# The Energy Performance and Techno-Economic Analysis of Zero Energy Bill Homes

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# Abstract

In the past 12 years, the United Kingdom (UK) has made significant progress in making domestic dwellings more efficient. Presently, the domestic sector is required to meet the UK's net-zero target in new and renovated dwellings by 2050. As a measure in this on-going determination, the UK has constructed a number of Zero Energy Bill Homes (ZEBH) in Corby, Nottinghamshire, which is currently a part of the European Union District of Future Project. For the effectiveness of a zero energy bill performance, a solar photovoltaic thermal-assisted heat pump (SPVTAH) was modelled, which represented building modelling, emphasising the essential outcomes through energy demand profiles (electricity, space heat, and domestic hot water), and occupant behaviour. To authenticate the building modelling, the baseline models were calibrated using the weekly electricity-use curve and validated using statistical indices. It is inferred that the evidence-based manual calibration technique has fairly validated the energy-use profiles of the chosen case studies and is found to be within acceptable tolerance levels. In addition, to verify the zero-energy bill status of the buildings, an economic analysis was extremely crucial. A feasibility assessment indicated that the ZEBH concept will be impractical if the UK government subsidies are withdrawn. Moreover, the Net Present Value analysis further signified that although SPVTAH seemingly generates revenues, the initial investment turned out to be the largest barrier to repay for the system. However, it was proven that the renewable energy technology operational in the domestic dwellings of the UK does offer major advantages, and reduction in costs appears to be the most significant one.


*Keywords: EnergyPlus, Building Modelling, Calibration, Heat pump, Simulation, Zero Energy Bill Homes, Economic Analysis, Solar Photovoltaic Thermal-Assisted Heat Pumps*

# 1. Introduction

During the past few years, the United Kingdom's (UK's) population has witnessed a reduction in the usage of fossil fuels since the Climate Change Act 2008 came into effect [1]. Fossil fuel usage has reduced with a shift to cleaner sources, due to generation change, with low-carbon supplies making up a record of 53% of the total fossil fuel usage in 2018. This mostly resulted from the growth of wind power, which increased by 16% in 2018 [1]. Reductions in coal use have driven the majority of carbon reductions in recent years, whereas reductions in gas use were more significant in driving this change in the last decade [2]. Currently, coal accounts for only 5.3% of the total primary energy consumed in the UK, down from 22% in 1995. Moreover, the UK government has pledged to close all coal-fired power stations by 2025 [3].

Coal use in the UK was mostly steady during the late 1990s till 2014, with declines in gas and oil uses causing most of the reductions in carbon emissions. However, coal use fell precipitously between 2014 and 2017, declining by nearly 75% compared to the values of 2013. The fall in coal use in recent years is responsible for the bulk of carbon dioxide (CO2) reductions in the UK over the past decade [4]. In 2017, the share of renewables generation was at a record high of 29.3%, up from 24.5% in 2016, due to increased renewables generation capacity (wind and solar) and more favourable weather conditions for wind generation [5]. Thus, the UK government, with support from the Business, Energy and Industrial Strategy (BEIS) Committee, has decided to achieve net-zero greenhouse gases (GHGs) emission by the year 2050, compared to the amount used in 1990 [6] [7].

In the UK, a considerably large number of buildings are supplied energy by national gas and electricity companies, which accounts for a significant amount of gas emissions. Therefore, to meet the above-mentioned targets, insulation levels of the building envelope are being increased, low carbon technologies (LCTs) such as solar photovoltaic thermal (PV/T) systems are being installed in dwellings [8], and air source heat pumps (ASHPs) are being implemented.

Since then, there has been a number of evaluations in different types of buildings, such as Zero Carbon Homes, Net Zero Energy Buildings, and Nearly Zero Energy Buildings; however, research on suitable techniques to evaluate the significance of Zero Energy Bill Homes (ZEBHs) is still lacking. Thus, this paper presents four models and simulations of ZEBHs, demonstrating the zero-bill status concept with the aid of an economic analysis along with a description of the technology applied. Previous researchers such as P. Foraboschi have used methods such as structural glass in order to achieve ZEBH [9], however, in this work detailed building modelling, dynamic simulations, calibration following the recommendations in ASHRAE Guideline 14 (for simulation validation purposes), and an economic analysis; in order to assess the ZEBH status. Furthermore, the technology applied in each ZEBH was SPVTAH systems. The SPVTAH systems used in the study of each ZEBH, refers to energy supply systems which supply heat and electricity in order to cater to the demands and needs of each household as well as interacting with the grid in terms of import/export, and FiT.

# 2. Literature Review

This section presents a review on the different type of buildings in the UK, and work achieved by other researchers. The type of buildings, that were reviewed are Zero Carbon Home (ZCH), Net Zero Energy Buildings (NZEB), and nearly Zero Energy Buildings (nZEB). Finally, the novel concept of ZEBHs was introduced, in order to elaborate on the different definitions, advantages/disadvantages and critically review the difference between ZEBHs and the above-mentioned buildings.

## *2.1 Zero Carbon Homes*

A Zero Carbon Home (ZCH) is a home that produces neutral or negative $CO_2$ emissions over a year. Such houses generate enough energy from zero-carbon sources such as solar photovoltaics (PVs) to offset any fossil fuel-derived energy [10]. However, the definitions, broadly speaking, the global definitions, of ZCH slightly vary. In the UK, ZCH is formally defined as follows:

'*Homes whose net carbon dioxide emissions, taking account of emissions associated with all energy use in the home, including heating, lighting, hot water, is equal to zero or negative across the year*' [11].

To achieve the status of a ZCH, a three-step approach is implemented. The first step requires achieving high-level energy efficiency in the building fabric and design, i.e. Fabric Energy Efficiency (FEE). This warrants improving the U-values of the building fabric or investigating the external and integral heat gains [12]. The second step necessitates meeting the minimum carbon reduction levels through on-site generation and implementation of other LCTs; this step is termed 'carbon compliance'. Finally, to achieve a zero-carbon status, a range of measures, known as 'allowable solutions', which go beyond meeting the minimum carbon compliance requirements must be implemented. These solutions include on-site measures such as installing smart appliances and off-site measures such as investing in energy-from-waste technologies or retrofitting LCTs and establishing communal buildings. However, the scope of the allowable solutions has been criticised, as it continues to expand, allowing further afield solutions to contribute to the attainment of ZCH status [13] and raising the question as to whether off-site investments should be considered during a zero-carbon evaluation of a home or not.

In response to the criticism related to allowable solutions and the broadening definition of ZCH [14], the UK government conducted a consultation. Upon the consultation, the government suggested that they themselves will provide a national framework for allowable solutions, rather than leaving it to the local authorities, so as to ensure national consistency and maximise the chances of fulfilling the aims [15]. However, studies have shown that a significant portion (37–45%) of GHG emissions from domestic energy use is not controlled by the above legislation [14] [15].

The Code for Sustainable Homes is a voluntary national standard that guides the designing and the construction of sustainable dwellings to ensure reductions in emissions and energy use beyond the current UK building regulations. Reaching the code's level 6 results in obtaining the ZCH status [14]–[16].

## *2.2 Net-Zero Energy Buildings*

The Net-Zero Energy Buildings (NZEB) approach is used to develop climate-neutral buildings, along with buildings of other concepts, based on energy-efficient buildings with almost carbon-neutral grid supply.

NZEBs are designed to overcome the presenting limitations through a non-100% 'green' grid infrastructure. This strategy involves exploiting the local renewable energy sources (RES) on-site and exporting the surplus energy generated there to utility grids in order to increase the share of renewable energy within the grids, thereby reducing resource consumption and associated carbon emissions [17].

However, the wide diffusion of distributed generation, especially in the power grid, may cause problems pertaining to power stability and quality in the current grid structures, mainly at the local-distribution grid level. At present, 'smart grids' are being developed to fully benefit from the distributed generation in the context of reducing their primary energy, carbon emission factors, as well as operating costs [18]. For the least-cost planning approach, the on-site measures have to be compared with the measures at the grid level, which take advantage of the economy of scale and equalisation of local peaks. However, mere satisfaction of the annual balance itself is clearly not a guarantee that a building is designed to minimise its (energy-use-related) environmental impact [19]. In particular, NZEBs should be designed – within the extent of the control of the designers – to ensure that they work in synergy with the grids and do not place additional stress on their functioning.

Notably, a formal, comprehensive, and consistent framework that considers all the relevant aspects that characterise NZEBs and allows a consistent definition of NZEB in accordance with the UK's political targets and specific conditions is absent. The framework described in this section is based on the concepts found in the literature and has been further developed in the context of Towards Net-Zero Energy Solar Buildings, a joint project of the IEA (International Energy Agency), the SHC (Solar Heating and Cooling programme) – Task40 – and the ECBCS (Energy Conservation in Buildings and Community Systems) – Annex 52 [20].

The underlying mechanism involved in describing an NZEB relates to defining the boundary of a building system, including on-site energy generation [21]. Incorporated in this boundary is the energy consumed from all energy sources – conventional and renewable – and also any form of renewable energy exported to the grid.

Following this, a weighted system of demand and supply is compared to assess whether or not a net-zero balance of the designer's choice can be achieved with the given technological solution that graphically depicts this framework. The evaluator could have chosen the weighted metric to be energy, $CO_2$ emissions, cost, or even comfort levels, highlighting the benefit of a flexible definition.

Reference [22] provided an overview of the relevant terminologies associated with energy use in buildings and the connection between buildings and energy grids. The reduction of emission from the domestic sector of NZEBs starts with promoting insulation and fabric efficiency, followed by energy efficiency, and finally, micro-generation. While renewable generation is essential in an NZEB, a primary reduction in heating demand through increased fabric efficiency and the use of energy-efficient technology are also important [22].

The key areas were improving the U-values of building components (walls, roofs, floors, and windows), reducing thermal bridging, and increasing the airtightness of buildings. Other possible measures such as energy-efficient ventilation and heat and wastewater recovery were also considered. It should be noted that heat transfer and building performance are influenced by thermal conduction, convection, and radiation. The U-value, which is derived from the thermal resistances of building materials, represents their thermal conductance, which is an important value that represents the heat transfer coefficient of buildings. Changing building materials or adding insulation can improve the U-value of building components such as walls, roofs, and floors; however, the feasible thickness of the provided space and thermal bridging must be accounted for [23]. An experimental analysis of an NZEB housing development conducted in the UK led to the finding that the overall effects of fabric efficiency, such as insulation or double glazing, aid in maintaining building performance for over at least the medium term of about 20 years [24]. The transition of the domestic sector into the role of an energy provider, and not solely a consumer of heat and electricity, will be necessary for the UK to meet both its renewable energy and carbon emission reduction targets [24]. A range of technologies that can be used for the development of NZEB has been presented in reference [25]. It should be noted that research has indicated the existence of a gap between energy savings and the cost of energy-saving or generation systems, which limits houses from achieving the NZEB status [25]. This emphasises the need for renewable technologies that help provide significant cost and performance benefits to an occupant, as compared to conventional energy systems.

## *2.3 Nearly Zero Energy Building*

Article 2 of the Energy Performance of Buildings Directive (EPBD) states the following:

'*A nearly-zero energy building is a building that has a very high energy performance for both-cooling and heating purposes. The nearly zero or very low amount of energy required should be covered to a very significant extent by energy from renewable sources, including energy from renewable sources produced on-site or nearby*' [26].

The EPBD provides a qualitative, not a quantitative, definition of a nearly Zero Energy Building (nZEB), which is different from the NZEB described in the previous section [27]. In the UK, the term 'nearly-zero carbon building' was introduced instead of the term 'nearly-zero energy building'. The use of renewable technologies is not obligatory; however, in light of the recast EPBD, it can be stated that proper consideration must be given to the use of 'high-efficiency alternative systems' such as renewables, district heating, heat pumps, and combined heat and power [28]. The EPBD recast requires the establishment of a comparative methodology framework for nZEBs using the cost optimality method; through this, the EPBD recast specifies the minimum energy performance requirements level for new buildings and renovations by developing a benchmark method in order to achieve cost-optimal outcomes [29]. The global cost (life-cycle cost) vs. the primary energy consumption of different packages of measures (combinations of compatible energy efficiency and energy-supply measures) can be assessed by calculating and comparing the energy-related costs [30].

As presented in reference [29], to establish a comprehensive overview, all the combinations of commonly-used and advanced measures should be assessed as packages of measures to identify the cost curve.

To meet the requirements of the building legislation, it is important to identify the main drivers and barriers to achieve the performance level of an nZEB. Regarding the refurbishment drivers that aid the existing buildings in reaching the nZEB level, the first precondition is the transposition of the definition of nZEB into the national legislation [31].

In the UK buildings, energy cost savings, lower dependence on energy suppliers, and improved comfort are the major common drivers of renovation.

The inclusion of energy aspects in planned renovations seems to depend greatly on government support programmes, such as grants, tax deductions, and low-interest loans. The Energy Performance Certification database makes it easy for energy experts to choose potential buildings for major renovations [28]. With respect to the major common barriers, some specific technical issues pertaining to the absence of a specific boundary in defining nZEB's balance were identified. High initial investment costs together with the lack of financial instruments and limited technical skills can also be considered as significant barriers [32]. Reference [33] lists the identified drivers and barriers in the context of the UK.

## *2.4 Zero Energy Bill Homes*

The concept of a Zero Energy Bill home (ZEBH) was first launched in March 2016 [34] at the Building Research Establishment (BRE) Innovation Park in Watford as an innovative response to the housing crisis at that time [35]. The ZEBH incorporates integrated energy-generation facilities, demonstrating how investment needed from hosuing facilities for centralised national infrastructure could be reduced by becoming net exporters of renewable energy. A ZEBH is a building that offsets energy bills, generating more electricity than the amount needed in a year, considering the Feed-in Tariff (FiT) concept. Such dwellings are built of construction materials with high resistance levels. Furthermore, the rooves of these dwellings are fitted with solar PV panels. Under the FiT scheme, the electricity generated by these PV panels helps earn revenues, which when combined with the surplus electricity generated by the PV panels results in income and saving that exceed the residual cost of electricity. This paper presents a number of ZEBHs that consider installing solar PV/T panels assisted by heat pumps. This type of home that integrates technology with huge potential helps deal with the ever-rising energy bills and reduce fuel poverty; however, a high capital cost is required during installation.
A ZEBH's thermal performance is balanced among insulation, thermal mass, and airtightness. Insulation assists in retaining heat inside the house, while thermal mass stores the heat in the house, ensuring a stable internal temperature. In addition, airtightness prevents undesired air exchange between the interior and exterior of the house. The ZEBHs presented in this study were modelled using the data related to the real building fabric material.

A ZEBH can consume approximately 50% of the energy generated by solar PV panels, reducing the need for electricity exported from the supply grid by 30%. On the other hand, the imported grid electricity constitutes approximately 20% of the annual energy load [35]. The FiT scheme is crucial for a ZEBH in achieving the annual zero-energy bill status. The PV/T panels presented in this paper are connected to the electricity grid so as to achieve the maximum income from the FiT for every kilowatt of surplus energy. This excess electricity is exported to the grid to allow every surplus electricity unit to be used as an offset.

From the different types of buildings, including ZCH, NZEB, and nZEB, it can be noted that in the NZEB and nZEB, there is a gap between energy savings and their costs, which limit houses from becoming NZEBs and/or nZEBs. However, the ZEBHs fill this gap by maximising FiT revenue streams from the electricity-generating systems of solar PV installed in such houses. Thus, households can benefit from the UK's FiT system and achieve the zero-energy bill status by producing more electricity than that is needed.

### *2.4.1 Reduction of FiT and Impact on ZEBHs Viability*

The FiT scheme was introduced to support the widespread adoption of proven small-scale (up to 5MW) low-carbon electricity generating technologies. The scheme was intended to give the wider public a stake in the transition to a low-carbon economy and in turn foster behavioral change that would support the development of local supply chains and reductions in energy costs.[36] The FiT scheme is funded through levies on electricity suppliers, and ultimately consumers, regardless of whether or not they directly participate in the scheme. That is why controlling costs was paramount in the reviews of the scheme in 2011 and 2015, the latter of which provided consumers and industry with clarity on levels of small-scale low-carbon electricity support until March 2019 [37].

Electricity generation has been a significant contributor to greenhouse gas emissions and government intervention has been necessary to ensure market incentives are sufficient to meet the UK's climate change commitments. To this end, the FiT scheme has been one of the key enablers in driving the uptake of a range of small-scale low-carbon electricity technologies. As costs decline and new, smart technologies become accessible, market incentives are beginning to align with government objectives meaning that it is important that interventions reflect such development and do not place an undue burden on consumer bills. Therefore, with a reduction in FiT, it could lead to a consequent lack of viability of achieving ZEBH in the UK [35].

# 3. Building Modelling Tool

The building modelling tool used in this study has certain unique attributes and specific applications. Such tools used for simulation purposes, such as modelling of building geometry, renewable energy systems, electrical/lighting equipment, and heating systems, include EnergyPlus and DesignBuilder [38] [39].

EnergyPlus, developed by the US Department of Energy (DOE) [39], is one of the most recognised and validated building energy simulation software tools. This tool employs dual energy simulation engines – DOE-2 and Building Loads Analysis and System Thermodynamics (BLAST) systems [40]. The BLAST indicates aggregation of programs developed to estimate energy consumption and the performance of energy systems using thermodynamic equations. Meanwhile, the DOE-2 uses the weighted heat balance approach.

Nevertheless, the E+ is not equipped with any graphical user interface (GUI) that would allow its users to clearly visualise the building concept. Therefore, as the E+ software is not equipped with a GUI, DesignBuilder with a GUI [38] was utilised to complete the task of modelling the geometry of the ZEBHs. In order to do so, first, floor plans were built as per the CAD format using the AutoCAD software package. Afterwards, the CAD files were imported from the DesignBuilder software package to develop the ZEBHs 3D model whilst using the building fabric data.

# 4. Zero Energy Bill Homes Description

This study investigated four residential single-family homes, with the standard semi-detached ZEBHs, which are referred to as Electric Homes (EHs) 272, 273, 274, and 349. This novel concept has been recently adopted in the community of Corby, England, under a European Union project called 'the District of Future' (DoF) [41]. In this study, each dwelling, along with its own energy supply system, were modelled by featuring characteristics such as occupancy, activity profiles, building fabric materials, and weather profiles.

Figure 1 illustrates the actual representation of the ZEBHs and the site plan, indicating each EH with the designated plot number facing the north-east direction.


*Figure 1: Left- ZEBHs building aspect and Right - site plan highlighting the Electric Homes facing North-East*

These dwellings feature building materials with low U-values, storage systems (thermal), heat pumps, and solar PV panels on top of the roof. A zero-energy bill status can be achieved with the UK's FiT and the export of excess electricity to the electricity distribution grid [42].

The target of ZEBHs is to produce sufficient energy that can fulfil their annual energy consumption need, and this target can perhaps be achieved using technologies such as photovoltaic thermal (PV/T) panels [43]–[45]. Since the UK has set targets on energy demand and GHGs emissions reduction [46], it is expected that ZEBHs will be commonly used in the future [46].

To meet the requirements of ZEBHs, the total amount of energy generated by the solar PV systems in the buildings can potentially cover the occupants' needs and return the excess energy to the grid (see Figure 2).

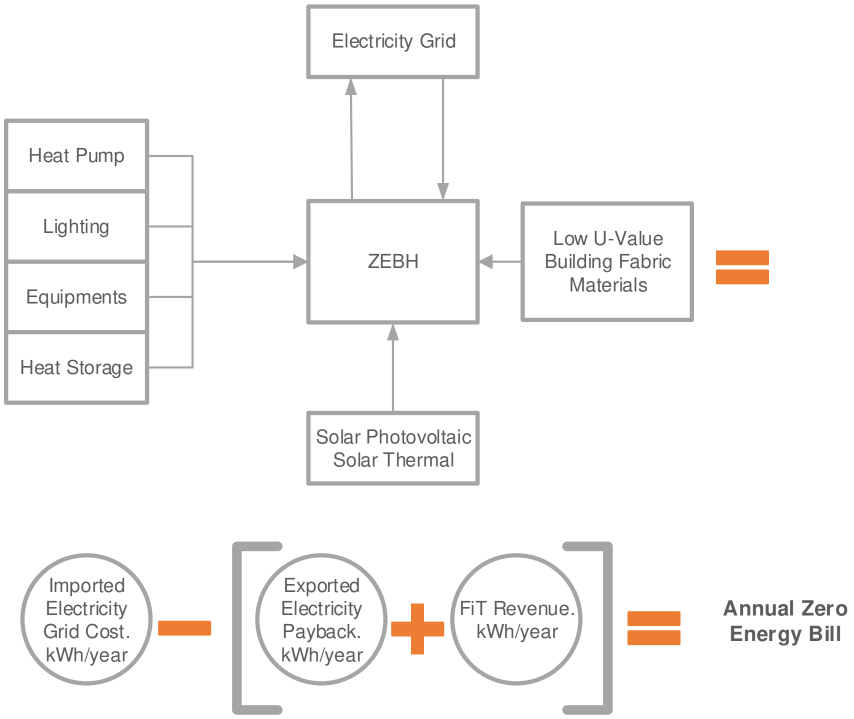



*Figure 2: ZEBH concept*

To ensure the feasibility of the ZEBHs, an economic assessment was conducted; thus, the following aspects were considered:

1. The cashback revenue of every electricity unit generated;
2. The financial reward for every excess unit exported to the grid;
3. The cost of electricity unit imported to cover the demand when no electricity is generated by the PV panels (e.g., during nights);
4. The period of time when only solar power is used without importing electricity from the grid;
5. The capital expenditure on a solar PV system and maintenance costs against the income generated during its lifetime.

Through building-grid interaction, the ZEBH has become an active part of the renewable energy infrastructure. A ZEBH possesses the unprecedented potential to transform the way buildings use energy. The advantage of a ZEBH is that it helps exempt its occupants from incurring additional costs due to future energy price increase. In addition, reduced thermal loss in the buildings helps keep indoor temperatures constant for a longer period with a reduction in the building envelope's U-values.

In summary, besides the UK's FiT and the revenues generated from exporting electricity to the grid, the annual zero-energy bill status of a ZEBH is achieved through the amalgamation of heat pumps, combined heat and power technology (e.g., solar PV thermal panels), and energy-efficiency measures such as high insulation levels of building fabric to reduce space heating demand. Figure 3 depicts the main features of the ZEBHs presented in this study.

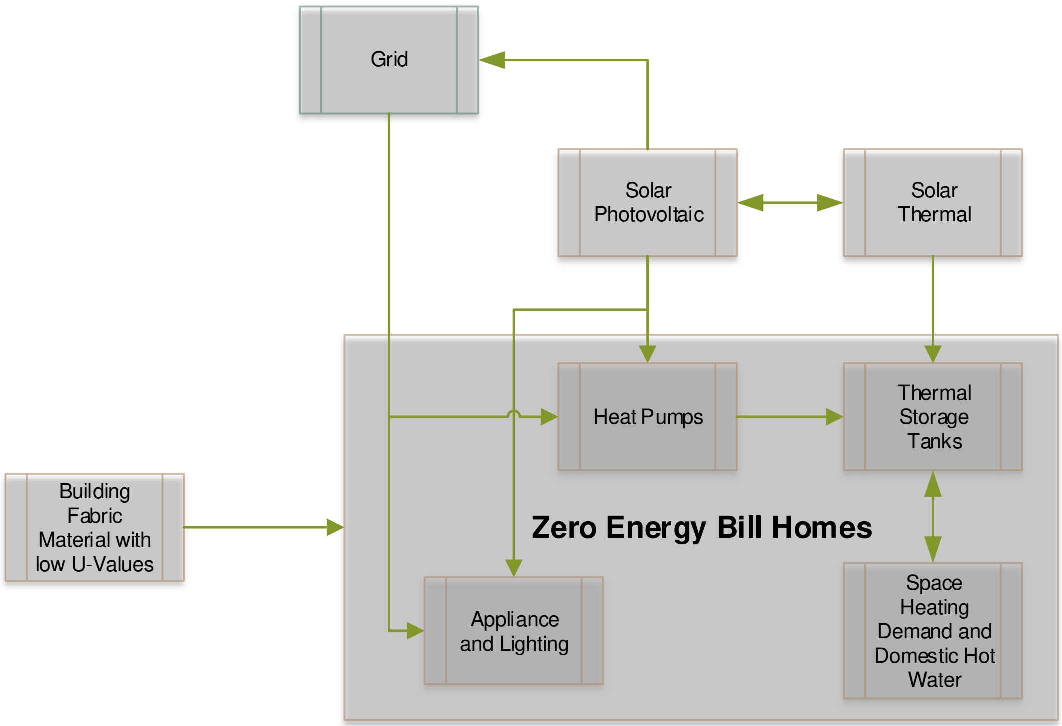



*Figure 3: Features of a ZEBH*

# 5. Methodology

This section presents an overview of the methodology used in the ZEBHs project at Corby, with an emphasis on the data measurement and calibration procedures as well as the building modelling/simulation approach, including economic analysis. Figure 4 displays the process used for this study.

As shown in the flow diagram, exhibiting the building modelling, initial simulations, and metered building electrical consumption data were used to create a calibrated simulation model from each ZEBH. In addition, an evaluation of the ZEBHs' building performance was carried out using the measured data representing the buildings' electricity consumption. Finally, a techno-economic analysis was performed to assess the feasibility of the SPVTAH installed in each dwelling and confirm whether ZEBHs can achieve a zero-energy bill status or not.

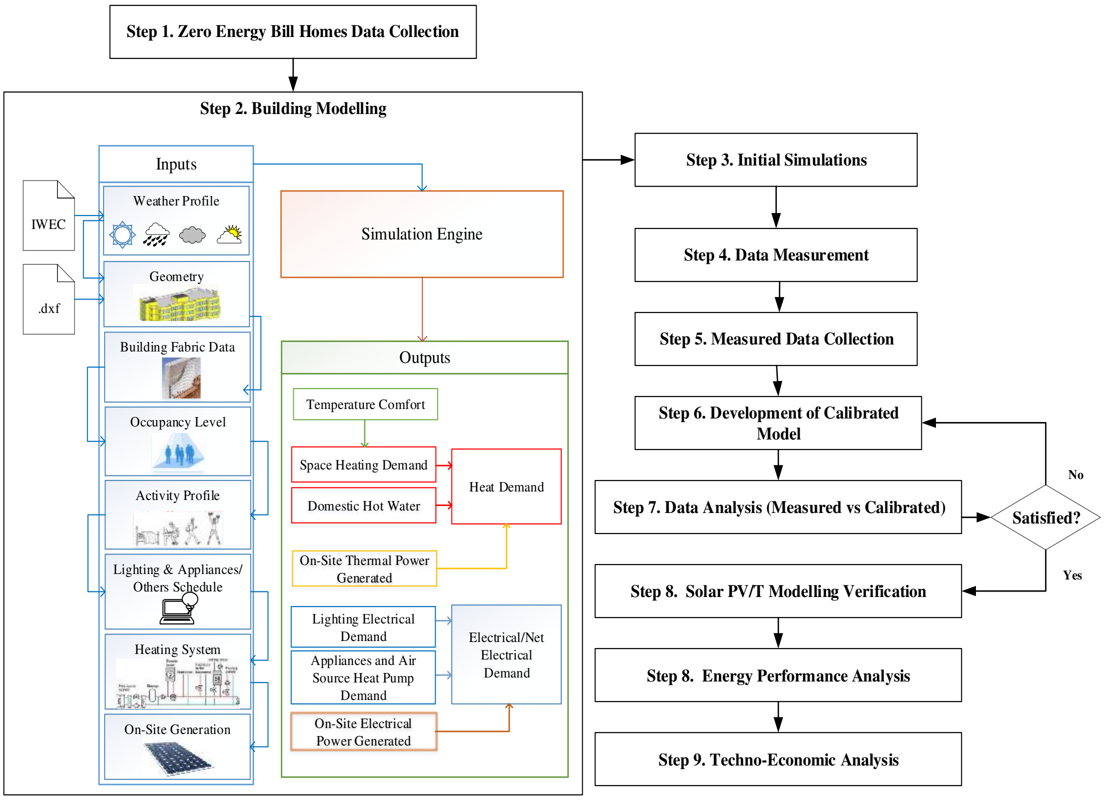



*Figure 4: Overview of the procedure used*

# 6. Zero Energy Bill Homes Data Collection

The selected ZEBHs were visited, and except weather and climate data, all information pertaining to the buildings was collected, including building fabric materials data, floorplans, occupants information (e.g., total number, profession, etc.), and the SPVTAH system data. The site visit and data collection could be accomplished with the help of Electric Corby Ltd. The company highly contributed to the energy use case analysis of the ZEBHs being built at Corby.

## *6.1 Building Modelling*

The buildings, as previously mentioned in Section 0, were modelled using the GUI and simulated with the EnergyPlus software. Figure 5 presents the final views on the developed 3D modelling of the studied dwellings. After completing the modelling, an initial simulation was performed to assess the electrical and space heat demand as well as the temperature comfort in each zone of the houses.

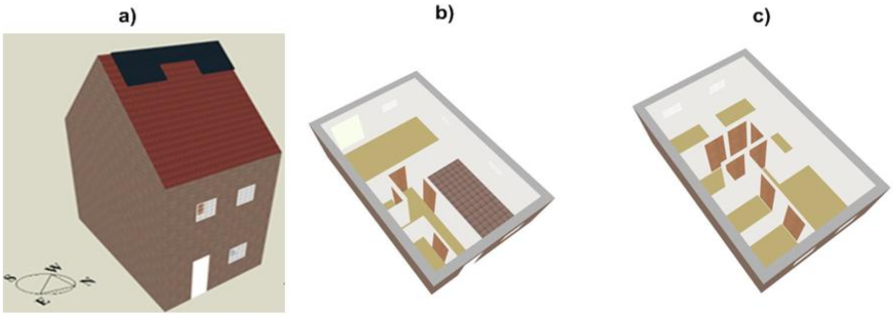



*Figure 5: Representation of the building model. a) axonometric view. b) ground floor. c) the first floor*

## 6.1.1 Weather and Climate

Environmental factors affect domestic energy requirements in many ways, and since all geographical areas have their own weather and climate, a weather file profile for the ZEBHs simulation was considered. These data files provide information about factors such as global and diffuse solar radiation, outdoor temperature, barometric pressure, wind direction, and wind speed. Building energy simulation for the ZEBHs with the modelling tool, uses EnergyPlus Weather Files (EPW) weather conditions. Therefore, an EPW (Europe WMO Region 6 – United Kingdom – Birmingham 035340 file) was obtained from EnergyPlus official website [47] and modified with Corby's PVGis [48] weather data for 2015–2016. Figure 6 illustrates the weather variation as displayed by EnergyPlus throughout January 2015 after adapting PVGis weather data in the EPW file.

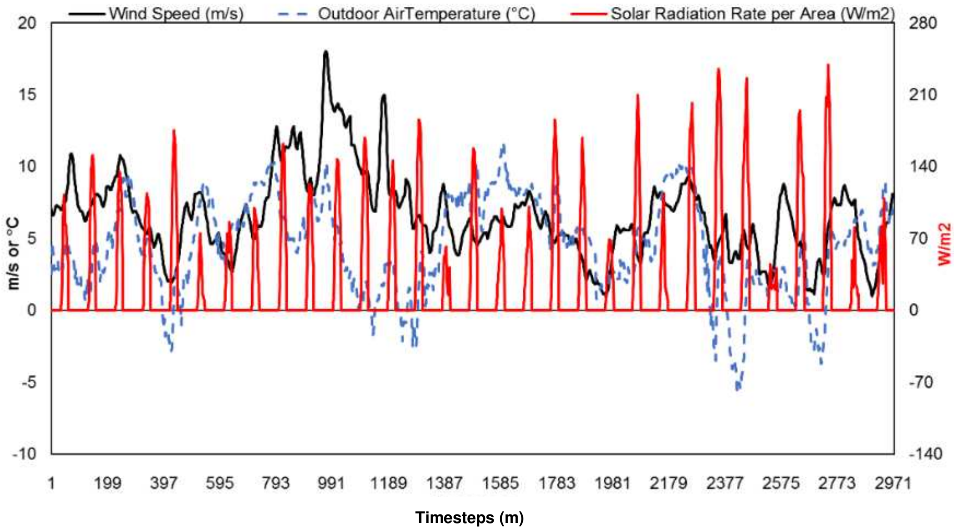



*Figure 6: January winter month profile in EnergyPlus*

## 6.1.2 Geometry and Buildings Envelope

The building structures of the selected domestic dwellings are in direct contact with the ground, and their externals walls are adjacent to the neighbouring buildings. Hence, models of the dwellings were designed using their floor plans, while real building fabric data was employed to model the building envelopes.

Figure 7 illustrates the floor plan of the examined dwellings, highlighting the building zones, including the living room, kitchen/dining area, three bedrooms, bathroom, cupboard (cup'd), en-suite bathroom, electrical equipment room (A/C), and storage room.

The types of structural materials used to build these domestic dwellings are bricks, insulation, and plaster/boards. More importantly, the overall heat transfer coefficients (U-values) were acquired from these materials. Air exchange between the environment and the dwellings creates natural ventilation and infiltration through the envelopes. The air exchange rate for ventilation and heat loss calculations can be determined through air changes per hour (ACH). It is worth noting that 0.50 ACH is the common value applied at most homes [49] [50]. Table 2 presents the U-values and ACH considered for modelling domestic dwellings.

*Table 1: Considered building standards for modelled domestic dwellings*

| **Parameters** | **Electric Homes** |
|---|---|
| Wall U-Value | 0.178 |
| Roof U-Value | 0.129 |
| Floor U-Value | 0.136 |
| Windows U-Value | 1.200 |
| Airtightness (*ACH*) | 0.50 |


*Figure 7: Domestic dwelling floorplan views with defined zones: a) front view; b) cross-section view; c) first-floor plan view; and d) and ground floor plan view*

### *6.1.3 Occupancy Levels and Activity Profiles*

Table 2 tabulates the occupancy for each domestic dwelling. A set of monitoring data of all the domestic dwellings was collected to acquire knowledge regarding the realistic activities and behavioural profiles of the occupants in terms of electrical appliances, lighting, heating systems, and DHW usages. The simulation results related to electrical appliances and lighting usages were calibrated to match the monitoring data results and consequently to validate the model. Section 6.3 presents the calibration method.

*Table 2: Occupancy information*

| Home and Plot Number | Occupants |
|---|---|
| EH Plot-272 | 4 |
| EH Plot-273 | 3 |
| EH Plot-274 | 5 |
| EH Plot-349 | 2 |

### *6.1.4 Electrical Appliances and Lighting*

Details regarding the electrical appliances used in the domestic dwellings were also modelled based on Richardson et al. [51]. These appliances include a computer, a monitor, a printer, a hairdryer, a television, a DVD player, and kitchen appliances. As for the lighting system, 12 $W_e$ lights was in each building zone. Tables 3 and 4 summarise the lighting and equipment data.

*Table 3: Distributed lighting system in the residential buildings*

| 12$W_e$ lights | No. per room | Total |
|---|---|---|
| Living | 3 | 36 |
| Bedrooms | 3 | 36 |
| Kitchen | 4 | 48 |
| Hall | 2 | 24 |
| Bathrooms | 1 | 12 |
| En-Suite | 1 | 12 |
| Storage Rooms | 1 | 12 |
| Electrical Equipment Rooms | 1 | 12 |

*Table 4: Overview of the considered household appliances and their required properties for the buildings modelling*

| Appliance Category | Appliance Type | Mean Cycle Power (W) | Power Factor |
|---|---|---|---|
| Wet | Washer Dryer | 792 | 0.8 |
| | Washing Mashing | 406 | 0.8 |
| Cooking | Hob | 2400 | 1.0 |
| | Oven | 2125 | 1.0 |
| | Kettle | 2000 | 1.0 |
| | Microwave | 1250 | 1.0 |
| | Toaster (small cooking group) | 1000 | 1.0 |
| Consumer Electronics | TV1/Monitor | 124 | 0.9 |
| | TV 2 | 124 | 0.9 |
| | Printer | 335 | 0.9 |
| | Personal Computer | 141 | 0.9 |
| | VCR/DVD | 34 | 1.0 |
| Cold | Fridge-Freezer | 190 | 0.8 |

### *6.1.5 Solar Photovoltaic Thermal Assisted Heat Pump*

The primary function of the energy supply systems is to supply heat and electricity to cater to the demands and needs of each household. As a matter of fact, the studied domestic dwellings employed a solar photovoltaic thermal-assisted heat pump (SPVTAH) system, along with an under-floor heating system and fan-assisted radiators as heat emitters (see Figure 8).

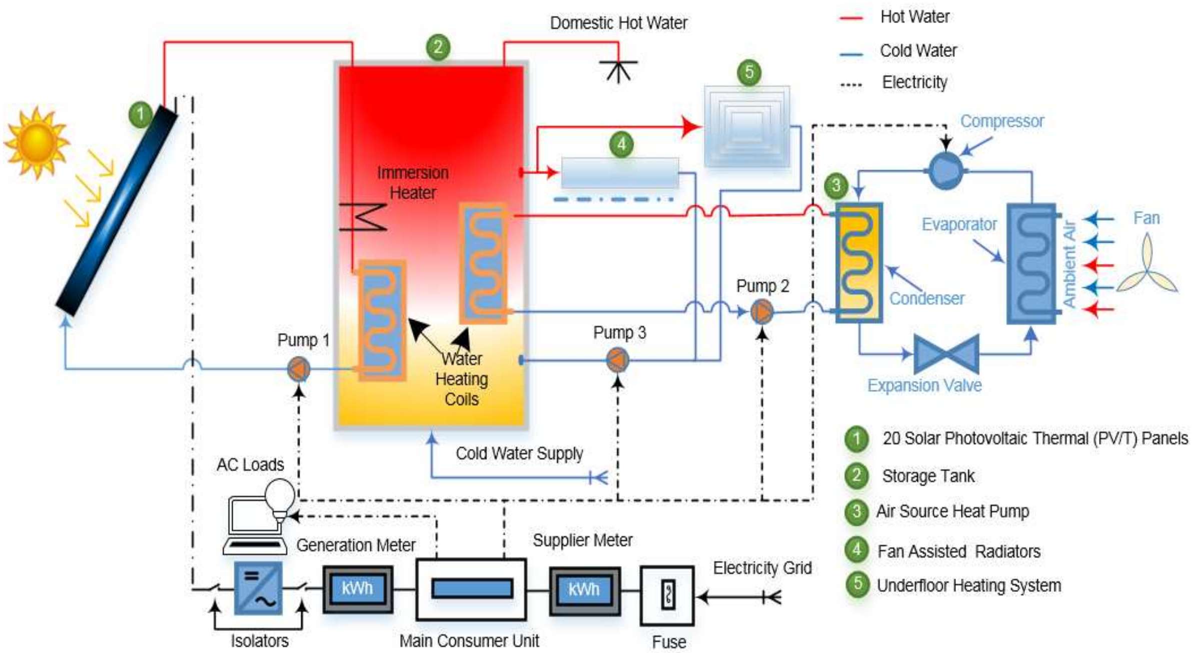



Figure 8: ZEBHs energy supply system

### *6.1.5.1 Solar Photovoltaic Thermal Panels*

The main, as well as the primary source of energy, is the solar photovoltaic thermal (PV/T) panels that are used to generate electricity and heat. The electricity supplied caters to the household's electricity demand, whilst the heat generated is stored in the water tank for space and water heating purposes. However, the intermittent energy generation from the solar PV/T panels makes maintaining a stable temperature in the water tank a little complicated; hence, an ASHP is needed to be installed in the water tank as a back-up heat device.
The PV/T system produces electricity when solar radiation falls onto the surfaces of the PV panels; upon this electricity generation, the inverter switches from direct current (DC) to alternating current (AC). When the sunlight falls on the PV panels, the temperature of these panels increases, and the heat, thus generated, is absorbed by the absorber plate to heat the water inside the tubes, and this hot water supplies heat to the domestic dwellings.

The solar PV/T system modelled for the selected ZEBHs had 20 roof-mounted solar PV/T panels. Table 5 summarises the key parameters of the modelled solar PV/T collectors.

*Table 5: PV/T Key parameters* [52]

| **PV/T Parameters** | **Value** |
|---|---|
| $A_{surf}$- Module area ($m^2$) | 1.37 |
| $E_o$- Cell Efficiency (%) | 17.5 |
| $E_t$- Temperature coefficient of Cell efficiency (%/°C) | 0.045 |
| $I_{mpp}$-Nominal Current (A) | 5.43 |
| $P_{mpp}$-Nominal Power at maximum power point (W) | 200 |
| $T$- Module Temperature at Normal Operating Cell Temperature (°C) | 25 |
| $V_{mpp}$-Nominal Voltage maximum power point (V) | 36.8 |
| $\alpha$- Collector Plate Absorptance | 0.70 |
| $\tau$- Cover Transmittance | 0.91 |
| $A_{abs}$-Absorber Area ($m^2$) | 1.19 |
| $FR$- Heat Removal Factor | 0.86 |
| $UL$- Collector Thermal Loss Coefficient ($W/m^2$ºC) | 0.30 |

### *6.1.5.2 Air Source Heat Pumps*

The role of the air source heat pumps (ASHP) is to maintain the temperature in the water storage tank between 50ºC and 55ºC (for space heating and DHW) using on/off controls, with a dead band variance of 5ºC in temperature.
The modelled ASHPs were directly attached to the water storage tank to support the heat supply needed for DHW usage and space heating. The thermal capacity of the ASHPs was set to the maximum of 4 $kW_{th}$, and a nominal coefficient of performance of 3.2 was also designated as the ratio of energy output to energy input. The configuration is inclusive of an evaporator, a compressor, a condenser, a valve, and a water circulation pump. The fan draws in outdoor air and spreads it across the evaporator coil such that the refrigerant can absorb the heat. Next, the refrigerant compresses the air and increases its temperature. Afterwards, the heat generated from the compressed air is transmitted to the heat sink through the condenser coil. Table 6 presents the ASHP model parameters.

*Table 6: ASHP parameters description*

| SHP parameters | Value |
|---|---|
| Max. rated heating capacity (kW) | 4 |
| Rated CoP | 3.2 |
| Evaporator max. inlet air temperature (ºC) | 29.44 |
| Condenser max. inlet water temperature (ºC) | 55.73 |
| Condenser water pump power (kW) | 0.150 |
| Fan total efficiency (%) | 70 |
| Fan pressure (Pa) | 600 |

### *6.1.5.3 Hot Water Tank and Domestic Hot Water Demand*

The solar PV/T panels and the ASHP work on the 250-L water storage tank at each dwelling using a water heating coil. The water storage tank modelled in this study is a joule sequentially stratified thermal storage tank with medium-sized solar DHW heating systems (Figure 9). The temperature of the water storage tank was set between 45ºC and 55ºC, with a maximum capacity of 70ºC. On top of that, the temperature of the storage tank was increased up to 60ºC once every ten days using a 3-kW$_e$ heater to prevent the growth of legionella bacteria [53].


*Figure 9: Modelled hot water storage tank. Courtesy of Electric Corby and EDP Consulting Limited*[54].

This study considered 150 L/day as the maximum usage for fulfilling the nominal daily hot water demand based on the standard outlined by the Department for Environment, Food and Rural Affairs [55] [56]. The DHW consumption schedule of each ZEBH occupant was determined according to the UK National Calculation Methodology templates [57]. When the occupants use the DHW, each water tap draw has the nominal draw flow rate, as presented in Table 7 [48].

*Table 7: DHW flow rate to calculate hot water demand*

| Fixture | Flow rate ($m^3/s$) | Flow rate ($m^3/day$) |
|---|---|---|
| Basins | 0.00008 | 6.912 |
| Sink and baths | 0.00015 | 12.96 |
| Shower | 0.00050 | 43.20 |

### *6.1.6 Space Heating Demand*

The heaters installed in the selected dwellings offer indoor temperature comfort to their occupants at a set temperature of 19°C for the entire dwelling space, except in the living room where the thermostat temperature is set at 21°C.

Heat load within the domestic dwellings was dictated by the indoor heat gain values and heat losses that vary over time.
The heat load of any building is simply determined using the differences between heat gains and heat losses. To determine the space heating demand, the Heating Degree Days (HDD) for a building should be measured. The HDD is a value that corresponds to the difference between baseline temperature (15.50°C in the UK) and the actual outdoor temperature, multiplied by the number of annual days [58]. However, HDD is set to zero in the case outdoor temperature exceeds the baseline temperature. Finally, the space heating demand is measured by subtracting the heat gains from the product of heat losses and HDD.

### *6.1.7 Electrical and Net Electrical Demand*

Electricity demand for every studied dwelling was determined in order to calculate the energy load to be adequately supplied by considering the varied energy usage activity profiles.
Total electricity demand denotes the sum of the building loads, the electric heating loads from ASHPs, and the water tank immersion heaters.
The net electrical demand refers to the variances between the demand for electricity in buildings and the electric power generated on-site. As revealed in this study, electricity is exported from grids when its demand exceeds the electricity generated from the solar PV/T panels.

## *6.2 Data Measurement*

To validate the actual electrical energy performance of each ZEBH, measured data from each building was needed to be collected. This data includes the Uniq solutions EM21 energy meter and Live View Pack [59], where the electricity consumption (appliances and lighting) for a period of one winter week (10th to 17th of December 2015) with a time frequency of 15 minutes was measured. Furthermore, the metered data only considered the electrical demand and not the net electrical demand.

## 6.3 Calibration Method

The calibration process required several manual iterations on the appliances and lighting usage before obtaining a model with acceptable accuracy. The limit proposed by the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) Guideline 14 [ASHRAE, 2002] was selected for this study. Accordingly, the normal mean bias error (NMBE) should be inside +/- 10%, and the coefficient of variation of the root mean square error (CVRMSE) should be lower than 30% when evaluated every hourly time interval. This entails determining the two dimensionless indicators of errors, NMBE and CVRMSE, using equations (1) and (2):

$$NMBE = \frac{\sum_{i=1}^{N_i}(M_i - S_i)}{\sum_{i=1}^{N_i} M_i} \quad (1)$$

$$CVRMSE = \frac{\sqrt{\sum_{i=1}^{N_i} \frac{\left[(M_i - S_i)\right]^2}{N_i}}}{\frac{1}{N_i}\sum_{i=1}^{N_i} M_i} \quad (2)$$

Here $M_i$ and $S_i$ denote measured and simulated data, respectively, at instance $i$, and $N_i$ is the number of values used in the calculation.

## 6.4 Solar PV/T Model Verification Method

It was not possible to model the functionality of ZEBHs solar PV/T panels using the DesignBuilder; hence, solar PV panels were modelled instead, and subsequently, the EnergyPlus model code files were modified in order to adapt solar PV/T panels for each home.

In this case, no reliable data could be measured using monitoring devices on the ZEBHs for validation purposes; therefore, the MATLAB software was used to replicate the EnergyPlus solar PV/T panels. This permitted the analysis of the solar PV/T panels performance, which consequently helped verify whether or not the EnergyPlus simulations results were accurate. Therefore, the PV/T model's performance was verified on a summer day (1st of June). The performance of a solar PV/T collector depends on design parameters and weather and operating conditions (e.g., irradiance, ambient temperature, absorber plate temperature, etc.). Thus, in order to complete the analysis with MATLAB, the parameters of the PV/T collector described in Appendix A were applied; the fluid inlet temperature ($T_i$) was considered to be 40ºC and the tilt angle 45°. Appendix A presents the results, the steps followed, and the equations used in MATLAB and EnergyPlus to attain this.

## *6.5 Techno-Economic Study*

This section outlines the methodology adopted for accomplishing the economic study. Based on the outcomes derived from the building energy simulations using EnergyPlus, a techno-economic assessment was performed on the SPVTAH of the dwellings over the course of a year. The three key parameters that helped determine the economic benefit include Feed-in Tariff (FiT), exported tariff price, and electricity cost (including standing charges).

The UK price tariffs directed by the Office of Gas and Electricity Markets (Ofgem) for the generation and export of electricity were adopted in this study. The electricity cost included the standing charges for providing electricity by the actual energy retailer (*BritishGas*) to the dwellings. Table 8 depicts the parameters embedded in the economic analysis, while Table 9 presents the cost parameters of the energy supply system.

The parameters from Table 8 were retrieved from Ofgem Standard Large Solar PV system charge export tariff, and FiT, whilst Table 9 represents cost of the Solar PV/T panels (obtained from the manufacturer), and total cost of installation and maintenance by the installation company- Convert Energy Ltd.

*Table 8: Tariffs used for feasibility calculations*

| **Tariffs** | **Price** |
|---|---|
| FiT | 0.0034£/kWh [a] |
| Export Tariff | 0.054£/kWh [a] |
| Electricity Tariff | 0.12£/kWh [b] |
| Standing Charge | 0.25£/day [b] |

[a]Ofgem- Standard large solar PV systems (1000-5000 kW) [60]
[b]BritihGas [61]

*Table 9: Energy supply system cost parameters*

| **Parameter** | **Value** |
|---|---|
| 20 x Solar PV/T panels cost[a] | £6600 |
| 20 x Solar PV/T panels installations cost[a] | £4200 |
| ASHP cost[a] | £5500 |
| ASHP installations cost[a] | £1800 |
| 20 x Solar PV/T panels and ASHP maintenance cost[a] | £220/year |
| Discount rate (d) | 10% |
| System life[b] | 25 years |

[a] Obtained from supplier. Source: https://www.convertenergy.co.uk/
[b] Obtained from manufacturers. Source: http://www.solimpeks.com/

The total cost incurred to operate the 20 solar PV/T panels and an ASHP at each dwelling is calculated as the total electricity cost minus the cost of displaced electricity imported from the grid, including the revenue accumulated from the electricity exported to the grid. The following equation mathematically represents this notion at each time step ($t$):

$$SPVTAH_{cost(t)} = \left[\left(\left(Elec_{dmd} \text{-} PVTElec_{out}\right)Cost_{Elec}\right) + \left(SC_{Elec}d\right)\right] - \left[\left(PVTElec_{out}FiT_{price}\right) + \left(Elec_{Exp}TariffElec_{price}\right)\right] \quad (3)$$

Now, the annual costs for the SPVTAH can be calculated by summing each time step over a year, with the following equation:

$$\sum_{t=1}^{t=N} TotalSPVTAH_{(t)} \quad (4)$$

Here, $SPVTAH_{cost}$ is the total cost of the solar PV/T assisted by the ASHP system in £, $PVTElec_{out}$ refers to the electricity generated from the PV/T panels ($kWh_e$), $Cost_{Elec}$ denotes the imported electricity cost in £/$kWh_e$, $SC_{Elec}$ indicates the electricity standing charge cost (£/day), $t$ is the time step, $N$ is the total number of time steps, $Elec_{dmd}$ is the electricity demand from the households ($kWh_e$), $FiT_{price}$ is the electricity tariff in £/$kWh_e$, $TariffElec_{price}$ is the exported electricity price (£/kWh), $Elec_{Exp}$ is the electricity exported to the grid in $kWh_e$, and the term $d$ is the number of days.

The present value (PV) of each annual cash flow can be discounted back to its PV. The net present value (*NPV*), as displayed in equation (5), can be determined by summing the cash flow for each year, starting from year 0 (investment) till the lifetime of the SPVTAH system, i.e. 25 years.

$$NPV \sum_{n=0}^{25} \frac{R_n}{(1+d)^n} \quad (5)$$

Here, *NPV* refers to the net present value in £, $R_n$ is the cash flow (£), and $d$ represents the discount rate (10%).

# 7. Results and Discussion

## *7.1 Measured Data Analysis*

Before attempting to generate highly detailed building energy models, the measured data from each ZEBH was analysed, as illustrated in Figure 10–14. This information was considered in the input activity schedules of the energy model. Moreover, it was important to get a reliable and predictable set of measured data to calibrate the model.

The EH-Plot 272 graph shows, at a glance, that there is a high consumption level between the $12^{th}$ and $13^{th}$ of December in the winter, especially in the mornings. The EH-Plot 273 had 3 occupants, and it can be noted that there were high peaks in the mornings when they woke up; however, a large power demand occurred in the evenings between 03:00h and 06:00h. Although EH-Plot 274 had 5 occupants in their dwelling, most of the time, the power demand remained only between 320W and 480W. EH-Plot 349 had been occupied by only 2 residents, differing from the total number of occupants in the other homes, the electrical power demand there was between 240 W and 480 W.

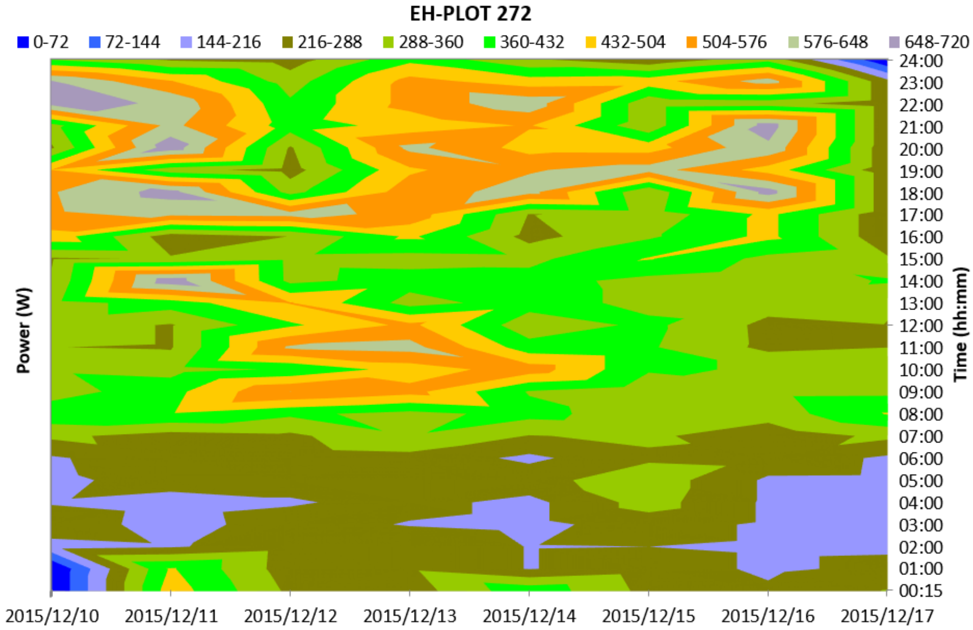



*Figure 10: EH-Plot 272 Contour Plot graph to analyse the measured data*

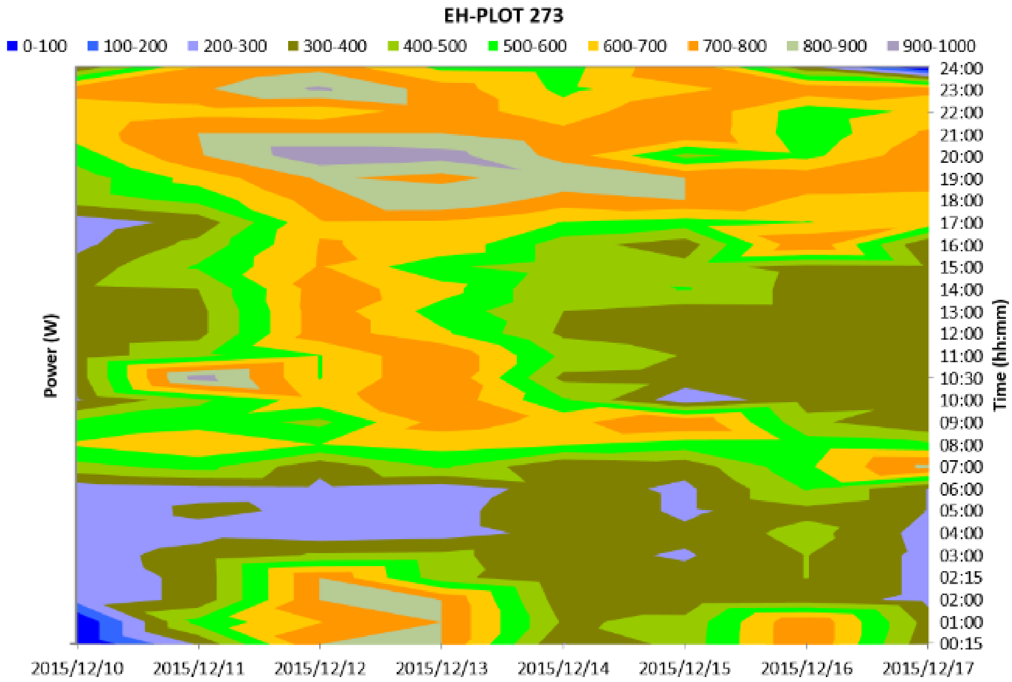



*Figure 11: EH-Plot 273 Contour Plot graph to analyse the measured data*

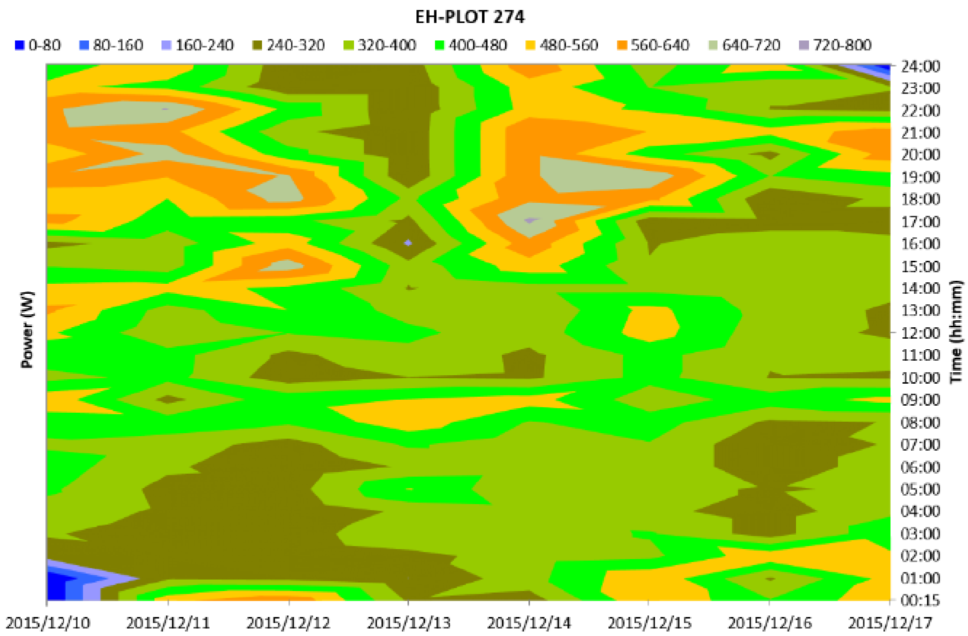



*Figure 12: EH-Plot 274 Contour Plot graph to analyse the measured data*

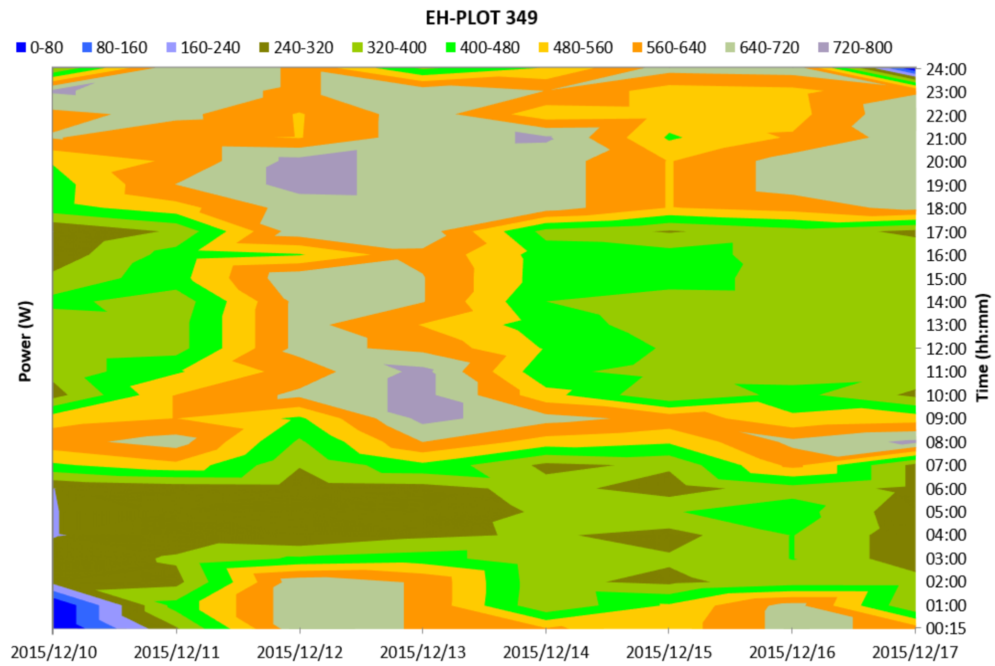
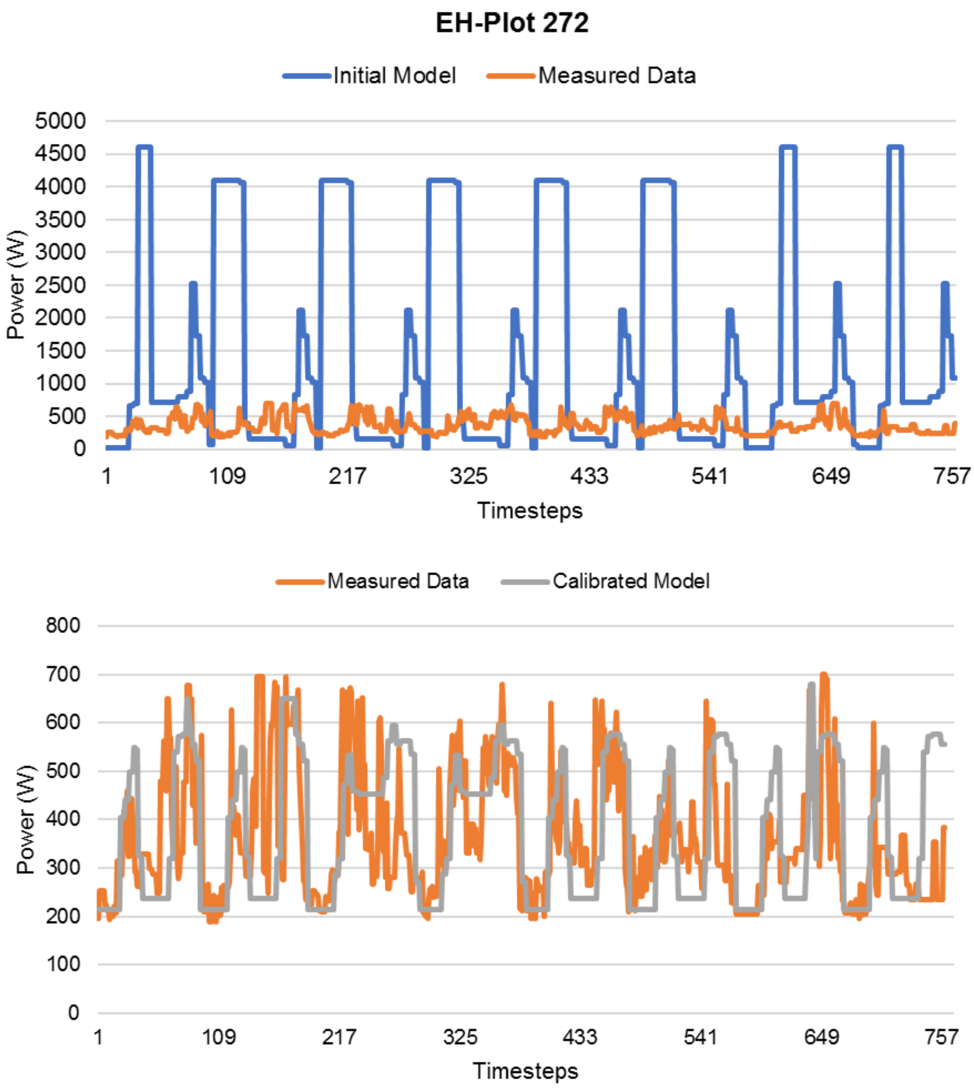



*Figure 13: EH-Plot 349 Contour Plot graph to analyse the measured data*

## *7.2 Measured Data vs. Initial and Calibrated Model*

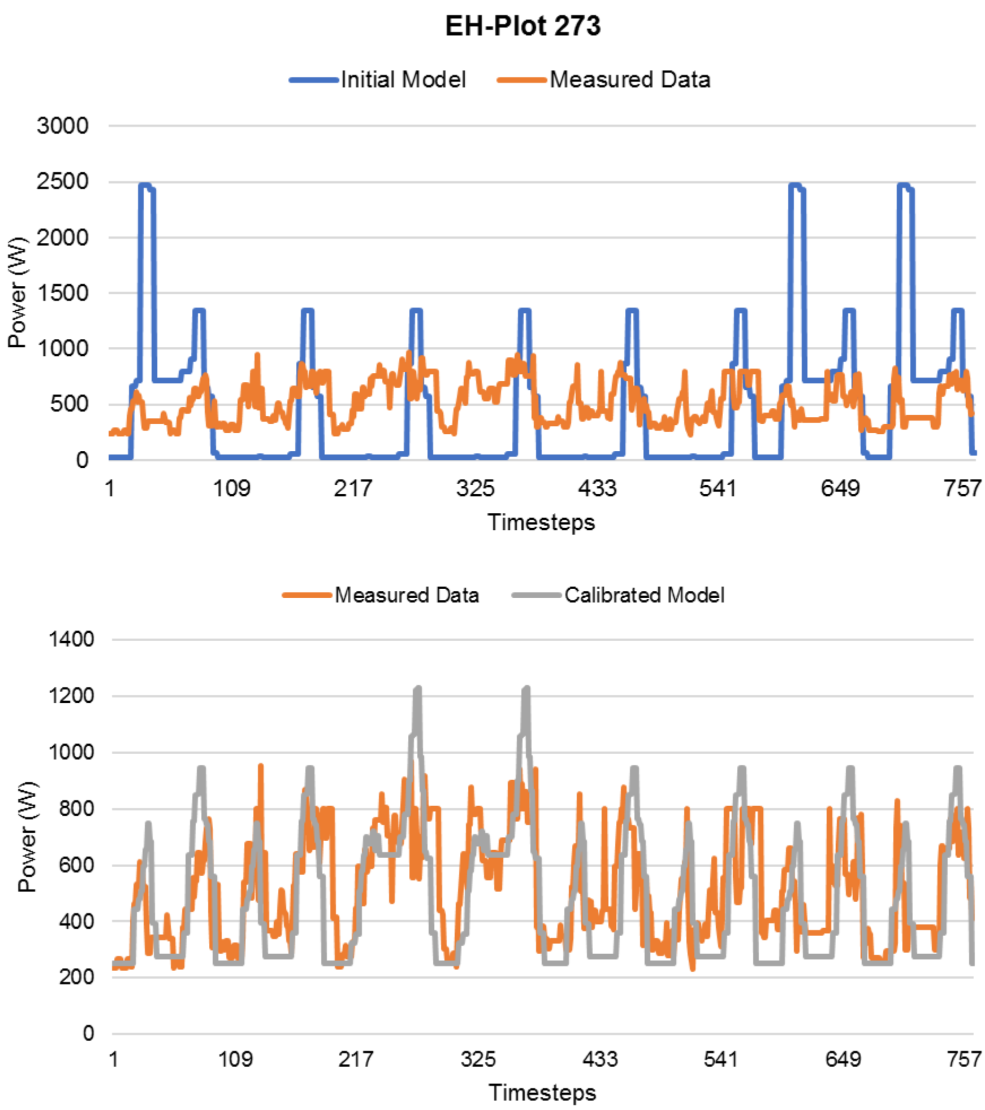
After obtaining the calibrated building energy models, an analysis to compare the measured and initial model simulation was conducted. First of all, operation schedules were compared using a 15-minute time stamp for a week, as shown in Figures 14–18. The figures enabled a quick visual inspection of the measured data against the initial and calibrated model values and the statistical variations, such as the maximum and minimum peaks, the total consumed energy, and the average power demand. From the initial model results, it can be noted that electricity consumption for appliances and lighting is more closely related to occupant activity, which deviates (randomly) from the deterministic occupancy initially used in the EnergyPlus model.

The electricity consumptions of the buildings during winter weeks were 275 kWh, 392 kWh, 309 kWh, and 372 kWh in EH-Plots 272, 273, 274, and 349, respectively, and the final calibrated models produced a sum of 286 kWh, 369 kWh, 338 kWh, and 363 kWh in the similar order. From the individual results in each ZEBH, it can be seen that EH-Plot 274 carries the highest accumulation of errors (9%) from the final calibrated model.



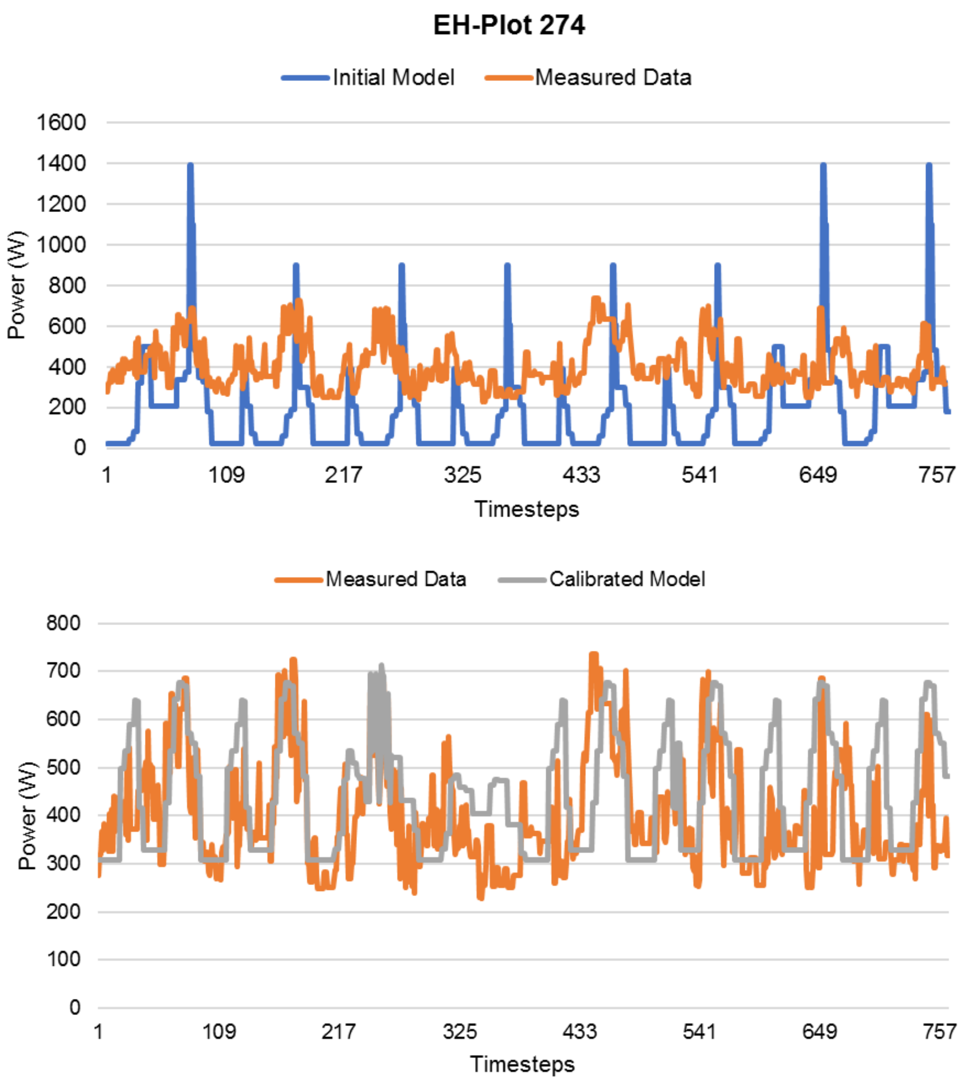

| Measured | | | Calibrated | | | Difference Error |
|---|---|---|---|---|---|---|
| Average | 362 | W | Average | 377 | W | 4% |
| Maximum | 699 | W | Maximum | 680 | W | |
| Minimum | 190 | W | Minimum | 215 | W | |
| Summation | 275 | kWh/week | Summation | 286 | kWh/week | |

*Figure 14: EH-Plot 272 Measured vs Initial and Calibrated model*



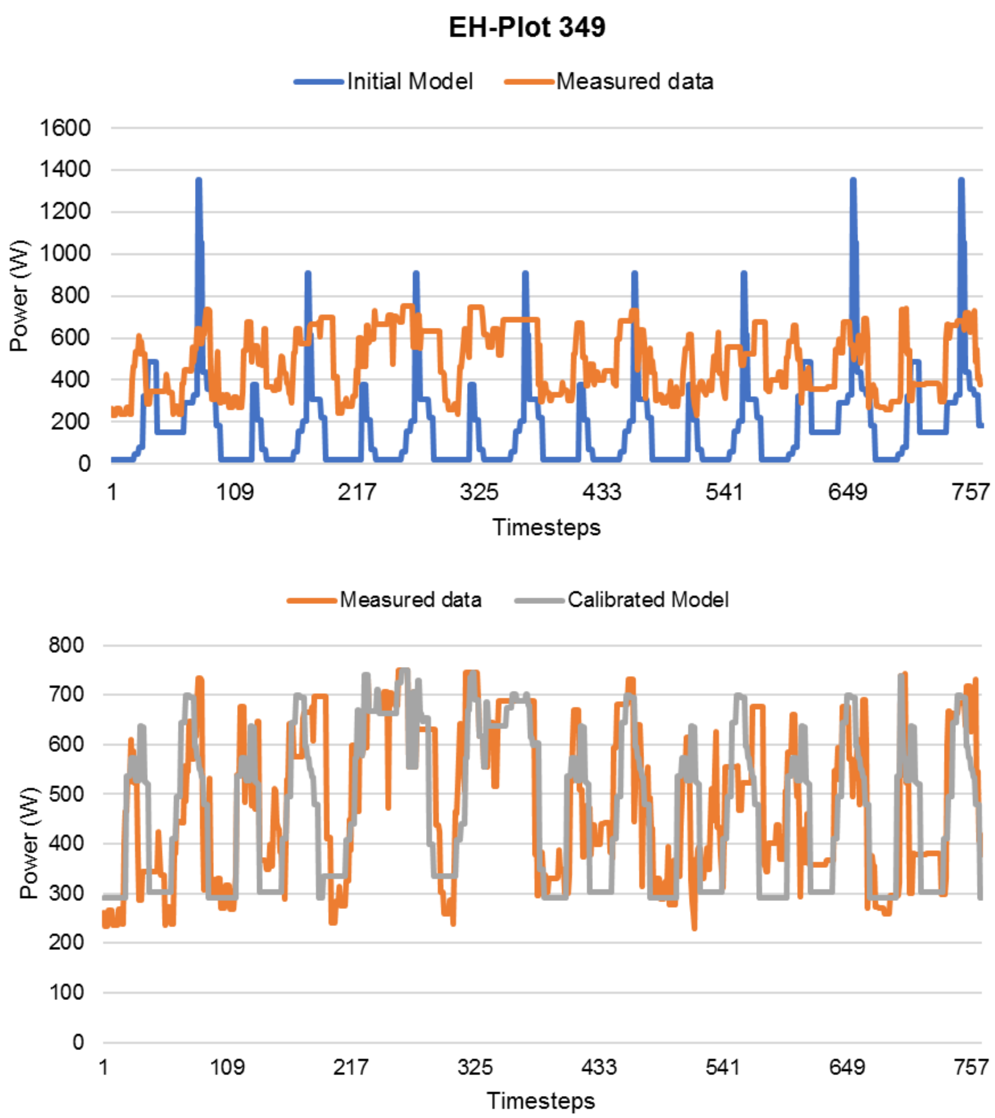

| Measured | | | Calibrated | | | Difference Error |
|---|---|---|---|---|---|---|
| Average | 513 | W | Average | 482 | W | 6% |
| Maximum | 968 | W | Maximum | 1230 | W | |
| Minimum | 230 | W | Minimum | 253 | W | |
| Summation | 392 | kWh/week | Summation | 369 | kWh/week | |

*Figure 15: EH-Plot 273 Measured vs Initial and Calibrated model*




| Measured | | | Calibrated | | | Difference Error |
|---|---|---|---|---|---|---|
| Average | 404 | W | Average | 442 | W | 9% |
| Maximum | 736 | W | Maximum | 714 | W | |
| Minimum | 227 | W | Minimum | 308 | W | |
| Summation | 309 | kWh/week | Summation | 338 | kWh/week | |

*Figure 16: EH-Plot 274 Measured vs Initial and Calibrated model*




| Measured | | | Calibrated | | | Difference Error |
|---|---|---|---|---|---|---|
| Average | 486 | W | Average | 473 | W | 2.5% |
| Maximum | 749 | W | Maximum | 749 | W | |
| Minimum | 230 | W | Minimum | 292 | W | |
| Summation | 372 | kWh/week | Summation | 363 | kWh/week | |

*Figure 17: EH-Plot 349 Measured vs Initial and Calibrated model*

## *7.3 Statistical Index Evaluations*

Figure 18–21 show the NMBE and the coefficient of variance of CVRMSE for the calibrated simulation model generated by the hourly simulation program. The calibration results could meet the limits of model calibration accuracy directed in the ASHRAE Guideline 14-2014.

The calibration models demonstrated accuracies of 26% for EH-Plot273, 29% for EH-Plot 273, 25% for EH-Plot274, and 21% for EH-Plot 349 over the full-week cycle.

Each of the NMBE and CVRMSE values provide a different set of insights. NMBE values possess the drawback of cancellation and hence might under-report the magnitude of the errors, as observed for the instance of electrical calibration, where the overall NMBE value of 5.9% was identical in both EH-Plot 273 and EH-Plot 274; however, this concealed much larger CVRMSE errors in EH-Plot 273 (Figure 19). Within this work, the CVRMSE in EH-Plot 273 carried the largest error and was the greatest source of uncertainty in the model energy prediction. This mostly affected the simulated electricity value. In contrast, the CVRMSE values provided a better indication in EH-Plot 349.

Interestingly, the difference error result from EH-Plot 274 (Figure 16) was higher than the CVRMSE results of EH-Plot 273 (Figure 19). This might be due to the different study approaches between the CVRMSE and the difference error. The CVRMSE is defined as the ratio of the root mean square error to the mean values, whereas the difference error is the difference between the measured data and the calibrated model, divided by the calibrated model results.

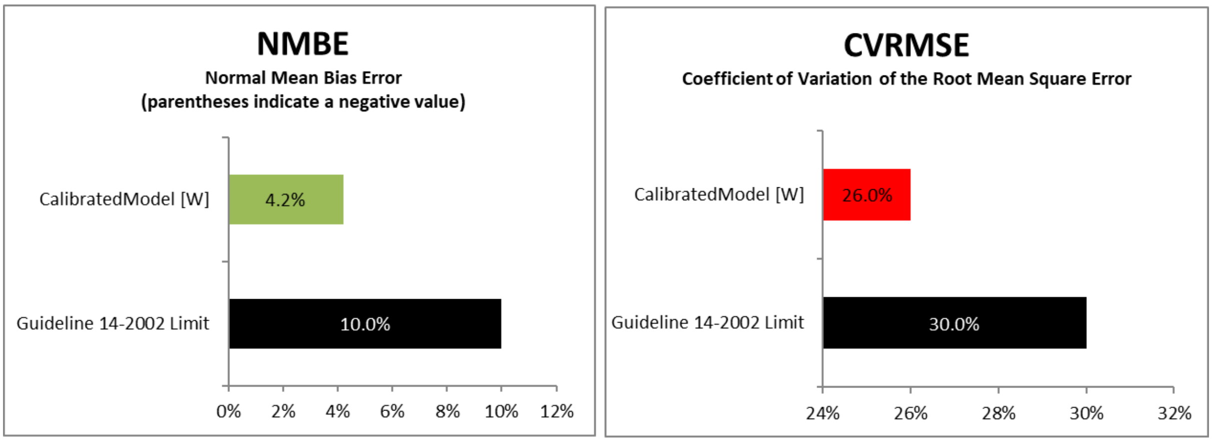



*Figure 18:EH-Plot 272 NMBE and CV(RMSE) calibration results*

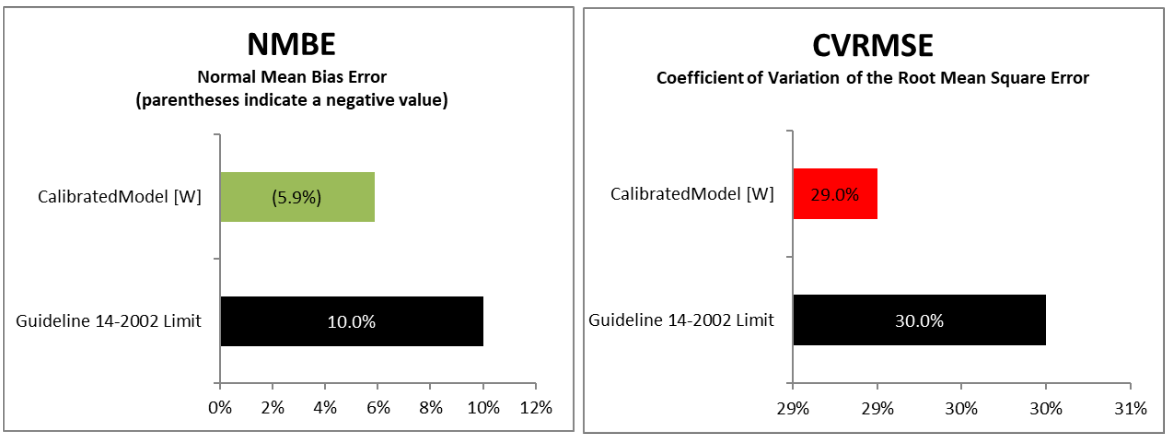



*Figure 19: EH-Plot 273 NMBE and CV(RMSE) calibration results*

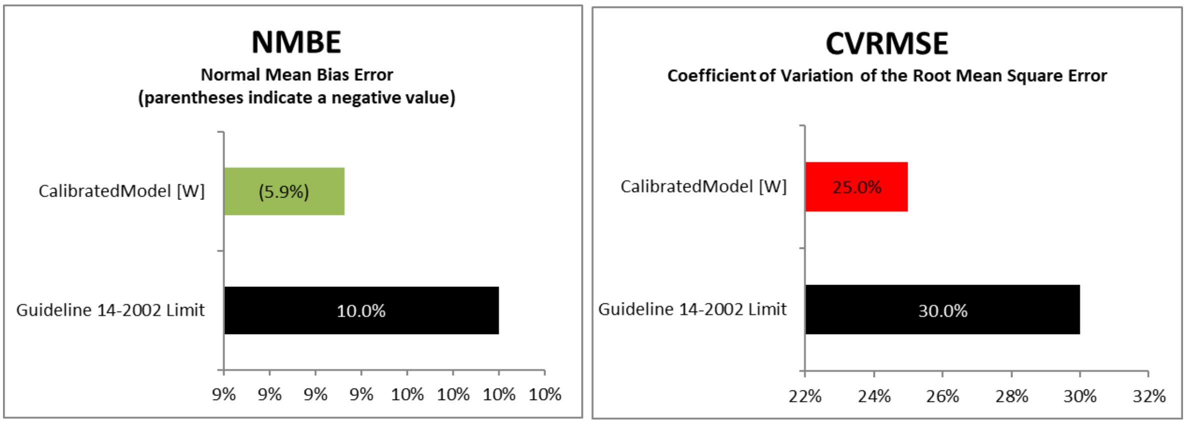



*Figure 20: EH-Plot 274 NMBE and CV(RMSE) calibration results*

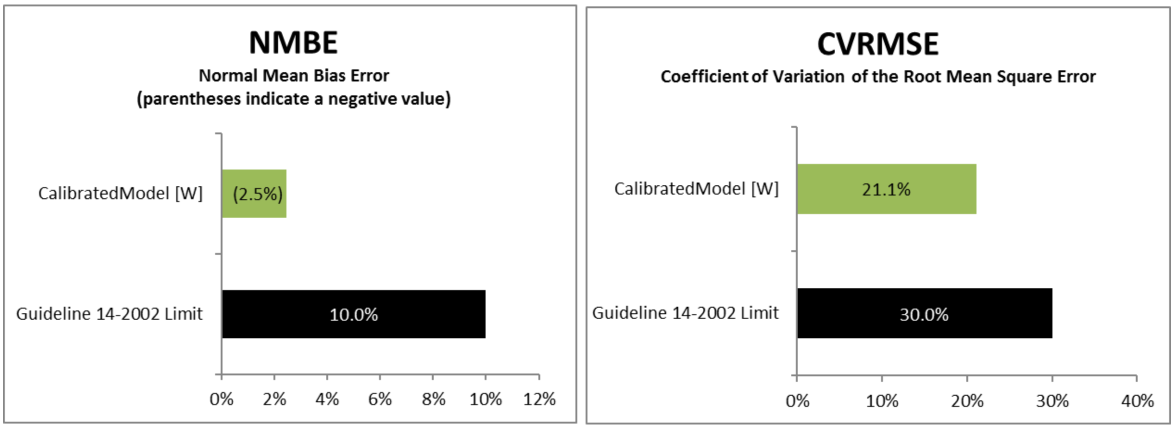



*Figure 21: EH-Plot 274 NMBE and CV(RMSE) calibration results*

## *7.4 Building Energy Performance*

### *7.4.1 Electrical Energy Demand*

This section presents the values of electricity end-use. Figure 22 illustrates the total electrical energy consumption broken down each month to emphasise the aspects related to appliances, lighting, and ASHP energy use.

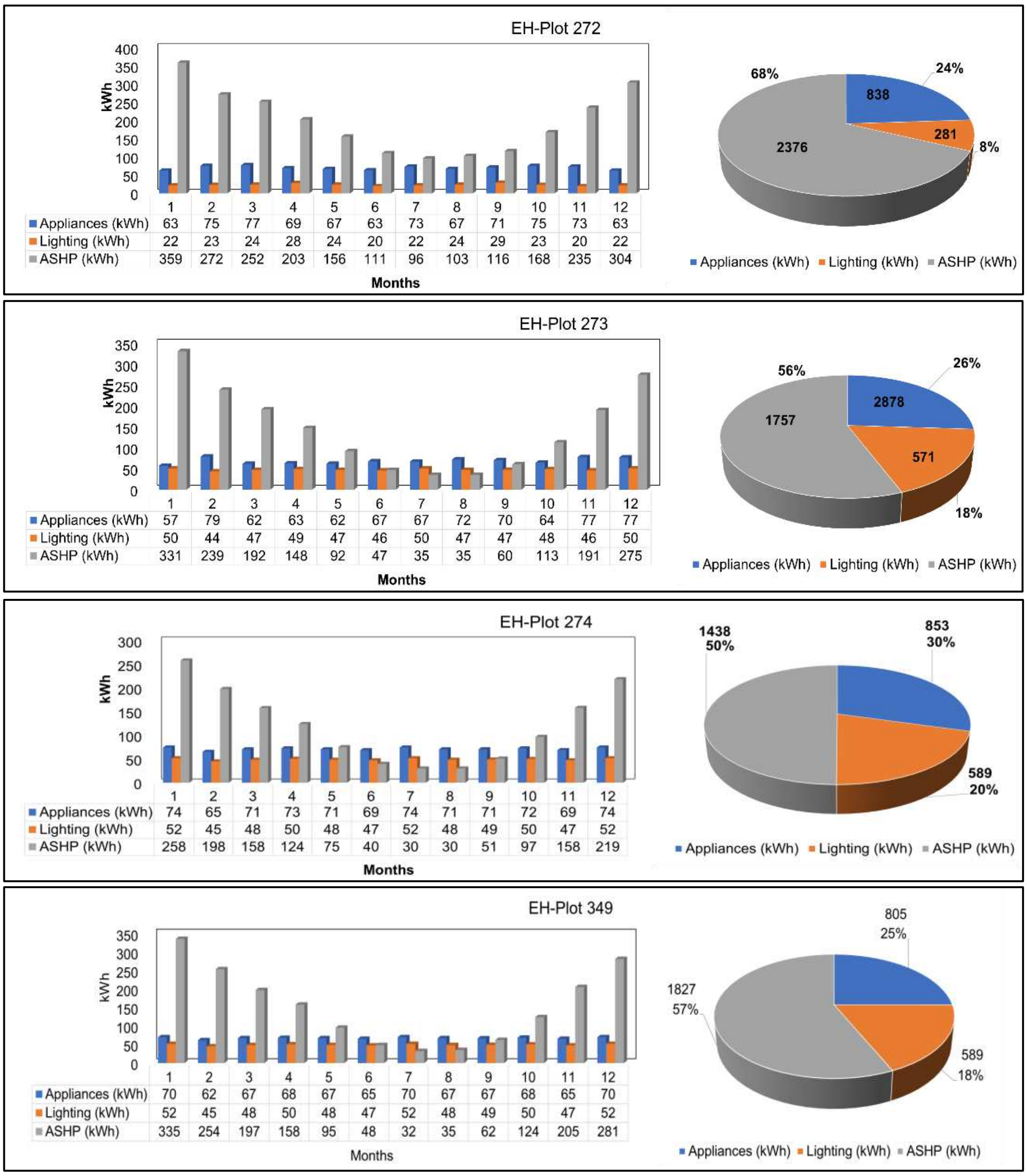



*Figure 22: Annual breakdown of electricity use in the Electric Homes*

The EH Plot-272 had the highest electrical consumption (3495 $kWh_e$ /year), primarily due to the high operation of ASHP in meeting the building's space heating demand. Furthermore, the maximum monthly electrical energy consumption for all domestic dwellings was found for the months of December and January, while it was the most minimum for July and August. Thus, it is obvious that variation in electrical energy consumption is linked to seasons, mainly due to the ASHP application.

### 7.4.2 Thermal Energy Demand

Thermal energy was also stimulated with E+ over the course of a year. The outcomes yielded for monthly required ($kWh_{th}$) energy for heating, DHW, and ASHP thermal power have been presented in Figure 23.

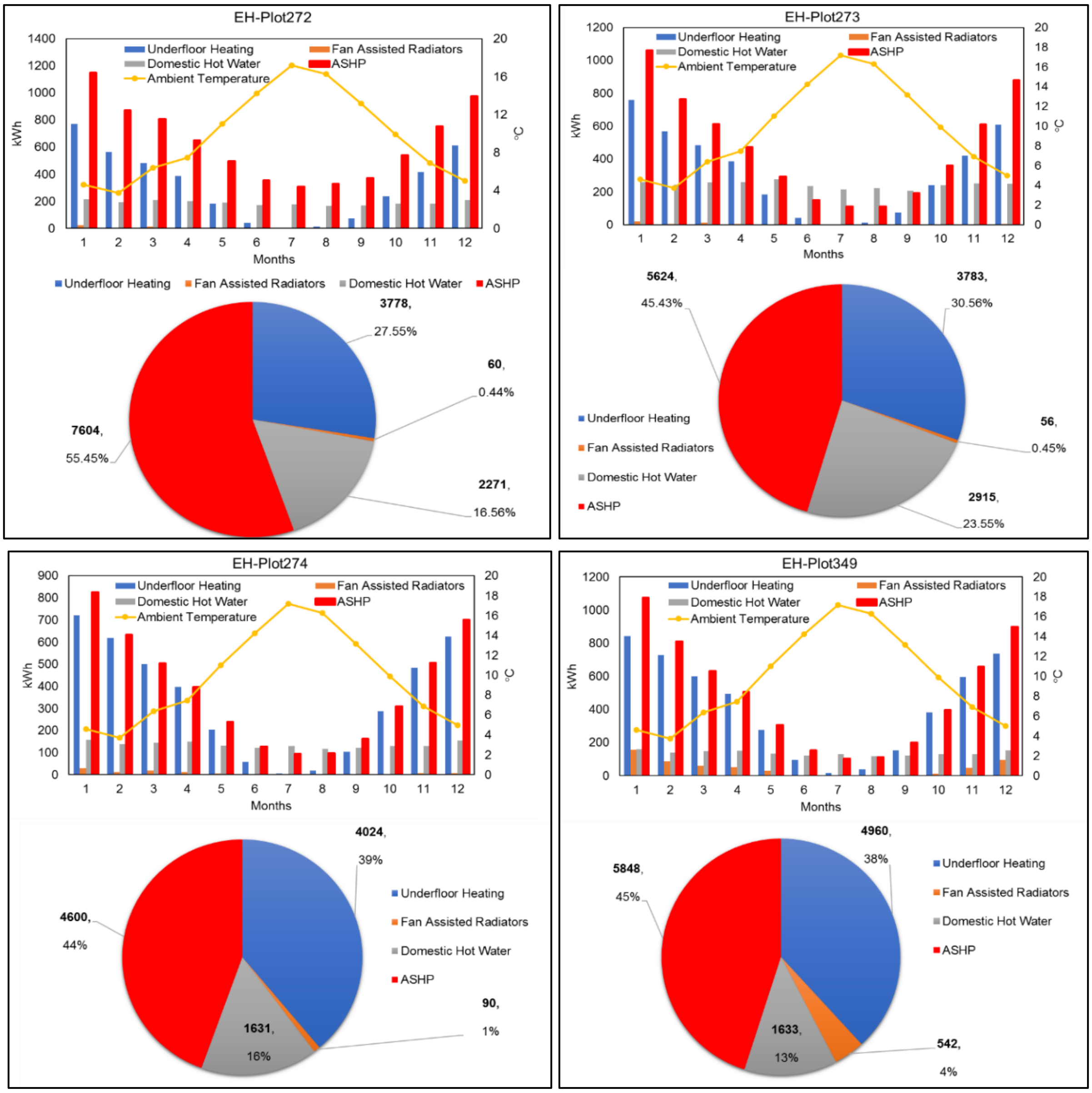



*Figure 23: Annual breakdown of thermal energy use in the electric homes*

The findings exhibited variation in terms of space heat demand over the course of a year, especially with only a little or nil heating energy consumption in summers, and high usage during the winter. Moreover, the consumption of heat energy seemed to vary amongst the dwellings, as portrayed in the outputs of the building modelling while considering the occupants and their activities.

The space heating demand and related deviations during winter months, usually occur in the mornings as well as in the evenings. The largest ASHP demand was recorded for EH-Plot 272, indicating that the activities and demand of the four occupants have a clear impact on the final ASHP thermal energy consumption.

The study results also assessed the heating demand of under-floor heating and fan assisted radiators. Notably, the type of heat emitter operated most in these homes is the under-floor heating system. The under-floor heating systems were modelled on the ground floor, whereas the fan-assisted radiators on the first floor. The usage discrepancies between the two types of heat emitters confirmed the notion that the under-floor heating can meet the space heating requirements on both floors most of the time; this is due to the fact that heat flows from ground to the upper floor. Furthermore, it is important to highlight that the heating system usage discrepancies amongst buildings are related to the space heating demand when heat loss occurs; thus, the buildings' air infiltration and ventilation have a major impact on the total heat loss. It is obvious that the main factors affecting heat loss are climate, environment data, and infiltration. Another factor considered in EnergyPlus was the transfer of heat across the rooms, especially due to the opening and closing of doors by the occupants. Heat loss occurs when the door of a heated room is opened to a colder one.

On the other hand, during summertime, solar heat gains seemed to have contributed to the decrease in heating system usage and the outcomes of heat losses. The discrepancies in outputs amongst the buildings exhibited an influence on the direction in which the buildings were facing, and hence, the extent of solar gains through the windows. Additionally, the lighting system appeared to have affected the discrepancies due to a decrease in operation during the summer period when there are more daylight hours. The number of occupants and their activities (metabolic rates) also had an effect on the heat gains, as the ZEBHs models incorporated variables such as the occupants' rising time in the morning, activities (e.g., cooking), and leaving home for school/work.

In short, upon analysing the outcomes and the variations noted in DHW consumption amongst the dwellings, the most highly influential factors in determining consumption of hot water are the climate, the number of occupants and their activities.

## *7.5 Solar PV/T Panels Energy Generated*

Figure 24–27 illustrated in this section present a breakdown of the monthly PV/T panels performance. The generation of electricity in every dwelling appeared to exhibit rather good performances during the summer. Nevertheless, only 20–40% of the electricity power expectation was generated during the four coldest months – November through February. This is almost exclusively due to low solar radiation and possible snow accumulation on the surfaces of the PV/T panel during those months. For instance, the maximum electricity generated in each dwelling was approximately 477 $kWh_e$ for July (month with the highest solar radiation), while the total annual electrical energy generated from the 20 PV/T panels in each domestic dwelling was 3243 $kWh_e$/year. Thus, timing is very critical for the performance of the PV/T panels, as thermal energy is only useful if it is used immediately or stored for future use. While total thermal energy outputs were relatively similar in magnitude over the course of a year (3710 kWh$_e$/year), it varies significantly by month, peaking in the summer months. Moreover, there is a seasonal mismatch between supply and demand, as the supply increases significantly in the shoulder season and summer months. Hence, the most reasonable method is to use seasonal storage in order to take advantage of the excess of thermal energy generated during this period. This indicates that without the use of heat pumps, effective PV/T performance is limited to warmer months.

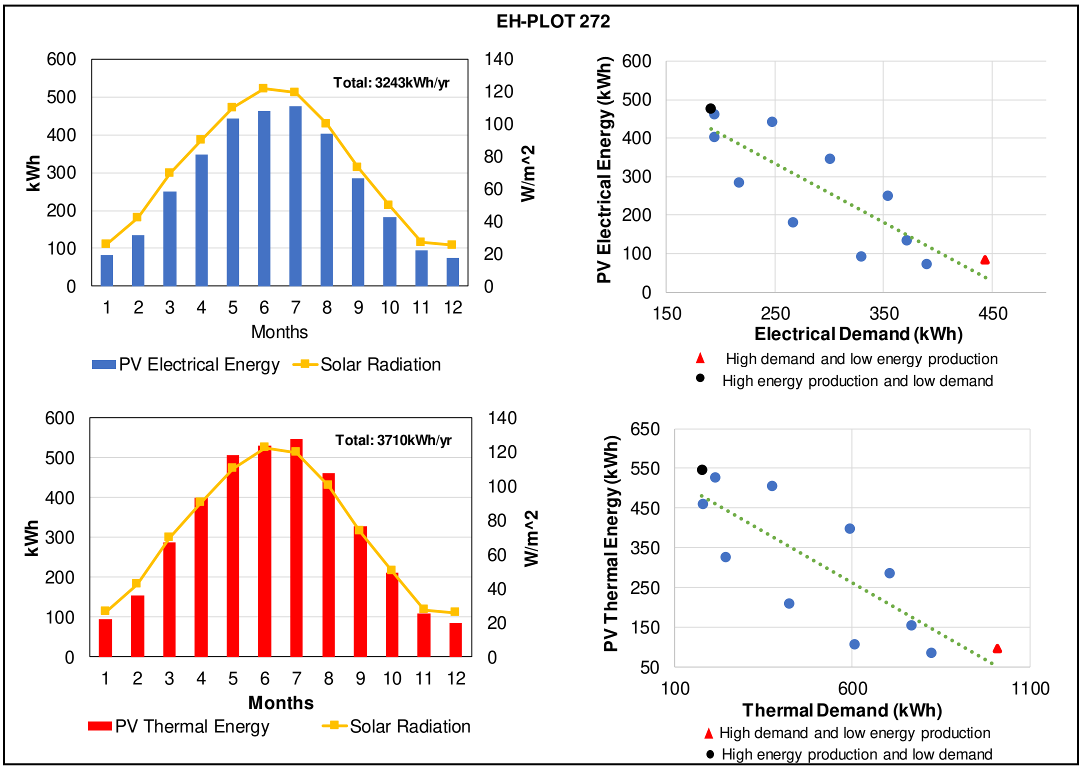



*Figure 24: Annual PV electrical and thermal energy generated in EH-Plot 272*

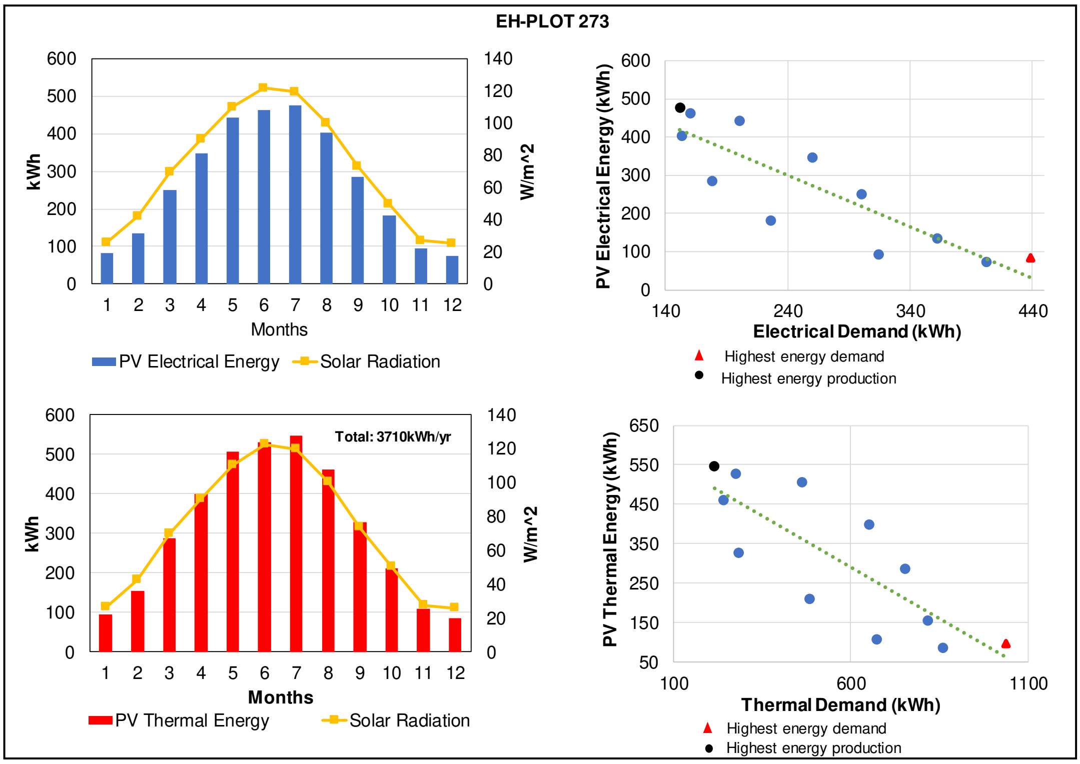



*Figure 25: Annual PV electrical and thermal energy generated in EH-Plot 273*

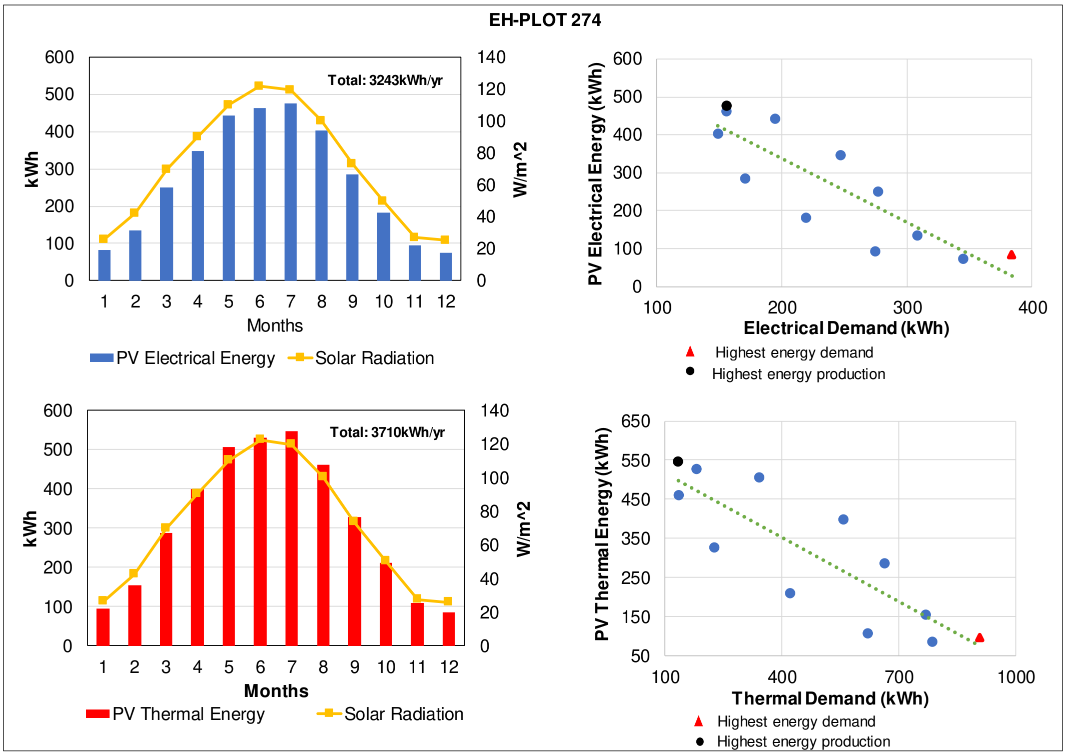



*Figure 26: Annual PV electrical and thermal energy generated in EH-Plot 274*

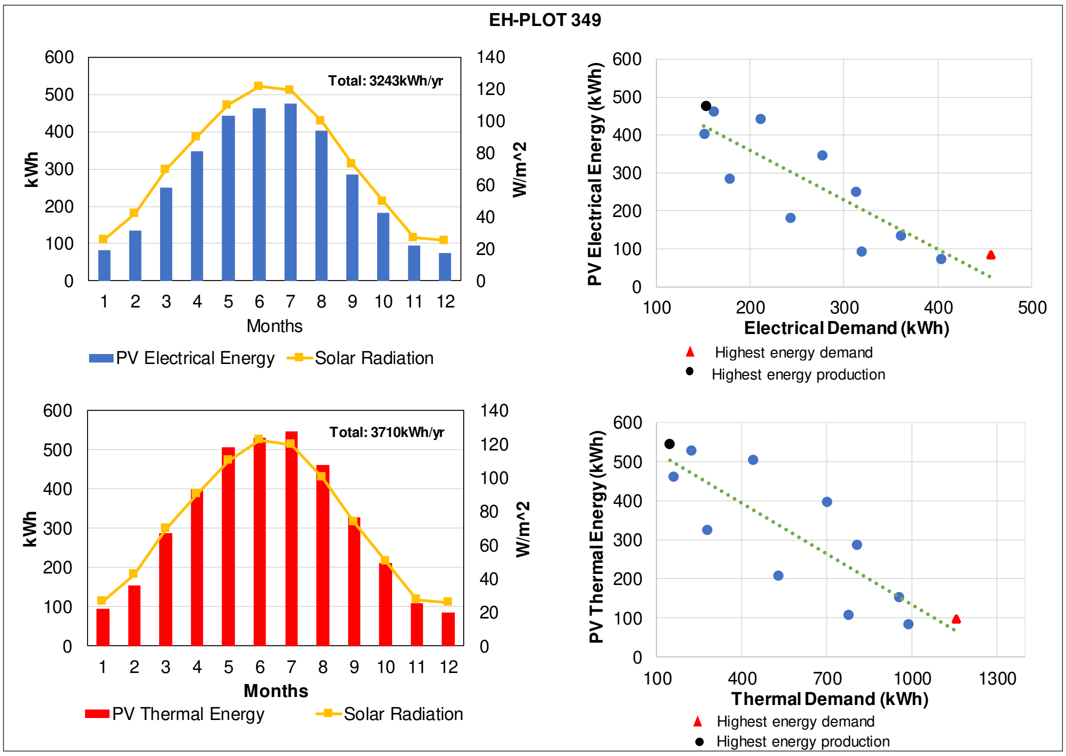
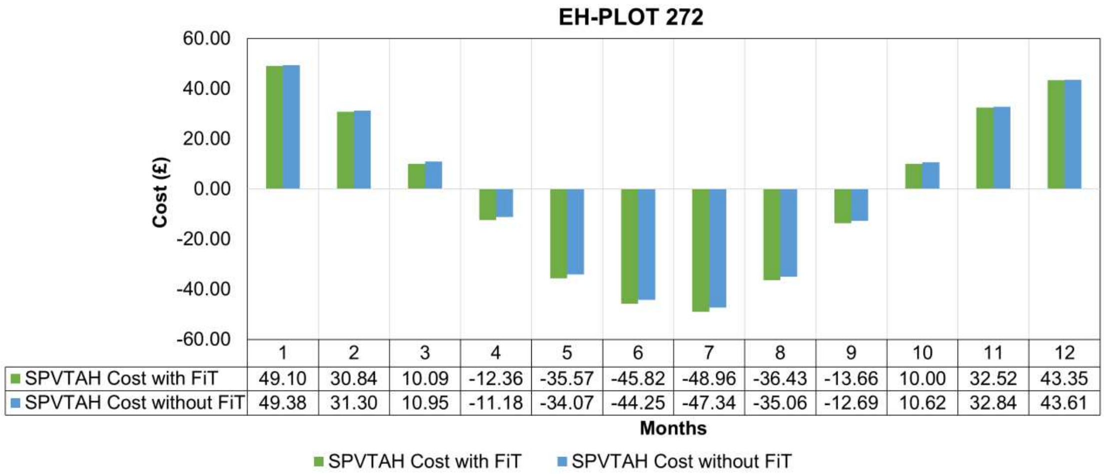



*Figure 27: Annual PV electrical and thermal energy generated in EH-Plot 349*

## 7.6 Techno-Economic Analysis

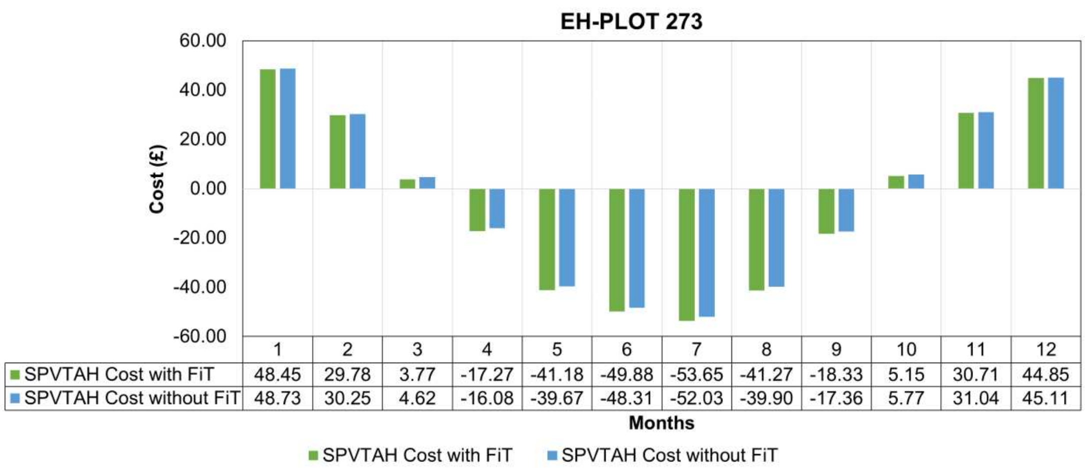
### 7.6.1 Zero Energy Bill Assessment

This section provides a detailed appraisal to assess the economic viability of the selected ZEB homes. The economics of ZEB homes is mainly driven by the running cost of the ASHP and the revenue generated by the exported electricity from the solar PV/T panels to the grid. Besides, the economics of the heating system, together with the SPVTAH system, is highly dependent on the magnitude of energy consumption, or, in particular, thermal demand. Figure 28–31 portray the related monthly electricity costs in each ZEB home over a year, with and without the FiT scheme. The outcomes showed that the status of the energy bill had been met. The simulation performed using E+ indicated that the zero-energy bill status may be attained when coupled with positive net income.




| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| SPVTAH Cost with FiT | 49.10 | 30.84 | 10.09 | -12.36 | -35.57 | -45.82 | -48.96 | -36.43 | -13.66 | 10.00 | 32.52 | 43.35 |
| SPVTAH Cost without FiT | 49.38 | 31.30 | 10.95 | -11.18 | -34.07 | -44.25 | -47.34 | -35.06 | -12.69 | 10.62 | 32.84 | 43.61 |

*Figure 28: EH-Plot 272 Economic analysis monthly plot*




| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| SPVTAH Cost with FiT | 48.45 | 29.78 | 3.77 | -17.27 | -41.18 | -49.88 | -53.65 | -41.27 | -18.33 | 5.15 | 30.71 | 44.85 |
| SPVTAH Cost without FiT | 48.73 | 30.25 | 4.62 | -16.08 | -39.67 | -48.31 | -52.03 | -39.90 | -17.36 | 5.77 | 31.04 | 45.11 |

*Figure 29: EH-Plot 272 Economic analysis monthly plot*

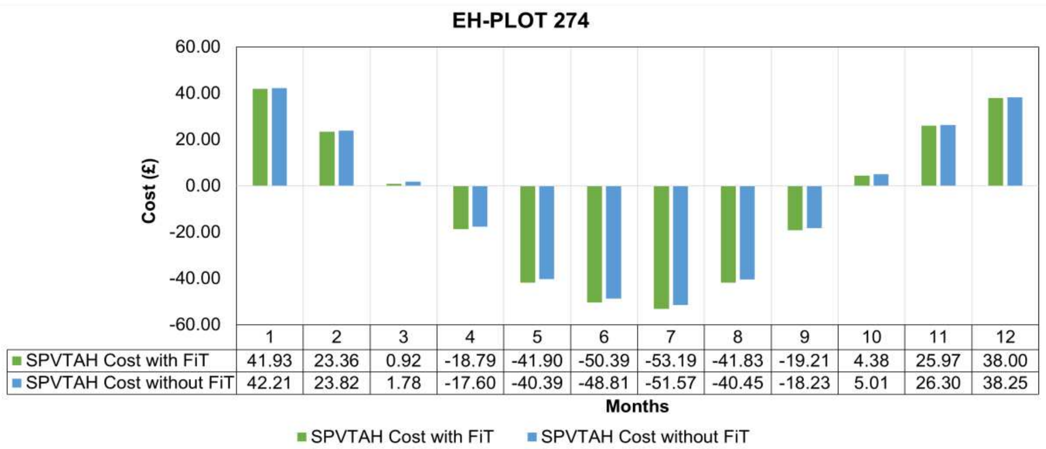



*Figure 30: EH-Plot 274 Economic analysis monthly plot*

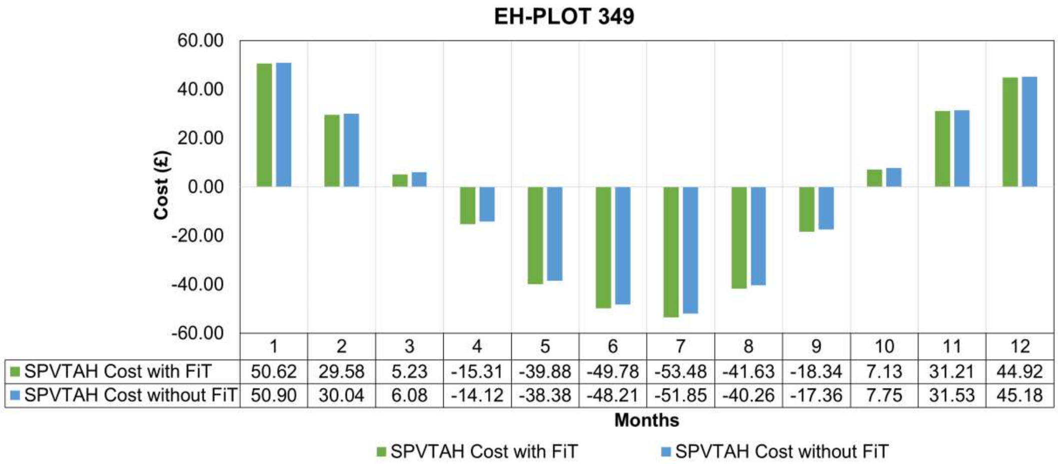



*Figure 31: EH-Plot 274 Economic analysis monthly plot*

Table 10 presents the implementation of the ZEB status through the SPVTAH system at the selected dwellings. The results highlight the significance of enabling an exceptional grid interaction between the SPVTAH system and the support mechanisms from the UK government, such as the FiT scheme, in generating higher profitable returns. The outcomes have been summarised as comparative economic appraisals on the SPVTAH system with the FiT against the SPVTAH without the FiT. In addition, the electricity consumption of the ASHP, appliances, and lighting was also incorporated.

*Table 10: Economic analysis results*

| ZEB home | SPVTAH with FiT* | SPVTAH without FiT* | Difference |
|---|---|---|---|
| EH-Plot 272 | -£16.91 | -£5.88 | -£11.03 |
| EH-Plot 273 | -£58.86 | -£47.83 | |
| EH- Plot 274 | -£90.73 | -£79.70 | |
| EH-Plot 349 | -£49.73 | -£38.70 | |

*The negative value means that the annual energy bill ends with net incomes.

### *7.6.2 NPV Analysis*

An NPV analysis was conducted at the condition of 10% interest. In fact, the cash flows in the analysis included the cost of the ASHP and 20 solar PV/T panels, along with installation cost, annual servicing, energy cost, and the revenues gained from FiT as well as the export tariffs. The values of these parameters were assumed to be constant for the entire 25-year NPV assessment period. See Figure 32.

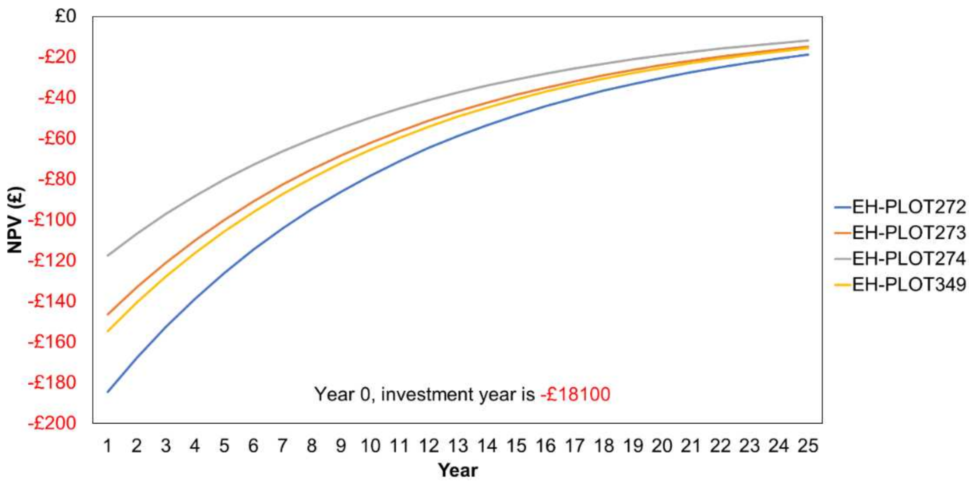



*Figure 32: NPV analysis results*

Table 11 presents a summary of the comparative results for the NPV analysis of the SPVTAH system against each ZEB home. Over the period of 25 years, assuming no escalation in maintenance costs or electricity prices, it was noted that increment of years led to a slump in the PV of each cash flow. The NPV at each home was - £19,943, - £19,563, - £19,273, and - £19,646 for EH-Plots 272, 273, 274, and 349, respectively. Notably, a higher NPV of the SPVTAH system was exhibited in EH-Plot 349.

*Table 11: Summary of the results of 25 years of NPV analysis*

| ZEB Home | NPV (£) * |
|---|---|
| EH-Plot 272 | -£19943 |
| EH-Plot 273 | -£19563 |
| EH- Plot 274 | -£19273 |
| EH-Plot 349 | -£19646 |

* The negative values mean an outgoing of cashflow

# 8. Conclusion

This paper implemented a building modelling approach by incorporating SPVTAH in ZEBHs. Thus, the modelling and the energy performance of the UK-based community ZEBHs were analysed. The modelling offered a baseline to assess energy performance, as it was imminent in identifying the parameters that influence the energy demand and the calibration method. Furthermore, a comparison of the modelling outputs by employing the measured data verified the performed assessments.

Modelling and simulation are still essential tools for conducting energy performance analysis of the ZEBHs. Pervasive-logged metered data offered information with focus points from the behaviour of the building occupants to the exploitation of the actual values facilitated by the calibrated model with accuracy. The following summarises the main findings of this work:

- Calibration should be conducted over an annual cycle with the use of hourly energy data, where impractical hourly primary data could be collected for shorter cycles (weekly or monthly) to 'validate' the simulation results.
- Local weather files should be measured and used for calibrating the models. Otherwise, any other type of weather file may assist in validating the models.
- The NMBE and CVRMSE calibration results, when presented in weekly intervals, will allow an assessment of the daily and hourly variations.
- The tolerated error levels of the models should be dictated by the function of the ZEBH models and primary data availability. There is scope for further work in defining the required levels of model accuracy for efforts such as optimisation and control studies.
- To that end, further refinement of the calibration guidelines should first reflect the model purpose. As demonstrated in this work, the models calibrated according to the limitations of the ASHRAE guideline can more confidently predict actual prevailing results within the building. The existing NMBE and CVRMSE values of ±10% and ±30%, respectively, can still be adhered, even when complete annual hourly data are not available to the analyst. In this case, such a model can be considered 'validated'.
- The economic viability, and FiT is absolutely vital. Variations in FiT prices may affect the status of the ZEBHs, particularly when space heat demand increases. In a nutshell, the economic analysis specifies that the zero-energy bill concept would be unfeasible if the UK FiTs are withdrawn.

The primary reason for integrating the measured data was to establish a benchmark for ZEBHs' energy performance, including occupancy behaviour in terms of appliance use and lighting. Therefore, the comparison outputs amongst the ZEBHs point out the significance of the occupancy elements as a factor that can influence thermal and electrical demand.
In addition, several key variances for the representation of the parameters influencing the ASHP thermal power demand have been determined. These variances seem to have mainly arisen due to the difference in occupant behaviours, DHW consumption, internal heat gains, and heat losses.

Furthermore, this paper also highlighted the energy production mapping on-site electrical/thermal power generation under various climatic conditions (e.g. irradiation). In fact, it has been proven that the use of PV/T panels is a clear optimum solution for such houses with the zero-energy target. However, this study emphasised the importance of back-up energy supply devices, such as ASHPs.

As the dwellings and their energy systems are part of the technical and economic subsystems, the aspect of cost-effective quantification at the level of each single building unwittingly externalised the costs. This notion certainly applies to the implementation of ASHPs, along with solar PV/T panels, as an energy-efficient method in providing space heating and/or domestic hot water. The economic analysis, prices, and tariffs is absolutely crucial. This is especially true since fluctuation in prices may affect the status of the ZEBHs, particularly when space heat demand increases. Moreover, the feasibility assessment indicated that the zero energy bill concept would be impractical if the UK government subsidies are withdrawn. Additionally, the NPV analysis further signified that even though the SPVTAH might generate revenues, repayment of the initial investment of £18100 in 25 years would turn out to be the largest barrier.

However, it cannot be denied that operating renewable energy technology in ZEBHs offers vast advantages, among which reduction in costs appears to be the most significant one. Nevertheless, the implementation of the SPVTAH systems grid interaction is essential for significant electricity cost reductions and the achievement of the ZEBH status. In addition, at present, the capital cost of the SPVTAH system has a stretched payback period (+25 years).

Excluding these attributes seemingly underestimates the overall societal cost of possible the future low carbon systems, resulting in a disproportionate trade-off between various viable policy measures. In this context, the primary objective of this study was to offer an initial estimate of the energy performance in ZEBHs with a presentation of a technical subsystem based on comprehensive building modelling, calibration, and energy simulations.

Therefore, future works related to this study should consider including the integration of ZEBHs and low voltage (LV) electrical networks. The link would allow the use of building energy models, inclusive of internal energy supply systems, in association with external energy supply systems such as the electrical grids. This can, therefore, permit the simulations of an integrated building and electricity network. The simulation of such systems can also depict an environment that would allow ASHP load-shifting strategy to be tested on the platform and assess energy demand flexibility of ZEBHs, especially when the intrinsic heat storage in the building can be used for the provision of ancillary services in LV networks.

# Acknowledgements

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# Appendix A

For the MATLAB PV/T model, it was necessary to obtain the absorptance ($\alpha = 0.70$) of the absorber plate that depends on the angle of incidence $(\theta)$. In this case, the transmittance $(\tau)$ value was set at 0.91, and the angle of incidence is calculated using the following equation:

$$AOI = \cos^{-1}(\cos(\theta_Z)\cos(\theta_T) + \sin(\theta_Z)\sin(\theta_T)\cos(\theta_A - \theta_{Z,Array}))$$

Here,

- $\theta_A$ and $\theta_Z$ are the solar azimuth and zenith angles, respectively. The azimuth angle convention is defined as the degrees east of north (e.g., North = 0°, East = 90°, West = 270°).
- $\theta_T$ is the tilt angle of the array, which is defined as the angle from the horizontal surface.
- $\theta_{A,\ Array}$ reflects the azimuth angles of the array. The array azimuth is defined as the horizontal normal vector from the array surface. An array facing south has an array azimuth of 180°.

The next step was the calculation of the incident solar radiation ($I_{dir} \cos\theta + I_{diff}$) on the PV/T panel surface. The incident solar irradiance can be determined by the direct solar irradiance ($I_{dir}$), the diffuse solar irradiance ($I_{diff}$), and the angle of incidence $(\theta)$. Subsequently, the amount of solar radiation absorbed by the absorber plate (($I_{dir} \cos\theta + I_{diff}$) $(\tau\alpha)$) was to be calculated. This value is a function of the transmittance ($\tau = 0.91$) and absorptance ($\alpha = 0.70$) of the collector. Thus, the result of the total of each solar radiation absorbed ($Q_{solar}$) by the PV/T panels has been presented in Figure A 1.

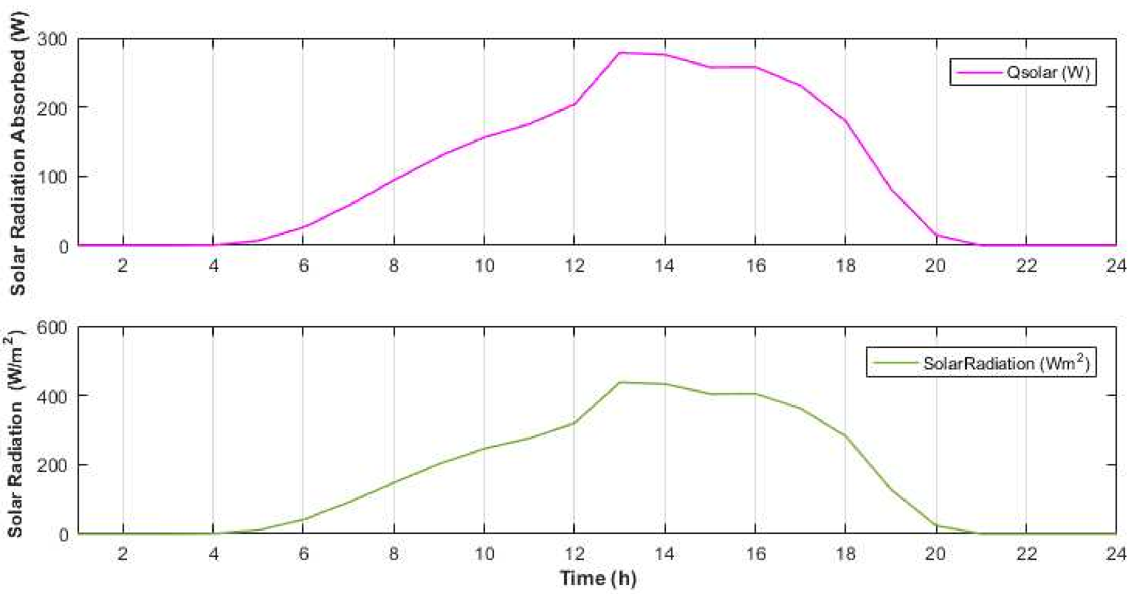


*Figure A 1: Solar radiation absorbed by the absorber plate (top) and solar radiation (bottom)-1st June*

The electrical energy produced by the PV/T collector is a function of the incident solar irradiance (($I_{dir} \cos\theta + I_{diff}$) and temperature difference ($T - T_{air}$) of the PV/T panel under standard conditions (STC) and in outdoor temperature. Hence, with every increase in the degree of the PV/T panel temperature, there will be a loss in the percentage of its power. In this case, the solar cells have a temperature coefficient ($E_t$) of 0.45% ºC, an efficiency ($E_o$) of 17.5%, a module temperature *(T)* of 25ºC at STC, and the total area ($A_{surf}$) of 1.37 m$^2$. The cell packing factor (P.F), which is *0.86*, was calculated using the following equation:

$$P.F = (A_{cell} Number\ of\ Cells) / (A_{surf}) = 0.86$$

Here, $A_{cell}$ is 0.0156 m$^2$, the total *Number of Cells* is 72, and $A_{surf}$ is 1.37 m$^2$.

Regarding the above premises and considering the transmittance value ($\tau = 0.91$), the total electrical energy produced ($Q_{el}$) from the collector on the 1st of June was 0.48 kWh. To obtain the useful heat generated by the PV/T panels, the heat losses *($Q_{loss}$)* should also be considered. For this reason, this step consisted of calculating the heat losses from the exposed surfaces of the collector. Taking the thermal loss coefficient ($U_L$) as 0.3 W/m$^2$ºC, fluid inlet temperature ($T_i$) as 40ºC, and the outdoor temperature ($T_{air}$), the $Q_{loss}$ resulted in values, as shown in Figure A 2.

As the final step, the useful heat generated ($Q_{useful}$) was calculated. Taking into account the heat removal factor *(FR)* of 0.86 and the total absorber area *($A_{abs}$)* of 1.19 m$^2$, the total $Q_{useful}$ generated on the 1st of June was given as 1.87 kWh$_e$.

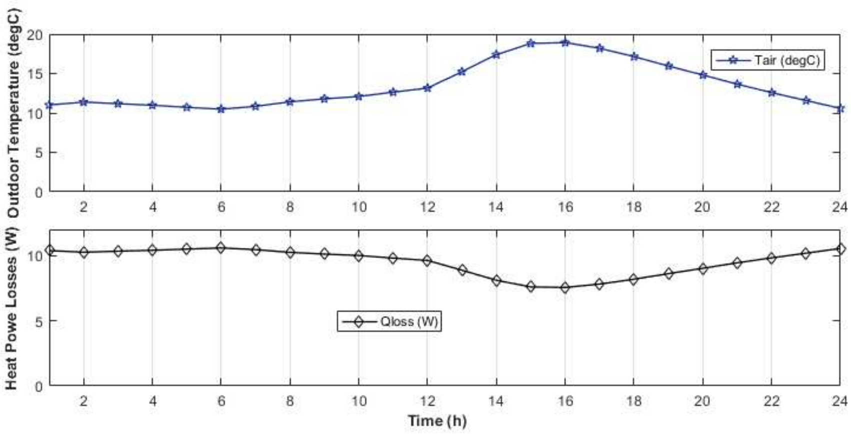


*Figure A 2: Outdoor temperature (top) and heat power losses by the PV/T panel (bottom)*

For the case of the EnergyPlus solar PV/T model, it was also modelled and simulated with an inclination angle of 45º. This step warranted setting PV/T panel input parameters. From the list of parameters, under '*Solar Collector: FlatPlate: PhotovoltaicThermal*', the surface was listed along with its performance characteristics defined under '*Solar Collector: FlatPlate: PhotovoltaicThermal: Simple*'. The PV cell, along with the working fluid type (water) and the corresponding inlet and outlet nodes, was defined.

The parameters have been summarised in Table A1. An important note is that the model disregards the module heat loss coefficient *($U_L$)*.

Table A 1: EnergyPlus PV/T panel input values

| PV/T Water System | |
|---|---|
| $A_{surf}$-PV/T Panel Area (m$^2$) | 1.37 |
| $\eta_{el}$- Module Efficiency | 15.6 |
| $P.F$-Packing Factor | 0.82 |
| $E_o$- Cell Efficiency (%) | 17.5 |
| $P_{mpp}$-200 (W) | 200 |

Finally, the simulation was achieved, and the total electrical and thermal energy were calculated. The PV modules determined the energy produced by the solar panels, and they are assumed to always function when the total incident solar ($I_{dir}\ cos\ \theta + I_{diff}$) is greater than 0.3 W/m$^2$. The usable electric power produced by each PV surface was calculated using the following equation:

$$Q_{el} = A_{surf} P.F(I_{dir} cos(\theta) + I_{diff})E_o$$

The PV/T model heats the circulating liquid through the pipes, and when the working fluid is flowing, the model calculates the collected heat with the following equation:

$$Q_{useful} = A_{surf} P.F(I_{dir} cos(\theta) + I_{diff})\eta_{thermal}$$

Here $\eta_{thermal}$ is the PV/T thermal efficiency.

*Table A 2: EnergyPlus PV/T panel simulation results-1st of June*

| $Q_{el}$ (kWh) | $Q_{useful}$ (kWh) |
|---|---|
| 0.63 | 1.95 |

In Figure A 3, it can be seen that the electrical power production of PV/T collector modelled in MATLAB and using EnergyPlus significantly deviates from 13:00 hours to 17:00 hours. During these hours, the deviation is larger, and this could be explained by the fact that E+ considers fewer input values than the MATLAB model.

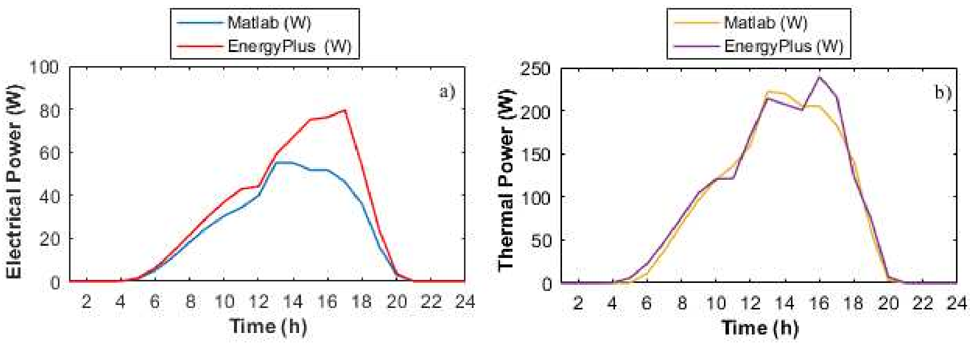


*Figure A 3: PV/T MATLAB and EnergyPlus results. a) electrical power generated and b) thermal power generated - 1st of June.*

As shown in Table A3, the percentage error between the EnergyPlus and the MATLAB results is 4.5% for the thermal energy generated and 24% for the electrical energy generated. The electrical energy generation has a high percentage of error, and this could be due to the power losses considered for the PV/T MATLAB model. The higher the solar radiation, the higher is the PV/T panel temperature, and therefore, the lower the electricity production. Conversely, the thermal energy production of the PV/T collector calculated by hand and using the simulation tool is approximately the same.

Table A 3: Solar PV/T simulation results difference between MATLAB and EnergyPlus

| **Parameter** | **MATLAB** | **EnergyPlus** | **Difference** |
|---|---|---|---|
| Thermal Energy | 0.48 kWh/day | 0.63 kWh/day | 24% |
| Electrical Energy | 1.87 kWh/day | 1.95 kWh/day | 4.5% |

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