299.38	227.13	225.94	4519.89	
Excess heat (kW h/month)	-243.29	-203.30	10.89	212.18	397.41	516.33	496.26	474.94	319.83	137.30	-100.02	-176.81	1841.72	
Feasibility of monthly self-heating	×	×	✓	✓	✓	✓	✓	✓	✓	✓	×	×	✓	
Hot water supply				★	★	★	★	★	★	★				

Table E.49 Scenario 34 simulation in mid-terraced property

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total	Energy saving
Monthly heating demand (kW h/month)	491.95	467.66	397.53	223.19	135.44	0.00	0.00	0.00	47.56	160.00	322.96	397.60	2643.89	81.57%
Roof PV panels outputs (kW h/month)	43.53	84.59	166.56	231.18	313.61	310.28	302.45	280.08	182.13	111.19	52.95	29.80	2108.36	
One wind turbine output (kW h/month)	133.58	103.20	120.65	73.17	57.64	48.29	42.17	49.74	73.42	96.71	104.78	127.10	1030.45	
Renewable final output (kW h/month)	141.69	150.23	229.77	243.48	297.00	286.85	275.70	263.86	204.44	166.32	126.19	125.52	2511.05	
Heat generation (**COP**=1.8)	255.04	270.42	413.58	438.26	534.60	516.33	496.26	474.94	368.00	299.38	227.13	225.94	4519.89	
Excess heat (kW h/month)	-236.91	-197.24	16.05	215.07	399.16	516.33	496.26	474.94	320.44	139.38	-95.83	-171.65	1876.00	
Feasibility of monthly self-heating	×	×	✓	✓	✓	✓	✓	✓	✓	✓	×	×	✓	
Hot water supply			★	★	★	★	★	★	★	★				

Table E.50 Scenario 34 simulation in end-terraced property

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total	Energy saving
Monthly heating demand (kW h/month)	517.52	491.96	418.19	234.79	142.47	0.00	0.00	0.00	50.03	168.31	339.75	418.26	2781.28	99.81%
Roof PV panels outputs (kW h/month)	87.07	169.18	333.12	462.36	627.22	620.55	604.91	560.17	364.27	222.38	105.90	59.61	4216.72	
Two wind turbines outputs (kW h/month)	267.16	206.40	241.30	146.34	115.28	96.58	84.34	99.48	146.84	193.42	209.56	254.20	2060.90	
Renewable final output (kW h/month)	283.38	300.46	459.53	486.96	594.00	573.70	551.40	527.72	408.89	332.64	252.37	251.05	5022.10	
Heat generation (**COP**=1.8)	510.08	540.83	827.16	876.52	1069.20	1032.67	992.52	949.89	736.00	598.75	454.27	451.88	9039.78	
Excess heat (kW h/month)	-7.43	48.87	408.97	641.73	926.73	1032.67	992.52	949.89	685.97	430.44	114.52	33.63	6258.50	
Feasibility of monthly self-heating	×	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	
Hot water supply		★	★	★	★	★	★	★	★	★	★	★		

Table E.51 Scenario 34 simulation in bungalow property

Appendix F

Scenario simulation results in South West region

Scenario 35 simulation in different property types with $151\,\mathrm{m}^2$ to $200\,\mathrm{m}^2$ floor area, 4 occupants and built pre-1919 in South West region

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total	Energy saving
Monthly heating demand (kW h/month)	2192.11	2083.84	1771.37	994.52	603.49	0.00	0.00	0.00	211.90	712.93	1439.10	1771.65	11780.93	84.58%
Roof PV panels outputs (kW h/month)	197.40	383.58	755.27	1048.30	1422.10	1406.98	1371.51	1270.07	825.91	504.20	240.11	135.15	9560.59	
Two wind turbines outputs (kW h/month)	668.04	554.42	558.42	435.94	349.02	257.50	255.82	282.32	338.48	519.46	566.78	637.06	5423.26	
Renewable final output (kW h/month)	692.36	750.40	1050.95	1187.39	1416.89	1331.58	1301.87	1241.91	931.51	818.93	645.51	617.77	11987.08	
Heat generation (COP=1.8)	1246.24	1350.72	1891.72	2137.31	2550.41	2396.85	2343.36	2235.44	1676.72	1474.08	1161.93	1111.98	21576.74	
Excess heat (kW h/month)	-945.87	-733.12	120.35	1142.79	1946.91	2396.85	2343.36	2235.44	1464.81	761.14	-277.17	-659.67	9795.81	
Feasibility of monthly self-heating	×	×	✓	✓	✓	✓	✓	✓	✓	✓	×	×	✓	
Hot water supply			★	★	★	★	★	★	★	★				

Table F.1 Scenario 35 simulation in mid-terraced property

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total	Energy saving
Monthly heating demand (kW h/month)	2314.43	2200.12	1870.21	1050.02	637.17	0.00	0.00	0.00	223.73	752.72	1519.40	1870.51	12438.30	83.06%
Roof PV panels outputs (kW h/month)	197.40	383.58	755.27	1048.30	1422.10	1406.98	1371.51	1270.07	825.91	504.20	240.11	135.15	9560.59	
Two wind turbines outputs (kW h/month)	668.04	554.42	558.42	435.94	349.02	257.50	255.82	282.32	338.48	519.46	566.78	637.06	5423.26	
Renewable final output (kW h/month)	692.36	750.40	1050.95	1187.39	1416.89	1331.58	1301.87	1241.91	931.51	818.93	645.51	617.77	11987.08	
Heat generation (COP=1.8)	1246.24	1350.72	1891.72	2137.31	2550.41	2396.85	2343.36	2235.44	1676.72	1474.08	1161.93	1111.98	21576.74	
Excess heat (kW h/month)	-1068.19	-849.40	21.50	1087.29	1913.24	2396.85	2343.36	2235.44	1452.99	721.36	-357.48	-758.53	9138.44	
Feasibility of monthly self-heating	×	×	✓	✓	✓	✓	✓	✓	✓	✓	×	×	✓	
Hot water supply				★	★	★	★	★	★	★				

Table F.2 Scenario 35 simulation in end-terraced property

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total	Energy saving
Monthly heating demand (kW h/month)	2548.11	2422.26	2059.04	1156.03	701.50	0.00	0.00	0.00	246.32	828.71	1672.81	2059.37	13694.15	79.72%
Roof PV panels outputs (kW h/month)	197.40	383.58	755.27	1048.30	1422.10	1406.98	1371.51	1270.07	825.91	504.20	240.11	135.15	9560.59	
Two wind turbines outputs (kW h/month)	668.04	554.42	558.42	435.94	349.02	257.50	255.82	282.32	338.48	519.46	566.78	637.06	5423.26	
Renewable final output (kW h/month)	692.36	750.40	1050.95	1187.39	1416.89	1331.58	1301.87	1241.91	931.51	818.93	645.51	617.77	11987.08	
Heat generation (COP=1.8)	1246.24	1350.72	1891.72	2137.31	2550.41	2396.85	2343.36	2235.44	1676.72	1474.08	1161.93	1111.98	21576.74	
Excess heat (kW h/month)	-1301.87	-1071.54	-167.32	981.28	1848.91	2396.85	2343.36	2235.44	1430.40	645.36	-510.89	-947.38	7882.59	
Feasibility of monthly self-heating	×	×	×	✓	✓	✓	✓	✓	✓	✓	×	×	✓	
Hot water supply				★	★	★	★	★	★	★				

Table F.3 Scenario 35 simulation in semi-detached property

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total	Energy saving
Monthly heating demand (kW h/month)	2436.97	2316.60	1969.23	1105.61	670.90	0.00	0.00	0.00	235.57	792.57	1599.85	1969.54	13096.86	81.28%
Roof PV panels outputs (kW h/month)	197.40	383.58	755.27	1048.30	1422.10	1406.98	1371.51	1270.07	825.91	504.20	240.11	135.15	9560.59	
Two wind turbines outputs (kW h/month)	668.04	554.42	558.42	435.94	349.02	257.50	255.82	282.32	338.48	519.46	566.78	637.06	5423.26	
Renewable final output (kW h/month)	692.36	750.40	1050.95	1187.39	1416.89	1331.58	1301.87	1241.91	931.51	818.93	645.51	617.77	11987.08	
Heat generation (COP=1.8)	1246.24	1350.72	1891.72	2137.31	2550.41	2396.85	2343.36	2235.44	1676.72	1474.08	1161.93	1111.98	21576.74	
Excess heat (kW h/month)	-1190.73	-965.88	-77.52	1031.70	1879.50	2396.85	2343.36	2235.44	1441.14	681.51	-437.92	-857.56	8479.88	
Feasibility of monthly self-heating	×	×	×	✓	✓	✓	✓	✓	✓	✓	×	×	✓	
Hot water supply				★	★	★	★	★	★	★				

Table F.4 Scenario 35 simulation in detached property

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total	Energy saving
Monthly heating demand (kW h/month)	2592.61	2464.56	2095.00	1176.22	713.75	0.00	0.00	0.00	250.62	843.19	1702.03	2095.33	13933.30	99.50%
Roof PV panels outputs (kW h/month)	394.81	767.16	1510.55	2096.61	2844.19	2813.95	2743.03	2540.13	1651.81	1008.41	480.23	270.30	19121.18	
Four wind turbines outputs (kW h/month)	1336.08	1108.84	1116.84	871.88	698.04	515.00	511.64	564.64	676.96	1038.92	1133.56	1274.12	10846.52	
Renewable final output (kW h/month)	1384.71	1500.80	2101.91	2374.79	2833.79	2663.16	2603.73	2483.82	1863.02	1637.86	1291.03	1235.54	23974.16	
Heat generation (COP=1.8)	2492.48	2701.44	3783.44	4274.62	5100.82	4793.69	4686.72	4470.87	3353.43	2948.15	2323.85	2223.97	43153.48	
Excess heat (kW h/month)	-100.13	236.88	1688.44	3098.40	4387.06	4793.69	4686.72	4470.87	3102.81	2104.97	621.83	128.63	29220.18	
Feasibility of monthly self-heating	×	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	
Hot water supply		★	★	★	★	★	★	★	★	★	★	★		

Table F.5 Scenario 35 simulation in bungalow property

Scenario 36 simulation in different property types with 151 m^2 to 200 m^2 floor area, 4 occupants and built post 1999 in South West region

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total	Energy saving
Monthly heating demand (kW h/month)	1703.92	1619.77	1376.89	773.04	469.10	0.00	0.00	0.00	164.71	554.16	1118.61	1377.10	9157.31	92.48%
Roof PV panels outputs (kW h/month)	197.40	383.58	755.27	1048.30	1422.10	1406.98	1371.51	1270.07	825.91	504.20	240.11	135.15	9560.59	
Two wind turbines outputs (kW h/month)	668.04	554.42	558.42	435.94	349.02	257.50	255.82	282.32	338.48	519.46	566.78	637.06	5423.26	
Renewable final output (kW h/month)	692.36	750.40	1050.95	1187.39	1416.89	1331.58	1301.87	1241.91	931.51	818.93	645.51	617.77	11987.08	
Heat generation (COP=1.8)	1246.24	1350.72	1891.72	2137.31	2550.41	2396.85	2343.36	2235.44	1676.72	1474.08	1161.93	1111.98	21576.74	
Excess heat (kW h/month)	-457.69	-269.05	514.83	1364.27	2081.31	2396.85	2343.36	2235.44	1512.00	919.91	43.31	-265.12	12419.43	
Feasibility of monthly self-heating	×	×	✓	✓	✓	✓	✓	✓	✓	✓	✓	×	✓	
Hot water supply			★	★	★	★	★	★	★	★				

Table F.6 Scenario 36 simulation in mid-terraced property

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total	Energy saving
Monthly heating demand (kW h/month)	1799.00	1710.15	1453.72	816.18	495.27	0.00	0.00	0.00	173.90	585.09	1181.03	1453.95	9668.29	90.85%
Roof PV panels outputs (kW h/month)	197.40	383.58	755.27	1048.30	1422.10	1406.98	1371.51	1270.07	825.91	504.20	240.11	135.15	9560.59	
Two wind turbines outputs (kW h/month)	668.04	554.42	558.42	435.94	349.02	257.50	255.82	282.32	338.48	519.46	566.78	637.06	5423.26	
Renewable final output (kW h/month)	692.36	750.40	1050.95	1187.39	1416.89	1331.58	1301.87	1241.91	931.51	818.93	645.51	617.77	11987.08	
Heat generation (COP=1.8)	1246.24	1350.72	1891.72	2137.31	2550.41	2396.85	2343.36	2235.44	1676.72	1474.08	1161.93	1111.98	21576.74	
Excess heat (kW h/month)	-552.76	-359.43	438.00	1321.13	2055.14	2396.85	2343.36	2235.44	1502.81	888.99	-19.11	-341.96	11908.45	
Feasibility of monthly self-heating	×	×	✓	✓	✓	✓	✓	✓	✓	✓	×	×	✓	
Hot water supply			★	★	★	★	★	★	★	★				

Table F.7 Scenario 36 simulation in end-terraced property

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total	Energy saving
Monthly heating demand (kW h/month)	1980.64	1882.82	1600.49	898.59	545.28	0.00	0.00	0.00	191.46	644.16	1300.28	1600.75	10644.46	87.65%
Roof PV panels outputs (kW h/month)	197.40	383.58	755.27	1048.30	1422.10	1406.98	1371.51	1270.07	825.91	504.20	240.11	135.15	9560.59	
Two wind turbines outputs (kW h/month)	668.04	554.42	558.42	435.94	349.02	257.50	255.82	282.32	338.48	519.46	566.78	637.06	5423.26	
Renewable final output (kW h/month)	692.36	750.40	1050.95	1187.39	1416.89	1331.58	1301.87	1241.91	931.51	818.93	645.51	617.77	11987.08	
Heat generation (COP=1.8)	1246.24	1350.72	1891.72	2137.31	2550.41	2396.85	2343.36	2235.44	1676.72	1474.08	1161.93	1111.98	21576.74	
Excess heat (kW h/month)	-734.40	-532.10	291.22	1238.72	2005.13	2396.85	2343.36	2235.44	1485.25	829.92	-138.35	-488.76	10932.28	
Feasibility of monthly self-heating	×	×	✓	✓	✓	✓	✓	✓	✓	✓	×	×	✓	
Hot water supply			★	★	★	★	★	★	★	★				

Table F.8 Scenario 36 simulation in semi-detached property

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total	Energy saving
Monthly heating demand (kW h/month)	1894.25	1800.70	1530.69	859.39	521.49	0.00	0.00	0.00	183.11	616.06	1243.56	1530.93	10180.19	89.10%
Roof PV panels outputs (kW h/month)	197.40	383.58	755.27	1048.30	1422.10	1406.98	1371.51	1270.07	825.91	504.20	240.11	135.15	9560.59	
Two wind turbines outputs (kW h/month)	668.04	554.42	558.42	435.94	349.02	257.50	255.82	282.32	338.48	519.46	566.78	637.06	5423.26	
Renewable final output (kW h/month)	692.36	750.40	1050.95	1187.39	1416.89	1331.58	1301.87	1241.91	931.51	818.93	645.51	617.77	11987.08	
Heat generation (COP=1.8)	1246.24	1350.72	1891.72	2137.31	2550.41	2396.85	2343.36	2235.44	1676.72	1474.08	1161.93	1111.98	21576.74	
Excess heat (kW h/month)	-648.01	-449.98	361.03	1277.92	2028.91	2396.85	2343.36	2235.44	1493.61	858.01	-81.64	-418.94	11396.55	
Feasibility of monthly self-heating	×	×	✓	✓	✓	✓	✓	✓	✓	✓	×	×	✓	
Hot water supply			★	★	★	★	★	★	★	★				

Table F.9 Scenario 36 simulation in detached property

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total	Energy saving
Monthly heating demand (kW h/month)	2015.23	1915.70	1628.44	914.28	554.80	0.00	0.00	0.00	194.81	655.41	1322.98	1628.70	10830.36	100.00%
Roof PV panels outputs (kW h/month)	394.81	767.16	1510.55	2096.61	2844.19	2813.95	2743.03	2540.13	1651.81	1008.41	480.23	270.30	19121.18	
Four wind turbines outputs (kW h/month)	1336.08	1108.84	1116.84	871.88	698.04	515.00	511.64	564.64	676.96	1038.92	1133.56	1274.12	10846.52	
Renewable final output (kW h/month)	1384.71	1500.80	2101.91	2374.79	2833.79	2663.16	2603.73	2483.82	1863.02	1637.86	1291.03	1235.54	23974.16	
Heat generation (COP=1.8)	2492.48	2701.44	3783.44	4274.62	5100.82	4793.69	4686.72	4470.87	3353.43	2948.15	2323.85	2223.97	43153.48	
Excess heat (kW h/month)	477.25	785.74	2154.99	3360.34	4546.02	4793.69	4686.72	4470.87	3158.63	2292.75	1000.87	595.26	32323.13	
Feasibility of monthly self-heating	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	
Hot water supply	★	★	★	★	★	★	★	★	★	★	★	★		

Table F.10 Scenario 36 simulation in bungalow property

Scenario 37 simulation in different property types with 101 m^2 to 150 m^2 floor area, 3 occupants and built pre-1919 in South West region

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total	Energy saving
Monthly heating demand (kW h/month)	1476.16	1403.25	1192.84	669.71	406.39	0.00	0.00	0.00	142.70	480.09	969.09	1193.02	7933.24	94.56%
Roof PV panels outputs (kW h/month)	148.05	287.69	566.45	786.23	1066.57	1055.23	1028.63	952.55	619.43	378.15	180.09	101.36	7170.44	
Two wind turbines outputs (kW h/month)	668.04	554.42	558.42	435.94	349.02	257.50	255.82	282.32	338.48	519.46	566.78	637.06	5423.26	
Renewable final output (kW h/month)	652.87	673.68	899.90	977.73	1132.47	1050.19	1027.56	987.90	766.33	718.09	597.49	590.74	10074.96	
Heat generation (**COP**=1.8)	1175.17	1212.63	1619.82	1759.92	2038.45	1890.33	1849.61	1778.21	1379.39	1292.56	1075.49	1063.33	18134.93	
Excess heat (kW h/month)	-300.98	-190.62	426.98	1090.21	1632.06	1890.33	1849.61	1778.21	1236.69	812.48	106.40	-129.70	10201.69	
Feasibility of monthly self-heating	×	×	✓	✓	✓	✓	✓	✓	✓	✓	✓	×	✓	
Hot water supply			★	★	★	★	★	★	★	★	★			

Table F.11 Scenario 37 simulation in mid-terraced property

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total	Energy saving
Monthly heating demand (kW h/month)	1575.36	1497.55	1272.99	714.71	433.70	0.00	0.00	0.00	152.28	512.35	1034.21	1273.20	8466.36	92.66%
Roof PV panels outputs (kW h/month)	148.05	287.69	566.45	786.23	1066.57	1055.23	1028.63	952.55	619.43	378.15	180.09	101.36	7170.44	
Two wind turbines outputs (kW h/month)	668.04	554.42	558.42	435.94	349.02	257.50	255.82	282.32	338.48	519.46	566.78	637.06	5423.26	
Renewable final output (kW h/month)	652.87	673.68	899.90	977.73	1132.47	1050.19	1027.56	987.90	766.33	718.09	597.49	590.74	10074.96	
Heat generation (**COP**=1.8)	1175.17	1212.63	1619.82	1759.92	2038.45	1890.33	1849.61	1778.21	1379.39	1292.56	1075.49	1063.33	18134.93	
Excess heat (kW h/month)	-400.18	-284.92	346.82	1045.21	1604.75	1890.33	1849.61	1778.21	1227.11	780.21	41.28	-209.87	9668.57	
Feasibility of monthly self-heating	×	×	✓	✓	✓	✓	✓	✓	✓	✓	✓	×	✓	
Hot water supply			★	★	★	★	★	★	★	★	★			

Table F.12 Scenario 37 simulation in end-terraced property

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total	Energy saving
Monthly heating demand (kW h/month)	1707.47	1623.14	1379.75	774.65	470.07	0.00	0.00	0.00	165.06	555.32	1120.94	1379.97	9176.38	90.12%
Roof PV panels outputs (kW h/month)	148.05	287.69	566.45	786.23	1066.57	1055.23	1028.63	952.55	619.43	378.15	180.09	101.36	7170.44	
Two wind turbines outputs (kW h/month)	668.04	554.42	558.42	435.94	349.02	257.50	255.82	282.32	338.48	519.46	566.78	637.06	5423.26	
Renewable final output (kW h/month)	652.87	673.68	899.90	977.73	1132.47	1050.19	1027.56	987.90	766.33	718.09	597.49	590.74	10074.96	
Heat generation (**COP**=1.8)	1175.17	1212.63	1619.82	1759.92	2038.45	1890.33	1849.61	1778.21	1379.39	1292.56	1075.49	1063.33	18134.93	
Excess heat (kW h/month)	-532.30	-410.51	240.07	985.27	1568.38	1890.33	1849.61	1778.21	1214.33	737.25	-45.46	-316.64	8958.55	
Feasibility of monthly self-heating	×	×	✓	✓	✓	✓	✓	✓	✓	✓	×	×	✓	
Hot water supply			★	★	★	★	★	★	★	★				

Table F.13 Scenario 37 simulation in semi-detached property

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total	Energy saving
Monthly heating demand (kW h/month)	1850.66	1759.26	1495.46	839.62	509.49	0.00	0.00	0.00	178.90	601.89	1214.94	1495.70	9945.91	87.47%
Roof PV panels outputs (kW h/month)	148.05	287.69	566.45	786.23	1066.57	1055.23	1028.63	952.55	619.43	378.15	180.09	101.36	7170.44	
Two wind turbines outputs (kW h/month)	668.04	554.42	558.42	435.94	349.02	257.50	255.82	282.32	338.48	519.46	566.78	637.06	5423.26	
Renewable final output (kW h/month)	652.87	673.68	899.90	977.73	1132.47	1050.19	1027.56	987.90	766.33	718.09	597.49	590.74	10074.96	
Heat generation (**COP**=1.8)	1175.17	1212.63	1619.82	1759.92	2038.45	1890.33	1849.61	1778.21	1379.39	1292.56	1075.49	1063.33	18134.93	
Excess heat (kW h/month)	-675.49	-546.63	124.36	920.31	1528.96	1890.33	1849.61	1778.21	1200.49	690.68	-139.46	-432.37	8189.02	
Feasibility of monthly self-heating	×	×	✓	✓	✓	✓	✓	✓	✓	✓	×	×	✓	
Hot water supply			★	★	★	★	★	★	★	★				

Table F.14 Scenario 37 simulation in detached property

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total	Energy saving
Monthly heating demand (kW h/month)	1927.86	1832.65	1557.84	874.64	530.75	0.00	0.00	0.00	186.36	626.99	1265.63	1558.09	10360.81	100.00%
Roof PV panels outputs (kW h/month)	296.11	575.37	1132.91	1572.46	2133.15	2110.47	2057.27	1905.10	1238.86	756.31	360.17	202.73	14340.88	
Four wind turbines outputs (kW h/month)	1336.08	1108.84	1116.84	871.88	698.04	515	511.64	564.64	676.96	1038.92	1133.56	1274.12	10846.52	
Renewable final output (kW h/month)	1305.75	1347.37	1799.80	1955.47	2264.95	2100.37	2055.13	1975.79	1532.66	1436.18	1194.98	1181.48	20149.92	
Heat generation (**COP**=1.8)	2350.35	2425.26	3239.64	3519.84	4076.91	3780.67	3699.23	3556.42	2758.78	2585.13	2150.97	2126.66	36269.86	
Excess heat (kW h/month)	422.48	592.62	1681.80	2645.20	3546.16	3780.67	3699.23	3556.42	2572.42	1958.13	885.34	568.57	25909.05	
Feasibility of monthly self-heating	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	
Hot water supply	★	★	★	★	★	★	★	★	★	★	★	★		

Table F.15 Scenario 37 simulation in bungalow property

Scenario 38 simulation in different property types with 101 m^2 to 150 m^2 floor area, 3 occupants and built post 1999 in South West region

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total	Energy saving
Monthly heating demand (kW h/month)	1242.63	1181.26	1004.13	563.76	342.10	0.00	0.00	0.00	120.12	404.14	815.78	1004.29	6678.20	99.30%
Roof PV panels outputs (kW h/month)	148.05	287.69	566.45	786.23	1066.57	1055.23	1028.63	952.55	619.43	378.15	180.09	101.36	7170.44	
Two wind turbines outputs (kW h/month)	668.04	554.42	558.42	435.94	349.02	257.50	255.82	282.32	338.48	519.46	566.78	637.06	5423.26	
Renewable final output (kW h/month)	652.87	673.68	899.90	977.73	1132.47	1050.19	1027.56	987.90	766.33	718.09	597.49	590.74	10074.96	
Heat generation (**COP**=1.8)	1175.17	1212.63	1619.82	1759.92	2038.45	1890.33	1849.61	1778.21	1379.39	1292.56	1075.49	1063.33	18134.93	
Excess heat (kW h/month)	-67.46	31.37	615.69	1196.16	1696.35	1890.33	1849.61	1778.21	1259.27	888.43	259.71	59.04	11456.73	
Feasibility of monthly self-heating	×	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	
Hot water supply			★	★	★	★	★	★	★	★	★	★		

Table F.16 Scenario 38 simulation in mid-terraced property

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total	Energy saving
Monthly heating demand (kW h/month)	1326.14	1260.64	1071.61	601.65	365.09	0.00	0.00	0.00	128.19	431.30	870.60	1071.78	7126.98	97.98%
Roof PV panels outputs (kW h/month)	148.05	287.69	566.45	786.23	1066.57	1055.23	1028.63	952.55	619.43	378.15	180.09	101.36	7170.44	
Two wind turbines outputs (kW h/month)	668.04	554.42	558.42	435.94	349.02	257.50	255.82	282.32	338.48	519.46	566.78	637.06	5423.26	
Renewable final output (kW h/month)	652.87	673.68	899.90	977.73	1132.47	1050.19	1027.56	987.90	766.33	718.09	597.49	590.74	10074.96	
Heat generation (**COP**=1.8)	1175.17	1212.63	1619.82	1759.92	2038.45	1890.33	1849.61	1778.21	1379.39	1292.56	1075.49	1063.33	18134.93	
Excess heat (kW h/month)	-150.96	-48.01	548.21	1158.28	1673.36	1890.33	1849.61	1778.21	1251.20	861.27	204.89	-8.45	11007.95	
Feasibility of monthly self-heating	×	×	✓	✓	✓	✓	✓	✓	✓	✓	✓	×	✓	
Hot water supply			★	★	★	★	★	★	★	★	★			

Table F.17 Scenario 38 simulation in end-terraced property

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total	Energy saving
Monthly heating demand (kW h/month)	1437.35	1366.36	1161.48	652.10	395.71	0.00	0.00	0.00	138.94	467.47	943.61	1161.66	7724.68	95.38%
Roof PV panels outputs (kW h/month)	148.05	287.69	566.45	786.23	1066.57	1055.23	1028.63	952.55	619.43	378.15	180.09	101.36	7170.44	
Two wind turbines outputs (kW h/month)	668.04	554.42	558.42	435.94	349.02	257.50	255.82	282.32	338.48	519.46	566.78	637.06	5423.26	
Renewable final output (kW h/month)	652.87	673.68	899.90	977.73	1132.47	1050.19	1027.56	987.90	766.33	718.09	597.49	590.74	10074.96	
Heat generation (COP=1.8)	1175.17	1212.63	1619.82	1759.92	2038.45	1890.33	1849.61	1778.21	1379.39	1292.56	1075.49	1063.33	18134.93	
Excess heat (kW h/month)	-262.18	-153.73	458.34	1107.82	1642.75	1890.33	1849.61	1778.21	1240.45	825.10	131.88	-98.33	10410.25	
Feasibility of monthly self-heating	×	×	✓	✓	✓	✓	✓	✓	✓	✓	✓	×	✓	
Hot water supply			★	★	★	★	★	★	★	★	★			

Table F.18 Scenario 38 simulation in semi-detached property

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total	Energy saving
Monthly heating demand (kW h/month)	1557.89	1480.94	1258.88	706.79	428.89	0.00	0.00	0.00	150.60	506.67	1022.74	1259.08	8372.46	92.98%
Roof PV panels outputs (kW h/month)	148.05	287.69	566.45	786.23	1066.57	1055.23	1028.63	952.55	619.43	378.15	180.09	101.36	7170.44	
Two wind turbines outputs (kW h/month)	668.04	554.42	558.42	435.94	349.02	257.50	255.82	282.32	338.48	519.46	566.78	637.06	5423.26	
Renewable final output (kW h/month)	652.87	673.68	899.90	977.73	1132.47	1050.19	1027.56	987.90	766.33	718.09	597.49	590.74	10074.96	
Heat generation (COP=1.8)	1175.17	1212.63	1619.82	1759.92	2038.45	1890.33	1849.61	1778.21	1379.39	1292.56	1075.49	1063.33	18134.93	
Excess heat (kW h/month)	-382.71	-268.31	360.94	1053.13	1609.56	1890.33	1849.61	1778.21	1228.79	785.90	52.75	-195.75	9762.47	
Feasibility of monthly self-heating	×	×	✓	✓	✓	✓	✓	✓	✓	✓	✓	×	✓	
Hot water supply			★	★	★	★	★	★	★	★	★			

Table F.19 Scenario 38 simulation in detached property

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total	Energy saving
Monthly heating demand (kW h/month)	1622.88	1542.72	1311.39	736.27	446.78	0.00	0.00	0.00	156.88	527.80	1065.41	1311.60	8721.73	100.00%
Roof PV panels outputs (kW h/month)	296.11	575.37	1132.91	1572.46	2133.15	2110.47	2057.27	1905.10	1238.86	756.31	360.17	202.73	14340.88	
Four wind turbines outputs (kW h/month)	1336.08	1108.84	1116.84	871.88	698.04	515	511.64	564.64	676.96	1038.92	1133.56	1274.12	10846.52	
Renewable final output (kW h/month)	1305.75	1347.37	1799.80	1955.47	2264.95	2100.37	2055.13	1975.79	1532.66	1436.18	1194.98	1181.48	20149.92	
Heat generation (COP=1.8)	2350.35	2425.26	3239.64	3519.84	4076.91	3780.67	3699.23	3556.42	2758.78	2585.13	2150.97	2126.66	36269.86	
Excess heat (kW h/month)	727.47	882.54	1928.25	2783.57	3630.12	3780.67	3699.23	3556.42	2601.90	2057.32	1085.57	815.06	27548.13	
Feasibility of monthly self-heating	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	
Hot water supply	★	★	★	★	★	★	★	★	★	★	★	★		

Table F.20 Scenario 38 simulation in bungalow property

Scenario 39 simulation in different property types with $51\,\mathrm{m}^2$ to $100\,\mathrm{m}^2$ floor area, 2 occupants and built pre-1919 in South West region

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total	Energy saving
Monthly heating demand (kW h/month)	997.83	948.55	806.32	452.70	274.71	0.00	0.00	0.00	96.46	324.52	655.07	806.44	5362.60	87.41%
Roof PV panels outputs (kW h/month)	98.70	191.79	377.64	524.15	711.05	703.49	685.76	635.03	412.95	252.10	120.06	67.58	4780.29	
One wind turbine output (kW h/month)	334.02	277.21	279.21	217.97	174.51	128.75	127.91	141.16	169.24	259.73	283.39	318.53	2711.63	
Renewable final output (kW h/month)	346.18	375.20	525.48	593.70	708.45	665.79	650.93	620.95	465.75	409.47	322.76	308.88	5993.54	
Heat generation (COP=1.8)	623.12	675.36	945.86	1068.66	1275.20	1198.42	1171.68	1117.72	838.36	737.04	580.96	555.99	10788.37	
Excess heat (kW h/month)	-374.71	-273.19	139.54	615.95	1000.50	1198.42	1171.68	1117.72	741.90	412.52	-74.11	-250.45	5425.77	
Feasibility of monthly self-heating	×	×	✓	✓	✓	✓	✓	✓	✓	✓	×	×	✓	
Hot water supply			★	★	★	★	★	★	★	★				

Table F.21 Scenario 39 simulation in mid-terraced property

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total	Energy saving
Monthly heating demand (kW h/month)	1096.62	1042.46	886.14	497.52	301.90	0.00	0.00	0.00	106.01	356.65	719.92	886.28	5893.50	84.57%
Roof PV panels outputs (kW h/month)	98.70	191.79	377.64	524.15	711.05	703.49	685.76	635.03	412.95	252.10	120.06	67.58	4780.29	
One wind turbine output (kW h/month)	334.02	277.21	279.21	217.97	174.51	128.75	127.91	141.16	169.24	259.73	283.39	318.53	2711.63	
Renewable final output (kW h/month)	346.18	375.20	525.48	593.70	708.45	665.79	650.93	620.95	465.75	409.47	322.76	308.88	5993.54	
Heat generation (COP=1.8)	623.12	675.36	945.86	1068.66	1275.20	1198.42	1171.68	1117.72	838.36	737.04	580.96	555.99	10788.37	
Excess heat (kW h/month)	-473.50	-367.10	59.72	571.14	973.30	1198.42	1171.68	1117.72	732.35	380.39	-138.96	-330.29	4894.88	
Feasibility of monthly self-heating	×	×	✓	✓	✓	✓	✓	✓	✓	✓	×	×	✓	
Hot water supply			★	★	★	★	★	★	★	★				

Table F.22 Scenario 39 simulation in end-terraced property

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total	Energy saving
Monthly heating demand (kWh/month)	1195.40	1136.36	965.97	542.34	329.10	0.00	0.00	0.00	115.56	388.78	784.77	966.12	6424.39	81.98%
Roof PV panels outputs (kWh/month)	98.70	191.79	377.64	524.15	711.05	703.49	685.76	635.03	412.95	252.10	120.06	67.58	4780.29	
One wind turbine output (kWh/month)	334.02	277.21	279.21	217.97	174.51	128.75	127.91	141.16	169.24	259.73	283.39	318.53	2711.63	
Renewable final output (kWh/month)	346.18	375.20	525.48	593.70	708.45	665.79	650.93	620.95	465.75	409.47	322.76	308.88	5993.54	
Heat generation (**COP**=1.8)	623.12	675.36	945.86	1068.66	1275.20	1198.42	1171.68	1117.72	838.36	737.04	580.96	555.99	10788.37	
Excess heat (kWh/month)	-572.28	-461.00	-20.11	526.32	946.11	1198.42	1171.68	1117.72	722.80	348.26	-203.81	-410.13	4363.98	
Feasibility of monthly self-heating	×	×	×	✓	✓	✓	✓	✓	✓	✓	×	×	✓	
Hot water supply				★	★	★	★	★	★	★				

Table F.23 Scenario 39 simulation in semi-detached property

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total	Energy saving
Monthly heating demand (kWh/month)	1323.82	1258.44	1069.74	600.60	364.45	0.00	0.00	0.00	127.97	430.54	869.08	1069.91	7114.56	78.43%
Roof PV panels outputs (kWh/month)	98.70	191.79	377.64	524.15	711.05	703.49	685.76	635.03	412.95	252.10	120.06	67.58	4780.29	
One wind turbine output (kWh/month)	334.02	277.21	279.21	217.97	174.51	128.75	127.91	141.16	169.24	259.73	283.39	318.53	2711.63	
Renewable final output (kWh/month)	346.18	375.20	525.48	593.70	708.45	665.79	650.93	620.95	465.75	409.47	322.76	308.88	5993.54	
Heat generation (**COP**=1.8)	623.12	675.36	945.86	1068.66	1275.20	1198.42	1171.68	1117.72	838.36	737.04	580.96	555.99	10788.37	
Excess heat (kWh/month)	-700.70	-583.08	-123.88	468.06	910.75	1198.42	1171.68	1117.72	710.39	306.49	-288.12	-513.92	3673.81	
Feasibility of monthly self-heating	×	×	×	✓	✓	✓	✓	✓	✓	✓	×	×	✓	
Hot water supply				★	★	★	★	★	★	★				

Table F.24 Scenario 39 simulation in detached property

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total	Energy saving
Monthly heating demand (kWh/month)	1175.65	1117.58	950.00	533.37	323.66	0.00	0.00	0.00	113.65	382.35	771.80	950.15	6318.21	100.00%
Roof PV panels outputs (kWh/month)	197.40	383.58	755.27	1048.30	1422.10	1406.98	1371.51	1270.07	825.91	504.20	240.11	135.15	9560.59	
Two wind turbines outputs (kWh/month)	668.04	554.42	558.42	435.94	349.02	257.50	255.82	282.32	338.48	519.46	566.78	637.06	5423.26	
Renewable final output (kWh/month)	692.36	750.40	1050.95	1187.39	1416.89	1331.58	1301.87	1241.91	931.51	818.93	645.51	617.77	11987.08	
Heat generation (**COP**=1.8)	1246.24	1350.72	1891.72	2137.31	2550.41	2396.85	2343.36	2235.44	1676.72	1474.08	1161.93	1111.98	21576.74	
Excess heat (kWh/month)	70.59	233.14	941.72	1603.94	2226.75	2396.85	2343.36	2235.44	1563.07	1091.72	390.12	161.83	15258.53	
Feasibility of monthly self-heating	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	
Hot water supply	★	★	★	★	★	★	★	★	★	★	★	★		

Table F.25 Scenario 39 simulation in bungalow property

Scenario 40 simulation in different property types with $51\,\mathrm{m}^2$ to $100\,\mathrm{m}^2$ floor area, 2 occupants and built 1919-44 in South West region

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total	Energy saving
Monthly heating demand (kW h/month)	1132.64	1076.70	915.25	513.86	311.82	0.00	0.00	0.00	109.49	368.37	743.57	915.39	6087.09	83.65%
Roof PV panels outputs (kW h/month)	98.70	191.79	377.64	524.15	711.05	703.49	685.76	635.03	412.95	252.10	120.06	67.58	4780.29	
One wind turbine output (kW h/month)	334.02	277.21	279.21	217.97	174.51	128.75	127.91	141.16	169.24	259.73	283.39	318.53	2711.63	
Renewable final output (kW h/month)	346.18	375.20	525.48	593.70	708.45	665.79	650.93	620.95	465.75	409.47	322.76	308.88	5993.54	
Heat generation **(COP=**1.8**)**	623.12	675.36	945.86	1068.66	1275.20	1198.42	1171.68	1117.72	838.36	737.04	580.96	555.99	10788.37	
Excess heat (kW h/month)	-509.52	-401.34	30.61	554.79	963.39	1198.42	1171.68	1117.72	728.87	368.67	-162.61	-359.40	4701.29	
Feasibility of monthly self-heating	×	×	✓	✓	✓	✓	✓	✓	✓	✓	×	×	✓	
Hot water supply			★	★	★	★	★	★	★	★				

Table F.26 Scenario 40 simulation in mid-terraced property

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total	Energy saving
Monthly heating demand (kW h/month)	1244.77	1183.29	1005.86	564.73	342.69	0.00	0.00	0.00	120.33	404.83	817.18	1006.02	6689.71	80.53%
Roof PV panels outputs (kW h/month)	98.70	191.79	377.64	524.15	711.05	703.49	685.76	635.03	412.95	252.10	120.06	67.58	4780.29	
One wind turbine output (kW h/month)	334.02	277.21	279.21	217.97	174.51	128.75	127.91	141.16	169.24	259.73	283.39	318.53	2711.63	
Renewable final output (kW h/month)	346.18	375.20	525.48	593.70	708.45	665.79	650.93	620.95	465.75	409.47	322.76	308.88	5993.54	
Heat generation **(COP=**1.8**)**	623.12	675.36	945.86	1068.66	1275.20	1198.42	1171.68	1117.72	838.36	737.04	580.96	555.99	10788.37	
Excess heat (kW h/month)	-621.65	-507.93	-60.00	503.92	932.52	1198.42	1171.68	1117.72	718.03	332.20	-236.22	-450.03	4098.66	
Feasibility of monthly self-heating	×	×	×	✓	✓	✓	✓	✓	✓	✓	×	×	✓	
Hot water supply				★	★	★	★	★	★	★				

Table F.27 Scenario 40 simulation in end-terraced property

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total	Energy saving
Monthly heating demand (kW h/month)	1356.90	1289.89	1096.47	615.60	373.56	0.00	0.00	0.00	131.17	441.30	890.80	1096.64	7292.33	77.63%
Roof PV panels outputs (kW h/month)	98.70	191.79	377.64	524.15	711.05	703.49	685.76	635.03	412.95	252.10	120.06	67.58	4780.29	
One wind turbine output (kW h/month)	334.02	277.21	279.21	217.97	174.51	128.75	127.91	141.16	169.24	259.73	283.39	318.53	2711.63	
Renewable final output (kW h/month)	346.18	375.20	525.48	593.70	708.45	665.79	650.93	620.95	465.75	409.47	322.76	308.88	5993.54	
Heat generation (**COP**=1.8)	623.12	675.36	945.86	1068.66	1275.20	1198.42	1171.68	1117.72	838.36	737.04	580.96	555.99	10788.37	
Excess heat (kW h/month)	-733.78	-614.53	-150.61	453.05	901.64	1198.42	1171.68	1117.72	707.19	295.74	-309.83	-540.65	3496.04	
Feasibility of monthly self-heating	×	×	×	✓	✓	✓	✓	✓	✓	✓	×	×	✓	
Hot water supply				★	★	★	★	★	★	★				

Table F.28 Scenario 40 simulation in semi-detached property

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total	Energy saving
Monthly heating demand (kW h/month)	1502.67	1428.46	1214.26	681.74	413.69	0.00	0.00	0.00	145.26	488.71	986.49	1214.45	8075.74	74.50%
Roof PV panels outputs (kW h/month)	98.70	191.79	377.64	524.15	711.05	703.49	685.76	635.03	412.95	252.10	120.06	67.58	4780.29	
One wind turbine output (kW h/month)	334.02	277.21	279.21	217.97	174.51	128.75	127.91	141.16	169.24	259.73	283.39	318.53	2711.63	
Renewable final output (kW h/month)	346.18	375.20	525.48	593.70	708.45	665.79	650.93	620.95	465.75	409.47	322.76	308.88	5993.54	
Heat generation (**COP**=1.8)	623.12	675.36	945.86	1068.66	1275.20	1198.42	1171.68	1117.72	838.36	737.04	580.96	555.99	10788.37	
Excess heat (kW h/month)	-879.55	-753.10	-268.40	386.92	861.51	1198.42	1171.68	1117.72	693.10	248.33	-405.53	-658.46	2712.64	
Feasibility of monthly self-heating	×	×	×	✓	✓	✓	✓	✓	✓	✓	×	×	✓	
Hot water supply				★	★	★	★	★	★	★				

Table F.29 Scenario 40 simulation in detached property

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total	Energy saving
Monthly heating demand (kW h/month)	1334.48	1268.57	1078.35	605.43	367.39	0.00	0.00	0.00	129.00	434.01	876.07	1078.52	7171.80	99.15%
Roof PV panels outputs (kW h/month)	197.40	383.58	755.27	1048.30	1422.10	1406.98	1371.51	1270.07	825.91	504.20	240.11	135.15	9560.59	
Two wind turbines outputs (kW h/month)	668.04	554.42	558.42	435.94	349.02	257.50	255.82	282.32	338.48	519.46	566.78	637.06	5423.26	
Renewable final output (kW h/month)	692.36	750.40	1050.95	1187.39	1416.89	1331.58	1301.87	1241.91	931.51	818.93	645.51	617.77	11987.08	
Heat generation (**COP**=1.8)	1246.24	1350.72	1891.72	2137.31	2550.41	2396.85	2343.36	2235.44	1676.72	1474.08	1161.93	1111.98	21576.74	
Excess heat (kW h/month)	-88.24	82.15	813.37	1531.88	2183.02	2396.85	2343.36	2235.44	1547.72	1040.07	285.85	33.47	14404.94	
Feasibility of monthly self-heating	×	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	
Hot water supply		★	★	★	★	★	★	★	★	★	★	★		

Table F.30 Scenario 40 simulation in bungalow property

Scenario 41 simulation in different property types with 51 m^2 to 100 m^2 floor area, 2 occupants and built post 1999 in South West region

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total	Energy saving
Monthly heating demand (kW h/month)	791.08	752.01	639.25	358.90	217.79	0.00	0.00	0.00	76.47	257.28	519.34	639.35	4251.47	94.64%
Roof PV panels outputs (kW h/month)	98.70	191.79	377.64	524.15	711.05	703.49	685.76	635.03	412.95	252.10	120.06	67.58	4780.29	
One wind turbine output (kW h/month)	334.02	277.21	279.21	217.97	174.51	128.75	127.91	141.16	169.24	259.73	283.39	318.53	2711.63	
Renewable final output (kW h/month)	346.18	375.20	525.48	593.70	708.45	665.79	650.93	620.95	465.75	409.47	322.76	308.88	5993.54	
Heat generation (COP=1.8)	623.12	675.36	945.86	1068.66	1275.20	1198.42	1171.68	1117.72	838.36	737.04	580.96	555.99	10788.37	
Excess heat (kW h/month)	-167.96	-76.65	306.61	709.75	1057.42	1198.42	1171.68	1117.72	761.89	479.76	61.62	-83.36	6536.90	
Feasibility of monthly self-heating	×	×	✓	✓	✓	✓	✓	✓	✓	✓	✓	×	✓	
Hot water supply			★	★	★	★	★	★	★	★	★			

Table F.31 Scenario 41 simulation in mid-terraced property

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total	Energy saving
Monthly heating demand (kW h/month)	869.40	826.46	702.53	394.43	239.35	0.00	0.00	0.00	84.04	282.75	570.75	702.64	4672.36	91.91%
Roof PV panels outputs (kW h/month)	98.70	191.79	377.64	524.15	711.05	703.49	685.76	635.03	412.95	252.10	120.06	67.58	4780.29	
One wind turbine output (kW h/month)	334.02	277.21	279.21	217.97	174.51	128.75	127.91	141.16	169.24	259.73	283.39	318.53	2711.63	
Renewable final output (kW h/month)	346.18	375.20	525.48	593.70	708.45	665.79	650.93	620.95	465.75	409.47	322.76	308.88	5993.54	
Heat generation (COP=1.8)	623.12	675.36	945.86	1068.66	1275.20	1198.42	1171.68	1117.72	838.36	737.04	580.96	555.99	10788.37	
Excess heat (kW h/month)	-246.28	-151.10	243.33	674.22	1035.86	1198.42	1171.68	1117.72	754.32	454.29	10.21	-146.65	6116.01	
Feasibility of monthly self-heating	×	×	✓	✓	✓	✓	✓	✓	✓	✓	✓	×	✓	
Hot water supply			★	★	★	★	★	★	★	★				

Table F.32 Scenario 41 simulation in end-terraced property

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total	Energy saving
Monthly heating demand (kW h/month)	947.72	900.91	765.82	429.96	260.91	0.00	0.00	0.00	91.61	308.22	622.17	765.94	5093.26	89.07%
Roof PV panels outputs (kW h/month)	98.70	191.79	377.64	524.15	711.05	703.49	685.76	635.03	412.95	252.10	120.06	67.58	4780.29	
One wind turbine output (kW h/month)	334.02	277.21	279.21	217.97	174.51	128.75	127.91	141.16	169.24	259.73	283.39	318.53	2711.63	
Renewable final output (kW h/month)	346.18	375.20	525.48	593.70	708.45	665.79	650.93	620.95	465.75	409.47	322.76	308.88	5993.54	
Heat generation (**COP=1.8**)	623.12	675.36	945.86	1068.66	1275.20	1198.42	1171.68	1117.72	838.36	737.04	580.96	555.99	10788.37	
Excess heat (kW h/month)	-324.60	-225.55	180.04	638.69	1014.30	1198.42	1171.68	1117.72	746.75	428.82	-41.20	-209.95	5695.11	
Feasibility of monthly self-heating	×	×	✓	✓	✓	✓	✓	✓	✓	✓	×	×	✓	
Hot water supply			★	★	★	★	★	★	★	★				

Table F.33 Scenario 41 simulation in semi-detached property

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total	Energy saving
Monthly heating demand (kW h/month)	1049.53	997.69	848.09	476.15	288.94	0.00	0.00	0.00	101.45	341.34	689.01	848.22	5640.42	85.85%
Roof PV panels outputs (kW h/month)	98.70	191.79	377.64	524.15	711.05	703.49	685.76	635.03	412.95	252.10	120.06	67.58	4780.29	
One wind turbine output (kW h/month)	334.02	277.21	279.21	217.97	174.51	128.75	127.91	141.16	169.24	259.73	283.39	318.53	2711.63	
Renewable final output (kW h/month)	346.18	375.20	525.48	593.70	708.45	665.79	650.93	620.95	465.75	409.47	322.76	308.88	5993.54	
Heat generation (**COP=1.8**)	623.12	675.36	945.86	1068.66	1275.20	1198.42	1171.68	1117.72	838.36	737.04	580.96	555.99	10788.37	
Excess heat (kW h/month)	-426.41	-322.33	97.77	592.50	986.27	1198.42	1171.68	1117.72	736.90	395.70	-108.04	-292.23	5147.95	
Feasibility of monthly self-heating	×	×	✓	✓	✓	✓	✓	✓	✓	✓	×	×	✓	
Hot water supply			★	★	★	★	★	★	★	★				

Table F.34 Scenario 41 simulation in detached property

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total	Energy saving
Monthly heating demand (kW h/month)	932.05	886.02	753.16	422.86	256.60	0.00	0.00	0.00	90.10	303.13	611.89	753.28	5009.08	100.00%
Roof PV panels outputs (kW h/month)	197.40	383.58	755.27	1048.30	1422.10	1406.98	1371.51	1270.07	825.91	504.20	240.11	135.15	9560.59	
Two wind turbines outputs (kW h/month)	668.04	554.42	558.42	435.94	349.02	257.50	255.82	282.32	338.48	519.46	566.78	637.06	5423.26	
Renewable final output (kW h/month)	692.36	750.40	1050.95	1187.39	1416.89	1331.58	1301.87	1241.91	931.51	818.93	645.51	617.77	11987.08	
Heat generation (**COP=1.8**)	1246.24	1350.72	1891.72	2137.31	2550.41	2396.85	2343.36	2235.44	1676.72	1474.08	1161.93	1111.98	21576.74	
Excess heat (kW h/month)	314.19	464.70	1138.56	1714.45	2293.81	2396.85	2343.36	2235.44	1586.62	1170.95	550.04	358.70	16567.66	
Feasibility of monthly self-heating	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	
Hot water supply	★	★	★	★	★	★	★	★	★	★	★	★		

Table F.35 Scenario 41 simulation in bungalow property

Scenario 42 simulation in different property types with $50\,m^2$ or less floor area, 1 occupant and built pre-1919 in South West region

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total	Energy saving
Monthly heating demand (kW h/month)	598.16	568.62	483.36	271.38	164.68	0.00	0.00	0.00	57.82	194.54	392.69	483.43	3214.69	98.33%
Roof PV panels outputs (kW h/month)	49.35	95.90	188.82	262.08	355.52	351.74	342.88	317.52	206.48	126.05	60.03	33.79	2390.15	
One wind turbine output (kW h/month)	334.02	277.21	279.21	217.97	174.51	128.75	127.91	141.16	169.24	259.73	283.39	318.53	2711.63	
Renewable final output (kW h/month)	306.70	298.48	374.42	384.04	424.03	384.40	376.63	366.94	300.57	308.62	274.73	281.85	4081.42	
Heat generation (COP=1.8)	552.05	537.27	673.96	691.27	763.25	691.91	677.94	660.49	541.03	555.52	494.52	507.34	7346.56	
Excess heat (kW h/month)	-46.11	-31.35	190.60	419.89	598.57	691.91	677.94	660.49	483.21	360.99	101.83	23.90	4131.87	
Feasibility of monthly self-heating	×	×	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	
Hot water supply			★	★	★	★	★	★	★	★	★	★		

Table F.36 Scenario 42 simulation in mid-terraced property

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total	Energy saving
Monthly heating demand (kW h/month)	590.51	561.34	477.17	267.90	162.57	0.00	0.00	0.00	57.08	192.05	387.66	477.25	3173.54	98.63%
Roof PV panels outputs (kW h/month)	49.35	95.90	188.82	262.08	355.52	351.74	342.88	317.52	206.48	126.05	60.03	33.79	2390.15	
One wind turbine output (kW h/month)	334.02	277.21	279.21	217.97	174.51	128.75	127.91	141.16	169.24	259.73	283.39	318.53	2711.63	
Renewable final output (kW h/month)	306.70	298.48	374.42	384.04	424.03	384.40	376.63	366.94	300.57	308.62	274.73	281.85	4081.42	
Heat generation (COP=1.8)	552.05	537.27	673.96	691.27	763.25	691.91	677.94	660.49	541.03	555.52	494.52	507.34	7346.56	
Excess heat (kW h/month)	-38.45	-24.07	196.79	423.36	600.68	691.91	677.94	660.49	483.95	363.48	106.86	30.09	4173.02	
Feasibility of monthly self-heating	×	×	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	
Hot water supply			★	★	★	★	★	★	★	★	★	★		

Table F.37 Scenario 42 simulation in end-terraced property

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total	Energy saving
Monthly heating demand (kW h/month)	621.19	590.51	501.97	281.83	171.02	0.00	0.00	0.00	60.05	202.03	407.81	502.05	3338.45	100.00%
Roof PV panels outputs (kW h/month)	98.70	191.79	377.64	524.15	711.05	703.49	685.76	635.03	412.95	252.10	120.06	67.58	4780.29	
Two wind turbines outputs (kW h/month)	668.04	554.42	558.42	435.94	349.02	257.5	255.82	282.32	338.48	519.46	566.78	637.06	5423.26	
Renewable final output (kW h/month)	613.39	596.97	748.85	768.07	848.05	768.79	753.26	733.88	601.15	617.25	549.47	563.71	8162.84	
Heat generation (**COP**=1.8)	1104.11	1074.54	1347.92	1382.53	1526.50	1383.82	1355.87	1320.99	1082.06	1111.05	989.04	1014.67	14693.12	
Excess heat (kW h/month)	482.91	4484.03	4845.95	41100.71	41355.48	41383.82	41355.87	41320.99	41022.02	4909.02	4581.24	4512.63	411354.67	
Feasibility of monthly self-heating	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	
Hot water supply	★	★	★	★	★	★	★	★	★	★	★	★		

Table F.38 Scenario 42 simulation in bungalow property

Scenario 43 simulation in different property types with $50\,\text{m}^2$ or less floor area, 1 occupant and built post 1999 in South West region

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total	Energy saving
Monthly heating demand (kW h/month)	435.05	413.56	351.55	197.37	119.77	0.00	0.00	0.00	42.05	141.49	285.60	351.60	2338.04	100.00%
Roof PV panels outputs (kW h/month)	49.35	95.90	188.82	262.08	355.52	351.74	342.88	317.52	206.48	126.05	60.03	33.79	2390.15	
One wind turbine output (kW h/month)	334.02	277.21	279.21	217.97	174.51	128.75	127.91	141.16	169.24	259.73	283.39	318.53	2711.63	
Renewable final output (kW h/month)	306.70	298.48	374.42	384.04	424.03	384.40	376.63	366.94	300.57	308.62	274.73	281.85	4081.42	
Heat generation (**COP**=1.8)	552.05	537.27	673.96	691.27	763.25	691.91	677.94	660.49	541.03	555.52	494.52	507.34	7346.56	
Excess heat (kW h/month)	117.01	123.71	322.41	493.89	643.48	691.91	677.94	660.49	498.98	414.04	208.92	155.74	5008.52	
Feasibility of monthly self-heating	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	
Hot water supply	★	★	★	★	★	★	★	★	★	★	★	★		

Table F.39 Scenario 43 simulation in mid-terraced property

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total	Energy saving
Monthly heating demand (kW h/month)	429.48	408.26	347.05	194.85	118.24	0.00	0.00	0.00	41.52	139.68	281.95	347.10	2308.11	100.00%
Roof PV panels outputs (kW h/month)	49.35	95.90	188.82	262.08	355.52	351.74	342.88	317.52	206.48	126.05	60.03	33.79	2390.15	
One wind turbine output (kW h/month)	334.02	277.21	279.21	217.97	174.51	128.75	127.91	141.16	169.24	259.73	283.39	318.53	2711.63	
Renewable final output (kW h/month)	306.70	298.48	374.42	384.04	424.03	384.40	376.63	366.94	300.57	308.62	274.73	281.85	4081.42	
Heat generation (**COP**=1.8)	552.05	537.27	673.96	691.27	763.25	691.91	677.94	660.49	541.03	555.52	494.52	507.34	7346.56	
Excess heat (kW h/month)	122.58	129.01	326.91	496.42	645.01	691.91	677.94	660.49	499.52	415.85	212.57	160.24	5038.45	
Feasibility of monthly self-heating	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	
Hot water supply	★	★	★	★	★	★	★	★	★	★	★	★		

Table F.40 Scenario 43 simulation in end-terraced property

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total	Energy saving
Monthly heating demand (kW h/month)	451.79	429.48	365.08	204.97	124.38	0.00	0.00	0.00	43.67	146.94	296.60	365.14	2428.06	100.00%
Roof PV panels outputs (kW h/month)	98.70	191.79	377.64	524.15	711.05	703.49	685.76	635.03	412.95	252.10	120.06	67.58	4780.29	
Two wind turbines outputs (kW h/month)	668.04	554.42	558.42	435.94	349.02	257.5	255.82	282.32	338.48	519.46	566.78	637.06	5423.26	
Renewable final output (kW h/month)	613.39	596.97	748.85	768.07	848.05	768.79	753.26	733.88	601.15	617.25	549.47	563.71	8162.84	
Heat generation (**COP**=1.8)	1104.11	1074.54	1347.92	1382.53	1526.50	1383.82	1355.87	1320.99	1082.06	1111.05	989.04	1014.67	14693.12	
Excess heat (kW h/month)	652.31	645.06	982.84	1177.56	1402.12	1383.82	1355.87	1320.99	1038.39	964.11	692.45	649.54	12265.06	
Feasibility of monthly self-heating	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	
Hot water supply	★	★	★	★	★	★	★	★	★	★	★	★		

Table F.41 Scenario 43 simulation in bungalow property

Appendix G

Components price lists & specifications

Fig. G.1 Price of TEC1-12706 module

Fig. G.2 Price of aluminum heat sink

Fig. G.3 Price of CYF-6043 cross flow fan

Fig. G.4 Price of 100 Watt 12 Volt polycrystalline solar panel

Fig. G.5 Price of 12v 200AH SLA/AGM battery

Smart choice for power™

xantrex™

Xantrex™ XW Hybrid Inverter/Charger

230 Vac / 50 Hz models

The NEXT generation inverter/charger for renewable energy systems and backup power applications

Xantrex™ brings the next generation of inverter/charger to market with the XW Hybrid Inverter/Charger, the heart of the XW System. Designed for off-grid and backup power applications, the XW can operate with generators and renewable energy sources to provide reliable power every time.

The XW Hybrid Inverter/Charger (XW) is a true sine wave inverter/charger that incorporates a DC to AC inverter, a battery charger, and an AC auto-transfer switch. It is the foundation for battery-based residential applications up to 18 kilowatts (kW), and commercial applications up to 36 kW in a three-phase configuration.

Designed with consultation and input from industry experts, dealers, and installers, the XW sets a new standard for battery-based inverter/chargers. Integrating the best features available in the market, innovative new features by Xantrex and balance-of-systems components, the XW Hybrid Inverter/Charger's design makes installation quicker and easier. The XW offers high efficiency and unprecedented surge capacity to maximize the owner's return on investment. No other inverter/charger looks or performs like the XW.

Product Features

- True sine wave output
- Single phase (230 Vac) and three phase (400/230 Vac) configurations possible
- Dual AC inputs
- Several units can be connected in parallel
- XanBus™-enabled network communication
- Unprecedented surge capacity
- Efficient, power factor corrected, high-current, multistage battery charging

Optional Accessories

Item Part Number:	
XW Conduit Box	865-1025
XW Solar Charge Controller	865-1030
XW System Control Panel	865-1050
XW Automatic Generator Start	865-1060

For more information on the XW System please visit www.xantrex.com/xw

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Fig. G.6 Specifications of bidirectional inverters

Smart choice for power™

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XW Series Hybrid Inverter/Charger - 230 Vac / 50 Hz Models

Electrical Specifications

	XW6048-230-50	XW4548-230-50	XW4024-230-50
Continuous output power	6.000 W	4.500 W	4.000 W
Surge rating	12.000 W	9.000 W	8.000 W
Surge current	53 A rms	40 A rms	35 A rms
Waveform	True sine wave	True sine wave	True sine wave
Peak efficiency	95,4 %	95,6 %	94,0 %
Idle consumption - search mode	< 7 W	< 7 W	< 7 W
AC connections	AC1 (grid), AC2 (generator)	AC1 (grid), AC2 (generator)	AC1 (grid), AC2 (generator)
AC input voltage range (bypass/charge mode)	156 to 280 Vac (230 V nominal)	156 to 280 Vac (230 V nominal)	156 to 280 Vac (230 V nominal)
AC input frequency range (bypass/charge mode)	40 to 68 Hz (50 Hz nominal)	40 to 68 Hz (50 Hz nominal)	40 to 68 Hz (50 Hz nominal)
AC output voltage	230 Vac +/- 3%	230 Vac +/- 3%	230 Vac +/- 3%
Maximum AC pass through current	56 A	56 A	56 A
AC output continuous current	26,1 A	19,6 A	17,4 A
AC output frequency	50 Hz +/- 0,1 Hz	50 Hz +/- 0,1 Hz	50 Hz +/- 0,1 Hz
Total harmonic distortion	< 5% at rated power	< 5% at rated power	< 5% at rated power
Typical transfer time	8 ms	8 ms	8 ms
DC current at rated power	131 A	96 A	178 A
Utility-interactive	Disabled (default), AC voltage range 198 to 253 Vac, AC frequency range 49,1 to 50,9 Hz		
DC input voltage range	44 to 64 V	44 to 64 V	22 to 32 V
Continuous charge rate	100 A	85 A	150 A
Power factor corrected charging	PF (0,98)	PF (0,98)	PF (0,98)

Mechanical Specifications

Mounting	Wall mount, backplate included		
Inverter dimensions (H x W x D)	580 x 410 x 230 mm (23 x 16 x 9")		
Inverter weight	55.2 kg (121.7 lb)	53.5 kg (118 lb)	52.5 kg (116 lb)
Shipping dimensions	711 x 565 x 267 mm (28 x 22.25 x 10.5")		
Shipping weight	76.7 kg (169 lb)	75 kg (165 lb)	74 kg (163 lb)
Supported battery types	Flooded (default), Gel, AGM, custom		
Battery bank size	100 to 10000 Ah		
Battery temperature sensor	Included	Included	Included
Non volatile memory	Yes	Yes	Yes
Display panel	Status LEDs indicate AC In status, faults/warnings, equalize mode, On/Off and equalize button battery level. Three-character display indicates output power or charge current		
Multiple unit configurations	Single phase: up to 3 parallel units. Three-phase: 1 unit per phase		
System network	Xanbus™	Xanbus™	Xanbus™
Warranty	5 years	5 years	5 years
Part number	865-1035	865-1040	865-1045

Environmental specifications

Enclosure type	IP 20 (sensitive electric components sealed inside enclosure)		
Operational temperature range	-25 to 70 °C	-25 to 70 °C	-25 to 70 °C

Accessories

Remote display	Optional XW System Control Panel monitors and configures all devices connected to Xanbus™ Network
Generator support	Optional XW Automatic Generator Start module connects to Xanbus™ Network. Automatically activates generator to recharge depleted battery bank or assist inverter with heavy loads
Conduit Box	Optional XW Conduit Box encloses the bottom of the inverter and protects the cabling. Provides knockouts for 3/4" (20 mm), 1" (25 mm), 1.25" (32 mm), 2.25" (60 mm), and 2.5" (65 mm) conduit
Solar Charge Controller	Optional XW Solar Charge Controller with maximum power point tracking delivers the maximum energy available from the PV array to the battery bank

Regulatory Approval

CE marked according to the following EU directives and standards: EMC Directive: EN61000-6-1, EN61000-6-3, EN61000-3-2, EN61000-3-3; Low Voltage Directive: EN50178

Specifications subject to change without notice.

Fig. G.7 Specifications of bidirectional inverters