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An experimental study of a thermoelectric heat exchange module for domestic space heating

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Abstract

The overall aim of this work is to develop a thermoelectric (TE) heating system powered by renewable energy that could compete, in the future, with current domestic heating system to reduce the greenhouse gas emissions. In this paper, our results suggest that TE modules can potentially be a solution for domestic indoor space heating whilst using renewable electricity. The test 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. Consequently and in order to ascertain its potential feasibility, a domestic heating application of TE modules to a Pre-1900s mid-terrace UK dwelling using hybrid renewable energy of solar energy and wind energy is presented. Our calculations suggest 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 64.03% and reduce the CO₂ emission of 4305.40 kg/year compared with using generic electricity radiator for the domestic space heating whilst the average heating COP remains at 1.8.

Keywords:

renewable energy, thermoelectric module, domestic heating, irradiation, solar

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1. Introduction

The Governments Low Carbon Plan sets out ambitious targets to reduce UK green house emissions by 80% of 1990 levels by the year 2050 [1]. In 2013 UK domestic dwellings contributed an approximately 16.6% to the total CO₂ emissions and were responsible for 31.1% of the UK total energy consumed [2] [3]. In 1990 and 2000 UK domestic dwellings energy consumption was 27.67% and 29.4% of the UK total, this reveals an upward trend which is driven by factors such as population growth, proliferation of household electronic devices, and increase of indoor thermal comfort level (i.e. average internal temperatures increased from 13 °C in 1970 to 18 °C in 2000) amongst others [3] [4]. If we analyse further the specific profile of the UK domestic load energy-consumption, in 2013, 66% of domestic energy-consumption was used for space heating, 17% for the water heating, 15% for lighting and appliances, and cooking accounted for a further 3 percent [3], it is clear that space heating demand accounts for the largest proportion of the total domestic final energy-consumption. Moreover, 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 [5]. The UK Government and Local Authorities are struggling to go beyond the so called "low-hanging fruit" energy efficiency measures such as loft and cavity insulation when retrofitting the existing domestic stock. Hence, if the domestic heating system could be further improved by using renewable energy sources, it could potentially contribute greatly to reducing energy consumption and carbon emissions, fuel poverty (i.e. many UK fuel poor households rely on inefficient heating systems [6]), and securing energy supply by making buildings less dependent on utility grid based heating technologies such as a gas boiler.

Currently, there are a number of theoretical and experimental studies which have explored the potential of TE modules for cooling purposes. On the other hand, the number of studies on the potential of TE modules for heating purposes is very limited. Furthermore, the main shortcoming on current research in TE modules for heating purposes in a domestic context is the lack of experimental results. Experimental results are essential so as to confirm that theoretical principles and calculations can be replicated via experimental work; and that the results are applicable to a domestic heating context. Thus, our study explores the potential of a TE air-source heat pump in a UK domestic heating context. Our results confirm theoretical expectations and, when applied to a domestic heating context, they show that a TE air-source heat pump can achieve sufficient temperature difference to satisfy theoretical UK thermal comfort levels (e.g. a temperature difference of 23.29 °C with 8 V input) whilst achieving an acceptable COP of 1.86. Moreover, we have carried 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. Our estimations show that TE heating system, powered by local hybrid renewable energy,

can partly meet the domestic heating demand and has energy and CO₂ emission saving potential (64.03% energy saving efficiency and reduce CO₂ emission by 4305.40 kg/year) for the domestic space heating whilst the average heating COP remains at 1.8.

2. Background

Thermoelectric (TE) modules are typical solid-state heat pump devices which rely on the Peltier effect and their heat exchange performance is characterised by the dimensionless figure-of-merit (ZT) (i.e. as a general rule, the larger ZT of the TE material is, the better heat pump performance (i.e. heating COP) [7]. The equation to derive the value of (ZT) can be found in [8]). Different from the traditional vapour 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 [9], 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 (see Figure 1). Thus, TE modules have zero ODP (Ozone Depletion Potential), zero GWP (Global Warming Potential), higher levels of reliability, lower working noisy and lower maintenance costs [10]. 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 (ZT) (e.g. Lincoln labs had improved the $ZT \geq 2.0$ [11]) 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 optimising the energy efficiency.

When compared with existing detailed TE studies for cooling applications [12], [10], [13], [14], [15], [16], there are relatively few studies for heating performance purposes. [17] study has shown that the heating COP of a typical VC air-conditioner (Brand: Hitach; Model: KFR-26) is 2.6-3.0 which is similar to its cooling COP values. [18] designed a system that cooled or warmed an airflow using TE units CP2-127-06L and its performance analysis reveals that for keeping the same temperature difference between the hot side and cold side of TE modules, the COP in heating mode is always better than in cooling mode. [18] test results also show that the heating COP near 2.0 can be easily reached with a temperature difference of about 10 °C but the relationships between the average temperature change, COP change and heating time if utilising this TE device to heat a enclosed indoor scenario are uncertain. A

Figure 1: (a) Schematic diagram of thermoelectric element. (b) Schematic diagram of thermoelectric module.

recent study [8] has designed a novel TE radiant air-conditioning system to cooling or heating a virtual office space with 70 m^2 floor area and 3.5 m height. This study [8] also provides theoretical simulation results of indoor heating by a TE radiant air-conditioning system but lack of experimental verifications. The simulation analysis results showed that it can produce a temperature difference of 30.1°C between the two sides of TE modules with 2.2 A current input per module when the ambient temperature is 0°C with theoretical maximum heating COP of 1.77. [19] studies an active building envelope (ABS) window-system which integrates photovoltaic (PV) and TE technologies. It reveals the test results 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 electrical connection designs and power inputs. On the other hand, in [19], although the specific heating/cooling temperature changes along with test time have been recorded and discussed, it does not provide a detailed analysis of the relationship between the COP changes and temperature difference changes of the two sides of TE modules. These results imply that the difference of the heating COP between the TE devices and conventional VC air-conditioners in the heating application should not be as large as the gap of their cooling COP comparison. Thus, these studies suggest that TE modules could be utilised for developing an indoor heating technology powered by renewable power which may compete with the traditional heating system (e.g. gas boiler or VC heat pump). However, these studies [18], [8], [19] also have shortcomings, mainly, there is a lack of experimentation data

to validate the performance of a TE module and its applicability. Hereby, there is a need for experimentation data to confirm achievable temperature differences, COP values, and operation times; and ascertaining potential feasibility in the domestic heating context whilst using renewable energy. Our paper addresses these shortcomings in the current scientific literature.

3. Experiments

The experimental set-up was designed to heat a 1 m^3 enclosed space by TEC1-12706 modules (see Table 1 and Figure 2 for specifications). Based on the test data records of the temperature change of the two surfaces of the module and the input power changes (voltage and current), we calculate the heating power outputs of TE modules and further compare the COP change under different operating conditions and ambient.

Table 1: Summary of TEC1-12706 module’s specification [20].

Specification	Range	
Hot Side Temperature ($^{\circ}\text{C}$)	25	50
$Q_{max}(\text{W})$	50	57
$\Delta T_{max}(\text{C})$	66	75
$I_{max}(\text{A})$	6.4	6.4
$V_{max}(\text{V})$	14.4	16.4
Resistance (Ω)	1.98	2.30
Length (mm)	40	
Width (mm)	40	
Thickness (mm)	3.9	

3.1. Description of experimental apparatus

A 1 m^3 enclosed test box with thermal insulation was set up for testing the space heating effect (temperature difference change) and heating performance (COP change) of the selected TEC1-12706 modules with different voltage input levels. Three pieces of this TE module were utilised to consume DC electricity and absorb heat from surrounding environment so as to heat the internal space of the box. The heating tests were conducted in lab environment and courtyard low-temperature environment.

The basic framework of the 1 m^3 volume (length 1 m; width 1 m; height 1 m) test container was built by 30mm-thick phenolic foam boards which have a fine closed cell structure with the low thermal conductivity. The test container was further covered by the loft roll (1.2m width, 150 mm thickness) for strengthening the thermal insulation between the internal test space and outside ambient. The three TEC1-12706 modules were fixed in a row and sandwiched by two aluminum fin heat sinks (dimensions: 182 x 44.5 x 200 mm; fins number: 19; thickness of the outer fin: 3mm; thickness of the internal fin: 2mm; thickness of the

bottom plate: 5mm). Both sides of TEC1-12706 modules were placed with thermal grease for promoting thermal contact with the bottom plate of heat sinks. Two cross flow fans (see Table A.1 in Appendix A) were utilized to match to the heat sinks of each side respectively for enhancing heat exchange between air flow and surface of heat sinks. The specific structure is shown in Figure 2(a, b).

Figure 2: (a) Exploded view of the container. (b) Material section, scale and dimensions. (c) Distribution of temperature measurement devices. (d) Experimental set-up in lab ambient. (e) Experimental set-up in low temperature open-air courtyard ambient.

The experiment employ a DC power supply (model: CPX400DP. See Table A.2 in Ap-

pendix A for detailed description of characteristics) which is capable of supporting a fixed range power supply by providing optional constant voltage output or constant current output. All the TEC1-12706 modules were connected electrically in parallel with this power supply. For the temperature measurements devices, the experiment utilises eight 3-wire platinum resistance temperature detector (RTD) sensors (model: PT100) (see Table A.3 in Appendix A for details) as the primary measure device to monitor the ambient temperature, internal average temperature, inlet airflow temperature, outlet airflow temperature, temperature of the hot side and cold side of TE modules respectively. All the temperature changes are recorded by a data logger (model: DT85 series3). A digital air pressure, temperature and humidity monitor (FZ-2012C) (see Table A.3 in Appendix A for details) and two digital thermometers (TL8009) (see Table A.3 in Appendix A for details) are used to monitor the data record of the internal test space before the testing and adjust the RTD test measurements if needed (i.e. in our tests experiments it was not needed). The specific distribution of the measurement devices is showed in Figure 2(c).

As shown in Figure 2(c), RTD④, RTD③ and RTD⑤ were fixed at the midpoint positions of the top one-third space, middle one-third space and bottom one-third space respectively for monitoring the temperature change. Thus the average temperature of internal space at any time is considered as the mean value of these three temperature measurement results. Moreover, RTD② and RTD① were applied to measure the airflow temperature of the inlet and outlet respectively. RTD⑥ were used to monitor the ambient temperature changes.

Caveat RTD⑦ and RTD⑧ were fixed with the bottom plate of aluminum heat sinks of 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 might 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.

3.2. Experimental operation, measurement, and assumptions

The test ambient contains lab (ambient temperature range: 19 °C to 21 °C) and open-air courtyard (ambient temperature range: 1 °C to 5 °C). The test months were December and January which usually are amongst the coldest months of the year in the UK. During each test process, the power supply keeps a constant voltage output value, and input current and temperature value of each point change with time. For the temperature monitor, the time interval setting of the data logger is 5 seconds per record. The change of the input current can be directly read via the digits screen of the power supply and recorded by notes (see in Figure 2(d, e) the lab and courtyard set-ups).

The specific voltage output range selections were: 4 V to 9 V for the laboratory environment; and 6 V to 9 V for the low temperature open-air courtyard environment. 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.

For this study, the following assumptions have been adopted: (1) the Thomson effect, and heat losses caused by convection and radiation are ignored as suggested by [21]; (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 calculations of TE modules can be simplified as:

$$W = 2N \times \alpha \times I \times \Delta T + I^2 \times R \quad (1)$$

$$Q_h = 2N \times \alpha \times I \times T_h + 0.5 \times I^2 \times R - K \times \Delta T \quad (2)$$

$$COP_h = Q_h/W \quad (3)$$

Where W is the power consumption (W); Q_h is the heat generation (W); N is the number of the thermocouples in each TE module; α is the Seebeck coefficient ($V K^{-1}$) which is determined by the properties of the conductor materials; T_h is the hot side temperature (K); ΔT is the temperature difference (K) between the hot side and cold side of the TE module; I is the transient current consumption (A) by the TE module; R is the internal electric resistance (Ω) of the TE module; and K is the total thermal conductivity ($W K^{-1}$).

The specific parameters of our tested TEC1-12706 module were given: 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 $\alpha_n = \alpha_p = 2 \times 10^{-4} V K^{-1}$; the internal electric resistance $R = 2.22 \Omega$; total thermal conductivity $K = 0.5808 W K^{-1}$; the figure-of-merit $Z = 2.3608 \times 10^{-3} K^{-1}$ (i.e. regarding the values of these parameters we have followed [22]).

Finally, [23] 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". In our study, we adopt this assumption. 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 [24]. The Chartered Institution of Building Services Engineers has more

precise guidelines [25] 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 [23].

4. Experimental results and discussion

4.1. Experimental results

In this section, we report on the experiments conducted to investigate the heating effect of our TE module. The tests were carried out in a laboratory ambient and in a low-temperature courtyard ambient, respectively.

4.1.1. Laboratory tests

Table 2: Data record of the internal test space before the testing.

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

Relevant data records of the internal test space before laboratory testing and corresponding test date are shown in Table 2. Table 3 shows data recorded at the end of the laboratory testing.

Figure 3 shows all the original temperature monitor records between the hot side and cold sides of TE modules 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 demonstrates that our TE module is 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 4 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 our TE module is 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

Figure 3: 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.

the test time goes on. To further compare the heating effects under the same conditions, within Figure 4 we have annotated the temperature values for four points in time: 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.

Table 3: Data record of the internal test space at the end of laboratory testing.

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

Figure 4: 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.

4.1.2. 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 4. Table 5 shows data recorded at the end of the open-air courtyard testing.

Table 4: Data record of the internal test space before the 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	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

Figure 5 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, the data curves in Figure 5 record all the temperature changes of 2-4 minutes before the test started, during test process, and 4-5 minutes after the test has ended. Thus, Figure 5 demonstrates that our TE module is 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 5: Temperature changes of hot side and cold side under 6 V, 7 V, 8 V, 9 V input in courtyard ambient.

Figure 6 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 6 we also annotated the temperature values for four points in time: when TE modules were powered up to start the heating test; 10 and 30 minutes after the start of test; and end of test.

The results of our courtyard tests as showed in Figure 6 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.

Figure 6: 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.

4.2. Performance discussion

Figures 3, 4, 5, and 6 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. In this section, we will use 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 our 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 litres 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 $W m^{-1} K \times \Delta T$) 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, we then define that the test reaches a steady-state regime. However, in our test results TE modules are able to reach temperatures sufficiently high from a thermal comfort perspective

Table 5: Data record of the internal test space at the end of open-air testing.

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

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.

4.2.1. The relationship between input voltage level and temperature difference

Figure 7: 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 as in Figure 7. 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. Our 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 we were to extend the heating time longer than our test time, 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.

4.2.2. The relationship between input voltage level and heating COP

Figure 8: (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

Figure 8 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 9). Moreover, Figure 8 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 a 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 our application perspective, our results suggest 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 9 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 $ZT \geq 2.0$ [11]) higher COP will be feasible.

Figure 9: Heating COP measured at the end of experiment for different ambient and input voltage levels.

4.2.3. The relationship between heating COP, temperature difference, and operation time

In this section, we analysed 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 analyse the relationship between the temperature difference, heating COP and the heat generation. Figures 10 and Figure 11 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 10(a) that

Figure 10: (a) Heating COP and temperature difference under 8V input in lab environment. (b) Heat generation and power consumption under 8V input in lab environment.

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 11(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, Figures 10(b) and 11(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.

Figure 11: (a) Heating COP and temperature difference under 8V input in courtyard environment. (b) Heat generation and power consumption under 8V input in courtyard environment.

5. Case study. A mid-terrace house.

Both solar energy and wind energy are abundant renewable source which can be directly converted into usable electricity via PV array and wind turbines respectively in a urban domestic context. Moreover, [10] shows that TE modules are capable of powering by DC electricity generated from renewable energy. Thus, combining a TE module 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. In here, we provide a case study description and relevant calculations for ascertaining an indication of the potential energy saving effect of a TE system powered with PV array and micro wind turbine to meet domestic heating demand throughout the year.

Figure 12: Case study house. (a) Surveyed plan drawings by an architect. (b) House areal view on Google®.

5.1. Design of TE modules and hybrid renewable energy system

Our case study house is a pre-1900s mid-terraced property located in Newcastle upon Tyne in the North East of England, it has 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 12). Figure 13 illustrates a potential model schematic design of the domestic heating system by employing TE modules, hybrid renewable energy supply (solar panel & small wind turbine), and suitable battery bank for our case study house. Furthermore, Figure 14 shows how the outlined schematic hybrid renewable energy supply and storage could be deployed in our case study.

Figure 13: Modeling the TE modules with hybrid energy supply & energy storage for domestic heating.

Figure 14: TE heating system with hybrid renewable energy applied in a typical mid-terrace dwelling

heat load estimation

We are able to estimate the average heat transfer (W) by the forced convection of the cross flow fan from TE modules to heating ambient (i.e. the 1 m^3 of internal space of the box) during the test processes using the Equation 4 [26].

$$P_h = C \times m \times \Delta T_{airflow} \div t \quad (4)$$

Where P is the heat transfer power, C is the specific heat capacity of the heated medium (i.e. air in this study $1004\text{ J kg}^{-1}\text{ K}^{-1}$ [27]), ($\text{J kg}^{-1}\text{ K}^{-1}$); m is the net weight of the heated airflow, (kg); t is the heating time, (s); $\Delta T_{airflow}$ is the temperature difference change (K) during the heating time t (the monitored temperature difference changes between the inlet airflow and outlet airflow are shown as in Figure 15). The airflow of the cross flow fan employed in the experiment is equal to $0.01628\text{ m}^3\text{ s}^{-1}$ whilst the air density is considered as the standard value of 1.225 kg m^{-3} . Hereby, the net weight of the heated airflow is calculated as $0.01628\text{ m}^3\text{ s}^{-1} \times 1.225\text{ kg m}^{-3} \approx 0.019943\text{ kg s}^{-1}$. Furthermore, if assume the height of the building is 3 m, then the heat transfer for each 1 m^2 floor area which is equal to 3 m^3 space will be estimated as: the average heat transfer results of the tests $\times 3$. The estimation results are shown as in Table 6.

Figure 15: Experimental temperature difference changes between outlet airflow and inlet airflow.

Table 6: Estimated heat transfer by forced convection from TE modules to heating ambient.

	Average temperature difference between outlet and inlet (°C)	Average heating power for each 1 m ² floor area (W m ⁻²)
4 V (lab)	1.07	64.41
5 V (lab)	1.27	76.35
6 V (lab)	1.70	102.06
7 V (lab)	2.05	123.43
8 V (lab)	2.49	149.66
9 V (lab)	2.92	175.33
6 V (courtyard)	2.21	132.84
7 V (courtyard)	2.73	164.12
8 V (courtyard)	3.52	211.22
9 V (courtyard)	3.96	237.74

Table 7: Case study’s building materials’ U-values and internal measurements. U-values obtained from: * [29], ** [30], *** [31].

	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 [28], carpet)	77.18	1.02 *

For calculating the heating load in our targeted mid-terrace house, we have utilised a ”whole house” procedure called: domestic heating sizing method which has been developed by the Energy Saving Trust [32], a non profit organisation 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 [29]. The domestic heating sizing method relies on a number of assumptions [29] and input parameters for heat loss calculations. In our case, the location factor is the North East of England which includes an allowance for design indoor temperatures of 19.2 °C, intermittent heating, distribution losses, 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 7). The infiltration/ventilation rate of air changes per hour uses an average value of 0.5 [30] as all chimneys of the case study property are blocked. The detailed heat losses through the building envelope are calculated as shown in Appendix A and the average heating load in the case study property is finally estimated as 87.33 W m^{-2} . Thus, it shows that the heating power of the TE system should be able to meet the domestic heating load with operating voltages equal and above 6 V (see Table 6). For meeting relatively lower domestic heating load during warm seasons, lower operating voltages (i.e. 4 V and 5 V) might be feasible.

5.2. Space heating demand and renewable energy supply

Our primary expectation is the domestic heating demands could be fully meet by the TE heating system with the local hybrid renewable energy supply throughout the year and off/on the utility grid supply. In this section, we first calculate space heating demand and then potential renewable energy supply (solar and wind) for our case study house.

Gas consumption has been recorded from Nov 2012 till Mar 2015 by using British Gas @smart energy meter reading. As a result, the calculated annual mean gas consumption of this house is 21 038.15 kWh. The median gas consumption of 20 300 kWh of the mid-terraced properties with 151 m^2 to 200 m^2 floor areas in England [33]. Thus, our case study house can be seen as representative of this type of dwelling in England.

Table 8: Gas consumption recorded from 30th Nov 2012 till 17th Mar 2015. * Data records between 18th Mar 2013 and 20th May 2013 were missing. ** Calculated monthly gas consumption based on the recorded number of days throughout the monitoring period from 30th Nov 2012 till 17th Mar 2015.

Seasons	Spring			Summer			Autumn			Winter			Annual (kW h)
Months	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	
Total gas record (kW h/month)	5067.97	1763.80	2076.17	1289.16	792.83	675.01	1458.92	2813.23	4781.12	8417.57	10084.65	9520.56	
Recorded days *	56	30	51	60	62	62	60	62	61	93	93	84	
Average monthly gas (kW h/month) **	2805.49	1763.80	1261.98	644.58	396.41	337.51	729.46	1406.62	2351.37	2805.86	3361.55	3173.52	21038.15

Table 9: Monthly gas consumption recorded for domestic heating demand. * The monthly gas consumption for domestic hot water & cooking is calculated as: $14.98 \text{ kW h/day} \times$ the actual days of each month (exclude Jun, Jul and Aug).

Months	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual kW h
Monthly gas kW h/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
Monthly hot water & cooking *	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
Monthly space demand kW h/month	2897.17	2754.08	2341.11	1314.40	797.60	0	0	0	280.06	942.24	1901.97	2341.48	15570.11

Furthermore, in general there is no space heating demand during the summer season. Then based on the calculation results from Table 8 the average daily gas consumption

in these three months (June, July and August) is calculated by $(644.58 \text{ kW h/month} + 396.41 \text{ kW h/month} + 337.51 \text{ kW h/month}) \div (30 + 31 + 31) \text{ days} \approx 14.98 \text{ kW h/day}$ which can be considered as the average daily gas consumption for the domestic hot water and cooking throughout the year. Thus if deduct these parts of gas consumption, the annual gas consumption only for meeting the domestic heating demand is finally estimated as Table 9.

Solar Energy

To calculate solar energy potential, we have used I-Scope ®[34], 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 our estimation results of the roof PV energy output. The estimated irradiator maps are shown in Figures 16. Based on the basic data harvested from i-Scope, we are able to directly estimate the monthly irradiation (kW h/month) of the total projected area of 90.32 m^2 on the case house roof. Moreover, if we employ these PV panels designed as tiles to cover all the roof area of the case house for power supply purpose, and consider the general efficiency of the Polycrystalline panel is 15.5% as suggested by i-scope calculation, then the corresponding electricity generation calculation in each month throughout the year could be simplify as: $\text{kW h/month (roof irradiation)} \times 15.5\%$ (conversion efficiency). All the detailed monthly electricity generation results by the roof PV arrays are finally given by Table 10.

Table 10: Monthly electricity generation by roof PV array of 90.32 m^2 . * The power coefficient of the Polycrystalline panel is generally considered as a average value of 15.5%.

Months	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual (kW h)
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
Monthly PV power output * kW h/month	188.34	365.96	720.58	1000.16	1356.78	1342.36	1308.52	1211.73	787.97	481.05	229.09	128.94	9121.48

Wind Energy

In additional to the solar energy potential, we have also considered the wind energy potential. By importing the specific Latitude & Longitude of Newcastle city into the NASA meteorological database [35], we obtained historical weather data (involve the monthly mean wind speed and horizontal solar radiation) as shown in Table 11. The weather statistics suggest wind resource is a strong energy candidate capable providing potential renewable energy to power the domestic TE heating system especially during the cold months when the monthly solar radiation outputs are shortage.

Based on the obtained monthly wind speed data, we employ the HOMER (Hybrid Optimization Model for Electric Renewable. See Figure 17) simulation software tool to obtain daily wind speed data with hourly resolution.

For our study, we utilise a SM-1000 wind turbine as it is suitable for the domestic context.

Figure 16: Case study house. Local roof irradiance data collected from the online i-scope irradiator map.

Table 11: Historical weather data statistics of Newcastle upon Tyne by NASA meteorological database. ([35])

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 (kW h/(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

Appendix Table A.4 and Figure A.20 summarise the performance parameters of a SM-1000 wind turbine. These performance parameters have been imported into HOMER as shown in Figure 18 so as to calculate the monthly wind power output (kW h/month) using SM-1000 daily wind energy output at an hourly resolution (see Table 12) .

Table 12: The simulation results of the monthly outputs of the SM-1000 wind turbine employed in Newcastle upon Tyne.

Region	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual (kW h)
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

5.3. Results and discussion

The following assumptions have been adopted to estimate the supply-demand relationship:

(1) PV arrays cover all the roof area (see Figure 14) and the PV panel efficiency can be generally considered as 15.5% suggested by I-Scope ®[34];

(2) 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 (see Figure 14);

(3) the average heating COP of TE modules is assumed as a minimum test value of 1.8;

(4) 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

Figure 17: Parameters used in HOMER for converting monthly wind speed data into daily wind speed data

and control the charging voltage of batteries) is assumed as 20% of initial power production of the hybrid renewable energy (solar and wind energy);

(5) when TE heating system needs additional power from the utility grid during any periods of the renewable energy shortage, the AC current supplied by the grid will 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;

(6) the energy efficiency of a general electric heater is typically considered as 100% [36].

The monthly supply-demand results can be estimated as shown in Figure 19.

Figure 19 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 1297.51 kWh/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

Add/Remove SM-1000

WIND TURBINE Name: SM-1000 Abbreviation: SKYM Remove Copy To Library

Properties

Name: SM-1000
Abbreviation: SKYM
Rated Capacity (kW): 1.50
Manufacturer: SkyMax Wind
Weight (lbs): 101

Costs

Quantity	Capital (\$)	Replacement (\$)	O&M (\$/year)
1	\$1,329.00	\$1,137.00	\$40.00

Click here to add new item

Multiplier:

Site Specific Input

Lifetime (years): Hub Height (m):

☐ Consider ambient temperature effects?

Electrical Bus ☐ AC ☒ DC

Power Curve **Turbine Losses** **Maintenance**

Wind Speed (m/s)	Power Output (kW)
0	0
2.49	0
2.5	0.007
3	0.0125
4	0.04

Wind Turbine Power Curve

Figure 18: SM-1000 wind turbine specifications in HOMER interface.

Figure 19: The supply-demand relationship of the domestic heating by using TE heating system with the hybrid renewable energy supply.

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 shortage period.

Furthermore, and based on the results of Figure 19, we could calculate 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: $(2202.78 \text{ kW h} + 1900.24 \text{ kW h} + 937.42 \text{ kW h} + 1253.24 \text{ kW h} + 1770.72 \text{ kW h}) \div 1.8 \div (1 - 20\% \text{ of the energy loss by the AC/DC conversion}) \approx 5600.28 \text{ kW h/year}$. Then if compare with the potential grid electricity consumption of the general electric heater which is equal to the total heating demand of $15\,570.11 \text{ kW h/year}$ 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: $(15\,570.11 \text{ kW h/year} - 5600.28 \text{ kW h/year}) \div 15\,570.11 \text{ kW h/year} \approx 64.03\%$.

In terms of potential carbon savings, 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 [37]. Therefore the carbon saving contributions of the entire system will also be simply estimated. The adopted assumptions, factors, and calculation in terms of the CO₂ emission estimation are presented in the appendix (see Appendix A). Thus, TE module's potential annual CO₂ emissions, when powered by the presented hybrid energy system, are $2856.85 \text{ kgCO}_2/\text{year}$. Similarly, for the same case study, a generic electric heater's potential annual CO₂ emissions are $7162.25 \text{ kgCO}_2/\text{year}$ (see Appendix A). Consequently, a potential estimation of CO₂ emission reduction is $4305.40 \text{ kgCO}_2/\text{year}$.

5.4. Discussion on application issues

To apply a TE heating system with a hybrid renewable energy supply serving in a UK domestic building, the solar panels ought to cover as much roof area as possible for maximising solar energy collection. The appropriate number of stand-alone micro wind turbines should be determined in a case by case basis based on local factors such as the house footprint area and wind speeds. 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, 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. As a result, the grid-connected circuit ought to be able to be used to provide additional power supply or trade excessive renewable energy generation.

Additionally, TE modules ought to be inlaid in the external wall of the building for absorbing outside ambient heat and heating the indoor space. Based on our experimental

and estimated results, for heating a building with total floor area of 180 m^2 , 1620 pieces of TEC1-12706 modules which would occupy about 2.6 m^2 of the exterior wall area whilst could provide minimum $11\,593.80\text{ W}$ and maximum $42\,793.20\text{ W}$ of heat to meet the building space heating load. Our experimental study results 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 the TE heating modules should be selected on the south-facing building exterior wall which intends to maximize the COP of TE modules. The system application should also consider to further inlay a certain amount of TE modules on the building interior walls for adjusting the heat distribution of the building interior space or to collect the waste heat from bathroom or kitchen. TE modules in interior walls should be positioned carefully, similarly to standard panel radiators, as potential high surface temperature may cause thermal discomfort due to radiant asymmetry. New smart heat control implementations should benefit from TE modules' capability of switching heat flow transfer direction by simply revising the electric current direction.

6. Conclusions

In this study a potentially hybrid renewable energy driven TE module for space heating is proposed and tested. A heating test apparatus has been built and theoretically contextualised. The experimental results has been provided both for a laboratory and a low-temperature courtyard environment. To ascertain an indication of the potential energy saving efficiency of the whole system to meet domestic heating demand, a realistic case study and relevant calculations have been presented. Conclusions can be drawn as follows:

1. TE modules could achieve the required temperatures differences so as to potentially satisfy UK thermal comfort levels. Furthermore, we have also indicated potential operational modes for TE modules as our results 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).
2. 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 (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 $ZT \geq 2.0$ [11]), TE modules with higher COP will be feasible.

3. An energy saving efficiency of 64.03% and a reduction of CO₂ emission of 4305.40 kg/year could be potentially achieved by utilising the TE heating system powered by hybrid renewable energy instead of using a generic electricity radiator for the domestic space heating. This suggests that our system has potential for both energy and carbon savings.

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Nomenclature

Acronyms

ABS	active building envelope
AR	absorption refrigeration
COP	coefficient of performance
GWP	global warming potential
ODP	ozone depletion potential
TE	thermoelectric
VC	vapor compression

Symbols

$\Delta T_{airflow}$	temperature difference between the inlet airflow and outlet airflow (K)
α	Seebeck coefficient (V K ⁻¹)
ΔT	temperature difference between between the hot side and cold side of TE module (K)
C	specific heat capacity of the heated medium (J kg ⁻¹ K ⁻¹)
COP_h	heating COP
I	current (A)
K	thermal conductivity of TE module (W K ⁻¹)

m	net weight of the heated airflow (kg)
N	number of thermocouple
P_h	heat transfer power from TE modules to heating ambient (W)
Q_h	heat generation (W)
R	electric resistance of TE module (Ω)
t	heating time (s)
T_h	hot side temperature of TE module (K)
W	power consumption (W)
ZT	figure-of-merit

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Appendix A. Appendix

Detail description of experiment and measurement devices' specifications

Table A.1: Cross flow fan parameters

Cross Flow Fan							
Model	Dimensions (mm)	Number	(DC) (V)	(Current) (A)	Speed (RPM)	AirFlow (CFM)	Max. Pressure (mmH ₂ O)
AXL30150HC-1201	195 x 50 x 48	2	12	0.28 ±10%	1750±10%	34.5	2.5

Table A.2: Power supply paremeters.

Power supply						
Model	Number	Output range DC (V)	Output range((A)	Power range (W)	Voltage setting accuracy	Current setting accuracy
CPX400DP	1	0 to 60	0 to 20	up to 420	1mV ±(0.05% + 10mV)	1mA ±(0.3% + 5mA)

Table A.3: Temperature measurement devices parameters

Devices								
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)/ ± 0.3(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%

Detail description of wind turbine specifications

Figure A.20: Performance parameters of SM-1000 wind turbine.

Table A.4: Wind turbine parameters

Wind turbine						
Model	Type	Rated output (kW)	Peak output (kW)	Start up speed (m/s)	Rated wind speed (m/s)	Rotor Diameter (m)
SM1000	HAWT	1	1.2	2	12	1.96

Heat loss estimations in the case study house

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

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

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

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

Heat loss from solid wooden doors half glazed with double glazing: $5.52 \text{ m}^2 \times 2.50 \text{ W m}^{-2} \text{ K}^{-1} = 13.80 \text{ W K}^{-1}$ (As indicated by [31], a solid wooden door (U-value of $3.00 \text{ W m}^{-2} \text{ K}^{-1}$ [31]) half glazed with double glazing (U-value $2.00 \text{ W m}^{-2} \text{ K}^{-1}$ [29]) could has a resultant U-value: $0.5 \times (3.00 \text{ W m}^{-2} \text{ K}^{-1} + 2.00 \text{ W m}^{-2} \text{ K}^{-1}) = 2.50 \text{ W m}^{-2} \text{ K}^{-1}$)

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

Heat loss from indoor roof: $79.08 \text{ m}^2 \times 0.29 \text{ W m}^{-2} \text{ K}^{-1} \approx 22.93 \text{ W K}^{-1}$

Heat loss from indoor floor: $79.08 \text{ m}^2 \times 0.66 \text{ W m}^{-2} \text{ K}^{-1} \approx 52.19 \text{ W K}^{-1}$

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

Therefore the total heat loss from external surface and infiltration/ventilation can be summarized by: $(12.24 \text{ W K}^{-1} + 18.00 \text{ W K}^{-1} + 7.50 \text{ W K}^{-1} + 7.92 \text{ W K}^{-1} + 13.80 \text{ W K}^{-1})$

$$+ 178.67 \text{ W K}^{-1} + 22.93 \text{ W K}^{-1} + 52.19 \text{ W K}^{-1} + 77.35 \text{ W K}^{-1}) \times 30 \text{ (location factor)} = 11\,718.25 \text{ W}$$

Moreover, heat losses to adjacent dwellings via party walls are suggested by [29] estimating based on a room temperature difference of 10.6°C includes an allowance for possible prolonged periods during which an adjacent property remains unheated.

The party heat loss to adjacent properties can be estimated as: $136.80 \text{ m}^2 \times 1.33 \text{ W m}^{-2} \text{ K}^{-1} \times 10.6^\circ\text{C} \approx 1928.61 \text{ W}$

Finally the average heat load demand estimation result in this property will be: $(11\,718.25 \text{ W} + 1928.61 \text{ W}) \div (79.08 \text{ m}^2 + 77.18 \text{ m}^2) \approx 87.33 \text{ W m}^{-2}$

Heat loss is a worse case scenario estimation. For instance, we have considered party wall losses but these could be completely ignored as adjacent properties could be heated to the same standards.

Carbon emissions assumptions, factors and calculation

(1) the average CO_2 emission factor of the UK grid electricity consumption will utilize the value of $0.46 \text{ kgCO}_2/\text{kW h}$ (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 [38];

(2) before connect into the batteries or the grid, the CO_2 emission factor of the initial output of roof PV array is assumed as $0.058 \text{ kgCO}_2/\text{kW h}$ [39] and the CO_2 emission factor of the micro wind turbine is assumed as $0.045 \text{ kgCO}_2/\text{kW h}$ [37]. 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.

Calculation: the annual CO_2 emission ($\text{kgCO}_2/\text{year}$) caused by TE modules, when powered by the presented hybrid energy system, in the case study domestic scenario is simply calculated as: solar electricity production which is potentially consumed for the domestic heating purpose throughout the year $\times$ CO_2 emission factor of PV arrays + the part of initial wind electricity production which is potentially consumed for the domestic heating purpose throughout the year $\times$ CO_2 emission factor of wind turbine + additional grid electricity consumed for the domestic heating purpose during the renewable energy shortage periods throughout the year $\times$ grid CO_2 emission factor $\approx 2856.85 \text{ kgCO}_2/\text{year}$.

Calculation: the annual CO_2 emission ($\text{kgCO}_2/\text{year}$) caused by employing generic electric heaters in the case study domestic scenario is simply calculated as: the annual grid electricity consumption of the generic electric heater $\times$ average CO_2 emission factor of the utility grid power $\approx 7162.25 \text{ kgCO}_2/\text{year}$.