MULTI-CRITERIAL DECISION-MAKING FRAMEWORK TO IDENTIFY THE OPTIMAL ON-SITE HYBRID RENEWABLE ENERGY SYSTEM FOR THE REPRESENTATIVE RETROFITTED DOMESTIC BUILDINGS IN WALES AND ENGLAND

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Preface

I have published one book chapter (first author) in my PhD journey.

The book chapter is online available:

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Abstract

The research project created a decision-making framework to identify the optimal hybrid renewable energy system (HRES) for the retrofitted home in Wales and England. The HRES combines at least two UK government-recognised renewable systems, working with or without energy storage to supply different demands simultaneously. The optimal HRES is the most economically and practically feasible and environmentally friendly solution, helping the UK government to achieve the agreed climate change target by 2050 in the building sector.

The development of the decision-making framework consists of two steps. The first step is to select the representative retrofitted home in Wales and England using the defined building character indicators. It then collects the economic-technical-environmental data of each potential renewable system and the representative energy tariff and emission factor of the national grid and natural gas in 2022. The second step is to create several different spreadsheets to evaluate the performance of HRES, calculate the weighting values and rank HRES. It first creates a spreadsheet to assess the economic-technical-environmental performance of HRES supported by the collected data from the first step. It also creates a spreadsheet to calculate the weighting values of such performance indicators based on the collected perceptions from the surveyed householders in Cardiff. Finally, it creates the spreadsheet to rank HRES supported by the evaluated performance results and the calculated weighting values.

The PV+ASHP+STC is the optimal combination under the weighting values from the surveyed householders' perceptions. However, PV+ASHP+STC+Battery is the optimal combination under the same weighting values for each selected decision-making indicator. This is because the economic performance was heavily weighted by the householders; PV+ASHP+STC has better economic performance than PV+ASHP+STC+Battery. It also discusses the advantages of using HRES combination with/without battery compared with the electricity grid and natural gas from the economic-technical-environmental perspectives. The discussion results drive the new energy policy and financial incentive development to encourage better householders to invest in renewable systems.

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List of Acronyms for terminology in context

Acronym	Full academic terminology	Acronym	Full academic terminology
A	Number of the questionnaire should be carried out	MCS	Microgeneration Certification Scheme
AC	Alternative Current	N	Number of occupants
AHP	Analytic Hierarchy Process	N	Number of occupants
ASHP	Air Source Heat Pump	N'	Total number of existing homes in Birmingham or Cardiff
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers	n’	Number of evaluated criteria
BCR	Benefit-cost ratio	NDC	Nationally Determined Contribution
BCR	Benefit Cost Ratio	NG	National Grid
BEIS	Department for Business, Energy, and Industrial Strategy	NPV	Net Present Value
BRE	Building Research Establishment	NREL	National Renewable Energy Laboratory
BREDEM	Building Research Establishment Domestic Energy Model	Ofgem	The office of Gas and Electricity Market

BREEAM	Building Research Establishment Environmental Assessment Method	PBP	Payback Period
BREEAM-INCTM	Building Research Establishment Environmental Assessment Method - International New Construction Technical Manual	PR	Performance ratio
BREEAM-RDBTM	Building Research Establishment Environmental Assessment Method - Refurbishment Domestic Building Technical Manual	PUA	Primary Urban Area
BREEAM-UKNCTM	Building Research Establishment Environmental Assessment Method - UK New Construction Technical Manual	PVB	Present Value of Benefits
BUS	Boiler Upgrade Scheme	RF	Renewable fraction
CCC	Committee on Climate Change	RHI	Renewable Heat Incentive
CI	Consistency index	RO	Renewable Obligation
CIBSE	Chartered Institution of Building Services Engineers	ROC	Renewable Obligation Certificates

CM	Capacity Margin	ROI	Return on Investment
CMA	Capacity Market Agreements	S/MOO	Single/Multi-Objective Optimisation
CMO	Capacity Market Obligation	SAP	Standard Assessment Procedure
COP	Conference of the Parties	SBP	System buy price
COVID	Coronavirus Disease	SCOP	Seasonal coefficient of performance
CR	Consistency Ratio	SEG	Smart Export Guarantee
CRF	Cost Recovery Factor	Solar PV	Solar Photovoltaic
CV	Coefficient of variation	SSP	System sell price
DC	Direct Current	STC	Solar Thermal Collector
DCP	Demand coverage percentage	TFN	Total floor area
DHW	Domestic Hot Water	TMY	Typical meteorological year
DNO	Distribution Network Operator	TOPSIS	Technique for Order of Preference by Similarity to Idea Solution
DPP	Discounted payback period	TRL	Technology Readiness Level
e	Confidence interval	VAT	Value-added Tax
EC	Embodied Carbon	VAWT	Vertical Axis Wind Turbine
ECO	Energy Company Obligation	VLA	Vented lead-acid
ECPP	Embodied Carbon Payback Period	VRLA	Valve-Regulated lead-acid

EHS	English Housing Survey	WEFO	Wales European Funding Office
EPC	Energy Performance Certificate	WHCS	Welsh Housing Condition Survey
ERDF	European Regional Development Fund	$A_{aperture}$	Aperture area of STC
EVs	Electric Vehicles	A_{pv}	Solar cell area
FAHP	Fuzzy-Analytical Hierarchy Process	$B_{SH\ or\ DHW}$	Monthly heat balance of the supply-demand calculation
FiT	Feed-in-Tariff	$Capacity_{HP}$	Commercially available size of heat pumps
GCV	Gross Calorific Value	n_m	The number of days in each month
GEI	Grid Electricity Independence level	N_1	Number of existing homes in Cardiff
GHG	Greenhouse Gas	N_2	Number of existing homes in Birmingham
GSHP	Ground Source Heat Pump	$D_{electricity}$	Overall calculated monthly electricity demand
HAWT	Horizontal Axis Wind Turbine	$D_{heating}$	heating days in a year
HRES	Hybrid Renewable Energy System	$D_{SH\ or\ DHW}$	Monthly space heating or DHW demand
IEA	International Energy Agency	P_{SH}	Electricity consumption of the heat pump
IRR	Investment Return Ratio	P_i	The final score for each HRES combination
LCC	Lifecycle Cost	E_A	The energy consumption of electrical appliances
LCC	Lifecycle Cost	E_{DHW}	Annual consumed energy to supply the calculated monthly hot water usage

LCF	Levy Control Framework	$E_{export\ to\ the\ grid}$	Generated electricity export to the grid
LCRI	Low Carbon Research Institute	Q_{HP}	Generated heat by heat pumps
MADM	Multi-Attribute Decision-Making	Q_{PV}	Annual generated electricity by solar PV
MCDM	Multi-Criteria Decision-Making	Q_{STC}	Generated DHW by STC
mCHP	Micro Combined Heat and Power system	η_0	The general zero-loss collector efficiency
		λ_{max}	The maximum weight

1. Introduction

In 2021, the UK's domestic building sector consumed 41.1 million tonnes of oil equivalent (mtoe) energy, and it is the second largest end-user, followed by the transport sector (BEIS, 2022a). Figure 1-1 presents the total energy consumption by four main end-users.

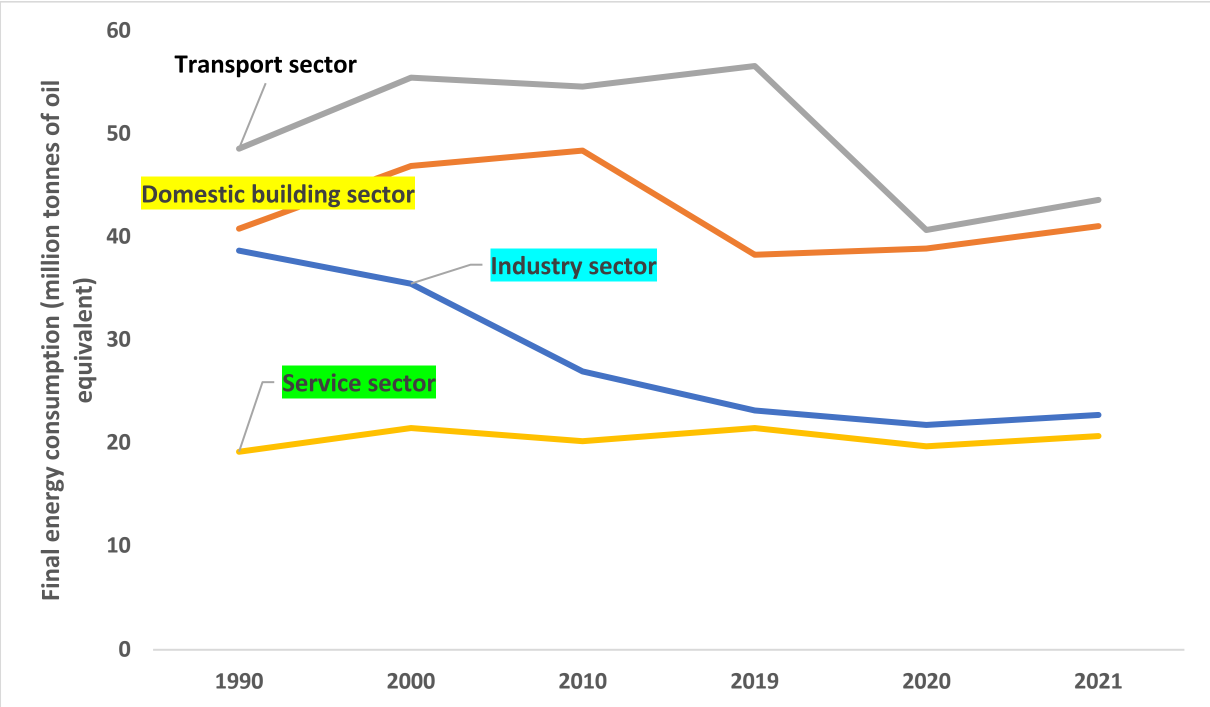


Figure 1-1 Total energy consumption by different end-users, figure reproduced from BEIS (2022)

The inefficient stock condition is the main reason caused the high energy consumption in UK homes. The EPC band of C is the basic level of the housing condition that the UK government accepted to meet the agreed climate change targets by 2050 (UK Government, 2017; UK government, 2021). Based on the statistical data presented by the Department for Levelling up, Housing & Communities (2021), about 47% of existing English homes meet the EPC band of C and above. About 42% of existing Welsh homes meet the EPC band of C and above.

While retrofitting can improve the energy efficiency of the building stocks. After the retrofitting, most of the homes still rely on using electricity from the grid and natural gas for heating purposes. The national grid has not been fully decarbonised (0.2123 kg CO_2 eq) (UK Government, 2022a), the natural gas is still the main resource either for electricity generation or heating purposes in UK homes (BEIS, 2022a). The government decided that heat pumps would be the main heating systems to supply domestic hot water (DHW) and space heating in UK homes. The decision further reflects the need to decarbonise the national grid faster to achieve the agreed climate change targets. The acceleration of the development of large-scale renewable systems, like solar farms and on-shore or off-shore wind turbines, enables an increasing percentage of using renewable energy in electricity generation at the national level. The contribution of renewable energy to electricity generation at the national level increased from 9.9TWh in 2000 to the maximum level of 134.7TWh in 2020, then slightly reduced to 122.2TWh in 2021 (BEIS, 2022a). Figure 1-2 presents the contribution to electricity generation by renewable resources.

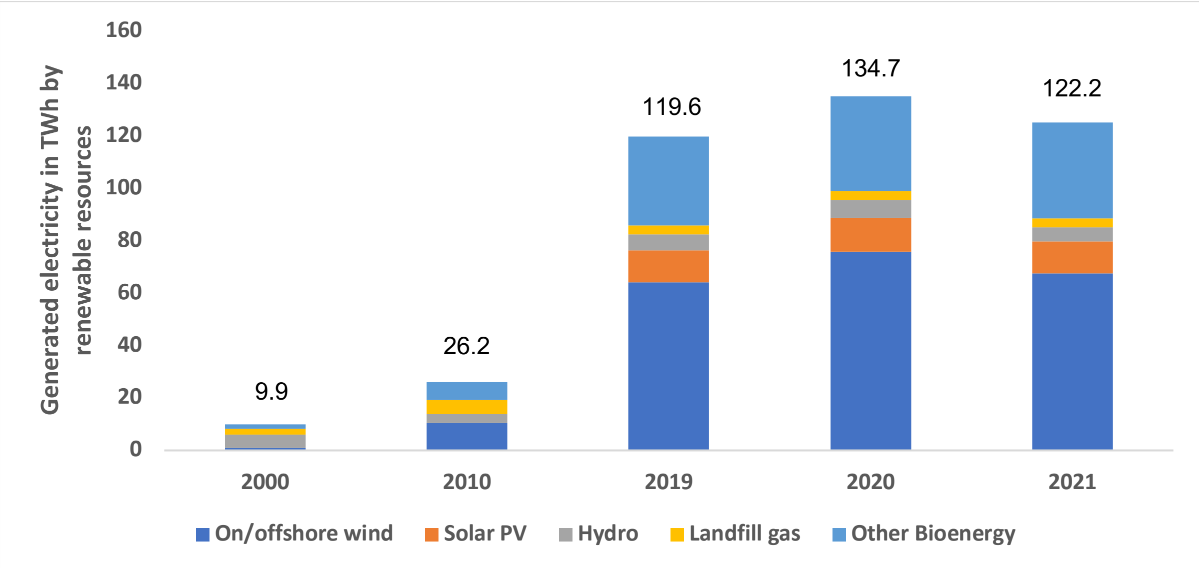


Figure 1-2 The contribution by renewable energy resources to electricity generation, figure reproduced from BEIS (2022)

However, large-scale renewable systems need more significant energy storage without using much fossil energy (e.g., natural gas) to secure the electricity supply. Such energy storages are expensive (high capital cost) and need ample installation space (IEA, 2022a; Rapier R, 2020). Then, the heat and buildings strategy (UK government, 2021) suggests that householders consider adopting renewable microgeneration systems to reduce their energy bills and secure the energy supply. Renewable microgeneration systems refer to government-recognised renewable power and heat systems that can be practically installed in at least the EPC band of C homes. This research investigates the potential combination of the government-recognised renewable system (hybrid renewable energy systems – HRES) to supply electricity and heat for UK homes. It evaluates whether such HRES is economical, practical, and environmentally viable solution for a typical EPC band C home in Wales and England.

1.1. Research aim

This research aims to create a multi-criteria decision-making framework and a supporting weighting system to evaluate the on-site hybrid renewable energy system (HRES) for the representative retrofitted house in Wales and England.

1.2. Research objectives

The following objectives are created to achieve the research aim.

- Objective 1: Review the English Housing Survey (EHS) and Welsh Housing Condition Survey (WHCS) to define the key indicators used to select the building case in this research. Then, design a modelling method based on the BRE domestic energy model (BREDEM) and standard assessment procedure (SAP) to simulate the energy demand of the selected building case.
- Objective 2: Analyse the findings from the permitted development requirement and existing financial incentives for installing government-recognised microgeneration systems in English and Welsh homes. The analysis results are used to form the potential HRES that can be practically installed in the selected building case.
- Objective 3: Collect the economic-technical-environmental data of the scoped potential renewable system from government-recognised brands. Meanwhile, analyse different UK energy suppliers, select the most representative energy supplier, and then collect the relevant energy tariff from the supplier. In addition, collect the carbon emission factors of the electricity from the grid and natural gas.
- Objective 4: Analyse the findings from the report published by the UK and worldwide climate change organisations to define the demand coverage percentage (DCP) scenarios. The defined scenarios are used to size the potential HRES combinations.

- Objective 5: Investigate BREEAM technical manuals, MCS installation standards, SAP and relevant research articles to select the most suitable indicators to evaluate the performance of the identified HRES combinations. In addition, investigate the preference value of the selected indicators from the representative householders' perspectives, converting such perspectives to the weights in supporting the final ranking to identify the optimal HRES combination.
- Objective 6: Develop a decision-making framework for householders to identify the optimal HRES combinations for their homes. The development of the framework is based on the achievements from objectives 1 to 5.

1.3. Thesis structure

This thesis consists of six chapters, from the introduction (chapter 1) to the conclusion (chapter 6).

Chapter 1 (introduction): It explains the motivations for choosing the research topic and how it sits in the context of the energy consumption of UK homes. It then stated the research aim and detailed objectives to achieve the aim.

Chapter 2 (literature review): this chapter gathers evidence from the relevant literature to demonstrate that HRES combinations can be an economic-technical-environmental viable solution to help the UK to achieve the agreed climate change target from the building sector. Meanwhile, it reviewed the practical evaluation criteria and indicators used to evaluate the performance of the building and the on-site renewable systems. The review findings help identify the most suitable criteria and indicators to evaluate the performance of the potential HRES combinations. By the end, this chapter reviewed the existing method used to rank different options under the multi-criteria or indicators weighted by different stakeholders' perspectives. The findings are used to decide the method to develop the decision-making framework and the supporting weighting system. The entire chapter helps to justify the importance to create the decision-making framework and gathering the relevant information to support the framework development.

Chapter 3 (methodology): this chapter explains the methods used to create the decision-making framework and the supporting weighting system. It also detailed the approach or method used to achieve each objective; all objectives are covered in this chapter.

- Approach to achieve objective 1: Section 3.1 defines the building character indicators and explains using such indicators to select the building case in this research. Section 3.8 explains the modelling method and simulates the energy demand of the chosen building case.
- Approach to achieve objective 2: Section 3.2 analysed the findings from the literature and then formed 6 different potential HRES combinations that can be practically installed on the chosen building case.
- Approach to achieve objective 3: Sections 3.3 to 3.5 explains in detail the approach used to collect the economic-technical-environmental data of the selected government-recognised renewable system. In addition, section 3.6 states the method used to determine the representative energy supplier, the collection of the energy tariff and carbon emission factors of the national grid and natural gas.
- Approach to achieve objective 4: Section 3.9 states the method used to define the DCP scenarios based on the analysis of the selected reports. Section 3.10 detailed the calculation method to work out the size of each renewable system under the defined DCP scenario.
- Approach to achieve objective 5: Sections 3.7 and 3.11 explains the selection of the most suitable criteria and indicators used to evaluate the performance of HRES combinations. Section 3.12 describes the method used to gather the preferences values from the representative householders and then convert those preferences values to weighting values for the selected suitable criteria and indicators. Finally, section 3.13 explains the method used to rank HRES combinations based on the created weighting system that is converted by the representative householders' preferences values.

Chapter 4 (results): this chapter presented the preliminary results for each objective using the associated methods explained in chapter 3.

Section 4.1 presents the selected representative building case that meets the defined building character indicators. It also presents the simulated energy demand of the chosen building case. – Objective 1

Sections 4.2 and 4.3 present the collected economic-technical-environmental data of the government-recognised renewable systems used to form the potential HRES combinations. – Objectives 2 and 3

Section 4.4 presents the economic-technical-environmental performance of the sized HRES combinations using the defined DCPs. The selected most suitable indicators are used to evaluate the performance of such RHES combinations. – Objectives 4 and 5

Sections 4.5 and 4.6 present the weighting system developed based on the collected representative householders' preference perspectives. The sections also present the ranking results of the potential HRES combinations based on the developed weighting system. – Objective 5

Section 4.7 presents the prototype of the developed decision-making framework. – Objective 6

Chapter 5 (discussion): this chapter continues to discuss the three topics (sections 5.1-5.3) based on the preliminary results. The discussion results reflect the in-depth discussion of the preliminary results for policymakers to plan future energy policies and financial incentive schemes that largely encourage householders to adopt renewable systems in their homes.

Section 5.1 discusses the economic-technical-environmental benefits of installing HRES combinations with/without battery than relying on the national grid and natural gas.

Section 5.2 compares the advantages and disadvantages of using grid-scale, community, and home-based batteries. This section also provides several suggestions for the current regulations and energy policy to encourage the adoption of batteries in the energy transition period.

Section 5.3 discusses the economic benefits of different financial incentives. The discussion results help re-evaluate the existing financial incentive schemes and guide future policies to support investing in renewable systems. In addition, the discussion helps to understand the economic performance gap between HRES combinations and individual renewable systems.

Chapter 6 (conclusion): this chapter summarised the whole thesis addressing the key findings of the research. In addition, the chapter stated the limitations and future research plans.

2. Literature review

This chapter is constituted of five sections.

Section 2.1: it reviewed the relevant energy policy in the building sector published by the department for the business, energy, industry, and strategy (BEIS); the office of gas and electricity markets (Ofgem), and the committee on climate change (CCC). The findings from this section identify the drivers and barriers to using the on-site renewable system(s) in UK homes.

Section 2.2: it reviewed the history, structure, and function of the UK's energy market after the privatisation. The findings help to understand the issues in the current energy market and whether the proposed on-site renewable system (s) can be an alternative solution to deal with the energy market's issue from the householders' perspectives.

Section 2.3: it reviewed the commercially available renewable systems in the UK market recognised by the UK government. The findings are used to explore the potential hybrid renewable energy system (HRES) that can practically be installed on typical homes in England and Wales.

Section 2.4: it reviewed the criteria and indicators used to assess the performance of the building and the relevant installed on-site renewable system. The reviewed criteria and indicators are from Standard Assessment Procedure (SAP), BREEAM technical manuals, MCS installation standards and the relevant research articles. The findings are used to identify the most suitable criteria and indicators that can effectively evaluate the performance of the on-site renewable system(s).

Section 2.5: it reviewed the decision-making method that can rank different options under the multi-criteria considering different stakeholders' perspectives. The findings are essential to determine the decision-making method in developing the decision-making framework.

2.1. UK energy policy pathway in the building sector

This section reviewed the UK's energy policy, particularly in the building sector, published by the department for the business, energy, industry, and strategy (BEIS), the office of gas and electricity markets (Ofgem), and the Committee on Climate Change (CCC). Such departments and organisations played an essential role in developing guidelines and policies to ensure the devolved government is on track to achieving the agreed climate change target by 2050.

The pathway started with the UK's commitment to Paris Agreement in 2016. The Paris Agreement demonstrates the 196 member countries' commitments to make suitable strategies in combatting climate change. The Paris Agreement entered force in December 2016; after that, the 196 member countries should develop a feasible plan and target in line with their commitment to Paris Agreement. Meanwhile, the member countries are required to publish the nationally determined contribution (NDC) by 2020, providing a detailed and feasible solution to achieve the agreed climate change target.

2.1.1. Between 2016 and 2019

Before the Paris Agreement entered force, only after finishing the COP-21 in 2015. CCC (2016) responded to the UK's commitment to the COP-21 (signed Paris Agreement) and published a progress report. The progress report analysed the feasibility of achieving the net-zero target based on the created three scenarios in the building sector. This report analysed the outcome of each scenario and conducted the feasibility analysis for the UK in achieving the net-zero targets. Due to the lack of evidence within the time, it did not clarify the feasible target by 2050, responding to commitment to the Paris Agreement.

As a part of the climate change target, future energy should be equally used by everyone and be affordable. BEIS drafted domestic gas and electricity (tariff cap) bill to regulate the energy bill, enabling the energy can be affordably used by every UK home. The tariff cap entered force in January 2019, indicating the energy bill has been regulated by a maximum charge. Meanwhile, BEIS introduced Energy Company Obligation (ECO) to help low-income families couple with the high energy bill during the intensive heating period.

In 2019, CCC published the report (CCC, 2019), which concluded that net-zero is necessary, feasible and cost-effective for the UK to achieve. The report recommended that the devolved government should legislate as soon as possible to achieve net-zero greenhouse gas (GHG) emissions by 2050. For the building sector, the report based on the clean growth strategy recommendations suggests improving the existing homes' efficiency by improving the insulation and using energy-efficient appliances. It detailed the heating thermostats should not be above 19 $°C$, and the heating flow temperature should not be higher than 55$°C$. Such detailed solutions provide the fundamental condition for homes adopting renewable energy systems in the future.

2.1.2. Between 2020 and 2021

In late 2020, the UK's prime minister announced the ten-point plan (Government, 2020). The plan sets out the method government will take to build back better, support green jobs, and accelerate the path to net-zero. BEIS then in December 2020 published UK's nationally determined contribution (NDC) (BEIS, 2020c). The NDC is based on the advice from the CCC, which is expected to be a starting point for the UK to accelerate its green transition and become an international frontier in achieving a low-carbon global economy. The NDC is the formal response of the UK to the Paris Agreement. It solid the commitment that the UK will reduce economy wide GHG by at least 68% by 2030. Following the ten-point plan, BEIS published the energy white paper (BEIS, 2020b). The energy white paper sets out plans for the UK to clean up its energy system and achieve net-zero emissions by 2050. It mainly addressed the transformation of the current UK energy system, prompting high-skilled green jobs and supporting resilient economic growth on the way towards net zero.

BEIS published the societal change analysis report in 2021. The analysis was conducted by Catapult (Mckinnon et al., 2021), which aims to understand the possible impact of different societal and behavioural changes in achieving the climate change targets by 2050. The report found that about 60% of the climate change approaches will involve either behaviour change, or a combination of behaviour change and technology solutions. BEIS also updated the green book supplementary guidance (BEIS, 2021c). The updated guidance better aligns with the latest agreed climate change target in appraising and evaluating public policies and projects to consider climate change and energy impacts. The heat and building strategy (UK government, 2021) was also released in 2021. The strategy sets out the detailed plans that the UK will take to decarbonise homes, commercial, industrial, and public buildings. It builds on the commitments made in the clean growth strategy (UK Government, 2017), energy white paper (BEIS, 2020b) and the ten-point plan (Government, 2020). It aims to provide a clear direction for the energy transition period by setting out the strategic decisions, demonstrating how such strategies meet climate change targets and are on track to net-zero by 2050. Different to the heat and building strategy, the net-zero strategy (BEIS, 2021a) sets out policies and proposals for decarbonising all sectors of the UK. It is also based on the ten-point plan (Government, 2020). It aims for a green economic recovery from the COVID pandemic recovery to help the UK at the forefront of the growing global green economy.

2.1.3. 2022 onwards

UK government adjusted the current financial incentive schemes for householders adopting renewable energy systems. The new financial incentive scheme is termed Boiler Upgrade Scheme (BUS) (Ofgem, 2022a). The new scheme (BUS) offers an upfront payment to encourage householders to replace boilers with an air source heat pump (ASHP) for £5000 or a ground source heat pump (GSHP) for £6000. The new scheme was started in April 2022 and the previous scheme, the renewable heat incentive also known as RHI stopped accepting new applications.

The differences between RHI and BUS are 1) the covered renewable heat systems and 2) the payment approach. RHI covers three renewable heat systems, solar thermal collector (STC) and ground or air source heat pump (G/ASHP), but BUS only covers G/ASHP. Regarding the payment approach, RHI pays for the generated energy generated by the recognised renewable heat system every three months for seven years for householders who installed such systems. In addition, RHI did not offer any upfront funds to support householders adopting renewable heat systems. Differently, BUS provides an upfront payment of £5000-£6000 for householders willing to replace the boiler with ASHP or GSHP. The BUS is more encouraging to householders who need financial support to upgrade boilers at the investment stage.

2.1.4. Summary

Based on the reviewed relevant energy policy in building sectors from BEIS, Ofgem and CCC. Such policies have the following advantages to moving towards a net-zero target forward in the building sector:

- Fundamental building stock condition: As CCC suggested, the existing homes should be upgraded to become energy efficient and airtight (minimum at EPC band C). The thermostat should not be set above 19 $°C$, and the heating flow temperature should not exceed 55$°C$. Therefore, such building stock conditions will be good to adopt the renewable power and heat system to meet the relevant comfort requirements defined in CIBSE Guide A.
- Regulated energy price cap: The government issued the energy price cap to ensure householders can afford energy from the national grid and natural gas pipeline to meet their energy demand. The policy partly aligns with the net-zero target, providing the energy can be equally accessed by everyone at an affordable price.

- Feasible climate change strategies: BEIS and CCC frequently updated and modified climate change policy and targets, enabling the policy to be realistic, achievable, and aligned with the commitments to the Paris Agreement, particularly after the COVID pandemic.
- Consideration of societal impact: The government started considering the impact of different societal and behavioural changes in achieving the climate change targets. Some of the feasible strategies have the potential to change occupants' behaviour at home. For example, the heating temperature etc. It is necessary and essential to developing a good understanding of the behavioural changes prior to practically implementing such strategies.
- Available financial incentives: The heat and building strategy (UK government, 2021)suggests the on-site renewable energy system as a feasible strategy against climate change. The government has placed some financial incentives to encourage householders to adopt suitable on-site renewable systems for their homes.

However, some limitations remain in the reviewed energy-related policy and guidelines.

- The increasing energy prices: Although the energy price cap better regulates energy prices to ensure the energy is affordable for UK homes. After the COVID pandemic and the conflict between Russia and Ukraine, the global fossil energy price has increased extensively. Ofgem has to adjust the price cap to align with the wholesale market's changing. The energy price cap then was increased by 12% in October 2021 and again by 54% in April 2022 (UK Parliament, 2022). The increased energy cap limited some low-income families living in poor energy efficiency stock conditions to purchase energy. Therefore, it needs to explore an alternative energy supply strategy with an affordable price to be used for all UK homes.
- The evaluation of the combined on-site renewable systems in multi-criteria: the upgraded house condition and the defined minimum EPC band C have provided the fundamental condition to adopt the on-site renewable system for UK homes. However, like the suggestions in heat and building strategy (UK government, 2021). It needs to investigate the suitable combination of the on-site renewable systems (with energy storage) that can replace the current energy supply strategy wherever is affordable, practical, and feasible for UK homes.

- Consideration of householders' perspectives: The current research started to understand the behavioural changes and implement feasible climate change strategies. It also needs to consider the householders' perspectives prior to extensively implementing the feasible strategy. For example, it is necessary to value householders' perspectives for the strategy of adopting an on-site renewable energy system. The householders' perspectives can improve the reliability of the decision-making for the relevant implementation policy.

2.2. UK energy market and domestic energy price

In 1990, the successful reforming of 12 regional state-own electricity companies across England and Wales to private-ownership, following the privatisation of the natural gas market, resulted in the energy market in the UK becoming privatised (Helm, 2017). The UK, therefore, become the first country to actively run a private energy market in Europe. Whilst some issues remained in the privatised energy market. For example, private electricity generation remained marginal; eligibility to become as a private electricity generation company; less effective and significant competition in the private energy generation market; and the most importantly, uneven distribution cost across the country (E. Hammond et al., 1989). Privatisation, especially for the electricity market, allows customers to choose and use the electricity from the most affordable supplier. In addition, various energy suppliers provide different fixed energy contracts with competitive prices to attract and secure customers. The competition among different energy companies was then formed. In theory, compared with the public-own energy market, the customers can freely switch to different energy suppliers based on their economic preferences. Therefore, the private energy market is becoming more inclusive, affordable, and equally used by every customer in the UK (E. Hammond et al., 1989).

In 2019, the government has taken further action by introducing an energy price cap to ensure that householders can afford the energy bills and decrease the number of fuel poverty homes. The energy price cap aimed to relieve the pressure from the increasing wholesale market price on householders; regulating the energy price charged by energy suppliers cannot go beyond the defined cap price (Heatable, 2022). However, the energy price cap had continuously increased by 12% in October 2021 and then by 54% in April 2022 (UK Parliament, 2022). The increased energy price cap might lead to more fuel poverty homes in the UK. Therefore, it is important to clearly understand the structure of the privatised UK energy market, the constitution of the UK market and the basic calculation mechanism to calculate energy price. An in-depth understanding of such factors helps identify the feasible solution to reduce the number of fuel poverty homes, enabling most UK homes can afford the energy to meet today's home demand requirements. In addition, a good understanding of these factors is useful to rethink the current energy system and energy market and what changes are needed for the UK energy market to drive the energy transition period forward.

This section is consisted of the following subsections:

- 2.2.1. This subsection reviewed the breakdown components included in the estimated electricity price in today's electricity market. It also indicated that the wholesale market is the dominant component and largely impacts electricity price changes. The detailed discussion of the wholesale market is explained in subsection 2.2.3.
- 2.2.2. This section briefly discussed the history of three mechanisms (the POOL, NETA and BETTA) in place to trade electricity in the wholesale market after privatised electricity market in the UK.
- 2.2.3. This subsection builds upon subsections 2.2.1 and 2.2.2 to explain the factors that impact the wholesale market. It also explained explicitly how the electricity is traded between generator, supplier, and customer in the privatised wholesale market.
- 2.2.4. This subsection explained the function and mechanism of capacity markets. The key function of the capacity markets is to determine the availability of power plants to generate sufficient electricity to meet the security of supply, particularly at peak times (Helm, 2017). In addition, this subsection briefly discussed the mechanism in the capacity market after privatisation.
- 2.2.5. This subsection first discussed the changing situation of renewable energy resources in electricity generation. It then explained the effectiveness of renewable obligation (RO) to incentivise suppliers to provide more electricity generated by renewables.

2.2.1. The structure of electricity price in the privatised energy market

After the privatisation, the four main components constructed UK's electricity price. They are, the generation cost, networks cost, supply cost and taxes and levies cost (Helm, 2017). The generation cost significantly impacts the changes in electricity prices compared with the other costs. The generation cost and the associated dimensions are then reviewed and detailly discussed in the following subsections.

The generation cost is constituted by three dimensions, the wholesale market (section 2.2.3); the capacity market (section 2.2.4); and the financial incentives and renewable generators (section 2.2.5). The wholesale market largely impacts the generation cost, as well as the electricity cost; it accounts for 40% of electricity bills in 2022 (Ofgem, 2022d). The networks cost is related to the cost of transporting energy from the national to the district or local level. It has two dimensions, the cost of transmission and the cost of distribution. The supply cost is related to the cost that energy suppliers provide the relevant energy service charge to the customers, only one dimension (the cost of supply) is included in the supply cost. The taxes and levies cost refers to the relevant energy taxes (e.g., carbon tax); it also includes one dimension, energy and carbon taxes and levies. Figure 2-1 presents the structure of electricity price.

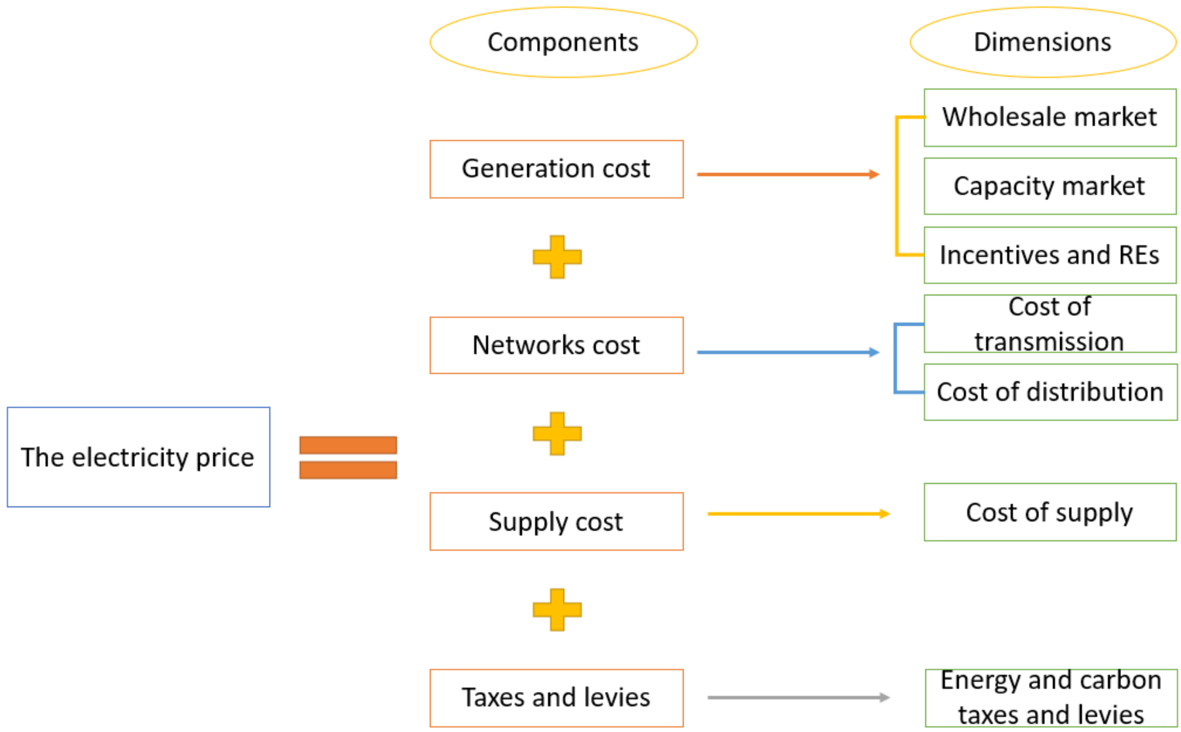


Figure 2-1.Structure of the electricity cost

2.2.2. A brief history of the privatised electricity market for the wholesale market trading

This section starts with several terms, POOL, NETA and BETTA. Such terms were used to regulate trading electricity in the wholesale market after the privatisation (Helm, 2017).

The POOL mechanism was established as the mechanism to trade electricity in the wholesale market across Wales and England just after the privatisation of the electricity market in 1990. On behalf of the POOL, the National Grid (NG) is responsible for providing an estimated energy demand. Everyday electricity generators submit to NG a schedule of the availability of their power stations for each half-hour for the following day. Electricity generators also provided the price they would be prepared to generate at each half-hour. The charged price depends on the most expensive plant on the system for each half-hour, which is determined as the system marginal price for all generated electricity. Figure 2-2 presented the work mechanism of the POOL.

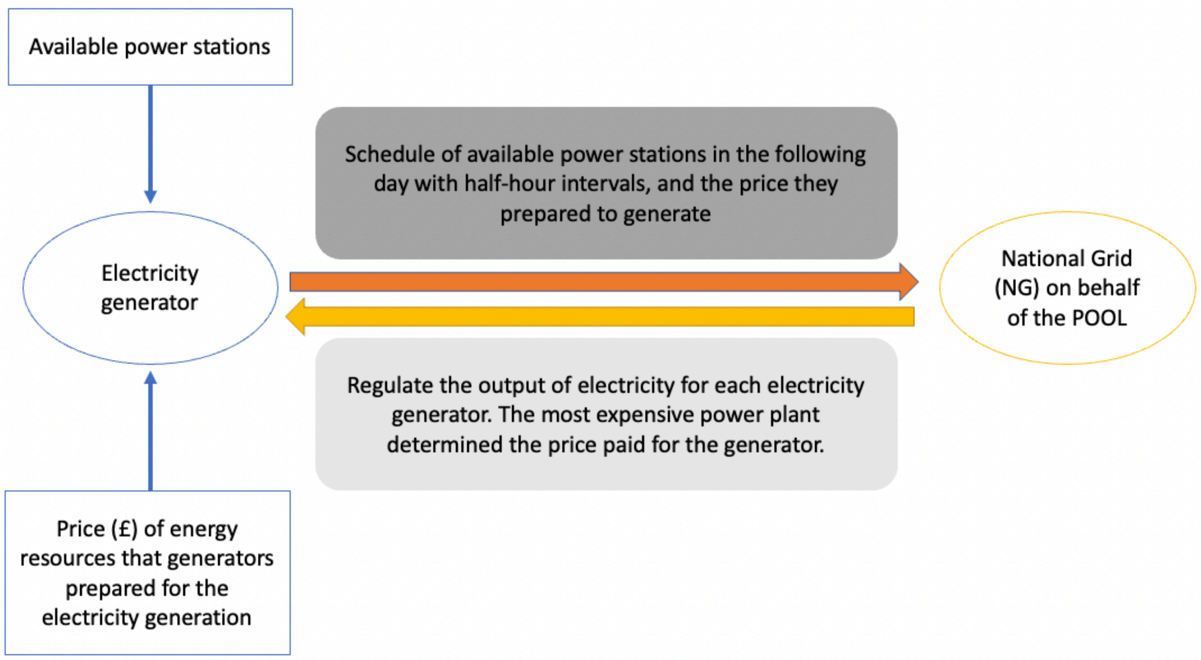


Figure 2-2. POOL mechanism

The POOL mechanism developed the regulation allows the electricity to be traded in the privatised market. However, the POOL mechanism only applied in Wales and England, but not in another two union member countries, Scotland and North Ireland. Then, in 1997, the UK government reviewed the electricity trading arrangements, with a view to increasing competition and reducing costs in the privatised electricity market (Helm, 2017). The UK government then introduced new electricity trading arrangements based on bilateral trading between generators, suppliers, traders, and customers through futures markets and short-term power exchanges (Helm, 2017). The term NETA is given to the name for the new electricity trading arrangements.

The NETA mechanism has the following differences in trading electricity compared with the POOL mechanism (BEIS, 2014a):

- Generators are responsible for determining the level of output from their available power stations. Generators will not submit the schedule to the NG (on behalf of the POOL).
- Generators would be paid at the bid price, rather than the price determined by the most expensive plant for the associated half-hour.
- The trading process would continue to happen until 3.5 hours ahead of the actual time. Different from the POOL, trading time happened a day ahead.

- The balancing system introduced would incentivise flexibility and penalise plants causing imbalance. The balancing system deal with any differences between the actual generation and the contracted demand.
- The balancing system relied on the cash-out prices that target the imbalance cost between generators and suppliers, providing incentives for generators to balance the differences between the actual generation and contracted demand.

Like the POOL mechanism, the NETA mechanism only applies to Wales and England. Before the BETTA mechanism was introduced, the Scottish suppliers were required to own power plants, negotiate directly with other generators, or even import through the interconnector (Helm, 2017). The prices were determined as the same as the POOL prices. After the proposal of the British Electricity Trading and Transmission Arrangements delivered by BEIS to implement an entirely competitive UK-wide wholesale electricity market. In 2005, the BETTA mechanism was introduced, and the associated characteristics were explained in the following (BEIS, 2014a; Helm, 2017):

- To extend the NETA mechanism into the Scottish market.
- Creating a single body to operate the transmission system in both Wales, England, and Scotland. Previously, the NG took on this role in England and Wales. But in Scotland, ScottishPower and Scottish & Southern Electricity took the role.
- Reforming access to the transmission system.

2.2.3. The wholesale markets.

The main responsibilities of the wholesale market are to schedule power plants for dispatch and ensure the supply can match exactly the demand at every time. The electricity is traded by the regulative mechanism introduced in section 2.2.2, enabling the energy market trade to be physically balanced and financially settled (Helm, 2017). The physical balance (the physical balance is the balancing system explained in the NETA mechanism) is based on the 'self-dispatch' system; within the system, suppliers and generators contract to buy and sell electricity and have to pay 'balancing costs' if they under or over-deliver. The system operator (the single body developed in the BETTA mechanism to operate electricity in Wales, England and Scotland) takes action to ensure the whole system keeps balanced. Such actions are then determined by the balancing cost of under or over-delivering (Helm, 2017).

Traders (generators and suppliers) can set up a bilateral contract to buy or sell electricity prior to the day of delivery; the process is named forward trading (Helm, 2017). The electricity is traded in half-hour slots on the day of delivery; the half-hour slots are named settlement periods. Each trading day has 48 settlement periods, starting with the first period (00:00 – 00:30) to the last period (23:30 – 00:00). The bilateral contract should be finalised prior to the trading, and the contract cannot be changed after the gate closure time (the gate closure currently set an hour before the settlement period). However, the traders (generators and suppliers) can change the trading volume of electricity which they think can impact the imbalance calculations up until the gate closure time.

In real delivery, the contracted volume is sometimes not as same as the actual volume. The generated electricity might exceed or shortfall of the actual demand. The imbalance pricing is then introduced to deal with the imbalance situation. The imbalance pricing includes two types of prices; the system buy price (SBP) and the system sell price (SSP). If the actual supply-demand volume exceeds the agreed bilateral contract, the suppliers must buy electricity at the SBP rate. Suppliers will buy electricity at the SSP rate if the actual supply-demand volume is lower than the agreed bilateral contract. The SBP and SSP rates are not static and are calculated based on the actions taken by the operator in the wholesale market. The actions include reducing generation or increasing demand when there is too much electricity in the wholesale market. The actions will be taken to increase generation or decrease demand when there is not enough electricity. The imbalance price can rise significantly when demand is high but the available additional power plants are limited. Figure 2-3 presents the structure of the imbalance pricing.

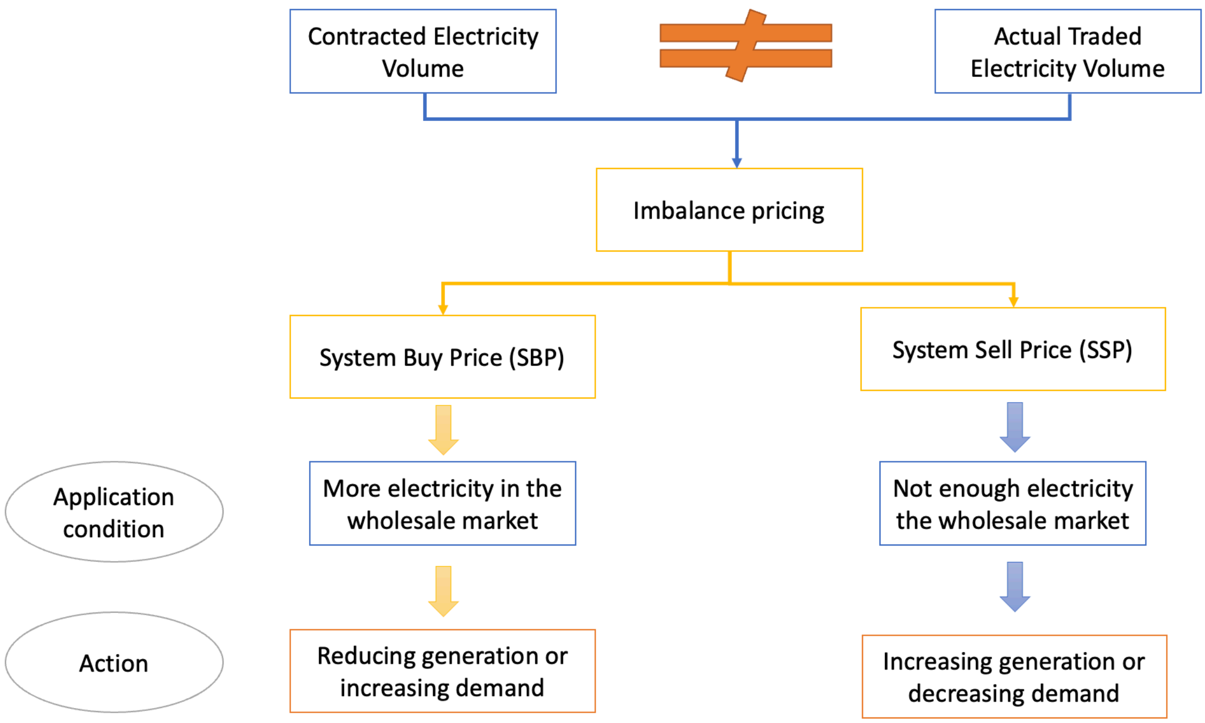


Figure 2-3. Imbalance pricing

The electricity generation costs vary across different power plants due to the following three factors:

- The differences in the input fuel prices.
- The differences in the costs of operating the power stations.
- And the costs of the carbon and other greenhouse gas (GHG) emissions.

After comparing such factors, Helm (2017) summarised the cost of using natural gas or coal in electricity generation as a reason that significantly impacts the trend of the wholesale market. In 2021, coal was limited to use (less than 1%) in electricity generation. However, natural gas still the main fossil energy in electricity generation (BEIS, 2021b). The cost of natural gas could indicate the trend of the wholesale market in electricity cost.

2.2.4. Capacity market

The UK government introduced the capacity market as a part of the privatised electricity system. The capacity market mainly is used to ensure the security of the electricity supply and to avoid the possibility of future blackouts across the entire country (Flexitricity, 2022). The capacity market uses the capacity margin (CM) to manage the security of the electricity supply. The CM is the proportion where the total expected available generation exceeds the maximum expected electricity demand at the time when the demand happens (Royal Academy of Engineering, 2013). The CM is an effective way to protect the customers away from occasional unexpected losses of power or surges in demand.

However, the private generators should be incentivised to generate excess electricity to reach the CM. The electricity will be depressed when the generated electricity exceeds the mean expected demand. The higher the excess generated electricity, the lower the wholesale price. Another important reason to introduce incentives for generators to reach the CM is, different from other energy markets, the limited options to store electricity. Therefore, the electricity must meet demand simultaneously, and it is necessary to use CM to cover the slack when demand spikes (Helm, 2017).

There was a mechanism to set up CM in the POOL mechanism regulated wholesale market. However, the mechanism to set up CM had a design flaw, which allows the generator to play games in declaring plant availability. The mechanism caused significant consequences in the cost of energy. Therefore, the CM was decided to be removed through the NETA mechanism (Helm, 2017). There was then no CM in place in the privatised electricity market until the new capacity market was developed in 2013 (BEIS, 2014b).

The new capacity market participants are incentivised (paid) to ensure they could respond to the high risk of the system stress event (Flexitricity, 2022). In addition, the new capacity market introduced 'auction' as the competitive process to award capacity market agreements (CMA) to meet the target capacity for the associated supply year (Helm, 2017). The CMA confirms the relevant capacity market obligation (CMO) and associated payments. There are two capacity auctions available each year (Flexitricity, 2022):

- T-4: This is the main auction. It purchases the capacity needed for delivery in four years' time, and it allows new generators to secure 15 years agreements.
- T-1: This is a top-up auction; it happens ahead of each supply year. It mainly applies to sites which were not ready in time for the T-4 auction.

The auction considered the demand curve which captures the trade-off between the cost of capacity and security of supply. The demand curve was developed by the government, and it is based on NG's electricity capacity report. Therefore, the demand curve can effectively set up the required CM (Helm, 2017). Meanwhile, compared with the original capacity mechanism, the new capacity market has two distinctive advantages:

- It is based on auctions.
- The decision was made upon the quantity of supply with the government and NG.

The new capacity market mechanism allows private companies to make decentralised decisions to invest in electricity generation. The NG only plays a role in the new capacity market to facilitate connections to a centralised central buyer system, enabling all new investments are in practice determined by government-backed contracts (Helm, 2017).

2.2.5. The role of renewable energy systems in electricity generation

The UK aims to achieve a net-zero target by 2050, as a key part of the strategy is to transition to a fully decarbonised electricity grid, with many expectations from renewable energy systems (National Grid, 2022). Fossil fuels contributed a significant greenhouse gas (GHG) to electricity generation. The renewable resources, however, emit low or no GHG, they then are considered the key action to tackling the climate change issue. In addition, the UK government set a target for energy providers to achieve that all electricity should come from 100% zero-carbon generation resources by 2035. Currently, there are four main renewable energy resources, the solar, wind, hydroelectric and bioenergy. Since 2013, the usage of renewable energy in generating electricity has been significantly improved.

Based on the data provided by the national grid (2022):

- By the end of 1991, renewable energy resources only account for 2% of electricity generation in the UK; The figure has increased to 14.6% in 2013 as a result of the introduced energy act.
- In 2017, the UK has been placed into the position of one of Europe’s leaders in the growth of renewable energy generation.
- In 2019, it is the first time that the electricity generated by renewables is more than from fossil fuels. Particularly, on 17th August, the generated electricity hit the highest share ever at 85.1% (wind 39%, solar 25%, nuclear 20% and hydro 1%).
- 2020 was the UK’s markable year for the record of the highest renewable energy resources involved in electricity generation. Low-carbon power in the

UK grew from 20% in 2010 to nearly 50% in 2021. The fossil fuels involved in electricity generation have decreased from over 75% in 2010 down to 35% in 2021. 2020 is also the longest run of coal-free electricity generation, with a total of 68 days.

- By 2021, wind power contributed 26.1% of the overall electricity generation in the UK (with onshore 12% and offshore 14.1). Bioenergy contributed 12.7%, solar contributed 1.8%, and hydropower contributed 2.1%.

The successful growth of renewable energy resources in electricity generation cannot be achieved without effective renewable incentive policies. The renewable obligation (RO) is regarded as the main financial mechanism for incentivising the deployment of renewable energy systems in electricity generation in the UK (Helm, 2017).

RO requires licensed electricity suppliers to source a specific amount of electricity they provide from renewable energy resources ('obligation'). The generators will be issued renewable obligation certificates (ROCs) for the generated electricity from the renewable resources. The generators then sell ROCs to suppliers, and suppliers can then demonstrate that they have achieved their obligations. The obligation is set a year ahead; the generators must then provide the required ROCs to meet the set obligations to the scheme administrator, Ofgem. However, a penalty is required to pay by suppliers if they fail to meet their obligations (penalty also known as buy-out price). After Ofgem issues ROCs to generators for the electricity generated from renewable resources, generators can then sell ROCs to suppliers or traders as tradeable commodities. The trading process allows generators to receive a premium related to the wholesale price of the electricity generated by renewables. The penalty (buy-out price) is recycled on a pro-rata basis to suppliers that demonstrated set ROCs. However, the suppliers cannot receive pro-rata without presenting ROCs. The buy-out price then encourages suppliers to choose ROCs over the penalty (buy-out price). The cost of RO to suppliers is assumed to pass on to customers through their energy bills. The RO is controlled through the levy control framework (LCF) which was designed to control the costs of supporting low carbon electricity, paid for through customers' energy bills (BEIS, 2016).

The RO is closed to the new applicant in March 2017, with some expectations that extend the deadline for some projects to January 2019. Most projects already registered with RO will continue receiving support for 20 years. However, ROCs will not be issued for any electricity generated by renewable resources after 31st March 2037 (Helm, 2017).

2.2.6. Summary

The privatisation of the UK's electricity grid aimed to provide a fair and equal electricity market for all customers to select the most appropriate supplier. Meanwhile, the privatised electricity grid should encourage customers to switch to suppliers who provide most electricity generated from renewable resources. It will help the UK to achieve the agreed climate change target by 2050. However, the following issues are barriers to customers freely switching to the most appropriate suppliers, and less encourage customers to use suppliers who provide most electricity generated by renewables.

- The capacity margin is a good strategy to ensure the security of the energy supply in the privatised electricity system. However, fossil fuels (e.g., natural gas) will always be the top option to reach the capacity margin instead of the low carbon resources (e.g., carbon capture and storage or renewables). The wholesale price will keep growing due to the usage of fossil fuels, which will lead to an increase in the energy bill cap as a result of the worldwide high cost of natural gas.
- The increased energy cap will lead to inequality for all customers living in the UK to freely switch suppliers and use affordable energy. It might go against the initial idea of privatising the UK's electricity market. Therefore, it is worth investigating other equal and affordable energy strategies that can also provide secure electricity for all UK customers.
- RO is an effective strategy to incentivise suppliers to provide more electricity generated by renewable resources. However, the RO was paid by customers through the energy bills. Therefore, the customers who use electricity from suppliers with ROCs can expect to pay more energy bills. It could form a barrier to stopping more customers living in poor financial conditions to switch to such suppliers. It is worth comparing the RO scheme with other alternatives (using renewables to generate electricity) from a long-term economic perspective.

2.3. Practical on-site renewable energy system and energy storage in UK homes

The renewable energy system has been seen as the alternative solution to replace the existing fossil energy system that aligns with the climate change target to supply energy. The price of the renewable energy system has dropped significantly in the past decades, along with the increased renewable manufacturing level. Based on the recorded data on BEIS (2021b), the average overall installation cost of solar PV (0-4kW) dropped from £2086 /kWp (KiloWatt Peak) between 2013 and 2014 down to £1642/kWp between 2020 and 2021. The on-site renewable energy system becomes an affordable and environmentally friendly choice to supply energy for householders. Meanwhile, the on-site renewable energy system can help UK homes to back on track toward net-zero homes, achieving the agreed climate change target by 2050 from the building perspective. Such on-site renewable energy systems are termed practical renewable systems for UK homes.

This section reviewed available on-site renewable energy systems that are recognised by the UK government to be installed and practically used in UK homes. The Microgeneration Certification Scheme (MCS) is the organisation where to issue the certificate to recognise the renewable system and the qualified installers. The certified product and installation service ensures the householders have high confidence in using the system and service. This section also reviewed the commercially available battery and hot water cylinder, which can work with on-site renewables, ensuring the stability of the energy supply.

This section is structured by the following subsections:

- 2.3.1 explained the main responsibility of MCS and the recognised renewable energy systems.
- 2.3.2 reviewed and discussed the MCS recognised renewable power systems that can be installed and practically used in individual UK homes.
- 2.3.3 reviewed and discussed the MCS recognised renewable thermal systems that can be installed and practically used in dividual UK homes.
- 2.3.4. reviewed and discussed the commercially available battery and hot water cylinder in the UK market between 2021 and 2022.

2.3.1. Microgeneration Certificate Scheme

The Microgeneration certificate scheme (MCS) issues certifications, and quality assures and provides customers protection for the on-site renewable energy system installation and installers (MCS, 2022). The scheme transferred to the MCS Service Company Limited (MCS SCL), and the MCS Charitable Foundation in 2018. It is a remarkable step toward guaranteeing the sustainability of renewables and energy efficiency consumer markets from the long-term perspective.

Renewable systems such as solar PV, combined heat and power system, biomass heating system, micro wind turbines, ground/air source heat pump (G/ASHP), and solar thermal collects are certified by MCS. This section mainly reviews and discusses the on-site renewable system that can be installed and used in individual UK homes. However, the combined heat and power system (CHP) is generally used at multi-buildings, community, or district levels. Therefore, CHP is excluded from this section. The rest certified systems are then categorised into two groups, renewable power and thermal systems, which are reviewed and discussed in subsections 2.3.2 and 2.3.3, respectively.

2.3.2. Renewable power system

2.3.2.1. Solar PV

Solar PV is one of the main renewable systems to generate electricity for buildings across the world. The crystalline silicon is the main component constituting solar cells in the PV manufacturing process. The crystalline silicon can also be classified as monocrystalline and polycrystalline silicon in relation to the crystalline forms of silicon. Both monocrystalline PV and polycrystalline are recognised by MCS.

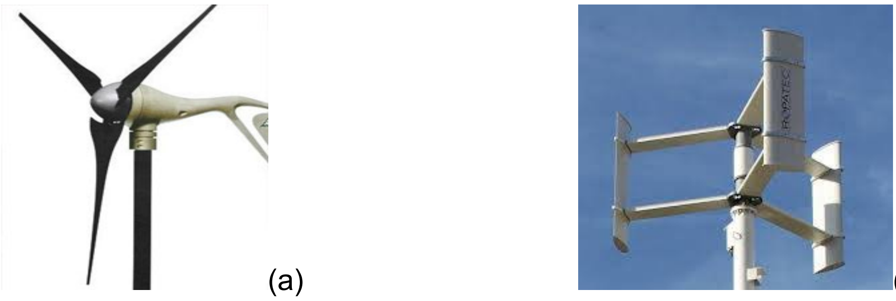
There are two main approaches recognised by MCS to install solar PV in UK buildings. The first approach is to mount solar PV on the roof. The second approach is to integrate solar PV into the roof or façade, making the solar PV to become as a part building structure (MCS, 2020b).

The general configuration of individual solar PV panels is from 230 to 410 Watt peak (Wp) (International Finance Corporation, 2015). The monocrystalline PV has an efficiency of between 15 to 20%. The polycrystalline PV has an efficiency ranging from 13 to 17% regardless of different installation approaches. The general lifespan of solar PV is between 25-30 years. The solar PV system can be used either on or off the grid.

Additionally, a power inverter is needed to convert electricity generated by solar from the direct current to an alternating current configuration.

2.3.2.2. Micro-WT

The micro-WT is another power generation system applied to UK buildings. The micro-WT refers typically to the wind turbine with a nominal power of less than 10kW (HIES, 2021). In addition, Greening (2014) found that wind turbine has superior environmental performance in terms of GHG emission and primary energy consumption against traditional energy systems. Based on the rotor types, the wind turbine can be categorised as a horizontal axis wind turbine (HAWT) and vertical axis wind turbine (VAWT) (shown in Figure 2-4); Wind turbines are normally standalone or mounted on building roofs.



(a) (b)

Figure 2-4. Wind turbine types. (a) is HWAT and (b) is VAWT.

The installation of wind turbines usually consists of the turbine and inverter. The mechanical energy from the rotations can be converted to direct current (DC) in the turbine and then be converted to alternative current (AC) by the inverter.

The rated power of the micro-WT installed on domestic or small business buildings ranges from 2.1 to 2.4 kW. Like the XZERES wind turbine (Wind turbine models, 2022), the designed lifespan of the wind turbine is about 20 years, the cut-in wind speed is around 3.2m/s, and the cut-off speed is about 11m/s.

2.3.3. Renewable thermal system

2.3.3.1. Ground/Air Source Heat Pump (GSHP/ASHP)

The heat pump is the system that ‘pump’ or transfer heat from one place to another by using a compressor and a circulating structure of liquid or gas refrigerant through heat from outside sources (water, air, and geothermal) pumped indoors. The CCC (Committee on Climate Change) considers the heat pump as a green and sustainable heating system. CCC (2016) encourages the household to install heat pumps on the property to replace the gas-assisted boiler for heating purposes. The Energy Saving

Trust (2013) also indicates that heat pump demonstrates a competitive economic and environmental performance against the traditional heating systems. On average, the GSHP or ASHP can save the annual operating cost of 8% to a gas condensing boiler, 36% on an oil condensing boiler and 67% on a direct electric heating system with an estimated carbon saving of 21%, 41% and 67%, respectively. Meanwhile, GSHP or ASHP uses less electricity than the traditional electrical heating system due to the higher coefficient of performance (COP). The existing commercial GSHP or ASHP has a COP of 3 to heat water up to 55 Celsius, which means the generated 3 kWh of 55 Celsius water needs 1 kWh electricity to run.

GSHP absorbs heat from the ground into the fluid and then passed through a heat exchanger into the heat pump. The ground temperature stays constant at the specific depth. GSHP therefore can be used throughout the year. GSHP consists of a ground heat exchanger, water to water/water to air heat pump, and heat distribution system. The vertical and horizontal are two approaches to placing ground source pipes and ground heat exchangers. Figure 2-5 presented two installation approaches. The existing commercially available GSHP configuration ranges from 3 kW to 30 kW. The bigger GSHP configuration such as 20 kW, 24 kW and 30 kW are dedicated to large homes or older non-retrofitted properties (Kensa Engineering, 2021). The expected lifespan of GSHP is about 25 years. The average COP of 3 generates hot water at 55 Celsius and the COP of 4 generates hot water at 35 Celsius.


(a) (b)

Figure 2-5. Vertical and horizontal installation approaches of GSHP. (a) is horizontal installation approach, (b) is vertical installation approach

Air source heat pump (ASHP) can extract heat from the outside air to provide space heating and hot water demand. The existing commercial ASHP can absorb heat from outside while air temperature as low as minus 15 Celsius. ASHP can deliver the generated heat to homes in two ways, air-to-water and air-to-air. Air-to-water heat pumps absorb heat from the outside air and transfer the heat to water, using water as the medium to deliver the generated heat to domestic buildings. Air-to-air HPs absorb heat from the outside air and use the air as the medium to deliver the heat to homes. Air-to-water HP is the most common model across the UK (Energy Saving Trust, 2021a), as it can distribute heat through the existing wet central heating system. Additionally, air-to-water-based ASHP is compliant with the relevant renewable application standards and building regulations and can benefit from the ongoing financial incentive schemes. Based on the collected data of ASHP in Appendix A, the commercially available MCS registered ASHP configuration ranges from 3 kW to 15 kW for domestic buildings. The expected lifespan is about 20 years. The average COP of 2.98 to generate heat at 55 Celsius and the average COP of 4.5 to generate heat at 35 Celsius.

2.3.3.2. Biomass heating system

The biomass heating system is an alternative solution to a traditional boiler. The biomass heating system can be applied to domestic buildings and small-scale commercial buildings in the UK (Energy Saving Trust, 2021b). There is about 44% of the energy source to run biomass heating system is wood-based such as logs, wood chips and pellets (Pullen & Hilton, 2021). The Energy Saving Trust (2021b) suggests storing biomass sources on site can minimise the embodied carbon from the transportation process.

The biomass stove and biomass boiler are two main biomass heating systems commercially available for UK domestic buildings. The biomass boilers can replace a traditional boiler to generate space heating and domestic hot water for the whole house. Stoves are generally used to heat a single room and usually work together with other heating systems. It can also provide domestic hot water when connecting with a back boiler. The output configuration of the biomass boiler ranges from 4 to 16 kW. The size of a biomass boiler is like a conventional boiler (about 2 cubic meters), and the efficiency is about 90%.

2.3.3.3. Solar thermal collector (STC)

The solar thermal collector is a system that can use solar radiation to generate heat for space heating, domestic hot water and cooling with an absorption chiller. In terms of the collector types, STC can be classified as flat-plate and evacuated tube collectors. In the flat-plate collector, the solar radiation heats the plate, and the plate collects as much energy as possible. The absorbed heat is then transferred to medium fluid like water, air, or other fluid for further use. The flat-plate collector can reach the maximum efficiency within the temperature from 30 to 80℃ (Kalogirou, 2009), some new collectors can even reach higher temperature (up to 100℃). The flat-plate STC has relative low product and maintenance costs. The flat-plate collectors are generally installed facing the equator, the optimal tilt of the collector plate is close to the latitude. The evacuated tube STC can achieve temperatures above 200℃ (Sunsystem, 2021). The evacuated tube STC is typically designed with parallel rows of twin glass tubes (shown in Figure 2-6). Each inner glass tube contains a metal heat pipe attached to an absorber fin. The air between the two parallel is evacuated (removed) to form a vacuum which can significantly minimise heat loss.

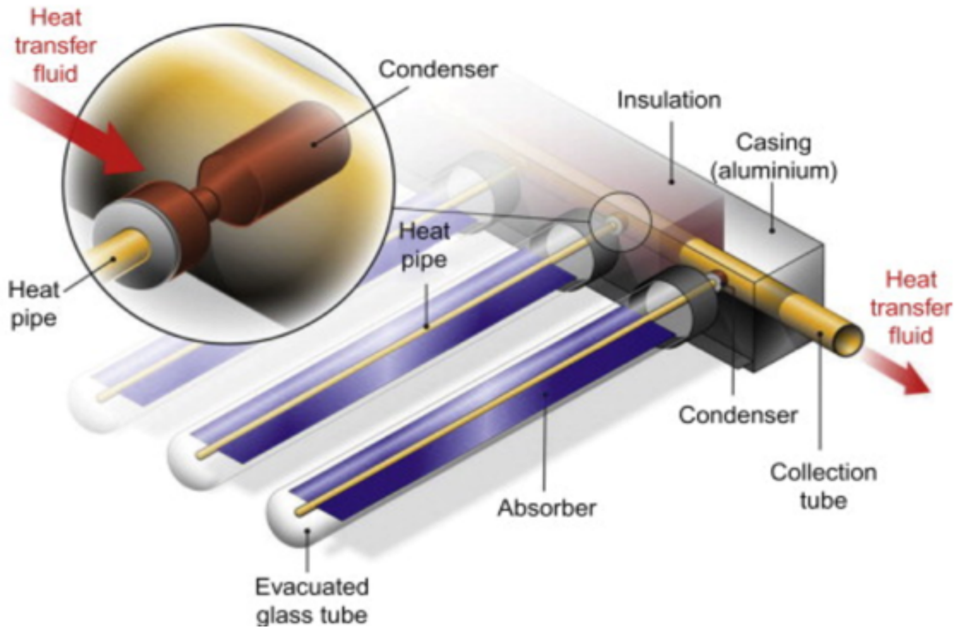


Figure 2-6. Diagram of the evacuated tube STC (Pandey et al., 2022)

The evacuated tube STC has better performance in colder weather conditions than flat-plate collectors in absorbing solar energy. This is because the evacuated tube's vacuum allows the tube to collect a high percentage of heat. However, this highly efficient tube might have trouble in areas with heavy snowfall, as evacuated tube collectors can hardly lose heat from the collector and therefore cannot melt snow as quickly as the flat-plate STC does.

Both evacuated tubes and flat-plate STC can be installed either on the roof or integrated into the façade or roof to become a part of the building structure. The STC is generally installed to generate domestic hot water for domestic buildings in the UK.

Based on the collected commercial data of the MCS registered STC. The absorption rate of the evacuated tube STC is above 90%, but the rate drops down to about 80% of the flat-plate STC. The expected lifespan of STC can be up to 25 years.

2.3.4. Energy storage

Building upon the gap between on-site energy supply and demand. Energy storage is a feasible alternative solution; it can store excess generated energy at a lower energy demand time, then be used at a higher energy demand time. For example, solar PV cannot generate electricity at night-time whilst night-time is the peak electricity consumption period for most UK homes. The battery, therefore, can store generated electricity from solar PV in the daytime and be used at night. The battery can increase the self-consumption rate of solar PV. The solar PV self-consumption rate demonstrates that the percentage of the electricity demand is covered by solar PV. The higher self-consumption indicates the home is more self-energy sufficient, has a higher grid electricity independence level, with the minimum electricity cost. Another example is to use energy storage like a hot water cylinder to store the heated water. Like solar PV system, solar thermal collectors (STC) can barely heat water in night. Whilst most UK homes use more hot water in the night instead of the daytime. The hot water cylinder can then store the heated water from STC during the daytime, ensuring households can use the heated water at night-time. Meanwhile, in the applications of using heat pumps to supply domestic hot water and space heating. Due to some heat pumps are not combi-systems, which are not like combi-boiler to supply domestic hot water and space heating load separately. The hot water cylinder is then rather essential and works together with heat pumps to supply domestic hot water for homes. This section then reviewed two broadly used energy storage system, battery, and hot water cylinder in UK homes.

2.3.4.1. Battery

The battery has been designed to extract surplus electricity generated by on-site renewable power generation systems, which allow users to store electricity for later use. Batteries can also help users use more generated electricity by on-site renewable systems, saving electricity cost. However, batteries might not be suitable for everyone, it needs a specific space to store, and it also needs to be aware of whether the selected batteries had been designed to work overpower-cuts (Bloomfied et al., 2016).

Domestic batteries are categorised into two main types, lead-acid and lithium-ion (Li-ion), based on a review report by (BEIS, 2020a). Lead-acid is broadly used in large-capacity rechargeable batteries. They are used in electric vehicles (EVs), automobiles, boats, and uninterruptible power supplies (UPS). The lead-acid battery comprises several individual cells containing layers of lead alloy plates immersed in an electrolyte solution (UMass, 2021). The vented lead-acid (VLA) and valve-regulated (VRLA) are two common lead-acid batteries. VLA allows gases to escape while the battery is charging. Differently, VRLA is sealed, and it does not allow for the addition or loss of liquid. Both VLA and VRLA have safety valves that allow pressure to be released when a fault condition causes internal gas to develop faster than it can be recombined (University of Massachusetts Amherst, 2022).

Li-ion batteries are rechargeable batteries and are broadly used in cell phones, laptops, drones, robotic equipment and EVs. Li-ion batteries contain lithium ions and an electrolyte solution that is always a mixture of organic carbonates (University of Massachusetts Amherst, 2022). Li-ion battery is different to lithium battery, as lithium battery is not rechargeable battery.

Both lead-acid and Li-ion batteries have safety issues in the application. As the when the cell rapidly heats and can emit electrolyte (e.g., sulfuric acid, flammable electrolytes), flames, and dangerous fumes (e.g., hydrogen sulphide gas). Li-ion battery is more likely to trigger a safety issue than a lead-acid due to the higher energy density.

In terms of the environmental perspective, the lead-acid battery performs poorly than the Li-ion battery due to the lead-acid battery needs more raw material than Li-ion to manufacture at the same configuration. Additionally, the lead processing industry is higher energy-intensive, causing a large amount of pollution. Li-ion battery is not environmental free, as lithium mining is resources explicitly intensive. However, lithium is only a tiny part of the whole battery, the other parts like the aluminium and copper environmental impacts are also significant. Due to geopolitical issues, the li-ion battery also faces supply difficulties of critical raw materials like copper, nickel, cobalt, and rare earth (IEA, 2023). The supply difficulties lead to the uncertainty of scaling up the Li-ion battery manufacturing level and using Li-ion battery as one of the key storage options. Thus, it is necessary to develop the Li-ion battery's recycling industry, which is growing, which leads the Li-ion battery to be more competitive than the lead-acid battery (Taylor, 2021). Although lead-acid battery already formed a mature recycling industry, as 99% of lead-acid battery is recyclable (battery accessories, 2021). Meanwhile, Li-ion has advantages like higher energy density (in general 250 Wh/L), longer cycle life, less maintenance and higher efficiency, enabling Li-ion batteries can be broadly found in the UK battery market.

Whilst Li-ion battery is a competitive solution and can bring users more flexibility and less electricity from the grid. It still has difficulties in economical and practical perspectives prior to the broader application in UK homes. Firstly, in general, the battery has a lower lifespan than other on-site renewable systems. Li-ion battery's lifespan is about 9 to 15 years on average. Meanwhile, Tesla claimed the Powerwall 3.0 has an expected lifespan of more than 15 years (Solar Reviews, 2022). Additionally, there are no relevant financial incentive schemes to encourage UK households to invest in batteries in the UK. No financial incentives also make the lower affordability of investing batteries in UK homes. Table 2-1 presents the specifications of several commercially available batteries (Electriccarhome, 2022; Tesla, 2022a).

Table 2-1. Technical data of battery

Manufacture	Configuration	Depth of discharge	Life cycle	Reference
Tesla Powerwall 3.0	Capacity: 13.5 kWh; Material: Lithium-ion;	Above 99%	Unlimited	Tesla, 2022b
SolaX 3.3	Capacity: 3.5 kWh or 6.5kWh; Material: Lithium-ion	95%	6000	SolaX, 2023
LG Chem RESU 6.5	Capacity: 6.5 kWh; Material: Lithium-ion	90%	6000	Europe Solar.Com, 2023
SamsungSDI	Capacity: 3.6kWh Material: Lithium-ion	97%	6000	Samsung, 2023
Nissan xStorage	Capacity: 4.2kWh and 6kWh Material: Lithium-ion	90%	NA	Nissan, 2023
Powervault 3	Capacity: 4kWh and 8kWh Material: Lithium-ion	Above 99%	Above 6000	Powervault, 2023
Duracell Energy Bank	Capacity: 3.3kWh Material: Lithium-ion	85% - 90%	NA	Duracell, 2023

2.3.4.2. Hot water cylinder

Solar water cylinder is also known as a solar unvented water cylinder. It is ideal for homeowners to explore a greener central heating solution. The solar water cylinder has a dedicated solar coil fitted inside of the unvented cylinder. The unvented cylinder can be connected directly to solar panels where it absorbs heat from the sun and heats the stored water through the dedicated solar coils.

In general, a properly designed, installed and well-maintained solar water cylinder should last in excess of 25 years. Some cases also found solar water cylinders are still functional after 30 years (PlumbNation, 2017). The cylinder size for a two-bedroom, one-bathroom with shower and bath function is about 100-150 litres (Viessmann Direct, 2021). Table 2-2 presents technical information of hot water cylinder.

Table 2-2 Technical data of hot water cylinder

Manufacturer	Model Configuration (Litres)	Model size (mm)	Source
Vitocell 200-V single coil	100	920*550	Thermal Store Cylinders, 2022
Telford TSMI150	150	510*1060	PlumbNation, 2022e
Telford TSMD125	120	510*935	PlumbNation, 2022c
Telford TSMI150SL	150	470*1200	PlumbNation, 2022g
Telford TSMI125	125	510*935	PlumbNation, 2022d
Telford TSMI125SL	125	470*1050	PlumbNation, 2022f
Telford TSMI125H(Horizon)	125	610*935	PlumbNation, 2022b
Indirect Cylinder Pluin150	150	550*1118	PlumbNation, 2022a

2.3.5. Summary

MCS has provided high-level confidence for householders to invest in renewable systems and the associated installations, householders are then encouraged to install renewable systems in their homes. However, the following issues existed that might be barriers stopping householders to install MCS-certified renewable systems.

- MCS certified several renewable power and thermal systems for householders to choose to install in their homes. However, there are no relevant guidance or codes for householders to select the most suitable renewables considering the house type, location, weather condition and local permitted requirements.

- MCS has provided some performance indicators that can demonstrate the estimated generation performance of the renewable system for householders to consider prior to purchasing such systems. However, no existing studies have investigated householders’ understanding of such performance indicators. Some technical performance indicators are not easy to be understood for a householder who only started knowing the renewables.
- Energy storage is becoming an important part to ensure supply stability by the on-site renewable energy systems. However, MCS has not issued any certification for energy storage, and it might be difficult for householders to choose the most reliable and high-quality energy storage from the market.

2.4. The key indicators for assessing the whole building performance and the on-site renewable energy system in UK homes

This section reviewed the criteria and indicators used to evaluate buildings' performance and the associated on-site renewable systems in the UK. It consisted of two subsections:

- Subsection 2.4.1 reviewed the performance evaluation criteria and indicators that are included in the current:
    - The UK government adopted regulatory guidance and the recognised technical manual for assessing the performance of new and existing buildings in the UK.
    - Renewable system installation standard in domestic buildings.

The reviewed criteria and indicators in subsection 2.4.1 can reflect the actual needs in the performance evaluation of UK homes and the associated on-site renewable systems.

- Subsection 2.4.2 reviewed the performance evaluation criteria and indicators for the on-site renewable systems from the published research articles. Within the review process, the identified keywords are used to search different journal databases to gather relevant research articles.

2.4.1. Review of the performance criteria and indicators from practical and regulatory documents

This subsection reviewed the following documents:

- UK government approved building energy performance assessment guidance (UK Government, 2013a).
    - The standard assessment procedure (SAP) is the guidance that approved and used by the Government to support the development of the energy performance certificate (EPC) for UK homes.
- UK government recognised assessment technical manuals to evaluate the whole building performance of the new and retrofitted building. These technical manuals are published by Building Research Establishment (BRE) to evaluate the whole building performance. This section reviewed the following technical manuals:
    - The BREEAM Refurbishment Domestic Buildings Technical Manual (BRE, 2016b);
    - The BREEAM UK New Construction Technical Manual (BRE, 2019);
    - and the BREEAM International New Construction Technical Manual (BRE, 2017).

Such technical manuals are practical and flexible to evaluate the performance of the whole building and on-site renewable energy system in the UK and worldwide buildings from the techno-economic-environment perspectives. Additionally, BREEAM technical manuals regularly update the weights of the building performance and actively respond to the agreed climate change target at national and worldwide levels. The BREEAM credited buildings are resilient and sustainable, better responding to climate change issues.

- UK domestic building renewable energy system installation standards: such standards guide UK householders to select, invest and install the most suitable renewable energy system. The MCS is responsible to create the associate standard to guide the registered installers to deliver the installed renewable energy system with a high level of confidence to UK households. The relevant MCS standards include:
    - The solar PV Standard – MIS 3002 (MCS, 2020c),
    - Requirements for MCS contractors undertaking the supply, design, installation, set to work, commissioning and handover of microgeneration heat pump systems – MIS 3005 (MCS, 2013a),
    - The Solar Thermal Standard – MIS 3001 (MCS, 2013c)

In summary, this section gathered the performance evaluation criteria and indicators from:

a) SAP;
b) BREEAM-RDBTM, BREEAM-UKNCTM and BREEAM-INC;
c) MCS installation standards.

The reviewed criteria and indicators are presented in Table 2-3.

Table 2-3. Identified indicators from the practical and regulatory documents

Indicative criteria	The identified indicators	The identified indicators from
Economic	Discounted capital cost	BRE, 2016a, 2018, 2020; MCS, 2013a, 2019, 2020b UK Government, 2013
	Discounted operation and maintenance cost	
	Discounted payback period	
	Life cycle costing benefits & life cycle costing planning	
Technical	Grid electricity independence level	MCS, 2020a
	Lifespan of system	BRE, 2016a, 2018, 2020
	The estimated renewable system performance – Renewable system performance (RF)	MCS, 2013a, 2019, 2020b, 2020a UK Government, 2013
Environmental	GHG emission at the operational stage	MCS, 2013a, 2019, 2020b, 2020a UK Government, 2013
	Embodied carbon of materials/systems	MCS, 2013a, 2019, 2020b, 2020a

2.4.2. Review of the performance criteria and indicators from research articles

This section reviewed the performance criteria and indicators to evaluate the performance of renewable systems in individual buildings from the existing research articles. The keywords including ‘hybrid renewable energy system’; ‘renewable energy system’; ‘building’; ‘techno-economic-environment’ are combined and used to compile relevant research articles from three academic journal databases, Web of Science, ScienceDirect and Scopus. The method is shown in Figure 2-7 and the screening method is clarified in Table 2-4.

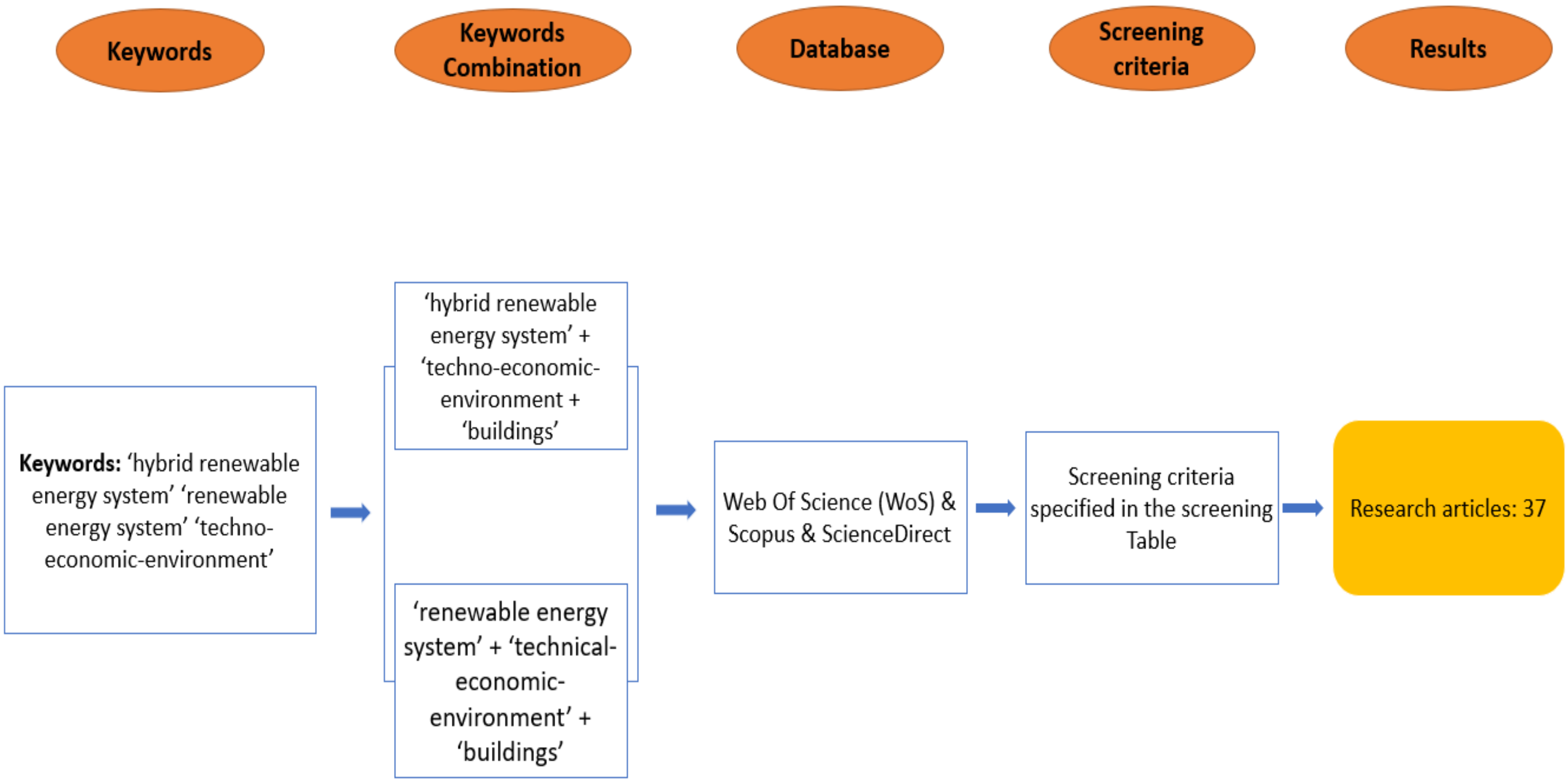


Figure 2-7. Review method of the performance criteria and indicators from research articles

Table 2-4. Screening method for the research article review method

NUMBER OF CRITERIA	DESCRIPTION
1	Written in English only
2	Peer-reviewed research articles
3	Research articles only investigate the performance of the renewable energy system on individual building
4	The renewable system or hybrid renewable energy system in the compiled research articles is same as defined relevant terms in this research

The keywords combinations are used to search on WoS, Scopus and ScienceDirect. Four screening criteria listed in Table 2-4 are used to exclude irrelevant research articles. Afterwards, 37 research articles were selected to gather the performance evaluation criteria and indicators of renewable energy systems in individual buildings. The identified performance indicators from the selected 37 research articles are presented in Table 2-5.

Table 2-5. Identified performance indicators from the selected research articles

Author	Year	Title	Building type	Summarised indicators
Fito et al	2021	Competitiveness of renewable energies for heat production in individual housing: A multicriteria assessment in a low-carbon energy market	Residential building	1. Capital cost. 2. Maintenance and replacement cost. 2. Cost of fossil energy. 3. Levelized cost of energy. 4. Greenhouse gas emission
Jahangir et al	2021	Multi-year sensitivity evaluation to supply prime and deferrable loads for hospital application using hybrid renewable energy systems	Hospital building	1. Capital cost. 2. Maintenance and replacement cost. 3. Net present cost. 4. Life Span. 5. Levelized cost of energy. 6. RF 7. Primary energy consumption.
Mokhtara et al	2021	Design optimization of off-grid Hybrid Renewable Energy Systems considering the effects of building energy performance and climate change: Case study of Algeria	Residential building in rural area	1. Capital cost. 2. Maintenance and replacement cost. 3. Loss of power supply probability. 4.Renewable fraction (RF). 5. CO2 emissions. 6. Grid independence level.
Taghavifar and Zomorodian	2021	Techno-economic viability of on grid micro-hybrid PV/wind/Gen system for an educational building in Iran	University building	1. Capital cost. 2. Maintenance and replacement cost. 3. Net Present Cost. 4. Cost Recovery factor (CRF). 5. Cost of fossil energy. 5. RF.
Tazay	2021	Techno-Economic Feasibility Analysis of a Hybrid Renewable Energy Supply Options for University Buildings in Saudi Arabia	University building	1. Capital cost. 2. Maintenance and replacement cost. 3. Net present cost. 4. Greenhouse gas emission at operation stage. 5. Levelized cost of energy. 6. CRF 7. RF 8. Primary energy consumption. 9. Annual energy generation. 10. Lifespan.
Alfonso-Solar et al	2020	Small-Scale Hybrid Photovoltaic-Biomass Systems Feasibility Analysis for Higher Education Buildings	University building	1. Capital cost. 2. Maintenance and replacement cost. 3. CRF. 4. Annual loss of energy supply. 5. RF.
Zhou and Cao	2020	Coordinated multi-criteria framework for cycling aging-based battery	Building with electric vehicle	1. Capital cost. 2. Maintenance and replacement cost. 3. NPV. 4. Discounted payback period. 5. Primary energy consumption

		storage management strategies for positive building–vehicle system with renewable depreciation: Lifecycle based techno-economic feasibility study		
Liu et al	2020	Techno-economic design optimization of hybrid renewable energy applications for high-rise residential buildings	High-rise residential building	1. Capital cost. 2. Maintenance and replacement cost. 3. Levelized cost of energy. 4. Financial incentive scheme. 5. CO_2 emission (reduction benefit).
Guo et al	2020	Techno-economic feasibility study of an electric-thermal coupling integrated energy system for commercial buildings in different latitudes	Commercial building	1. Capital cost. 2. Maintenance and replacement cost. 3. Return on investment (ROI). 4. Net Present Cost.
Tazay et al	2020	A Techno-Economic Feasibility Analysis of an Autonomous Hybrid Renewable Energy Sources for University Building at Saudi Arabia	University building	1. Cost of fossil energy. 2. Net Present Cost.
Udovichenko and Zhong	2020	Techno-economic analysis of air-source heat pump (ASHP) technology for single-detached home heating applications in Canada	Detached home	1. Capital cost. 2. Maintenance and replacement cost. 2.CO_2 emission. 3. Cost of fossil energy.
Narula et al	2020	Assessment of techno-economic feasibility of centralised seasonal thermal energy storage for decarbonising the Swiss residential heating sector	Residential building	1. CO2 emission. 2. Cost of fossil energy. 3. Capital cost. 4. Maintenance and replacement cost. 5. Levelized cost of energy. 6. Total primary energy supply. 7. RF.

Goudarzi et al	2019	Techno-economic assessment of hybrid renewable resources for a residential building in tehran	Residential building	1. Capital cost. 2. Maintenance and replacement cost. 3. Replacement cost. 4. Net Present Cost. 5. Cost of fossil energy. 6. CRF.
Jahangir et al	2019	A techno-economic comparison of a photovoltaic/thermal organic Rankine cycle with several renewable hybrid systems for a residential area in Rayen, Iran	Residential building	1. Capital cost. 2. Maintenance and replacement cost. 2. Levelized cost of energy. 3.Net Present Cost. 4. RF. 5. Cost of fossil energy.
Imam et al	2019	Techno-Economic Feasibility Assessment of Grid-Connected PV Systems for Residential Buildings in Saudi Arabia—A Case Study	Residential building	1. Capital cost. 2. Maintenance and replacement cost. 3. Levelized cost of energy. 3.Lifecycle cost (LCC). 4. Net Present Value. 5. Investment Return Ratio (IRR). 6. Payback period (PBP). 7. Renewable generation. 8. Cost of fossil energy
Oueslati and Mabrouk	2019	Techno-economic analysis of an on-grid PV/Wind/Battery hybrid power system used for electrifying building	Grid-connected research centre	1. Net Present Cost. 2. CRF. 3. Cost of fossil energy. 4. Annually generated energy.
Islam	2018	A techno-economic feasibility analysis of hybrid renewable energy supply options for a grid-connected large office building in south-eastern part of France	Office building	1. Capital cost. 2. Maintenance and replacement cost. 3. Net Present Value. 3. LCC. 4. Cost of fossil energy.
Ma et al	2018	Techno-Economic evaluation for hybrid renewable energy system: Application and merits	Domestic and Non-domestic buildings	1. Loss of power supply probability. 2. Net Present Cost. 3. IRR. 4. PBP. 5. Benefit Cost Ratio (BCR). 6. Cost of fossil energy. 7. Capital cost. 8. Maintenance and replacement cost. 9. RF. 10. Energy loss. 11. Proportion of developed RE. 12. Carbon emission.
Mancic et al	2018	TECHNO-ECONOMIC OPTIMIZATION OF CONFIGURATION AND CAPACITY	Public swimming pool building	1. NPV. 2. Annual energy savings. 4. Capital cost. 5. Maintenance and replacement cost

		OF A POLYGENERATION SYSTEM FOR THE ENERGY DEMANDS OF A PUBLIC SWIMMING POOL BUILDING		
Nicholas et al	2018	Impacts of valuing resilience on cost-optimal PV and storage systems for commercial buildings	Commercial building	1. Capital cost. 2. Maintenance and replacement cost). 3.NPV. 4. Efficiency of renewables
Kristiwan et al	2018	Technical and economic feasibility analysis of photovoltaic power installation on a university campus in Indonesia	Institution building	1. NPV. 2. IRR. 3. Capital cost. 4. Maintenance and replacement cost. 5. BCR.
Farahi and Fazelpour	2018	Techno-economic assessment of employing hybrid power system for residential, public, and commercial buildings in different climatic conditions of Iran	residential, public and commercial building	1. Capital cost. 2. Maintenance and replacement cost. 3.NPV. 4. Cost of fossil energy.
Jo et al	2018	Parametric analysis for cost-optimal renewable energy integration into residential buildings: Techno-economic model	Residential building	1. NPV. 2. Capital cost. 3. Maintenance and replacement cost. 4. Levelized cost of energy. 5. IRR. 6. PBP.
Vishnupriyan and Manoharan	2018	Multi-criteria decision analysis for renewable energy integration: A southern India focus	Institution building	1. NPV. 2.Cost of fossil energy. 3.PBP. 4. RF. 5. CO_2 emission.
Singh et al	2017	Techno-economic feasibility analysis of hydrogen fuel cell and solar photovoltaic hybrid renewable energy system for academic research building	Institution building	1. Capital cost. 2. Maintenance and replacement cost. 3. Net Present Cost. 4. Levelized cost of energy. 5.Cost of fossil energy. 6. generated energy by renewable system.

Okonkwo et al	2017	Techno-Economic Analysis of the Potential Utilization of a Hybrid PV-Wind Turbine System for Commercial Buildings in Jordan	Hotel	1. Capital cost. 2. Maintenance and replacement cost. 3. Net Present Cost. 3. LCC. 4. CRF 5. RF. 6. BCR 7. Annual energy generation 8 Greenhouse gas at operation stage
Tomar and Tiwari	2017	Techno-economic evaluation of grid connected PV system for households with feed in tariff and time of day tariff regulation in New Delhi – A sustainable approach	Residential house	1. Cost of fossil energy. 3. NPV. 4. Capital cost. 5. Maintenance and replacement cost.
Khalid et al	2017	Techno-economic assessment of a solar-geothermal multigeneration system for buildings		1. NPV. 2. Capital cost. 3. Maintenance and replacement cost. 4. Levelized cost of energy. 5. Cost of fossil energy
Sommerfeldt and Madani	2017	Revisiting the techno-economic analysis process for building-mounted, grid-connected solar photovoltaic systems: Part one - Review	Grid-connected building	1. BCR. 2. Capital cost. 3. Maintenance and replacement cost. 4.NPV. 5. IRR. 6. Levelized cost of energy. 7. PBP. 8. Discounted payback time. 8. LCC
Fazelpour et al	2016	Techno-economic analysis of hybrid power systems for a residential building in Zabol, Iran	Residential building	1. Cost of fossil energy. 2. NPV
Khalid et al	2016	Techno-economic assessment of a renewable energy based integrated multigeneration system for green buildings	Green Building	1. Capital cost. 2. Maintenance and replacement cost). 3. Salvage cost
Lsa et al	2016	A techno-economic assessment of a combined heat and power photovoltaic/fuel cell/battery energy system in Malaysia hospital	Hospital building	1. Capital cost. 2. Maintenance and replacement cost. 2. LCC. 3. Net Present Cost. 4. Levelized cost of energy. 5. CRF. 6. Salvage cost.

Ataei et al	2015	Optimum design of an off-grid hybrid renewable energy system for an office building	Office building	1. Capital cost. 2. Maintenance and replacement cost. 3. NPV. 4. cost of fossil energy. 5. excess electricity. 6. Renewable generation
Zhang et al	2015	The early design stage for building renovation with a novel loop-heat-pipe based solar thermal facade (LHP-STF) heat pump water heating system: Techno-economic analysis in three European climates	Retrofitted building	1. Capital cost. 2. Maintenance and replacement cost. 3. CO_2 emission. 4. Cost of fossil energy. 4. NPV. 5. IRR. 6. PPB
Huang et al	2013	A techno-economic assessment of biomass fuelled trigeneration system integrated with organic Rankine cycle	Commercial building	1. CO_2 emission. 2. Cost of fossil energy. 4. Capital cost. 5. Maintenance and replacement cost
Chong et al	2011	Techno-economic analysis of a wind-solar hybrid renewable energy system with rainwater collection feature for urban high-rise application	urban high-rise application	1. Capital cost. 2. Maintenance and replacement cost. 3.NPV. 4.Financial incentive schemes. 5. Annual energy savings.
Shaahid and Elhadidy	2008	Economic analysis of hybrid photovoltaic–diesel–battery power systems for residential loads in hot regions—A step to clean future	Two-bed room house	1. Capital cost. 2. Maintenance and replacement cost. 3. Net Present Cost. 4. Cost of fossil energy. 5. RF. 6. Primary energy consumption. 7. Annual cost. 8. Annual energy generation.

2.4.3. Summary

Subsection 2.4.2. reviewed the economic-technical-environment criteria and indicators that have been used to assess the performance of the on-site renewable systems in individual buildings. However, some of the reviewed criteria and indicators from the research papers are not used in practice to assess the performance of the on-site renewable system in UK homes. The existing studies have not compared such criteria and indicators from the research papers across-over the reviewed UK government recognised whole-building performance guidance and the on-site renewable system installation standards in subsection 2.4.1. Such UK government-recognised guidance and standards can reflect the actual needs of evaluating the performance of the on-site renewable systems in UK homes. Therefore, future research needs to take the following steps to identify the representative economic-technical-environment criteria and indicators to evaluate the on-site renewable system(s) in UK homes.

- To create a clear and transparent criteria/indicator screening process to identify the representative economic-technical-environment criteria/indicators to assess the on-site renewable system(s) in UK homes.
- To ensure the identified representative economic-technical-environment criteria/indicators are aligned with the UK government's climate change policy and building regulations. Such criteria/indicators can support future decision-making in widely implementing the on-site renewable system(s) in UK homes.

2.5. Decision-making method to identify the optimal renewable system in buildings

2.5.1. Review of Multi-criteria decision-making method and relevant studies

Multi-criteria decision-making (MCDM) is a branch of operations research (OR), as OR was originally invented in England during World War II for decision-making on the best war materials. Today, OR is a dominant decision-making tool (Taha, 2005). The multi-criteria decision-making (MCDM) is usually applied to identify the optimal solution or strategies in the decision-making process under multi-conflicting criteria based on different stakeholders' viewpoints.

The MCDM method is constituted by two sub-methods, multi-attribute decision-making (MADM) and single/multi-objective optimisation (S/MOO) method. MADM is used to decide the 'best' alternative compared to a finite number of alternatives under multi-criteria. Differently, MOO is applied to compute the optimal alternatives under the pre-defined objectives and constraints through optimisation algorithms. The identified optimal alternatives are equally performed of the pre-defined objectives, and MOO cannot rank or decide the 'best' and 'worst' alternatives. This section used the keywords 'renewable energy system combination' 'mix renewable energy system' 'decision-making' 'multi-criteria decision making' 'building/buildings' to gather the relevant studies on the web of science and Elsevier. The selected articles are presented in Table 2-6.

Table 2-6. Decision-making study of renewable-related applications in domestic buildings

Author	Year	Building type	Location	Method	Techniques
Deng et al.,	2020	Residential Building block	China	MADM	Fuzzy-AHP is used to allocate the weights to the evaluation criteria. TOPSIS is applied to work out the mark to each alternative solution
Chen et al.,	2020	Residential Building	Norway	MADM	A novel ranking factor EEES (environmental, energy, economic and social) had been used in MADM
Wang et al.,	2020	Hotel	China	MOO+MADM	Mixed integer nonlinear programming to find out the pareto frontier solutions; Shannon-entropy-based and Euclidean-distance-based decision-making method
Mazzeo et al.,	2020	Residential Building	Italy	MCDM	Parametric analysis
Liu et al.,	2020	Low energy Building	China	SOO+MADM	Single objective optimisation for finding the Pareto solution. Weighted sum product and minimum distance to the euler point methods used for trade-offs
Jing et al.,	2019	Hotel	China	MOO+MADM	MOO method like NSGA-II and CLPEX have been used for system optimisation. Four different decision-making algorithms used to make decision
Karunathilake et al.,	2019	Apartment	Canada	MADM	Combinatorial optimisation for identifying the Pareto solutions. Fuzzy-AHP has been used as decision making algorithm
Tekin et al.,	2019	Eser Green Building	Turkey	Scenario based decision making	Parametric analysis method
Seddiki & Bennadji,	2019	Residential Building	Algeria	MADM	Delphi is used to find the most relevant criteria for this research. FAHP is applied to do the decision-making.
Harkouss et al.,	2019	Low energy apartment	China, India, Norway	MOO+MADM	Multi-objective building optimisation tool for pareto solution selection ELECTRE algorithm for decision-making.
Vishnupriyan & Manoharan,	2018	Institutional Building	India	MADM	HOMER software is used to compute the size of system. AHP and best worse method (BWM) have been used for MCDM
Bonamente et al.,	2018	Residential building	Northern Italy	MOO+MADM	NSGAII used to find the Pareto front. Euclidean-distance-based method used for decision making

Saleki,	2018	Residential Building	Iran	MOO+Parametric	Software assisted system optimisation and parametric analysis for decision-making
Džiugaitė-Tumėnienė et al.,	2017	Energy-efficient building	Lithuania	MADM	The AHP has been used to allocate percentage to each weight. Weighted aggregates sum (WAS) and product assessment (PAS) have been used to rank solution
Yousefi et al.,	2017	Commercial Building	Iran	MOO+MADM	GA has been used for system optimisation to achieve the specific objectives. AHP is used in de Yousefi decision-making
Harkouss et al.,	2017	Apartment	Lebanon	MOO+MADM	Multi-objective building optimisation tool for pareto solution selection ELECTRE algorithm for decision-making.
Ataei et al.,	2015	Off-grid Commercial Building	Iran	MOO	Multi-objective optimisation method
Y.-Y. Jing et al.,	2012	Residential Building	China	MADM	Fuzzy-AHP has been used in decision making

2.5.2. Review of the Multi Attribute Decision-Making (MADM) method

Based on Table 2-6, in general, four steps are used to apply MADM for the decision-making of renewable combinations in buildings.

The first step is the problem definition. In building-related renewable technology or renewable combination decision-making studies, this step usually clarifies the scope of renewable systems and the potential renewable combination alternatives. The second step is to select the target building and work out the associated energy demand. The third step is to determine the evaluation criteria; the economic, technical, and environmental are three criteria used as the performance criteria. In addition, the selected evaluation criteria should reflect local stakeholders' actual needs in applying renewable technology/renewable combinations to the target building. The fourth step is configuring each potential alternative to reflect the required performance in the pre-defined evaluation scenarios. The fifth step uses the suitable decision-making method collaborated with/without the collected stakeholders' preference to decide the optimal alternative for the specific usage purpose under the selected criteria. The last step is to validate the sensitivity of the identified solution and analyse the performance of using the decided solution to practice. In Table 2-6, the following techniques are normally used in the fifth step to identify the optimal alternative under the chosen criteria for the specific application purpose:

- The analytical hierarchy process (AHP);
- Fuzzy-analytical hierarchy process (FAHP);
- and technique for order performance by similarity to ideal solution (TOPSIS).

The AHP and FAHP are served as powerful tools in calculating weights to proceed with the decision-making process. Then the calculated weights are fed to TOPSIS to obtain the ranking results to support decision-making strategies.

Analytical Hierarchy Process (AHP) and Fuzzy Analytical Hierarchy Process (FAHP)

AHP is a developed multi-criteria decision-making method based on pairwise comparisons, and it has been widely used in practice. AHP is a powerful tool for applying MADM and it was introduced and developed by Saaty in 1980 (Kordi, 2008). The AHP method is used to calculate the weights or priority vector of the alternatives or the criteria through the pairwise comparison technique (Raju Meesariganda & Ishizaka, 2014). In the AHP, the process starts with breaking down the problem into a hierarchy of issues which are considered in the specific work. These hierarchy orders help to simplify the illustration of the problem and ensure the problem can be easily understood. In each hierarchy level, the weights of the elements are calculated. The decision on the final goal is to obtain the weights of the specific criteria or alternatives (Kordi, 2008).

Different participants might have different viewpoints or preferences regarding different criteria. The pairwise comparison technique is then used to allocate weights to each criterion after pairwise or mutual importance ratios between the criteria. To proceed with the pairwise comparison technique, Saaty's nine-point scale (Saaty, 2005) (Figure 2-8) is generally applied as a system to indicate how much one criterion is more important than another (Kordi, 2008).

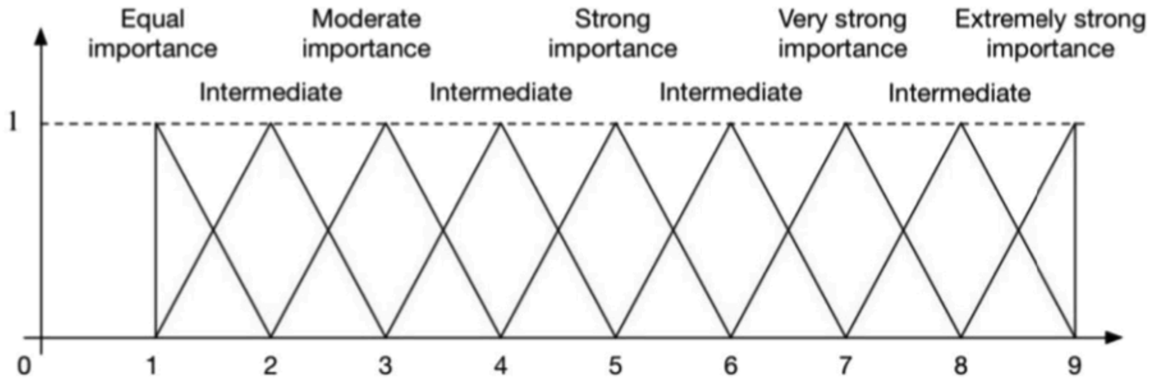


Figure 2-8. Structure of Saaty's nine-point scale importance (Saaty, 2005)

Saaty's nine-point scale has been criticised due to the different participants would express the nine-point scale differently; therefore, the nine-point scale would be challenging to represent reality (Raju Meesariganda & Ishizaka, 2014). Meanwhile, some participants can hardly distinguish the differences, for example, between equal importance and the importance between equal and moderate importance. Therefore, a seven-point and a five-point Likert scale are sometimes used to convert participants' verbal expressions to associate figures (khandelwal, 2021). It is necessary to choose the appropriate scale for the specific problem. Raju Meesariganda & Ishizaka (2014) suggested that individual scales need to be developed to better deal with the specific issue.

The two alternatives or criteria weights would be calculated after the pairwise comparison process. It needs to ensure the calculated weights are consistent; it is less realistic to consider the calculated weights based on the participants' expressions are exactly consistent. This is because expressing the real feelings of participants leads to the weights sometimes not being consistent. Therefore, the consistency ratio (CR) is introduced to evaluate the consistency of the calculated weights (Kordi, 2008). Eq. 1) and Eq. 2) are used to calculate the weights' consistency ratio.

$$Consistency\ Index(C.I.) = \frac{\gamma_{max} - n}{n - 1} \quad \text{Eq. 1)}$$

Where, n is the number of criteria and γ_{max} is the biggest eigenvalue.

$$C.R. = \frac{C.I.}{Random\ Index\ (R.I.)} \quad \text{Eq. 2)}$$

Where, R.I. is the consistency index of a randomly generated pairwise comparison, it depends on the number of elements which are compared, and it is shown in Table 2-7.

Table 2-7. Random Index (R.I.) (Kordi, 2008)

n	1	2	3	4	5	6	7	8	9	10	11	12
R.I.	0	0	0.58	0.9	1.12	1.24	1.32	1.41	1.45	1.49	1.51	1.48

If the C.R. < 0.10, it indicates a reasonable level of consistency in the pairwise comparison techniques. However, if the C.R. >= 0.10, it indicates inconsistent judgments.

The AHP method is a good strategy to calculate weights for each criterion considering actual participants' feelings. However, it is limited to some level of uncertainty due to the method itself (Saaty, 2005). For example, the participants might express feelings of uncertainty sometimes. Therefore, the fuzzy analytical hierarchy process (FAHP) is introduced to deal with the uncertainty issue by using the standard AHP method to calculate the weight for each criterion (Kordi, 2008). The main difference between FAHP and AHP is that FAHP uses fuzzy numbers instead of crisp numbers to compare the importance between the alternative or criteria. The fuzzy numbers are mainly used to reduce uncertainties.

2.5.2.1. Technique for Order Performance by Similarity to Ideal Solution (TOPSIS)

The TOPSIS could be a useful and valuable strategy for positioning and selecting the best alternatives by measuring Euclidean distances (Uzun Ozsahin Hüseyin Gökçekuş Berna Uzun James LaMoreaux Editors, 2021). The basic concept of TOPSIS is to have the most limited distance from the positive ideal solution (PIS) and must be far from the negative ideal solution (NIS).

The PIS is acted as the combination of all the most positive ideal (excellent) values that can be achieved for each criterion. However, the NIS contains all the worst scores achieved for each criterion. After comparing the relative distance for each alternative, elective priority arrangement of action could be achieved. This approach is widely used to unravel practical decisions (Uzun Ozsahin Hüseyin Gökçekuş Berna Uzun James LaMoreaux Editors, 2021). The TOPSIS is broadly used in solving decision-making problems due to the following reasons:

- The concept is straightforward to follow.
- The TOPSIS can measure the relative execution of choice options (alternatives) in a basic numerical frame.
- The TOPSIS method can rank alternatives based on the calculated weights using the AHP or FAHP method.

The following six steps are necessary to implement the TOPSIS method (Uzun Ozsahin Hüseyin Gökçekuş Berna Uzun James LaMoreaux Editors, 2021):

Step-1: To construct the decision matrix and importance weights of the criteria based on the stakeholder's preference.

Step-2: To normalise the decision matrix.

Step-3: To allocate weight onto the normalised decision matrix.

Step-4: To calculate a PIS and NIS for each criterion.

Step-5: To separate measures from the PIS and NIS.

Step-6: To calculate the relative closeness to the PIS.

The advantages of using TOPSIS include (Uzun Ozsahin Hüseyin Gökçekuş Berna Uzun James LaMoreaux Editors, 2021):

- The method is easy to follow, and it is straightforward to obtain and evaluate a single alternative.
- It is an efficient computation method.
- The differences between the alternatives can be quantified using normalised values.
- Instinctive and rational logic that forms the basis of human choice.

There are also some limitations of using TOPSIS, for example (Uzun Ozsahin Hüseyin Gökçekuş Berna Uzun James LaMoreaux Editors, 2021):

- It is difficult to weight at the same time keeping the consistency of the judgement.

- Euclidean distance application does not correlate with the criteria.
- It is a less objective method (Sharma et al., 2020).

The TOPSIS is applicable to any decision-making problems where objective or quantitative information is available. In general, the TOPSIS starts with forming the decision matrix that represents the combination of the criteria of each alternative. The decision matrix is then normalised, and the normalised values are multiplied by the importance weights of the corresponding criteria. Then, the PIS and NIS are formed, then separate measures of each alternative to PIS and NIS are calculated based on a distance degree. Finally, the choices are positioned based on their relative closeness to the PIS. The TOPSIS method facilitates decision-making by optimising the issues, conducting investigations, comparing, and positioning the alternatives.

2.5.3. Summary

Based on the review results in subsections 2.5.1 and 2.5.2, it found that:

- Limited case studies are found to explore the optimal individual renewable system or renewable combinations in UK homes.
- In general, S/MOO can identify the optimised configuration for the potential renewable system or renewable combinations for the specific building under the pre-defined, limited number of criteria. However, the MADM method can be used to identify the 'best' renewable system or renewable combinations under a broad of criteria regarding different stakeholders' perspectives on the criteria. Therefore, deciding the suitable MCDM method (e.g., S/MOO or MADM) is essential to deal with the specific decision-making problem.
- It is necessary to identify the most suitable scale range to implement the pairwise comparison techniques in AHP or FAHP. The suitable scale range can reflect a more realistic preference from the participants, which will then lead to a reliable weight to the specific criteria.

3. Methodology

This chapter explains in detail the methods used in the decision-making framework development. The entire decision-making framework is constituted of two steps, 1) the framework preparation step and 2) the framework development step. The methods used in the framework development addressed all the research objectives, as shown in Figure 3-1.

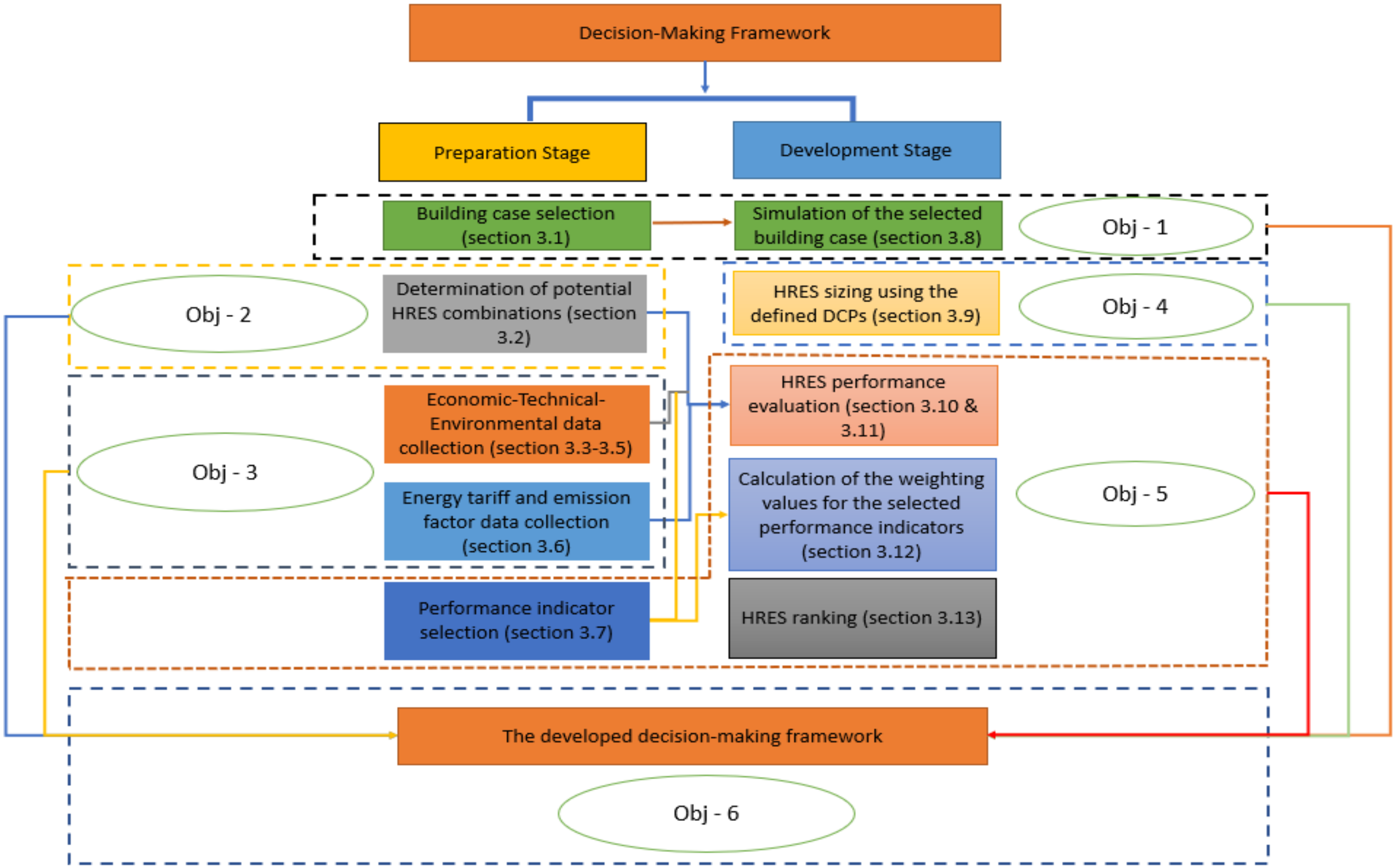


Figure 3-1 Structure of the methodology

Different approaches were used to collect economic, technical, and environmental data on the shortlisted renewable systems and the battery. The adopted different approaches are used to ensure the collected data is consistent and valid. Apart from the collection of the relevant data on renewable energy systems and energy storage, this research also collects the tariff and carbon emission factor of the selected representative energy supplier – E. ON.

This research collected the economic and technical data of renewable energy systems and the battery from the following resources:

- Different UK renewable system trading online markets, research articles.
- The UK government published technical report (Delta-ee, 2018)
- and the cost database created by the UK government (e.g., solar PV cost database BEIS, 2021)

The data collected from the above resources for the specified Microgeneration Certification Scheme (MCS) recognised renewable systems. The environment data of renewable systems like embodied carbon, is collected by reviewing the existing academic articles and technical report using the identified keywords.

The following paragraphs provide a brief introduction for each section and an overview of the method for the framework development.

The framework preparation steps include:

Section 3.1 - Representative domestic building selection: This research compiled housing data from the Welsh Housing Condition Survey (Welsh Government, 2019b) and English Housing Survey (UK Government, 2021a) and selected 6 building parameters to identify the representative domestic building in Wales and England. The domestic building type chosen for this investigation is a terraced or semi-detached house in the urban area, built-in between pre-1919 and 1980, with a floor area above 50 m^2 and at least a valid EPC band of C. The chosen domestic building type accounts for the highest proportion of the defined 6 building parameters in two housing databases. Therefore, it represents the typical energy consumption condition of most existing homes in England and Wales.

Section 3.2 - Practical HRES combination selection: This section explains the individual renewable energy system considered in this research to form potential HRES are certified by the Microgeneration Certification Scheme (MCS). The MCS is an industry-led and nationally recognised quality assurance scheme. It certifies renewable systems and installers that align with the relevant standards recognised by the UK government. The customers would have a high confidence level in the installed renewable system delivered by MCS. This research considers MCS recognised renewable systems, including Solar PV, Solar thermal collector (STC), Ground/Air Source Heat Pump (G/ASHP) as they can be practically installed into the representative domestic building. This research also considers the solar battery and hot water cylinder to work with the renewable system, strengthening the stability of the energy generation by renewable systems.

Section 3.3 - Cost data collection of the renewable energy system, battery, hot water cylinder, and solar inverter; Section 3.4 - Technical data collection of the renewable energy system, battery, hot water cylinder, and solar inverter; and Section 3.5 - Embodied carbon data collection of the renewable energy system, battery, hot water cylinder, and solar inverter: These three sections use the combined approach from the Literature review and UK-based renewable online retailing websites to collect the cost (section 3.3), technical (section 3.4) and embodied carbon (section 3.5) of the selected renewable energy systems. Prior to using the combined approach, this research has tried surveying the MCS accredited installers to collect the cost and technical data of the selected renewable energy systems (Section 3.3). However, data was less reliable and consistent due to the limited responses from the installers. Additionally, there is no available robust embodied carbon database of renewable energy systems in the UK. Hence, section 3.5 introduces the method of gathering the embodied carbon of the selected renewable energy system from the relevant studies as a practical approach to creating the associated reliable embodied carbon dataset.

Section 3.6 - Energy cost collection from the representative energy supplier: This section chooses E.ON as the representative energy supplier. The E.ON uses mixed renewable and conventional energy to supply electricity and natural gas. It has publicly accessible regional-level average energy tariffs across the UK. The regional level average energy tariff Can better reflect the energy bill for the selected representative city. The energy bill is used to assess and compare the economic-technical-environmental performance of potential HRES combinations in Cardiff as the representative city in section 3.12.

The energy bill for natural gas and electricity has been significantly increased after the review of the energy price cap in April 2022, and the energy cap is unlikely to decrease in the following review (Ofgem, 2022c). This section collected the energy price before and after the increased energy price cap to compare the economic performance of using energy from the continuously increasing energy bill and the potential HRES combinations.

This section also explained the method to collect the associate latest carbon emission factor of the electricity grid and natural gas pipeline from BEIS (2022). The carbon emission factor data reflect the actual steady condition of the UK electricity grid and natural gas in a specific period. Therefore, it is reliable to use the carbon emission factor to analyse the environmental performance of the existing electricity national grid, natural gas and potential HRES combinations.

The collected energy tariff and carbon emission factor data are used in section 3.11 to demonstrate the performance comparison between the existing energy supply strategy (using electricity from the grid and natural gas for space heating and DHW) and different potential HRES combinations.

Section 3.7 - Renewable system performance evaluation criteria and indicators selection: This section introduces using the created selection approach to identify suitable criteria and indicators to assess the performance of renewable energy systems. The potential criteria and indicators are gathered based on the findings in subsections 2.4.1 and 2.4.2:

- Findings from subsection 2.4.1: UK government recognised whole building performance evaluation manual, guidance, and domestic renewable system installation standards;
- Findings from subsection 2.4.2: Relevant research articles.

The selection approach compares the criteria and indicators from the above resources. However, it prioritises the criteria and indicators from the UK government recognised whole building performance evaluation manual, guidance, and renewable system installation standards. As they reflect the actual needs of assessing the performance of homes and on-site renewable systems from the UK's stakeholders' perspectives.

The framework development step includes:

Section 3.8 - Building modelling: This section detailed construction material, heating setpoint, occupancy activity schedule and the associated indoor comfort requirements to develop building model. The detailed information is from:

1) Standard Assessment Procedure (SAP) (UK Government, 2013a);

2) Building Research Establishment Domestic Energy Model (also known as BREDEM) (BRE, 2015);

3) CIBSE Guide A (CIBSE, 2015).

Then, such detailed information was used to create the representative building model in DesignBuilder and simulate the corresponding energy demand in EnergyPlus. This section also explained the method to evaluate the effectiveness of the created building model. The ASHRAE Guideline-14 (ASHRAE, 2002) was used to construct the effectiveness evaluation method.

Section 3.9 - HRES sizing scenario development: This section explains the development of the HRES sizing scenario based on the published decarbonisation plan published by CCC (2016; 2019), the technical report published by IEA (2019) and the identified representative case studies (Janko et al., 2016; Sakiliba et al., 2020; Sharafi et al., 2015). Such documents are used to develop sizing scenarios which are feasible and practical to investigate the performance of HRES combinations.

Section 3.10 - HRES energy generation spreadsheet development: explains the energy generation equations of each renewable energy system. It also describes the calculations to work out the size of each HRES combination in different sizing scenarios developed in section 3.10. Finally, it introduces the approach to calculating the energy supply-demand balance of each HRES combination in different sizing scenarios.

Section 3.11 - HRES performance criteria and indicator spreadsheet development in the decision-making process: This section explains the approach to developing and carrying out a questionnaire survey among the representative UK householders.

Section 3.12 - Performance criteria and indicators weighting: This section describes converting the collected householders' viewpoints as the weights towards the decision-making performance criteria and indicators based on the Analytical Hierarchy Process (AHP) method. AHP method is widely used to calculate the weights for multi weighting criteria and indicators based on different participants' viewpoints.

Section 3.13 - Decision-making spreadsheet development: This section describes the method to quantify and rank the potential HRES combinations in different sizing scenarios through the weighted decision-making performance indicators using the Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) method. TOPSIS can incorporate the calculated weights for each criterion and indicator through the AHP method, calculating the final mark for each potential HRES combination. Then, each potential HRES combination is ranked based on the calculated final mark.

3.1. The representative domestic building selection

The Welsh Housing Condition Survey (WHCS) (Welsh Government, 2019b)and the English Housing Survey (EHS) (UK Government, 2021a) are used as references to select the building characteristic indicators and identify the representative domestic building. These references were selected as they include comprehensive and up-to-date information of domestic buildings in England and Wales. Several building characteristic indicators have categorised the domestic building data like the built year, floor area, Energy Performance Certificate (EPC) band etc., in both sources.

This research compared and then selected building character indicators in both reference databases. The selected indicators were location, house type, floor area (in m^2), number of households, built year and EPC band. The domestic building with the higher proportion in the selected indicators is then chosen as the representative building in this research. This research identified that the representative domestic building should be a terraced or semi-detached house in an urban area connected to the national grid and natural gas. It was built between pre-1919 and 1980, with a floor area between 50 and 80 m^2 and at least a valid EPC band of C. The EPC band of C guarantees the house is in energy-efficient condition, enabling a lower heating temperature system (E.g., A/GSHP) to work efficiently to meet the required indoor thermal comfort. Climate Change Committee (CCC, 2021) stated that the existing domestic building in the UK should be retrofitted to achieve at least an EPC band of C over the next 10 to 15 years, in order to achieve the agreed climate change target by 2050. Households of two adults is a typical scenario that is then carried into the energy consumption calculations based on the analysis of the reference databases in this research.

3.2. Practical HRES combination selection

3.2.1. Potential individual renewable energy system selection

MCS recognised several renewable systems, including solar PV, solar thermal collector (STC), micro wind turbine, ground/air source heat pump (G/ASHP), and micro combined heat and power system (mCHP), could be practically installed on existing or new domestic buildings. This research selects the individual potential renewable system from the MCS recognised systems to form practical HRES combinations aligned with the relevant regulations and standards on the selected representative domestic buildings. The applicable regulations and standards are used as follows:

- The local permitted development requirements in England (Department for Communities and Local Government, 2012; UK Parliament, 1995.) and Wales (UK Parliament, 2004; UK Parliament, 2009; National Assembly for Wales, 2012;): enabling the selected potential renewable systems are granted permission to install domestic buildings without additional applications. Meanwhile, the detailed installation requirements of each renewable energy system are helpful to shortlist the potential renewable system for the representative domestic building.
- The MCS renewable installation standards: identifying the energy generation function and delivered energy type of each renewable energy system in domestic buildings.
- The Ofgem regulations: Matching the applicable ongoing financial incentives to the selected practical HRES combinations. The potential practical HRES combinations should benefit from one financial incentive for electricity generation and one for heat generation.

This research shortlisted the potential renewable energy systems as: solar PV, STC, G/ASHP. The micro wind turbine and mCHP are excluded due to the restrictions of the selected representative domestic building. The roof-mounted micro wind turbine has no permitted development rights to install on domestic buildings in Wales. In addition, even where it is permitted (as in England) there are difficulties installing it on the domestic building, especially on the mid-terraced house. The selected representative domestic buildings cannot install the ground-mounted micro wind turbine because the limited ground space can make it challenging to meet the permitted development requirements.

Natural gas and biomass are two main sources to run mCHP to generate energy. However, this research does not regard natural gas as a renewable energy source. Biomass is a type of renewable energy source. But it is difficult for the selected domestic building type with the associated floor area to store the sufficient biomass used for the central heating. In addition, according to the Ofgem regulations and MCS renewable installation standards, biomass-driven mCHP is mainly used in rural areas where has no natural gas.

3.2.2. Potential HRES combination selection

The shortlisted individual renewable systems, solar PV, STC and G/ASHP, are used to form potential HRES combinations. The formed potential HRES combinations can supply energy in the following two conditions:

- Electricity and space heating.
- Or electricity, space heating and domestic hot water.

The combinations are compliant with Ofgem regulations and MCS renewable installation standards in terms of the generated energy types and installation approaches. For example, (Air-to-water) ASHP and GSHP can be used for either space heating or space heating plus domestic hot water. However, using GSHP or ASHP to supply space heating and domestic hot water demand is complex. The heat pumps need to corporate different backup systems to achieve the most cost-effective, practical, and stable energy supply strategy. It is also difficult to model heat pumps' seasonal coefficient of performance (SCOP) while they supply space heating and domestic hot water together. Due to SCOP changes while supplying space heating or domestic hot water. Thus, this research used (Air-to-water) ASHP or GSHP to supply space heating load only but used the STC system for domestic hot water purpose.

The potential HRES combinations should benefit from at least one ongoing or future financial incentive scheme in electricity or heat demand-supply. The ongoing financial incentive scheme for electricity generation is Smart Export Generator (SEG) and Boiler Upgrade Scheme (BUS) from April 2022 onwards. The previous Renewable Heat Incentive (RHI) scheme is due to closure for the new applications in April 2022.

This research then considered HRES combinations that are eligible for RHI and BUS schemes. Table 3-1 presents potential HRES combinations.

Table 3-1. Potential HRES combinations

Combination	Electricity	Space Heating	DHW	Battery	Hot water cylinder
Solar PV + GSHP	Yes	Yes	No	No	No
Solar PV + GSHP	Yes	Yes	No	Yes	
Solar PV + ASHP	Yes	Yes	No	No	
Solar PV + ASHP	Yes	Yes	No	Yes	
Solar PV + GSHP + STC	Yes	Yes	Yes	No	Yes
Solar PV + GSHP + STC	Yes	Yes	Yes	Yes	
Solar PV + ASHP + STC	Yes	Yes	Yes	No	
Solar PV + ASHP + STC	Yes	Yes	Yes	Yes	

3.3. Cost data collection of renewable system, battery and hot water cylinder

This section first explains the method to collect the cost data of the shortlisted renewable systems, batteries, hot water cylinders, and solar inverters. The cost data of the system mentioned above is constituted by the capital cost (section 3.3.1) and the whole lifecycle servicing cost (3.3.2). After collecting the relevant cost, this section continues to explain using the collected cost to identify the representative cost of such systems.

3.3.1. Capital cost

The capital cost is defined as the cost that includes the product and installation of the renewable energy systems, batteries, hot water cylinders and solar inverters. This research initially carried out a questionnaire to collect the total cost of the shortlisted individual renewable system from MCS registered installers between April and July 2021. However, an insufficient response was received within the period. Therefore, the alternative two approaches were taken to collect the capital cost for the shortlisted renewable systems.

- The first alternative approach is to review the current robust and holistic cost database created by the UK government. It found out that the UK government developed a capital cost database of solar PV in 2013 (BEIS, 2021b). The database that compiled UK PV annual (0-50 kWp) capital cost data since 2013. It updates the cost data every year, and the latest available data is 2021. The PV annual capital cost data includes product and installation costs with the applicable VAT charge. The PV database reflects the actual PV installation condition in the UK. The VAT rate depends on the ratio of installation and equipment costs, so it is useful to have this specified for each recorded cost dat. The database was then used to identify the representative capital cost of solar PV within the shortlisted configurations for the selected representative domestic building. Subsection 3.3.1.1 explains using firster alternative approach to identify the representative capital cost of solar PV.

- Unlike the capital cost of solar PV database (BEIS, 2021b), no such robust and holistic capital cost database are available for GSHP, ASHP, STC, battery and hot watery cylinder. MCS installation database recorded the product and installation cost in the unit of £/kW of GSHP, ASHP and STC in UK homes since 2010. However, this research has not been granted permission to access the MCS database. Some online commercial renewable consultancy websites (i.e., GreenMatch: https://www.greenmatch.co.uk/) and energy organisation websites (i.e., Energy Saving Trust https://energysavingtrust.org.uk/) provide the average total cost for such systems. The provided average product and installation cost from the websites mentioned did not clarify 1) the data collection period. 2) the VAT charging rate in the average total cost was not defined, it is difficult to identify which VAT rate was included in the average total cost. 3) the product brands had not been specified in the average total cost from such websites, this research does not consider brands that are not recognised by MCS. The second alternative approach is then used to collect the relevant cost and identify the representative capital cost for such systems. The second alternative approach breaks down the capital cost into product and installation costs. It collects the product cost of the MCS recognised brands for such systems from the relevant UK-based retailing websites. The product cost was initially collected in November 2020, the cost then updated regularly to ensure the collected product cost can reflect the UK renewable system market in a specific period. The product cost was updated in March, June, and November in 2021; the last update was in January 2022. The representative articles and published technical reports (Delta-ee, 2018; Renaldi et al., 2021) were selected and used as the reference data to identify the representative installation cost of ASHP, GSHP and STC. Then, it explains using the second alternative approach to work out the installation cost based on the reference to add the relevant product cost to obtain the capital cost for ASHP, GSHP and STC.

The second alternative approach was also used to collect the relevant cost and identify the representative capital cost for battery and hot water cylinders. However, the MCS has no recognised brand list of battery and hot water cylinders. This research then first scopes the widely installed brands of batteries, hot water cylinders and solar inverter from the following websites:

- UK-based green energy consultancy website, GreenMatch (https://www.greenmatch.co.uk/),
- the UK trusted renewable trade website (the website has its stringent quality assessment of the products and installers to align with the MCS standards. In addition, the website accepts ratings from customers, ensuring all reviews are trustworthy) SolarGuide (https://www.solarguide.co.uk/)
- and the UK boiler and plumbing quotes websites, HeatingForce (https://heatingforce.co.uk/blog/installation-cost-vented-unvented-hot-water-cylinders/); and BoilerGuide (https://www.boilerguide.co.uk/articles/best-unvented-cylinders).

Once identified the widely used brands of such systems are from the websites listed above, the second alternative approach is used to collect the relevant cost of such systems with the identified brands. Subsection 3.3.1.5 explains the detailed method to collect the relevant cost and identify the representative capital cost of the battery and hot water cylinder.

3.3.1.1. Capital cost of solar PV

This subsection collects the capital cost of less than 4kWp solar PV from the database (BEIS, 2021b), as the selected representative domestic building no needs solar PV with configuration more than 4kWp. The capital cost from the database between January 2015 and October 2019 was collected to identify the representative capital cost of solar PV due to the following two reasons. 1) Leading up to 2015, the solar PV market in the UK developed to a point where economies of scale reduced PV total costs significantly. Therefore, the total cost of solar PV prior to 2015 is no longer relevant. 2) The VAT rate of 5% is specified in the recorded capital cost of solar PV in the database before October 2019. After the date, the VAT rate varies and is subject to a 60% test; the VAT rate was not specified in the capital cost after October 2019. It is then challenging to compare the trend of capital cost without VAT charge and to identify the representative capital cost between 2015 and 2019 due to the unspecified VAT rate.

This section calculates the average cost of the collected capital cost of solar PV with the requirements mentioned above. The average capital cost can represent the general cost of solar PV in the UK with the configuration of less than 4kWp between January 2015 and October 2019. Therefore, the average capital cost can be used as the representative capital cost of solar PV to carry out the economic performance evaluation in this research. The collected capital cost from the database (BEIS, 2021) remains the same at 5% between January 2015 and October 2019. The calculated average capital cost can also be used to calculate the average capital cost without VAT charge by dividing the VAT rate of 5% in the selected period.

3.3.1.2. Capital cost of ASHP

This section collects the product cost of seven MCS recognised ASHP manufacturing brands from the relevant UK-based retailing websites. The collected product cost (excl. VAT) in £/kW, brands, the relevant source information, and the collection time is presented in Appendix A. The reason to collect product costs without VAT is to assess if the identified representative capital cost of ASHP can pass the 60% test and then is eligible for the reduced VAT rate at 5% instead of 20% (UK Government, 2021b). It is the same reason for collecting the product cost (excl. VAT) of GSHP and STC. It calculates the average product cost based on the collected seven MCS recognised ASHP brands, using the representative product cost of ASHP in this research.

The research conducted by Renaldi et al. (2021) is used as the reference data to calculate the representative installation cost for ASHP, GSHP and STC in this research. Renaldi et al (2021) was granted permission to access the MCS installation database. They then collected the annual average installation cost of ASHP, GSHP and STC in £/kW between 2010 and 2019. This research calculated the average installation cost (£/kW) of ASHP between 2010 and 2019. It assumed the calculated average installation cost of STC between 2010 and 2019 will remain the same in the next 20 years due to the annual installation cost between 2010 and 2019 has not been changed more than 50%.

Once the representative product and installation cost were identified, the representative capital cost of ASHP can be found by adding the representative product and installation cost. Figure 3-2 presents the method to calculate the representative capital cost of ASHP described above.

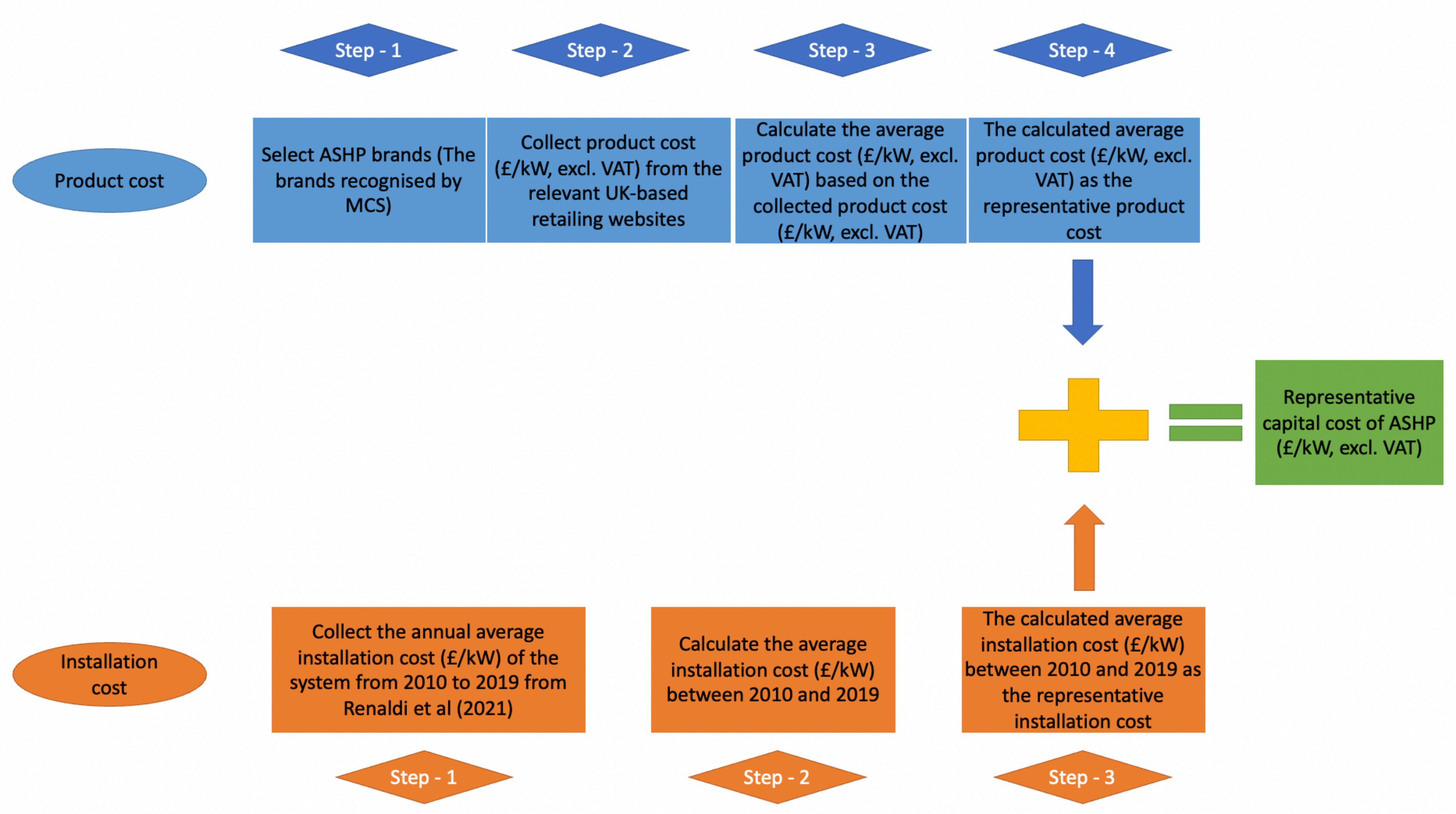


Figure 3-2. The calculation method to identify the representative capital cost of ASHP

3.3.1.3. Capital cost of GSHP

This section collects the product cost of five MCS recognised GSHP manufacturing brands from the relevant UK-based retailing websites. The collected product cost (excl. VAT) in £/kW, brands the relevant source information and the collection time are presented in Appendix A. The representative product was calculated by averaging the collected product cost of five MCS recognised GSHP brands.

Like the approach that used to collect the installation cost of ASHP, the installation cost of GSHP is also referenced the research conducted by Renaldi et al (2021). However, Renaldi et al (2021) did not consider the groundwork cost in the installation cost. The groundwork cost of GSHP is an important part in the overall installation cost of GSHP, and it should not be lack considered in the evaluation of economic performance. This research consults the research conducted by Delta-ee that investigated the cost of installing different heating measures in UK domestic buildings in 2018. Delta-ee (2018) has adopted the following approaches to collect the installation cost of GSHP:

- In-depth interview with 7 installers whom Delta-ee has a good relationship with.
- In-depth interviews with 4 large manufacturers.
- Cold calling exercise with 48 installation companies.

Delta-ee (2018) collected two installation costs of installing a 12 kW GSHP with and without groundwork cost in UK homes.

- First installation cost (£14,850): 12 kW GSHP fully installed, including fittings and buffer tank but excluding groundworks and the outside heat distribution system.
- The second installation cost (£20,850): 12 kW GSHP fully installed, including fittings, buffer tank and groundworks but excluding the outside heat distribution system.

The average groundwork cost for a 12 kW GSHP is calculated as £6,000 based on the two collected costs. This research used the calculated £6,000 as the representative groundwork cost in the economic performance evaluation of GSHP. The required GSHP size for the selected representative home would not need a GSHP above 12 kW to supply space heat and even with DHW demand. The relevant groundwork cost of installing such GSHP with less than 12 kW configuration would not be beyond £6,000. However, this research acknowledged that there could be significant variation in the practical groundwork cost calculation.

For any GSHP with a configuration less than 12 kW, the overall representative installation cost can be calculated by the following steps:

1. Work out the representative installation cost (without the groundwork cost) by averaging the installation cost between 2010 and 2019 in the research of Renaldi et al (2021). The average installation cost is assumed to remain the same in the next 20 years, the variation of the annual installation cost is less than 40% between 2010 and 2019.
2. Using the specified configuration multiply the calculated representative installation cost (£/kW) (without groundwork cost).
3. Secondly, add the calculated representative installation cost of the specified configuration with the representative groundwork cost (£6,000) to obtain the overall installation cost of the GSHP with the specified configuration.

The representative capital cost can be calculated by adding the representative product cost from five MCS recognised GSHP brands and the calculated representative installation cost in £/kW based on the research conducted by Renaldi et al (2021). The calculated capital cost should add another £6,000 which is considered as the representative groundwork cost of installing any GSHP with the configuration of less than 12 kW in UK homes. Figure 3-3 presents the calculation method for the capital cost of GSHP.

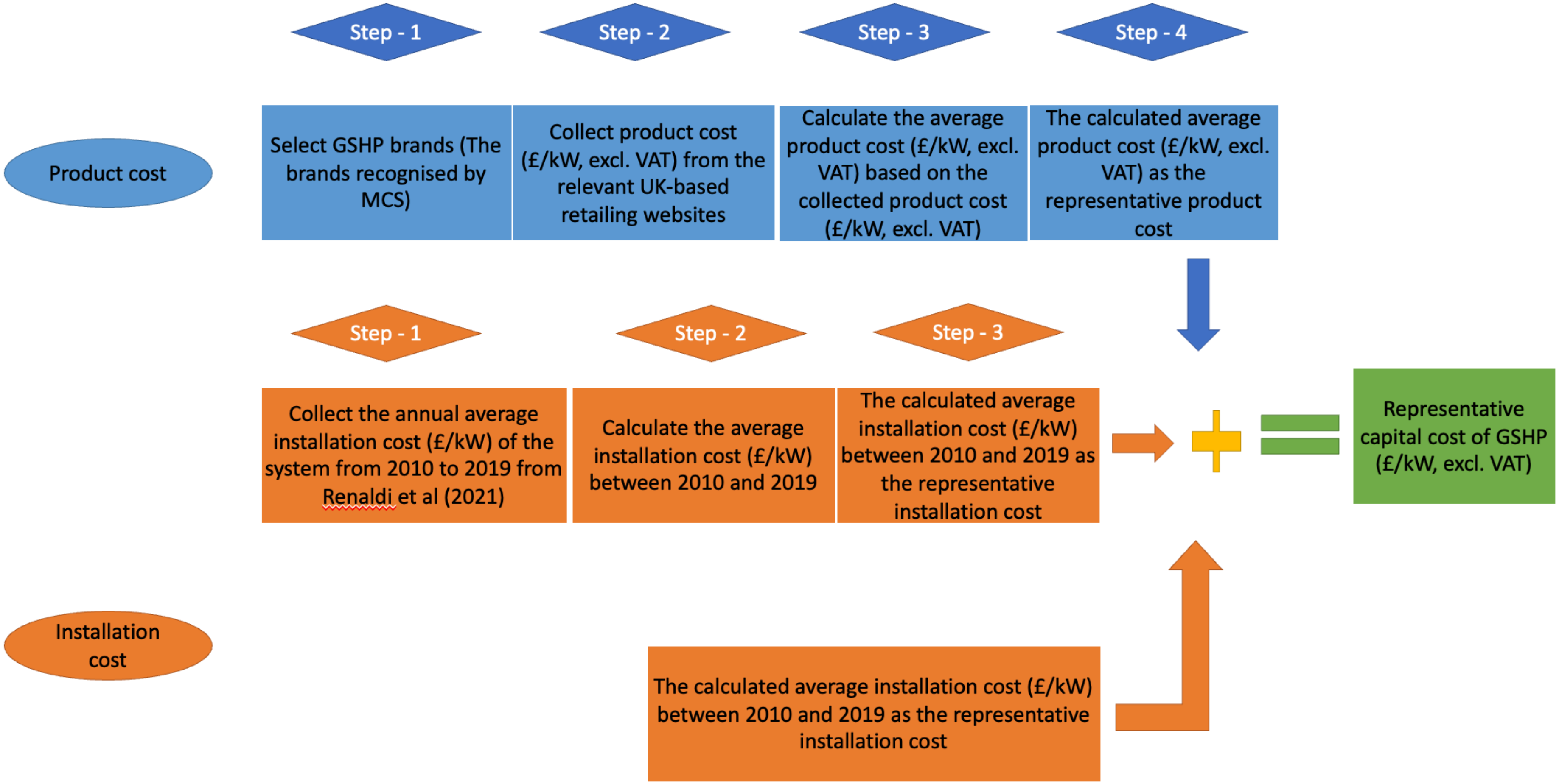


Figure 3-3. The calculation method to identify the representative capital cost of GSHP

3.3.1.4. Capital cost of STC

This section collects the product cost of two MCS recognised STC manufacturing brands from the relevant UK-based retailing websites. The collected product cost (excl. VAT) in £/m^2, brands the relevant source information and the collection time are presented in Appendix A. The representative product was calculated by averaging the collected product cost (£/m^2) of two MCS recognised STC brands.

The representative installation cost of STC was calculated based on the research (Renaldi et al., 2021b). Like the method of calculating the representative installation cost for GSHP and ASHP. It calculated the average installation cost in £/kW of STC between 2010 and 2019. The calculated average installation cost is used as the representative cost of installing STC in UK homes. Like the assumption made in calculating the representative installation cost of GSHP and ASHP, it assumed that the average installation cost of STC between 2010 and 2019 will remain the same in the next 20 years.

The representative capital cost of STC is then adding the representative product cost and representative installation cost together. However, the calculated representative product cost is presented in £/m^2, which is different to the unit presented in the representative installation cost (£/kW). Thus, this research used the conversion factor of 0.7 defined in the Solar Heating and Cooling Programme (IEA, 2016) to convert £/m^2 to £/kW. IEA (2016) defined using the aperture area(m^2) of the STC area multiply 0.7 to obtain the installed capacity of STC (kW). Figure 3-4 presents the method to calculate the representative capital cost (£/kW) for STC.

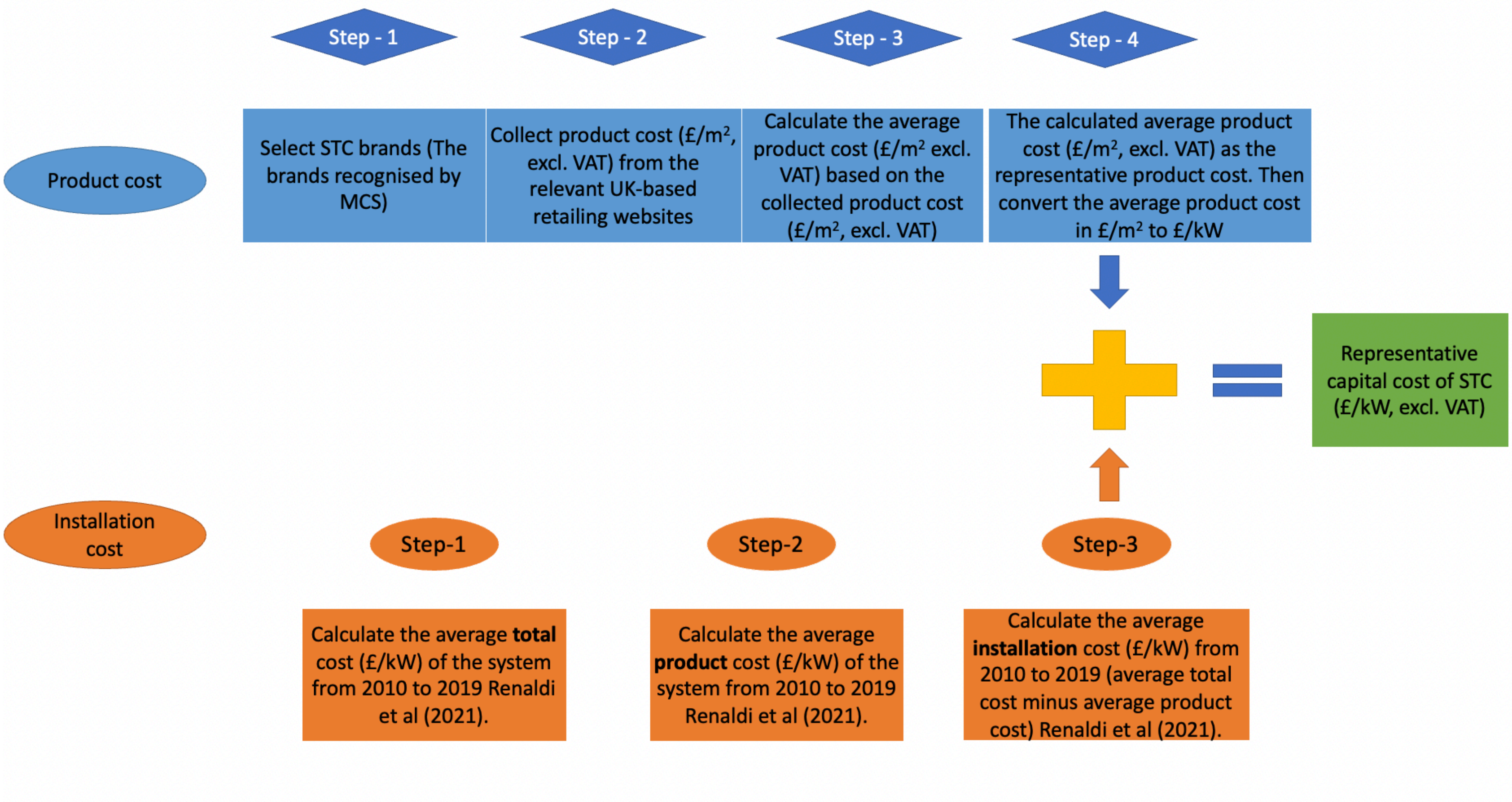


Figure 3-4 The calculation method to identify the capital cost of STC

3.3.1.5. The capital cost of batteries, hot water cylinder and solar inverter

This research selects Tesla Powerwall as the battery brand due to Tesla has the extended warranty period (up to 15 years) and reliable performance. The product cost of the Tesla Powerwall is transparent and publicly available to check on the official website (Tesla, 2022b). The battery size (13.5kWh) is reasonable to cover the daily electricity balance of the selected representative domestic building. Additionally, the Tesla company has a strong manufacturing capacity to ensure the stability of the supply chain, it claims that it could build 100 MW of battery storage (about 129MWh of battery capacity) in 100 days (Mathew Hampshire-Waugh, 2021). This research collected installation cost of Tesla Powerwall battery from the UK trusted renewable trade website, SolarGuide (https://www.solarguide.co.uk/) and the UK based energy system specialists website, UK Alternative Energy (the UK based energy system specialists website, UK Alternative Energy (https://www.ukalternativeenergy.co.uk/tesla-Powerwall-faq/). These websites provide a general installation cost range of Tesla Powerwall battery based on the compiled installation cases in the UK between 2018 and 2020. This research calculates the average installation cost based on the collected general installation costs to work out the representative installation cost of the Tesla Powerwall battery. Then, the product cost of the Tesla Powerwall from the official website to add the calculated representative installation cost to obtain the representative capital cost of the Tesla Powerwall battery.

This research chosen Viessmann, Telford, and Gledhill as the hot water cylinder brands. The selected brands have a cylinder capacity of between 100 and 150 Litres, and as such cylinder capacity range is sufficient and practical to be installed on the selected representative domestic building to cover the daily hot water consumption. The scoped brands were searched on two hot water cylinder retailing websites (https://viessmanndirect.co.uk/Catalogue/Domestic-Cylinders and https://www.plumbnation.co.uk/site/viessmann-vitocell-200-v-120l-unvented-thermal-storage-cylinder/) to collect the product cost. The representative product cost of hot water cylinders is calculated averaging the collected product cost from the retailing websites mentioned above. The installation cost of the hot water cylinder is compiled from a UK based renewable energy consultancy website, the ECO experts (https://www.theecoexperts.co.uk/boilers/megaflow-boilers). Charlie Clissitt (2022) summarised the general installation cost of unvented hot water cylinders in UK homes on the ECO experts. The installation cost of the hot water cylinder was updated in January 2021. In general, the installation cost of an unvented hot water cylinder (100-150L) ranges from £500 to £1500 excluding VAT. The replacement cost of an existing unvented hot water cylinder for a new unvented hot water cylinder (100-150L) is between £275 and £450. The installation is significantly more expensive than replacement due to the complexity of the first fit-in work. This research calculates the average installation cost based on the collected unvented hot water cylinder (100-150L) installation costs. The calculated average installation cost was then converted to the cost per litre (£/L) to better represent a general installation scenario with a medium amount of installation work.

The maximum configuration (power ratings) of solar PV to be installed on the selected representative domestic building is 4kWp. In practice, the required configuration of the solar inverter would be generally 0.5kW smaller than the required PV configuration (power ratings) (Energy Saving Trust, 2022c). Thus, the required configuration (power ratings) of the solar inverter would not be beyond 3.5kW. This research then identified brands with commercial solar inverters with configurations less than 3.5kW. The compiled solar inverter brands include ABB, Fronius, Bosch, Danfoss, Soils and SolarX. Like other systems, the solar inverter's representative product cost is calculated by averaging the collected cost from different retailing websites for a solar inverter with a configuration (power ratings) of less than 3.5kW. The installation cost of solar inverters is included in the capital cost of solar PV. Therefore, the installation cost of a solar inverter is not separately calculated in this section.

3.3.2. The whole lifecycle servicing cost

The whole lifecycle servicing cost refers to the cost of the maintenance and component replacement in the expected lifespan of the system. Regular servicing enables the system to work efficiently to the expected lifespan without any major breakdown or the unexpected replacement within the lifespan. However, the whole lifecycle servicing cost varies by systems, servicing frequency, installation strategies, and the expected lifespans. There is no available database to show the holistic and robust servicing cost data of renewable systems, batteries, hot water cylinders and solar inverters. Therefore, this research uses the grey literature, UK renewable installer websites (where listed the servicing cost for such systems on their websites), and UK renewable consultancy websites as the information sources to collect the generic, reliable, and representative servicing cost of such systems. The following resources were used to collect the whole lifecycle servicing cost of the systems:

- The UK based green energy consultancy websites, GreenMatch (https://www.greenmatch.co.uk/), the eco experts (https://www.theecoexperts.co.uk/), WestWard Energy Service (https://www.westwardservices.com/), YouGen (https://yougen.co.uk/about/).
- The UK trusted renewable trade website, Checktrade (https://www.checkatrade.com/).
- The UK based renewable system and storage design, installation and maintenance websites, GreenerGroup (https://thegreenergroup.com/), IMS Heat Pumps (https://www.imsheatpumps.co.uk), EES (https://www.ees.co.nz/), Solar guide (Tesla Powerwall 2.0 Cost, Specs and Reviews | Solar Guide), Gregor Heating and Plumbing Ltd (http://gregoryheatingltd.com/gregory-heating-and-plumbing-ltd/central-heating-maintenance/), Boilerbooker (https://boilerbooker.com/).

  The UK independent energy organisations, Energy Saving Trust (https://energysavingtrust.org.uk/).

The following approach is used to calculate each renewable system's representative whole lifecycle servicing cost. It first needs to identify the expected lifespan of the selected renewable energy system from the websites mentioned above. Once the expected lifespan for each renewable energy system is identified, it then needs to gather the recommended servicing frequency of the chosen renewable system within the expected lifespan. The recommended servicing frequency is the frequency suggested by qualified system technicians or renewable energy system professionals. But the recommended servicing frequency might not always align with the actual system servicing frequency. For example, the recommended servicing frequency of solar PV is yearly from the scoped websites. However, householders in the UK with installed solar PV on the pitched roof are unlikely to ask the technician to check their solar PV every year. It calculated the average servicing cost for each renewable system based on the collected servicing cost of such system from the selected websites. Finally, to work out the whole lifecycle servicing cost for each renewable system by using the calculated average servicing cost, with the consideration of the identified lifespan and recommended servicing frequency. The calculated average servicing cost is used as the representative servicing cost of each renewable system and considered in the economic performance evaluation of HRES. This research uses the calculated whole lifecycle servicing cost as the representative whole lifecycle servicing cost of each renewable system.

The following approach was used to identify the representative whole lifecycle servicing cost for the battery, hot water cylinder and solar inverter. This research selected the servicing frequency, the expected lifespan and the relevant servicing cost from the Tesla official website. Such data was used to calculate the representative whole lifecycle servicing cost for Tesla Powerwall battery. Based on the collected data from Tesla official website, Tesla Powerwall does not require frequent servicing within the expected lifespan unless the major component is broken down or a fault issue appears in the control panel. Like Tesla Powerwall, the solar inverter does not require frequent servicing. However, the lifespan of the solar inverter is shorter than the renewable energy system, generally between 10 to 15 years, based on the information found on the selected websites (GreenMatch, 2022b; the ECO experts, 2021). Thus, there is no recommended servicing frequency and cost for the solar inverter.

The frequent servicing is necessary to ensure hot water cylinder working efficiently avoid heat loss while storing hot water. The hot water cylinder servicing includes

- Check the pressure in the expansion vessel.
- Test the expansion relief bar and temperature relief valve.
- Clean the mesh filter
- Test DHW 2 port value
- Check the operation of the controller

Based on the data collected from the selected websites, the hot water cylinder typically needs annual servicing with a servicing cost range between £72 to £85 plus a VAT charge of 20% (Boilerbooker, 2022; Gregor Heating and Plumbing Ltd, 2022). The typical lifespan of hot water cylinder is between 25 and 30 years. This research then calculated the average annual servicing cost based on the collected cost data with the VAT charge. The calculated average annual servicing cost then multiplies the identified typical lifespan to work out the representative whole lifecycle servicing cost. The calculated average annual servicing cost of hot water cylinder is used as the representative annual servicing cost to evaluate the economic performance of hot water cylinder.

3.4. Technical data collection of the renewable energy system, battery, hot water cylinder and solar inverter

This section explains the method to collect the essential technical information on renewable energy systems, battery, hot water cylinders and solar inverters. Such essential technical information was used to evaluate the relevant economic-technical-environment performance. The collected essential technical data is aligned with the adopted energy generation numerical expressions that explained in section 3.12. This section is constituted by three subsections:

- Section 3.4.1 – Technical data collection for solar PV and solar inverter
- Section 3.4.2 – Technical data collection for GSHP and ASHP
- Section 3.4.3 – Technical data collection for STC and hot water cylinder

Each subsection explains the required technical data to support energy generation and supply as well as the performance evaluation of different renewable energy systems.

3.4.1. Technical data collection for solar PV, solar inverter, and battery

This subsection describes the method to compile the technical data of solar PV including the PV panel size (in square meters), PV efficiency and performance ratio. PV panel size (in meters) and PV efficiency are normally in the commercial solar PV technical manual. Therefore, the method was used to collect the essential technical data of the scoped solar PV brands from the different UK-based online solar PV retailing websites (https://www.renugen.co.uk/; https://www.cclcomponents.com/; https://solarstone.co.uk/shop/; https://www.sunstore.co.uk/). This subsection then created a dataset to store the gathered solar PV configuration and the associated solar PV panel size (in meters) and efficiency. However, the performance ratio could not be found in the technical manual of any solar PV with the scoped brands.

The performance ratio is the ratio describing the relationship between the actual and theoretical energy outputs of the PV. It then shows the percentage of the energy that is available for use after the deduction of energy loss (e.g., due to thermal and conduction losses) (Solar Technology, 2022). Unlike PV efficiency, which is used to calculate the generated electricity by a specific solar PV at the standard testing condition (STC). The performance ratio is used to calculate the amount of the electricity that could be used for covering demand or exporting back to the grid after the calculation of energy loss.

Thus, this research considers the performance ratio of 0.75, as the ratio is suggested by National Renewable Energy Laboratory (S. Pless et al., 2005) and International Energy Agency (Sarah Kurtz et al., 2013). They investigated the performance ratio of different solar PV in various locations by using the simplified performance ratio model and the monitored data. The suggested solar PV performance ratio is representative and reliable, and therefore, it was used in the relevant generation calculation of solar PV in this research.

The solar PV self-consumption rate also needs to be considered in the performance evaluation of solar PV and battery. The solar PV self-consumption rate is a measure of the proportion of electricity generated by the solar PV system and consumed in the building (MCS, 2019). MCS published a generic solar PV self-consumption database for three typical occupancy electricity consumption profiles of UK homes. The published database is based on combined domestic electricity consumption and renewable system model that was developed by Loughborough University and Advance Further Energy Ltd. The model was validated by BRE National Solar Centre (MCS 2019). Thus, the solar PV self-consumption rate database is used in this research to consider the suitable rate for different solar PV size with or without battery in the performance evaluation process.

3.4.2. Technical data collection for GSHP and ASHP

The energy generation calculation considered the essential technical factors, including the capacity of a heat pump (in kW) and seasonal coefficient of performance (SCOP). Both technical factors are generally recorded in the technical manual of the commercial air or ground source heat pump. Hence, this research collected SCOP and heat pump capacity based on the scoped MCS registered brands. Like solar PV, the collected technical data of GSHP and ASHP is stored in a developed dataset. Some brands provide a coefficient of performance (COP) instead of SCOP for A/GHP. COP considers the performance for a single set of conditions, whereas SCOP considers the performance from both the heating/cooling and non-heating/cooling period. GSHP and ASHP are used to generate energy for space heating, and it is reliable to use SCOP to calculate the energy generation in this research.

3.4.3. Technical data collection for STC and hot water cylinder

The aperture area (A_{aper}) and zero-loss collector efficiency (η_0) are two essential technical factors that were considered in the energy generation calculation of STC. η_0 is generally found in the technical manual of commercially available STC with the scoped brands. However, η_0 value varies in different selected brands. The average η_0 of STC from the selected brands were calculated as the representative zero-loss collector efficiency to use in the calculation process. Some scoped STC brands might not provide A_{aper} but gross area (A_{gross}) of STC. This research applies the conversion method introduced by SAP (UK Government, 2013a). The method uses A_{gross} to multiply 0.9 to obtain A_{aper}. The factor of the chosen hot water cylinder (defined in subsection 3.3.1.5) is another technical factor that needs to be considered in the energy generation calculation of STC.

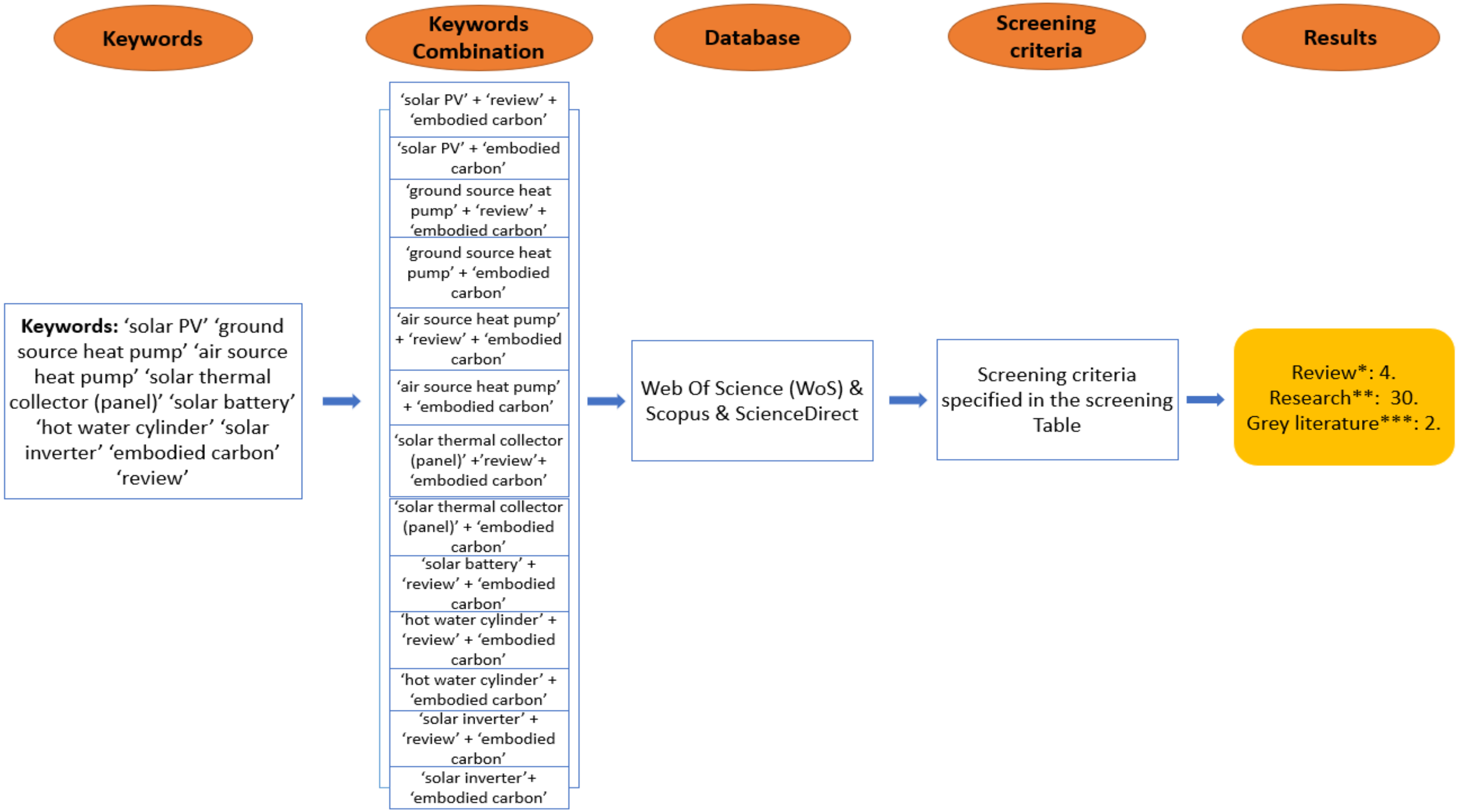
3.5. Embodied carbon of the renewable energy system, battery, hot water cylinder, and solar inverter

Embodied carbon (EC) impact has not been considered in the existing Building Regulation Part L (UK Government, 2022). In addition, EC is not yet widely considered in the current government approved building performance assessment method (i.e., SAP) or the whole building environment performance guidance (i.e., BREEAM). However, following the reduction of operational carbon, the embodied carbon, particularly the upfront carbon, would be responsible for half of the total carbon emission in the building sector globally (World-GBC, 2019). It is necessary to explore the embodied carbon performance of the identified renewable energy systems, understanding whether they would pose a carbon risk in a long-term perspective for the building sector.

Environmental Product Declarations (EPDs) are documents that transparently communicate the environmental performance or impact of products and services throughout the lifespan (EPD International, 2022). EPDs are aligned with international and European standards like ISO14040/14044, ISO 14025, EN 15804 or ISO 21930, developing a holistic method to compile, verify and compare life-cycle environmental impacts of products and services. EPDs help architects, engineers, and designers to choose the most sustainable option for their projects. EPDs also guide the building design practitioners towards the best environmental practices recognised by LEED, BREEAM and other equivalent certification bodies. The inventory of carbon and energy (ICE) (Geoffrey. Hammond et al., 2011) suggested general EPD resources and databases like EPD library, (https://www.environdec.com/library) and GreenBook Live (https://www.greenbooklive.com/search/scheme.jsp?id=9). Apart from EPDs, the UK-based whole building carbon benchmark database, RICS Building Carbon Database (https://wlcarbon.rics.org/Secure/MyHomepage.aspx) can also be used to reference the reliable embodied carbon data for the required material and service systems in buildings.

However, such resources and database mentioned above have not included the lifecycle environmental impact for the shortlisted renewable energy systems, battery, hot water cylinder and solar inverters with the MCS recognised brands.

This research then reviewed relevant literature to compile EC data of the systems mentioned above. Figure 3-5 presents the keywords and databases used to compile relevant articles. Table 3-2 shows criteria that are used to screen relevant articles.



Review*: The selected review papers that included any keywords combinations.
Research**: The selected research papers that included any keywords combinations.
Grey literature***: The selected technical reports that included any keywords combinations.

Figure 3-5. Literature review-based method for EC data collection

Table 3-2. Literature review screening criteria

NUMBER OF CRITERIA	DESCRIPTION
1	Written in English only
2	Published review or research articles must be peer-reviewed
3	Grey literature published by the globally recognised professional government-supported organisations, relevant professional non-government organisation (NGOs) or research institutions
4	Research articles published after 2000.

The first criterion is limited to selecting English written articles only for two reasons. Firstly, the author has not been permitted to access the most non-English written data resources without extra charge. Secondly, this research aimed to investigate the performance of the HRES in UK homes, and most of the relevant studies were written in English.

The fourth criterion limits the selected articles published after 2000. Prior to 2000, most studies investigated EC mainly for solar PV but not for other systems. Thus, the fourth criterion enables the consistent study period of the selected EC articles for the shortlisted systems.

Followed the screening criteria in Table 3-2, this research selected 3 review articles, 30 research articles and 2 grey literatures. It then created an EC dataset constituted by the required information from the selected articles. The required information types are defined in the EC dataset, including system types, EC boundaries, EC value, application scale or country, and publication year. The defined information types enable the information listed in the dataset to be transparent and comparable.

The dataset is used to work out the average EC value for each shortlisted system within the same EC boundary and periods from the selected different articles. The average EC value is considered in the environmental performance evaluation.

3.6. Energy cost collection from the representative energy supplier and the associated emission factor

E.ON updated energy plan on 1st April 2022 to align with the increased energy tariff cap. E. ON's website provides an up-to-date energy tariff for domestic buildings in different UK regions (https://www.eonenergy.com/content/dam/eon-energy-com/Files/price-cap/E.ON%20EnergyPlan%20Credit.pdf). Therefore, this section collected the updated energy tariff (unrestricted electricity and standard gas tariff) in South Wales after 1st April 2022 from E. ON's website. The unrestricted electricity tariff applies to those who are not Economy 7/10 users. The reason for not using economy 7 and 10 tariffs is that such tariffs consider a more complex carbon and occupancy behaviour-related issue that is not discussed in this research.

The UK Government GHG conversion factors for company reporting are developed and regularly revised by BEIS (2022). The reporting is a spreadsheet that contains robust greenhouse gas data of different energy sources and electricity grid in each year. The recorded greenhouse gas data has been used by the UK and international organisations to report on annual greenhouse gas emissions. The latest greenhouse gas reporting was revised in January 2022. The revised data can reflect the UK-wide average greenhouse gas condition for natural gas and national electricity grid prior to January 2022.

This research collects the carbon emission factor of the electricity grid from the 'UK electricity' tab in the reporting. It also collects the carbon emission factor of natural gas from the 'fuels' tab in the reporting, unlike the emission factor of electricity that changed significantly due to the mixed energy resource in the electricity generation. The emission factor of natural gas is relatively stable, and the gross calorific value (GCV) is collected and used to represent the emission factor of natural gas. Most organisations typically use GCV to report the carbon emission of natural gas. In addition, most energy bills consider the consumption of natural gas on a GCV basis (BEIS, 2022a).

3.7. Renewable system performance evaluation criteria and indicators selection representative building selection

Subsections 2.4.1 and 2.4.2 reviewed indicators used to evaluate the performance of the on-site renewable system in buildings from the UK building performance guidance, technical manuals, on-site renewable system installation standards and relevant research articles. There are more than 30 indicators have been identified based on the findings from subsections 2.4.1 and 2.4.2. The indicators from the relevant research articles reflect the considerations from the research and policy-makers perspectives in assessing the feasibility of the on-site renewable systems in buildings. However, the indicators used in the UK building performance guidance, technical manuals and on-site renewable system installation standards can reflect the actual need to install the renewable system in UK homes from installers, building assessors and householders' perspectives. This section then creates a method to identify the indicators that can reflect the need for research and decision-makers to evaluate the future policy in using renewable systems in buildings. Meanwhile, such indicators can be used practically to demonstrate the fundamental information in installing renewable systems in UK homes.

The developed method first categories the findings of indicators from subsections 2.4.1 and 2.4.2 into three groups:

- A1: indicators from UK building performance guidance, technical manual and on-site renewable system installation standards (findings from subsection 2.4.1).
- A2: indicators from the relevant research articles (findings from subsection 2.4.2).

Secondly, it compares the indicator from A1 and A2 using the selection criteria presented in Figure 3-6

- Indicators are presented in the UK building performance guidance, technical manual and on-site renewable system installation standards (A1). In addition, the same indicators are presented in the relevant research articles (A2). The decision was made to select such indicators, as they were considered in the research, policymaking and practice of installing renewable systems in buildings. In addition, the selected indicators are aligned with the current UK climate change target and relevant renewable energy policy. As the UK building performance guidance, technical manual and on-site renewable system installation standards are approved by the UK government and comply with the UK energy policy.
- Indicators are presented in the relevant research articles (A2). However, the same indicators need to be presented in the UK building performance guidance, technical manual and on-site renewable system installation standards (A1). The decision was made to reject such indicators, as the indicators were only used in the research and policymaking but might not be suitable to apply in the installation practice in UK buildings. In addition, the indicators might not be suitable to evaluate the on-site renewable systems in UK buildings against the current UK's energy policy and climate change targets.

After the selection process, this section identified 10 indicators that can be used to evaluate the economic-technical-environment performance of the on-site renewable systems in UK homes. The identified indicators are presented in Table 3-3.

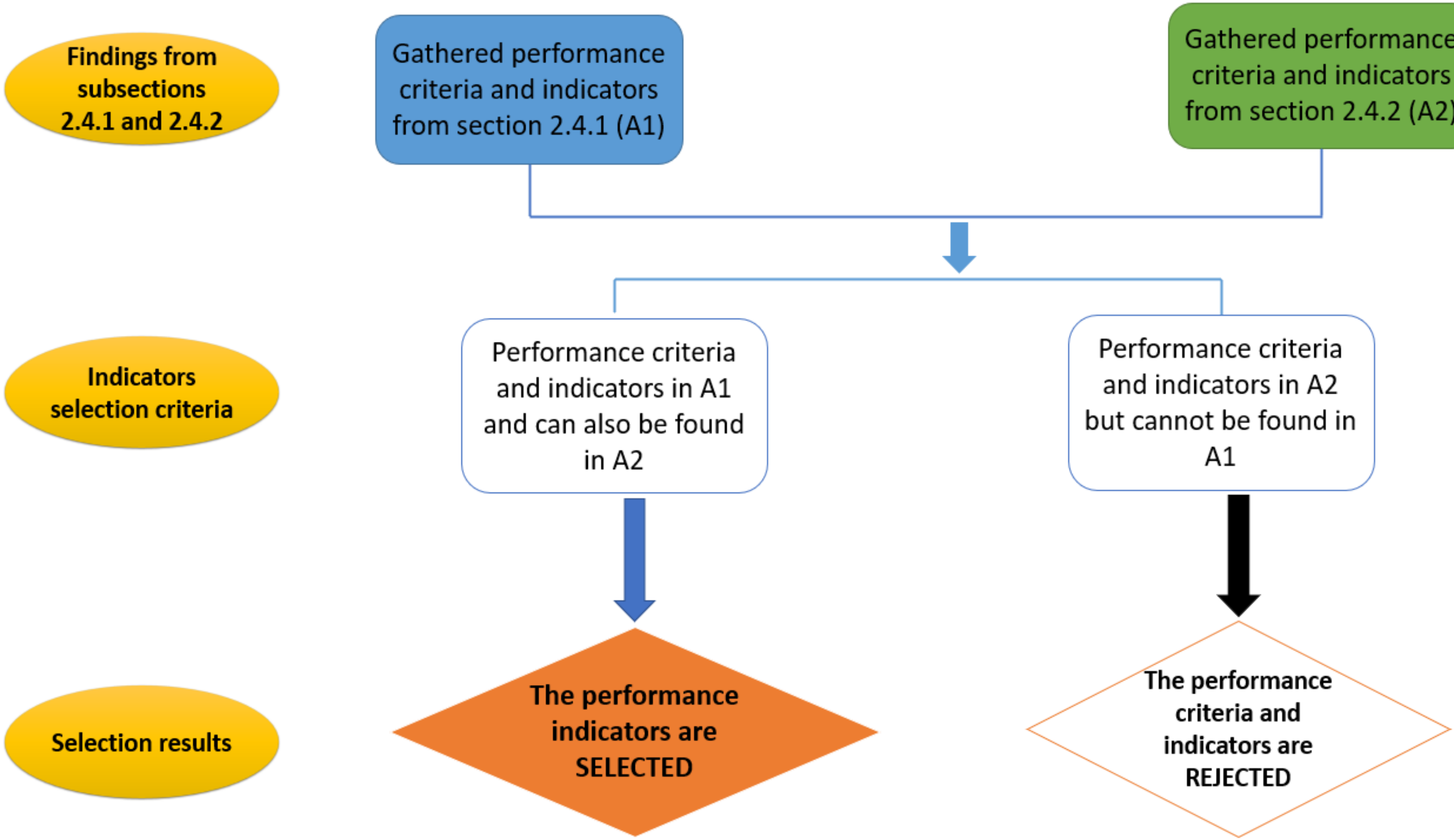


Figure 3-6. Indicators selection method to identify the potential HRES performance evaluation indicators

Table 3-3 The identified performance evaluation indicators

Indicator category	Indicator	Definition	Expression
Economic	Benefit-Cost Ratio (BCR)	It is a ratio to summarise the relationship between the overall costs and benefits of renewable systems. BCR equals or greater than 1.0 indicates renewable systems are expected to deliver a positive net present value within the defined lifespan. (Chekwube Okonkwo et al., 2017; Kristiawan et al., 2018; Sommerfeldt & Madani, 2017)	$BCR = \frac{Net\ present\ benefits}{Net\ present\ costs}$
Economic	Capital Cost (C_{cap})	It is the total cost needed to bring renewable systems to the operable status. It includes the cost of renewable products (C_{pro}) and the relevant installation cost (C_{ins}). (Fitó et al., 2021; Jahangir et al., 2021)	$C_{cap} = C_{pro} + C_{ins}$
Economic	Discounted Payback Period (DPP)	It is the number of years it takes to break even from undertaking the capital cost by discounting future cash flows and recognising the time value of money. The discounted rate 3.5% (HM Treasury 2020) is used to carry out the calculation.(Zhou & Cao, 2020)	$DPP = Net\ present\ benefits - C_{cap} = 0$
Economic	Life Cycle Cost (LCC)	The overall cost includes the capital (C_{cap}) and operational costs ($c_{operational}$) of using the specific renewable system throughout the lifespan. The operational cost consists of the maintenance cost.	$LCC = C_{cap} + c_{operational}$
Technical	Grid Electricity Independence level (GEI)	It demonstrates the percentage of the generated electricity by the renewable system towards the electricity demand. $E_{cover\ demand}$ refers to the generated electricity to cover the electricity demand. $E_{overall}$ is the electricity demand. (MCS, 2020a)	GEI = $\frac{E_{cover\ demand}}{E_{overall}}$
Technical	LifeSpan	It describes the years that existing commercially available renewable systems work in a standard condition. (Jahangir et al., 2021)	NA
Technical	Primary energy consumption	The consumed energy from the electricity grid and natural gas pipeline. (Jahangir et al., 2021)	NA
Technical	Renewable Fraction (RF)	It measures the proportion of renewable energy in the whole building energy supply process. (Jahangir et al., 2021)	RF = $1 - (\frac{Energy\ from\ non-renewables}{Energy\ from\ renewables})$
Environmental	Embodied Carbon Payback Period (ECPP)	It calculates the number of years of saved CO2 emissions at the operation stage to cover the embodied carbon of the specified renewable systems. (BRE, 2016b; Ma et al., 2018)	ECPP $= \frac{Saved\ operational\ carbon}{Embodied\ Carbon}$
Environmental	GHG emission at operational stage	CO2 emission calculated from the electricity grid and natural gas pipeline. (BRE, 2016b; Chekwube Okonkwo et al., 2017)	NA

3.8. Building modelling

This section explains the method for the as-built and retrofitted models of the selected representative domestic building. The as-built building model is used to verify the validity of the adopted modelling method. Once the as-built building model is validated, the same method would be used to create the retrofitted building model. Thus, the simulated energy demand of the retrofitted building model could reflect the actual energy consumption condition of the selected representative domestic building. The retrofitted building model (EPC band at C) is compliant with the planned net-zero strategy to better adapt to various future energy supply scenarios. This section comprises three subsections:

Subsections 3.8.1 explains the method used to model DHW, electrical appliances, space heating and lighting consumption in the as-built model. The method for modelling the DHW and electrical appliance is based on the SAP (UK Government, 2013a). It also explains the method used to model space heating and lighting consumption of the as-built in DesignBuilder. The associate energy consumption is simulated in EnergyPlus under the historical Cardiff meteorological data. The modelling method is based on the domestic building survey results in Wales and England (UK Government, 2021a; Welsh Government, 2019b), and the planned strategy on the pathway towards net-zero (CCC, 2016). The reasons of selecting EnergyPlus to simulate the energy demand are:

- EnergyPlus is one of the most robust energy simulation software available at both academic and commercial levels (Office of Energy Efficiency & Renewable Energy, 2014).
- EnergyPlus has been tested against the IEA BESTest building load and HVAC tests. The testing results demonstrated EnergyPlus is a reliable software to simulate the energy demand of the buildings (Office of Energy Efficiency & Renewable Energy, 2014).
- The information from the created building models in DesignBuilder can entirely feed into EnergyPlus without losing data.

Subsection 3.8.2 explains the method based on The American Society of Heating, Refrigerating and Air-Conditioning Engineers Guideline (ASHRAE, 2002) to validate as-built building model. Once the method to create the as-built building model has been validated as effective. The modelling method is then used to develop retrofit model that explains in subsection 3.8.3.

Subsection 3.8.3 explains the method to model the associated energy demand in the retrofitted building model. The new modelling method was modified based on the validated effective as-built model.

3.8.1. Energy demand modelling in the as-built model

3.8.1.1. DHW and electrical appliances modelling

The UK government adopts the SAP method to support the generation of EPC certificates. In addition, SAP created equations to calculate the general consumption of DHW and electrical appliances based on the historically monitored energy consumption data from UK homes. The developed equations can reflect the general consumption of the DHW and electrical appliances for the specific building by using the relevant number of occupants and overall floor area. Therefore, the SAP method is adopted to simulate the consumption of DHW and electrical appliances in the selected home.

Unlike the energy consumption for space heating, the DHW and electrical appliances calculation considers the number of occupants and floor area instead of the U-value and air tightness. Therefore, the method explained in the following is used to calculate the energy consumption for DHW and electrical appliances in both as-built and retrofitted building model.

The annual average hot water usage ($V_{DHW,average}$) is based on the assumed two-occupants scenario is calculated through Eq. (1).

$$V_{DHW,average} = (25 \times N) + 36 \qquad \text{Eq. (1)}$$

Where, $V_{DHW,average}$ is the annual average hot water usage in litres per day.

The hot water usage in litres per day for each month ($V_{d,m}$) is calculated through Eq. (2)

$$V_{d,m} = V_{DHW,average} \times f_{usage} \qquad \text{Eq. (2)}$$

Where, f_{usage} is the usage factor and it can be found in Table 3-4.

Then, the annually consumed energy to supply the calculated monthly hot water usage in litres is calculated through Eq. (3)

$$E_{DHW} = {}^{4.18 \times V_{d,m} \times n_m \times \Delta T_m}/_{3600} \qquad \text{Eq. (3)}$$

Where, n_m is the number of days for each month. ΔT_m is the temperature rise for each month (shown in Table 3-5).

Table 3-4. Monthly DHW usage factors, table reproduced from UK Government (2013a)

Jan	Feb	Mar	Apr	May	Jun	July	Aug	Sep	Oct	Nov	Dec	Annual
1.1	1.06	1.02	0.98	0.94	0.9	0.9	0.94	0.98	1.02	1.06	1.10	1.00

Table 3-5. Temperature rises of hot water drawn off (in K), table reproduced from UK Government (2013a)

Jan	Feb	Mar	Apr	May	Jun	July	Aug	Sep	Oct	Nov	Dec	Annual
41.2	41.4	40.1	37.6	36.4	33.9	30.4	33.4	33.5	36.3	39.4	39.9	37.0

Energy Saving Trust (2008) compared the data in Table 3-4 and Table 3-5 against the monitored data from 112 UK domestic buildings. Energy Saving Trust (2008) verified that the usage factors listed in Table 3-4 can reflect the actual DHW usage in domestic buildings. It then confirmed that the data in Table 3-5 can meet the actual DHW usage scenario, with the supply cold water at about 15.3 Celsius and delivery temperature at about 52.2 Celsius in average across UK homes.

This study created a spreadsheet based on the method mentioned above to calculate hot water demand. The spreadsheet only needs users to type the number of occupants and the total floor area as the inputs. The spreadsheet can then automatically calculate the overall energy consumption for the domestic hot water based on the user-provided inputs.

The electricity consumption of the electrical appliances used in the representative domestic building is calculated through Eq. (4) (UK Government, 2013a).

$$E_A = 207.8 \times (TFN \times N)^{0.4714} \qquad \text{Eq. (4)}$$

Where, E_A is the energy consumption of electrical appliances. TFN is the total floor area. N is the number of occupants.

This research created a separate spreadsheet to calculate the electricity demand of the electrical appliances based on Eq. (4). Like the spreadsheet used to calculate domestic hot water demand, only the number of occupants and total floor area are required as inputs to calculate the electricity demand of the electrical appliances.

3.8.1.2. Space heating and lighting modelling

In the modelling of space heating and lighting in as-built building model, the building material type is referenced from the EPC website (UK Government, 2022b) with the postcode of the selected domestic building. The EPC website recorded the pre-retrofit material information of the selected representative domestic building. Once the building material type has been identified from the EPC website. The relevant U-value of such identified material types were then cross-referenced against Appendix S of SAP (UK Government, 2013a).

This research assumed a condensing combi boiler was installed to supply space heating, as more than half of UK homes have condensing combi boilers (Welsh Government, 2019b) and (UK Government, 2021a) . The boiler efficiency was set as 92% in the building model based on findings on SEDBUK (2022) where reported condensing combi boilers have a running efficiency from 92%-94%. A lower bound efficiency was used to set boiler efficiency that could reflect a general and basic condensing combi boiler application scenario. The heating flow temperature was set as 75°C for two reasons. First, 75 °C helps to achieve the best setting for a modern condensing combi boiler (Boilerbooker, 2022). Secondly, model is based on an older home which has poorer insulation property. Low-temperature heating flow (like 35 to 55 °C) would struggle to achieve appropriate indoor thermal comfort in a poorly insulated home. This research used an occupied heating temperature of 21°C for all domestic rooms which complies with the thermal comfort requirements defined in CIBSE Guide A (CIBSE, 2015) and SAP (UK Government, 2013a).

The occupants' active periods were created based on the findings from the energy follow-up survey report (BRE, 2013) and BRE Domestic Energy Model (BREDEM) (BRE, 2015). From these sources, the model assumed that during weekdays the heating system would be running for 2 hours in the morning and 5 hours in the evening. During weekends the heating system would run for 14.5 hours. Occupants are active for 15 hours in the home over the weekend, but the survey results (BRE, 2013) found that the heating system would generally run 14.5 hours in existing homes. Thus, this research assumed that occupants would turn off the heating system half an hour earlier before sleeping on weekends (at 10.30pm, as most occupants go to sleep at 11pm). Table 3-6 presents the heating system operation schedule that modified with the energy follow-up survey report.

Table 3-6. Heating operation timetable

Heating system operation times (times/day)	Weekday/Weekends & Holidays	Operation hours
Twice a day	Weekday	7.00 -9.00 am and 4.00 - 10.00 pm
Once a day	Weekends & Holidays	8.00 am - 10.30 pm

DesignBuilder is enabled to reflect the changing outdoor environment when simulating lighting consumption. The required indoor illuminance of each room is referenced from CIBSE Guide A (CIBSE, 2015). The illuminance is set at 300 lux for the living room and 150 lux for the kitchen and bathroom. The lowest illuminance at 100 lux is set for the bedrooms and landings.

After setting up the model in DesignBuilder, the simulation is carried out using EnergyPlus. This enables calculation of lighting demand, space heating demand and the associated primary energy consumption (e.g., natural gas and electricity from the grid).

3.8.1.3. Historical meteorological data for the energy demand simulation

This research uses the historical meteorological data of the testing locations from the PVGIS-SARAH database (EU Science Hub, 2020) to run the building energy simulation in EnergyPlus. The reasons of selecting the PVGIS-SARAH database are:

1) PVGIS-SARAH has good coverage of the historical meteorological data in UK cities.
2) PVGIS-SARAH stored at least ten years of historical meteorological data of many UK cities. Typically, the recorded historical data from 2006 to 2015.
3) PVGIS-SARAH database uses geostationary satellites data combined with some complicated mathematical functions to consider uncertainties relating to atmospheric water vapour, dust, particles, and ozone to compute climate data at ground level to a specific location (EU Science Hub, 2020). The accuracy of the satellite method is generally good, and it is only limited by lack of coverage of polar areas (EU Science Hub, 2020). However, the limitation of the satellite method does not affect this investigation.
4) PVGIS-SARAH is free to access, providing various meteorological data formats (e.g., CSV, json, and epw) to download. The epw format meteorological data

can be directly imported to EnergyPlus as the weather data file to run the building simulation of the representative domestic building.

This research created a weather datafile for the simulation by averaging across the years of data available at the location. This was done by downloading the latest available ten years' (between 2005 and 2016) typical meteorological year period (TMY) of the specific location from the PVGIS-SARAH database. The resolution of the downloaded TMY data for the specific location is 60 minutes in each year. The same resolution was maintained to calculate the average TMY data (between 2005 and 2016) for the selected location-Cardiff. The calculated average TMY data was then imported into EnergyPlus as the weather file to run the building simulation in Cardiff.

3.8.2. Effectiveness validation of the building modelling method

This section explained the approach to validate the effectiveness of the building modelling method used to create as-built and retrofitted building models. After the effectiveness assessment, the validated building modelling method ensures the simulated energy usage can reflect the actual energy consumption condition.

The American Society of Heating, Refrigerating and Air-Conditioning Engineers Guideline (ASHRAE, 2002) created an approach to assess the effectiveness of the building modelling method. The assessment approach considers the selected building model or modelling method is effective when the performance gap between the building model and the monitored data is less than 15% in coefficient of variation (CV) value. The used CV equation is shown in Eq. (5).

$$CV = \frac{\sqrt{\frac{\sum_{i=1}^{N}(E_{simulated} - E_{monitored})^2}{N}}}{\overline{E_{simulated}}} \qquad \text{Eq. (5)}$$

Where, $E_{simulated}$ is the simulated energy data of the selected representative domestic building. $E_{monitored}$ is the monitored energy data of the region where the selected building located. $\overline{E_{simulated}}$ is the average simulated energy data.

There is no recorded monitoring energy data for the selected representative domestic building after the retrofitting work. However, the sub-national electricity and natural gas database stored the regional monitoring energy data for the selected domestic building prior to the retrofitting. The sub-national electricity and natural gas database was created and updated by BEIS, and it was initially available for public access in 2013 (UK Government, 2013b). The database updates annually; the latest available data is 2020. The selected representative domestic building was entirely retrofitted by 2020 to EPC band at C based on the recorded data on EPC website. Therefore, the energy data from the sub-national database between 2013 and 2019 are used to validate the effectiveness of the building modelling method for the as-built building model. The calculated average energy data between 2013 and 2019 can avoid data inconsistency caused by occupants' energy usage behaviour and ongoing retrofitting works. The average energy data can also reduce the impact of the yearly meteorological data changes.

The simulated energy demand of the created as-built building model (described in section 3.9.1) was compared with the calculated average energy data from the sub-national database between 2013 and 2019 and the variance assessed using ASHRAE's effectiveness calculation (Eq. 5). As long as the variance is less than 15% in CV value, the building modelling method is considered effective, and can be used to develop the retrofitted building model.

3.8.3. Energy demand modelling in the retrofitted building model

Once the modelling method in the as-built building model has been validated as effective. The modelling method is then modified to model energy demand in the retrofitted building model. The modification process explains in the following.

The modelling method for the DHW and electrical appliance energy consumption is the same as explained in 3.9.1.1. The modelling method was based on the floor area and number of occupants in the selected representative domestic building. Such factors remain the same in the retrofitted building model.

However, the modelling method for space heating and lighting consumption needs modifications due to the building materials and U-values were updated after the retrofit. The retrofitted building materials are found on the EPC websites (UK Government, 2022b) and the associated U-values were referenced from Appendix S of SAP (UK Government, 2013a). The reduced U-value enables low-temperature heating flow (55 ^{o}C) for the heating system, which is reflected in the model. 55 °C flow temperature is compliant with the climate change target (CCC, 2016) and the building regulation Part L (Department for Levelling up, Housing and Communities and Ministry of Housing, Communities and Local Government, 2023). In addition, most existing commercial heat pumps can reach this temperature.

The radiator size remains the same as in the as-built building model. It might be challenging to achieve the required thermal comfort by using the same size radiator running at a low heating flow temperature (55°C) instead of high heating flow temperature (i.e., 75°C). Particularly with a lower heating setback temperature (e.g., 12°C). Therefore, heating setback temperature was defined as 16 °C. This defined temperature enables UK homes to achieve the required thermal comfort temperature 21°C within a reasonable time (e.g., about 1 hour) in the winter period (WarmUp, 2018). In addition, the defined heating setback temperature can prevent the condensation happening in the retrofitted building model.

3.9. HRES sizing scenario development

This section explains the development of scenarios used to size the potential HRES combinations. The developed sizing scenarios are compliant with the decarbonisation plan in the building sector published by CCC (Climate Change Committee) (2016, 2019) and IEA's report (IEA, 2019). The demand coverage percentage (DCP) is used to size the HRES combination that can cover the required energy demand of the specific building at the energy planning stage. The DCPs are aligned with the existing energy transition and decarbonisation plan; the defined DCPs scenarios can better investigate the performance of different HRES combinations along with the agreed climate change targets.

This section explains the sizing scenarios through three subsections:

- Define DCPs based on electricity demand (3.9.1).
- Define DCPs based on heat demand (3.9.2).
- Sizing scenario development based on the defined DCPs (3.9.3).

3.9.1. Defined DCPs based on electricity demand

No relevant report discussed the feasible DCPs of electricity using on-site renewable energy systems in UK domestic buildings. However, several case studies (Sakiliba et al. 2020; Janko et al. 2016; Sharafi et al. 2015) found that using less than 20% of grid electricity can make the annual energy cost more economically viable. This on-site generation reduces electricity imports from the national grid and in turn reduces the regional / national requirements for off-site renewable system development. Such large-scale developments often take up significant land which can now be used for other purposes (e.g., to grow local food). Additionally, this research investigated the performance of the on-site HRES combination that can generate 100% of electricity demand at the energy planning stage. The performance of such on-site HRES combination can reduce the grid's dependence level, helping planners re-evaluate the size of energy generation for the regional or national electricity grid. Therefore, this research defines DCPs as from 80% to 100% of electricity demand should be covered by the on-site renewable energy system.

3.9.2. Define DCPs based on heat demand

This subsection explains the method to create DCPs for space heating and DHW demand. The following reports are used to scope the feasible space heating demand range that existing heat pumps can cover to achieve the UK's climate change targets:

- CCC's reports (2016 & 2019) which indicated that a renewable heating system covering 70-80% of space heating demand in domestic buildings is considered a feasible, cost-effective, and sustainable energy supply strategy.
- IEA's report (IEA, 2019) which identified that most commercially available heat pumps can cover at least 90% of space heating in buildings.

The UK Government plans to replace existing gas boilers with heat pumps or other alternative renewable energy systems as the main heating system (UK government, 2021). Therefore, it is necessary to investigate the performance of the selected renewable systems that can cover 100% of space heating demand at the energy planning stage. In addition, the domestic renewable system installation standards (MCS, 2013a) require the installed renewable system have the capacity to cover the overall required heat demand of the target building. This research then defines DCPs as 100% of heat demand – this is used to size the associated renewable systems in HRES combinations.

In addition, the DCPs for DHW demand is defined as:

- DCPs=100% of DHW demand refers to the overall DHW demand covered by the on-site HRES combinations.

  DCPs=0% of DHW demand refers to the on-site HRES combinations that do not cover DHW demand, and DHW demand is covered by using natural gas.

3.9.3. Sizing scenario development based on the defined DCPs

This subsection uses DCPs that defined in subsection 3.9.1 and 3.9.2 to create different sizing scenarios. The created scenarios are used to size potential HRES combinations and then explore the associated performance.

Based on the defined DCPs in heat and electricity demand, 6 scenarios were created to size HRES combinations. After sizing, such HRES combinations will be analysed using the performance criteria and indicators defined in section 3.8. Table 3-7 presented the developed 6 HRES combinations sizing scenarios.

Table 3-7. The developed sizing scenarios

SCENARIO	DCP OF SPACE HEATING (%)	DCP OF ELECTRICITY (%)	DCP OF DHW (%)
1	100	80	0
2	100	80	100
3	100	90	0
4	100	90	100
5	100	100	0
6	100	100	100

3.10. HRES energy generation spreadsheet development

This section explains the calculation method used to compute the energy generation of each individual renewable energy system in the potential HRES combinations. The method is based on MCS installation standards (MCS, 2013c, 2013a, 2020) and SAP(UK Government, 2013a). The method is embedded in the spreadsheet requiring simple inputs (e.g., local annual solar radiation, energy demand, heating operation time etc.) to calculate the energy generation.

This section is constituted by five sub-sections,

- Solar PV energy generation calculation method (3.10.1)
- STC energy generation calculation method (3.10.2)
- GSHP and ASHP energy generation calculation method (3.10.3)
- Sizing and energy generation (3.10.4)
- Energy supply-demand balance calculation method (3.10.5)

3.10.1. Solar PV

The simplified electricity generation calculation approach (shown in Eq. (6)) is based on SAP (UK Government, 2013a) and MGD-003 (MCS, 2021).

$$Q_{PV} = A_{PV} \times r \times PR \times H \qquad \text{Eq. (6)}$$

Where, A_{PV} is the solar cell area, r is the average PV efficiency (calculated from data on commercial PV products), PR is the performance ratio. In this study, PR is 0.75 (the suggested factor by IEA and NREL for rooftop PV). H is the annual solar radiation

3.10.2. STC

The energy calculation approach for STC is compliant with SAP (2012) and MCS 024 (2013). The energy calculation approach is used to calculate energy generation for a glazed, flat-plate STC. The general zero-loss collector efficiency (η_0=0.75) and the ratio of aperture area to gross area ($R_{area} = 0.9$) are found in SAP (UK Government, 2013a). Zero-loss collector efficiency is the proportion of incident solar radiation absorbed in the absence of thermal loss. None or very little overshading factor ($f_{overshading} = 1.0$) is defined (UK Government, 2013a). The domestic hot water (DHW) in this research including the hot water and shower demand of the selected representative domestic building. Equations 7 to 11 are used to work out the energy generation of STC.

Firstly, it calculates the available solar energy ($E_{solar\ energy\ available}$)

$$E_{solar\ energy\ available} = A_{aperture} \times \eta_0 \times H \times f_{overshading}$$

Eq. (7)

Where, $A_{aperture} = A_{gross} \times 0.9$. H is the annual overall solar radiation of the selected location.

The collector performance factor (f_1) is calculated using Eq. (8).

$$f_1 = 0.97 - 0.0367 \times collector\ performance\ ratio + 0.0006 \times (collector\ performance\ ratio)^2$$

Eq. (8)

Where, collector performance ratio is the ratio between the second order heat loss coefficient of the collector and zero-loss collector efficiency (η_0). The second order heat loss coefficient of the flat plate collector is defined as 6 in SAP (UK Government, 2013a).

A dedicated solar storage volume (V_s) refers to the volume of water that only the solar input can heat. The hot water association (2009) defined two approaches to work out the dedicated solar volume to align with the Building Regulation Part L (UK Government, 2022a). The first approach uses a minimum of 25 litres of V_s per square metre of the net panel area, and this approach has been regarded as the most efficient. The second approach calculates V_s based on 80% of the hot water usage. The hot water usage is calculated through the SAP (UK Government, 2013a) method.

This study applies the first approach to carry out V_s. The V_s for selected representative domestic building is about 50-100L. Hot Water Association (2009) defines the accumulated floor area between 50 and 70 m^2 need the STC panel net area of 2 and 3 m^2. The chosen representative domestic building is 67 m^2, and the required STC panel net area is between 2 and 3 m^2. V_s should at least meet the requirement of 25L per STC panel net area. Therefore, based on the collected STC technical data, V_s for the presentative domestic building should be at least 60L.

Once the dedicated solar volume is calculated, the effective solar volume (V_{eff}) is calculated through Eq. (9).

$$V_{eff} = V_s + 0.3 \times (V_d - V_s) \quad \text{Eq. (9)}$$

Where, V_s is the dedicated solar storage volume; V_d is the total volume of cylinder. Then, the solar storage volume factor (f_2) is calculated through Eq. (10).

$$f_2 = 1 + 0.2 \times \ln\left(\frac{V_{eff}}{V_{d,average}}\right) \quad \text{Eq. (10)}$$

Where, f_2 must less than 1.0; $V_{d,average}$ is the daily average DHW of the selected representative building.

Finally, the annual generated DHW (Q_{STC}) by STC is calculated in Eq. (11).

$$Q_{STC} = E_{solar\ energy\ available} \times f_1 \times f_2 \quad \text{Eq. (11)}$$

3.10.3. GSHP and ASHP

The energy generation calculation method is created based on the MIS-3005 (MCS, 2013b) where the method is used to size of heat pumps to cover 100% required heat demand. The generated heat load (Q_{HP}) from the heat pumps is calculated through Eq. (12).

$$Q_{HP} = Capacity_{HP} \times D_{heating} \times H_{heating} \quad \text{Eq. (12)}$$

Where, $Capacity_{HP}$ is the commercially available size of heat pumps that can provide the required heat demand. $D_{heating}$ stands for the heating days in a year and $H_{heating}$ refers to the typical daily heating hours. This research considers using GSHP/ASHP to cover the heating period (from October to March) that defined in BRE (2013). Therefore, $D_{heating}$=182. The weekday heating operation hours defined in BRE's report (BRE, 2013) are used as the typical daily heating hours ($H_{heating}$). Thus, $H_{heating} = 7$.

Heat pumps need electricity to run; so, the electricity consumption associated with the generated heat load must be calculated. Eq. (13) is used to compute the electricity consumption (P_{SH}).

$$P_{SH} = \frac{Capacity_{HP}}{SCOP} \qquad \text{Eq. (13)}$$

Where, $SCOP$ is the seasonal coefficient of performance of the selected heat pump.

3.10.4. Sizing and energy generation

Having determined the defined scenarios, the next steps are to size the technology for the representative home and identify appropriate commercially available technologies. The Q_{PV} is used as the required electricity demand of the selected representative domestic building under the associated sizing scenario. The required electricity demand is calculated using the simulated annual electricity demand to multiply the required DCP of electricity in the associated sizing scenario. For example, sizing scenario 1 requires the HRES combination to cover 80% of the simulated electricity demand (3000kWh/year). Therefore, $The\ required\ electricity\ demand = 3000 \times 80\% = 2400kWh/year$. Once Q_{PV} is calculated, the required solar cell area can be calculated through Eq. (6). This research considers that the typical solar cell area in a panel is 1.7m^2. The typical solar cell area is based on a 320W solar PV panel which is the standard configuration of the mono-crystalline PV panel. It then uses the calculated solar cell area to divide by the typical cell area (1.7 m^2) to determine the required number of 320W solar PV panels. If the calculated 320W solar PV panel is not a whole number, it needs to round up to the nearest whole number. For example, if the calculated required number of 320W solar PV panels is 6.4, it needs to round to 7 of 320W solar PV panels. The nearest bigger whole number enables the calculated PV configuration can generate sufficient electricity to meet the demand.

In the sizing of STC, $E_{solar\ energy\ available}$ is used as the required DHW demand of the selected representative domestic building under the relevant sizing scenario. For example, the simulated DHW demand is 1600kWh/year, in the associated sizing scenario that requires the on-site HRES should cover 100% of the simulated DHW demand. Thus, $E_{solar\ energy\ available} = 1600 \times 100\% = 1600kWh/year$. The aperture area of solar STC can then be calculated through Eq. (7). It needs to compare the calculated aperture area with the aperture area of the compiled commercially available STC. The nearest bigger aperture area of the compiled commercially available STC is selected to compute the generated energy, enabling the selected STC configuration to meet the required DHW demand.

The generated heat load (Q_{HP}) is used as the required space heating demand of the selected representative domestic building under the associated sizing scenario. The required space heating demand is calculated using the simulated space heating demand of the representative domestic building to multiply the DCPs of heat demand in the associated sizing scenario. For example, in sizing scenario one, the DCPs of heat demand is 100%, the simulated heating demand is 6000kWh/year. Then, the required space heating demand is $6000 \times 100\% = 4200kWh/year$. Once the required space heating demand has been calculated, the required capacity of GSHP/ASHP can be calculated through Eq. (12). It then needs to compare the calculated capacity of GSHP/ASHP with the configuration of the compiled commercially available GSHP/ASHP. The nearest bigger configuration of GSHP/ASHP is selected to carry out the energy consumption to ensure the generated heating load can meet the required space heating demand.

The identified size of renewable energy system is aligned with the compiled commercially available renewable energy systems. once renewable energy system size is established, energy generation is calculated using Eq (6) to Eq (12) for each scenario. The GSHP/ASHP needs electricity to generate the heating load, the consumed electricity (Eq (13)) should be added to the simulated electricity demand to form a new electricity demand. The, increased new electricity demand should be used to calculate the required electricity demand under each sizing scenario to size solar PV. For example, the GSHP/ASHP consumed 1500kWh of electricity per year. The simulated electricity of the selected representative domestic building is 3000kWh/year. The new electricity demand is 1500kWh/year + 3000kWh/year=4500kWh/year. The sizing scenario 1 requires DCP of electricity demand is 80%. Therefore, the required electricity demand is $4500 \times 80\% = 3600kWh/year$. The calculated electricity demand of 3600kWh/year should be then used to size solar PV in the HRES combination in sizing scenario.

3.10.5. Energy supply-demand balance calculation method

This subsection explains the method used to work out the energy supply-demand balance based on the calculated sizing of each HRES combination under the defined scenarios. This section explains the energy balance calculation for electricity and heat demand separately. Subsection 3.10.5.1 explains the electricity supply-demand balance calculation. The heat demand includes space heating and DHW, the associated calculation is explained in subsection 3.10.5.2.

3.10.5.1. Electricity supply-demand balance calculation

The electricity demands considered in the supply-demand balance calculation are:

- the simulated monthly lighting and electrical appliances consumption of the selected representative domestic building.
- and the consumed electricity by heat pumps in each HRES combination. The monthly lighting demand is simulated from EnergyPlus.

The monthly consumption of the electrical appliances varies month to month and is calculated based on the method explained in SAP (UK Government, 2013a). The daily electricity consumption by the heat pump is calculated through Eq. (13), the monthly electricity consumption by the heat pump is then calculated using the daily consumption multiplied by heating days in the month. For example, the daily electricity consumption by a 4kW GSHP is 8kWh, then the electricity consumption of using such GSHP to provide space heating in January is $8 \times 31 = 248$kWh. Thus, the monthly electricity demand (non-heating season) is calculated as the monthly lighting and electrical appliance from April to September. The monthly electricity demand (heating season) changes to the monthly lighting, electrical appliance, and the consumed electricity from heat pumps for space heating months (October to March).

The solar PV is the only system for electricity generation in all identified HRES combinations in section 3.2. The monthly generated electricity by solar PV can be calculated through Eq. (16). The PV self-consumption percentage (MCS, 2019) indicates the percentage of the generated electricity by solar PV that can be used to cover electricity demand rather than export to the grid. The PV self-consumption percentage changes along with the configuration (power ratings) of the installed solar PV, the connection of the battery and the annual electricity demand. The PV self-consumption percentage can better reflect the real condition of using the solar PV generated electricity in homes. Hence, this research applies the PV self-consumption percentage (compiled and published by MCS) to the electricity supply-demand balance calculation in Eq. (16). The monthly generated electricity for the electricity demand ($E_{onsite\ demand}$) is calculated through Eq. (16).

$$E_{onsite\ demand} = G_{electricity} \times PV_{self-consumption\ percentage} \quad \text{Eq. (16)}$$

Where, $G_{electricity}$ is the monthly generated electricity by the solar PV.

The monthly generated electricity export to the grid ($E_{export\ to\ the\ grid}$) is then calculated using Eq. (17).

$$E_{export\ to\ the\ grid} = G_{electricity} - E_{onsite\ demand} \quad \text{Eq. (17)}$$

The monthly import electricity from the grid ($E_{import\ from\ the\ grid}$) is calculated using Eq. (18).

$$E_{import\ from\ the\ grid} = E_{onsite\ demand} - D_{electricity} \quad \text{Eq. (18)}$$

Where, $D_{electricity}$ is the overall calculated monthly electricity demand of the selected representative domestic building. Eq. (18) only needs to calculate the imported electricity from the grid when $E_{onsite\ demand} < D_{electricity}$. When $E_{onsite\ demand} > D_{electricity}$, it indicates the monthly generated electricity for the electricity demand can meet the monthly electricity demand. Therefore, this condition does not need to import electricity from the grid.

3.10.5.2. Heat supply-demand balance calculation

Heat demand refers to the selected representative domestic building's overall space heating and DHW demand (section 3.10). Space heating demand is assumed only happens from October to March in this research but varies within the period. DHW usage varies from month to month and is represented by the usage factors in BRE (2013). The supply-demand calculation uses monthly data to address variations in energy usage.

The monthly space heating demand of the selected representative domestic building is generated in the EnergyPlus. The monthly DHW demand is calculated through the identified DHW usage factors in SAP (UK Government, 2013a) and BRE's report (BRE, 2013). The monthly heat supply-demand balance is calculated using Eq. (14).

$$B_{SH\ or\ DHW} = G_{SH\ or\ DHW} - D_{SH\ or\ DHW} \quad \text{Eq. (14)}$$

Where, $B_{SH\ or\ DHW}$ is the monthly heat balance of the supply-demand calculation. $G_{SH\ or\ DHW}$ is the monthly generated space heating or DHW load by HRES combinations. $D_{SH\ or\ DHW}$ is the monthly space heating or DHW demand of the selected representative home. A negative $B_{SH\ or\ DHW}$ indicates the generated monthly space heating or DHW load cannot cover the required monthly associated demand. Therefore, the condensing combi boiler is used to compensate such negative balance via natural gas. The required natural gas is then calculated through Eq. (15).

$$Gas = B_{SH\ or\ DHW} \div 92\% \quad \text{Eq. (15)}$$

Where, 92% is the selected efficiency rate for a typical condensing combi boiler (SEDBUK (Seasonal Efficiency of Domestic Boilers), 2022). For example, $B_{SH\ or\ DHW}$ for the space heating in January is -180kWh, which means the HRES combination in January cannot cover 180kWh of space heating. Therefore, 180kWh space heating demand should be covered by natural gas using the condensing combi boiler. The associated natural gas consumption is kWh.

3.11. Decision-making performance criteria and indicator spreadsheet development

Once the performance indicators have been selected following the method explained in section 3.7, they are classified as decision-making or supporting indicators. The decision-making requirements are:

- The selected performance criteria and indicators have been used in the decision-making process in existing relevant studies.
- The representative performance criteria and indicators have been used in MCS installation standards, which installers should explain to the customer prior to the purchase. For example, the representative performance indicators like the grid independence level, primary energy consumption.

The supporting indicators are used to work out the decision-making indicator at a specific time point. For example, the net present value (NPV) is the difference between the present value of cash inflows and the present value of cash outflows over a period. The NPV value in a specific year is difficult to reflect the financial benefits of different HRES combinations quantitatively or qualitatively compared with other indicators. (E.g., Benefit-cost ratio (BCR). Therefore, NPV is selected as a supporting economic indicator to carry out the decision-making indicator like BCR and lifecycle cost (LCC). Also, like the primary energy consumption indicator, it can be used to support the calculation for several decision-making indicators like; performance of the life cycle cost (LCC), benefit-cost ratio (BCR), renewable fraction, and GHG emission at the operational stage. Such indicators can reflect the performance of the primary energy consumption. Then, the primary energy consumption is used as the supporting indicator.

Based on the selection requirements mentioned above, this research specified 9 different decision-making performance indicators from the economic-technical-environment perspective in this research. The definitions and relevant numerical expressions of each indicator are shown in Table 3-8. The specified decision-making performance indicators and the associated numerical expressions were programmed into three spreadsheets calculating the performance criteria. The obtained performance results of the potential HRES combination in different sizing scenarios were used in the final decision-making process to identify the most optimal HRES for the selected representative domestic building.

Table 3-8 The selected decision-making indicators

Indicator category	Indicator	Definition	Expression
Economic	Benefit-Cost Ratio (BCR)	It is a ratio to summarise the relationship between the overall costs and benefits of renewable systems. BCR equals or greater than 1.0 indicates renewable systems are expected to deliver a positive net present value within the defined lifespan.	$BCR = \frac{Net\ present\ benefits}{Net\ present\ costs}$
Economic	Capital Cost (C_{cap})	It is the total cost needed to bring renewable systems to the operable status. It includes the cost of renewable products (C_{pro}) and the relevant installation cost (C_{ins}).	$C_{cap} = C_{pro} + C_{ins}$
Economic	Discounted Payback Period (DPP)	It is the number of years it takes to break even from undertaking the capital cost by discounting future cash flows and recognising the time value of money. The discounted rate 3.5% (HM Treasury 2020) is used to carry out the calculation.	$DPP = Net\ present\ benefits - C_{cap}$=0
Economic	Lifecycle Cost (LCC)	The overall cost includes the capital and operational costs of using the specific renewable system throughout the lifespan. The operational cost consists of the maintenance cost.	$LCC = C_{cap} + c_{operational}$
Technical	Grid Electricity Independence level (GEI)	It demonstrates the percentage of the generated electricity by the renewable system towards the electricity demand. $E_{cover\ demand}$ refers to the generated electricity to cover the electricity demand. $E_{overall}$ is the electricity demand.	GEI = $\frac{E_{cover\ demand}}{E_{overall}}$
Technical	LifeSpan	It describes the years that existing commercially available renewable systems work in a standard condition.	NA
Technical	Renewable Fraction (RF)	It measures the proportion of renewable energy in the whole building energy supply process.	RF = 1 − $(\frac{Energy\ from\ non-renewables}{Energy\ from\ renewables})$
Environmental	Embodied Carbon Payback Period (ECPP)	It calculates the number of years of saved CO2 emissions at the operation stage to cover the embodied carbon of the specified renewable systems.	ECPP =$\frac{Saved\ operational\ carbon}{Embodied\ Carbon}$
Environmental	GHG emission at the operational stage	The energy from the national grid or natural gas is used to compensate for the demand that on-site renewable systems cannot cover. The annual GHG emission is calculated using the portion of energy imported from the national grid or natural gas multiplied by the associated carbon emission factor.	$GHG = (D_{demand} - E_{RE}) * carbon\ emission\ factor$

3.12. Decision-making performance criteria and indicator weighting

This section explains the method to define the weighting of the decision-making performance criteria and indicators based on the surveyed viewpoints of the England and Wales representative householders. Section 3.12.1 explains the questionnaire development. Section 3.12.2 explains the approaches to achieve the required number of responses from the representative householders in England and Wales. Section 3.12.3 explains the method used to convert the viewpoints of representative householders to numerical weightings of performance indicators using the Analytical Hierarchy Process (AHP) method (Raju Meesariganda & Ishizaka, 2017).

3.12.1. Questionnaire development

The questionnaire was developed to understand the representative householders' perspectives of adopting renewable systems to combat climate change. It is also used to incorporate householders' preferences as a weighting for the decision-making performance criteria and indicators. It was estimated that the questionnaire would take 10-15 mins to complete. The survey was developed on Google Forms.

The questionnaire comprises three sections of questions:

First section: demographic questions relating to the householders and their home. The questions are designed to understand the basic information of house location, housing type and stock condition of the respondents.

Second section: the renewable system-related questions are related to motivations or barriers to adopting the renewable energy system. If respondents have already installed the renewable energy system in their homes, they are encouraged to relate to the motivations for adopting the renewable energy system. The respondents are also asked about their satisfaction with current renewable energy systems in their homes.

And the third section: the preference questions, ask the respondents to rate each decision-making indicator from number 1 to number 5, reflecting their preferences towards each indicator prior to installing renewable energy systems in their homes. The definitions of the rating numbers are explained in the following.

- Number 1 indicates least preferred.
- Number 2 indicates no preferred.
- Number 3 indicates less preferred.
- Number 4 indicates preferred.

- Number 5 indicates the most preferred

This research initially received approval to conduct the questionnaire from the ethics committee of the Welsh School of Architecture in April 2021. Two non-substantial amendments (in January and May 2022) were approved. The approval number is No.2116.

3.12.2. Surveying representative householders in England and Wales

Representative cities in England and Wales were required for the survey and a representative number of survey respondents are required from each city. This section describes how the cities were chosen and the required respondent number calculated.

Primary urban area (PUA) is normally used to define the urban area of UK cities. It is then used as the basis to select the representative cities in England and Wales where carrying out questionnaires. Cardiff has the largest PUA in Wales. Although London has the largest PUA in England, it was not selected because house types differ in London compared with other English cities. Birmingham has the second largest PUA in England; it was then selected as the representative English city instead.

The number of respondents required is based on the population of the selected cities using the simplified formula for proportions (Yamane, 1967) presented in Eq. (19).

$$n = {N'}/{(1 + N(e)^2)} \qquad \text{Eq. (19)}$$

Where, N' is the total number of existing homes in the city. e is confidence interval from 3-10% while using 95% as the confidence level, and this research uses e=10% to reduce the sample size. The number of existing homes (N1) in Cardiff is 151200 in 2019 (Welsh Government, 2019a). The number of existing homes (N2) in Birmingham is 434190 in the city (Miller and Rodger, 2017).

The number of surveys which need to be issued is based on the calculated sample size (n) and the expected response rate. The expected response rate for the online survey is between 10% and 30% (Cleave, 2020; Lindemann, 2021). Using an expected response rate of 20% the required number of questionnaires (A) was calculated through Eq. (20).

$$A = {n}/{expected\ response\ rate} \qquad \text{Eq. (20)}$$

The survey was piloted by sending 20 questionnaires to householders living in Wales, South-West England, Southern England, East and North-East England. The purpose of the pilot was to find any issues (e.g. question which needed clarification). The pilot questionnaire was conducted between February and March 2022.

After the pilot questionnaire, this research used three approaches to carry out questionnaires to a broad spectrum of householders living in Cardiff and Birmingham:

- Social network: this approach sent questionnaires to a householders in Cardiff and Birmingham using social apps (i.e., Facebook, WhatsApp).
- Letter posting: this approach posted questionnaire letter to the identified householders. The posted questionnaire letter explained the purpose of the questionnaire. The letter had a QR code to access the online questionnaire, with the explanation to guide householders of using QR code to participate in the online questionnaire.

  To ensure that letters were sent to representative householders, the following process was followed (illustrated in Figure 3-7).
  - The information (i.e., street name, postcode) of existing homes with installed renewable energy systems in Cardiff and Birmingham was obtained from the EPC database then mapped on My GoogleMap.
  - Streets where existing homes had installed renewable energy systems were identified from My GoogleMap.
  - Once the street has been identified, homes on the street were randomly selected through the GoogleMap. This ensured equal the numbers of selected existing homes with or without renewable energy systems to avoid bias.
- In-person contacting: Due to the lower than expected response rate from the letter posting approach (9%) an in-person contacting approach was adopted. This involved directly contacting representative householders and asking if they were willing to complete the questionnaire. The same method as for letter posting was used to identify representative householders (Figure 3-7). The in-person approach boosted the response rate to the expected level of about 20%.

After trying different survey approaches, the response rate in Birmingham is still low (response rate is lower than 3%) and not close to the number in Cardiff. In addition, the author has limited time travelling from Cardiff (the research-based in Welsh School of Architecture, Cardiff University) to Birmingham. Therefore, this research selects Bristol as the alternative representative English city. Bristol is close to Cardiff and has a big PUA in south England. The in-person contacting approach was used to survey householders in Bristol.

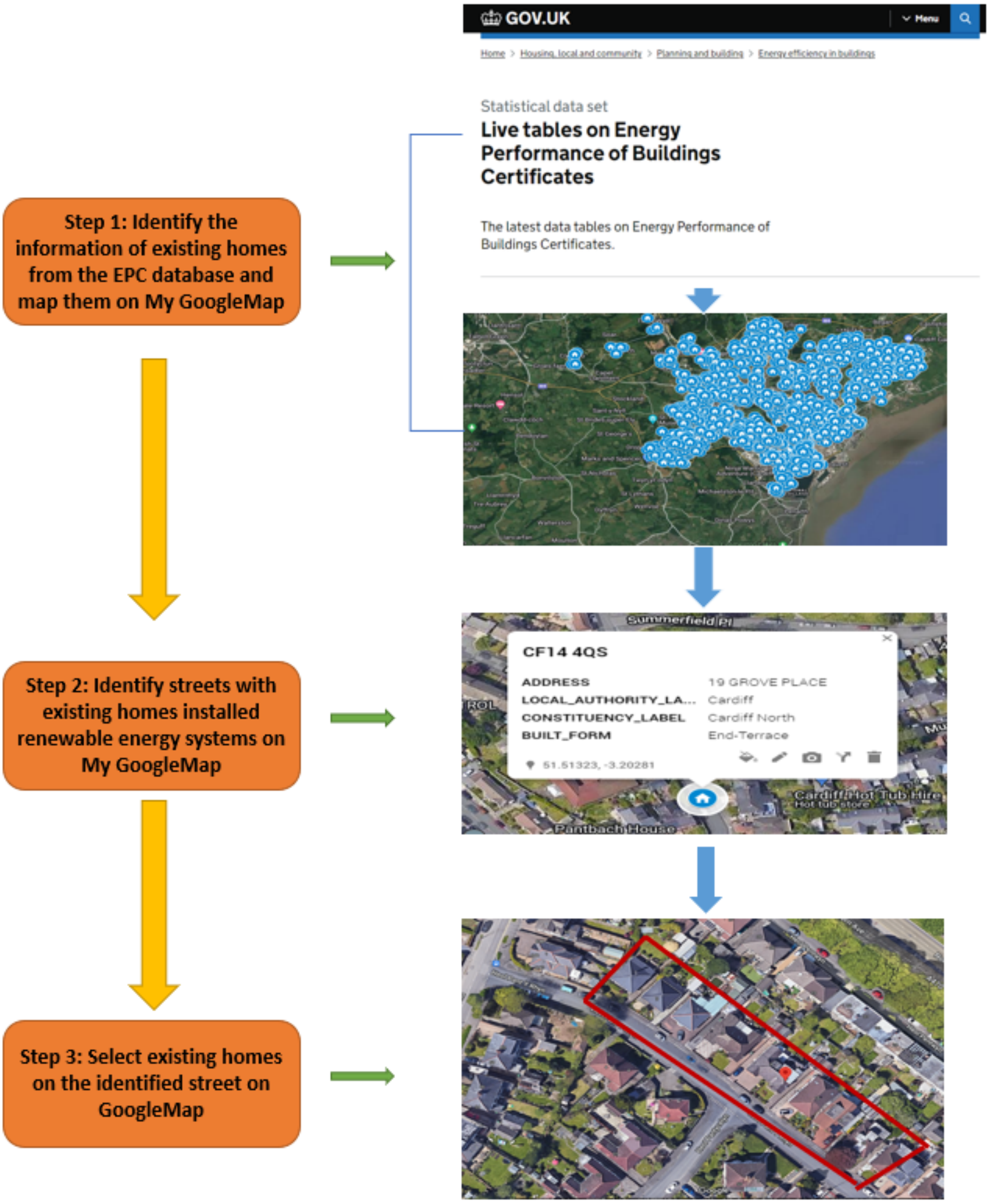


Figure 3-7. The method to identify the representative householders

3.12.3. Decision-making indicators weighting process

After collecting preferences from the representative householders in Cardiff and Bristol, the next step is to convert the preferences to weightings for each specified decision-making indicator. The weighting process should be based on each householder's preference response towards the specified decision-making indicators. The Google Form allows checking each respondent's response and the summary of overall preference responses towards the specified decision-making criteria and indicators. The developed approach is illustrated in Figure 3-8.

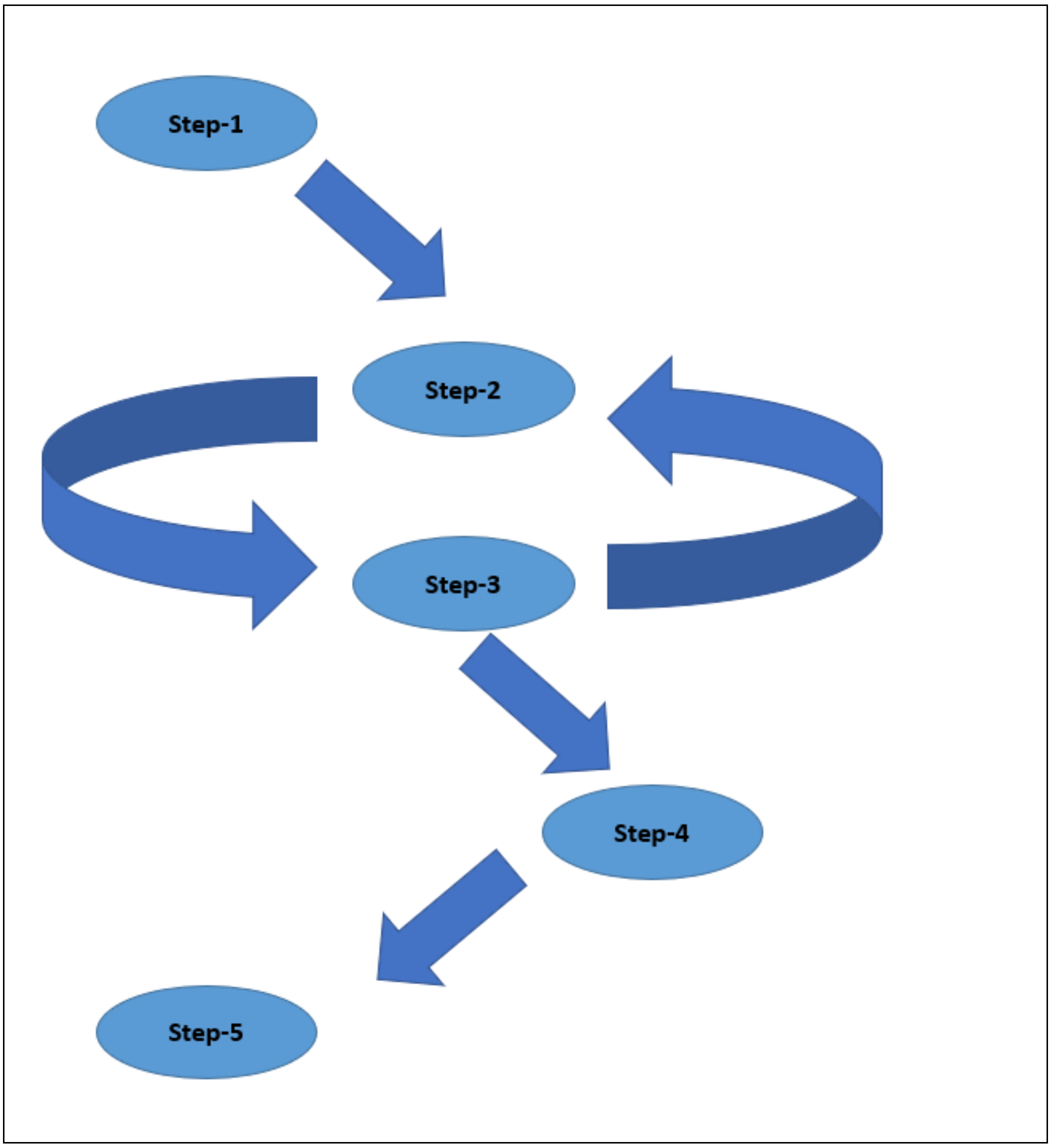


Figure 3-8. Weighting approach for the decision-making criteria & indicators

The weighting approach is used first to calculate the weights based on each respondent's preference value for the economic-technical-environment criteria. Then, the approach is used again to calculate the weights for the selected indicators under the specified criterion based on the collected preference value from householders. Figure 3-9 presents the hierarchy to calculate the weights for the criteria and indicators.

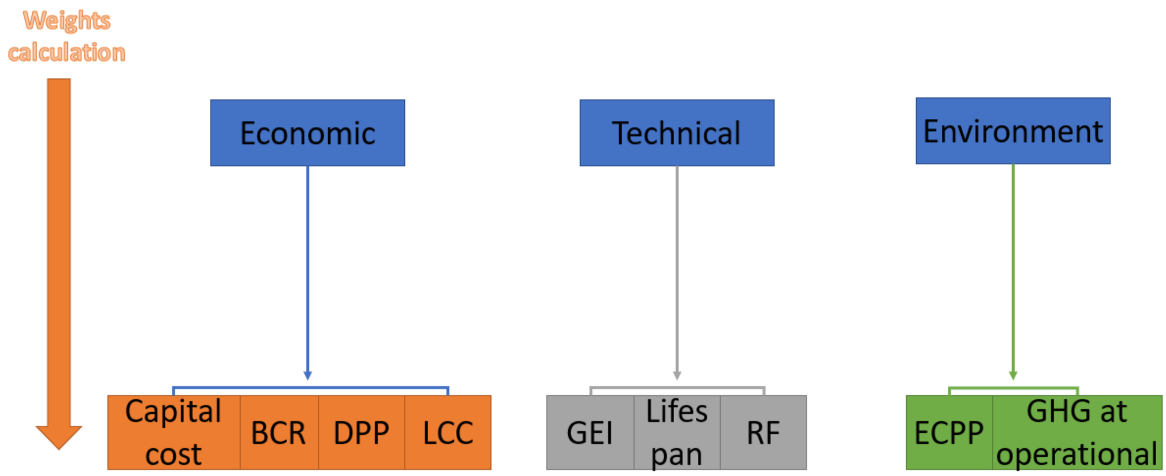


Figure 3-9 Weights calculation hierarchy

The following example shows the weights calculation for the economic-technical-environment criteria based the received preference value from one respondent.
The first step is to list the collected preference value for each criterion/indicator from the surveyed householders in Cardiff and Bristol. Table 3-9 presents examples of the collected preference value to the economic-technical-environment criteria from three householders.

Table 3-9. Example of listing the collected preference value to the decision-making criteria/indicators from the surveyed householders

	Economic	Technical	Environment
Participant - 1	5	4	5
Participant -2*	4	5	4
Participant -n*	5	3	3

* muted text font for participants 2 and n is intentional to emphasise that the process below is carried out separately for each individual's response.

The second step is to calculate the weights for each criterion/indicator based on the categorised preference value from each participant using Analytical Hierarchy Process (AHP) method.

Within the weighting process, this research assumes that participant x selects ‘a’, ‘b’ and ‘c’ as the preference value for the economic, technical and environment criterion, respectively. Secondly, it needs to establish the comparison matrix as shown in Table 3-10.

Table 3-10. Comparison matrix development

	Economic	Technical	Environment
Economic	a/a = 1	a/b	a/c
Technical	b/a	b/b = 1	b/c
Environment	c/a	c/b	c/c = 1
Average	(a+b+c)/a	(a+b+c)/b	(a+b+c)/c

Once the comparison matrix has been developed, each column value within the comparison matrix needs to be divided by the sum value to form a developed comparison matrix. The calculation process is shown in Table 3-11.

Table 3-11. The calculation within the developed comparison matrix

	Economic	Technical	Environment
Economic	(a/a)/((a+b+c)/a)	(a/b)/((a+b+c)/b)	(a/c)/((a+b+c)/c)
Technical	(b/a)/((a+b+c)/a)	(b/b)/((a+b+c)/b)	(b/c)/((a+b+c)/c)
Environment	(c/a)/((a+b+c)/a)	(c/b)/((a+b+c)/b)	(c/c)/((a+b+c)/c)

Then, the approximate and exact eigenvector for each criterion must be calculated – this process is illustrated in Table 3-12.

Table 3-12. Approximate and Exact weight for each criterion

	Approximate weight	Exact weight
Economic	{[(a/a)/((a+b+c)/a)]+[(a/b)/((a+b+c)/b)]+[(a/c)/((a+b+c)/c)]}/3 = 'q'	‘q’/S
Technical	{[(b/a)/((a+b+c)/a)]+[(b/b)/((a+b+c)/b)]+[(b/c)/((a+b+c)/c)]}/3 = 'p'	‘p’/S
Environment	{[(c/a)/((a+b+c)/a)]+[(c/b)/((a+b+c)/b)]+[(c/c)/((a+b+c)/c)]}/3 = 'r'	‘r’/S
Sum	S = ‘q’ + ‘p’ + ‘r’	q/S + p/S + r/S =1

The third step is to validate the consistency ratio based on the calculated exact weight for the specific preference combination. Firstly, it needs to calculate the maximum weight (λ_{max}) the as shown in Table 3-13.

Table 3-13 Calculation of the maximum weight

Exact weight	Total sum from Table 10	λ_{max}
'q'/S	(a+b+c)/a	$\left(\frac{'q'}{S}\times\frac{\text{a+b+c}}{\text{a}}\right)+\left(\frac{'p'}{S}\times\frac{\text{a+b+c}}{b}\right)+\left(\frac{'r'}{S}\times\frac{\text{a+b+c}}{c}\right)=\lambda_{max}$
'p'/S	(a+b+c)/b	
'r'/S	(a+b+c)/c	

Then, the consistency index (CI) can be calculated through Eq. (21).

$$CI = \frac{\lambda_{max} - n'}{n' - 1} \qquad \text{Eq.(21)}$$

Where, n' is the number of evaluated criteria.

The consistency ratio (CR) is then calculated using Eq. (22)

$$CR = \frac{CI}{RI} \qquad \text{Eq.(22)}$$

Where RI is the random consistency index which is associated with the number of evaluated criteria. The RI value and the corresponding number of the evaluated criteria are shown in Table 3-14 (Saaty, 2005).

Table 3-14. RI value and the associated number of the evaluation criteria (Saaty, 2005)

N	1	2	3	4	5	6	7	8	9	10
RI	0	0	0.58	0.9	1.12	1.24	1.32	1.41	1.45	1.49

The preference combination is considered as consistent when the CR value of less than 10% (Saaty, 2005). Once the preference combination passes the CR validation, the calculated weight will be used to calculate the average weight in step 4. It will repeat Step-2 and 3 to calculate the weights for the economic-technical-environment criteria and the associated indicators based on the collected preference values from householders. The calculated weights from different householders are then fed to step 4 to work out the average weights as the representatives for the criteria and indicators.

3.13. Decision-making spreadsheet development

The Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) method is used to develop the decision-making spreadsheet. TOPSIS is a multi-criteria decision-making method, and it has been widely used to incorporate with AHP to rank potential solutions (Sharma, Sridhar and Claudio, 2020). The following paragraphs explain the development process using the TOPSIS and the weighting values in subsection 3.12.3.

The first step of using TOPSIS to rank potential solutions is to form the evaluation matrix in terms of the evaluation criteria and potential solutions. The evaluation matrix example is shown in Table 3-15. It assumes A, B and C are three potential HRES combinations, $a_{i=1}^{3}$, $b_{i=1}^{3}, c_{i=1}^{3}$ are performance values in the associated evaluation criteria.

Table 3-15 Evaluation matrix development

Potential HRES Combination	Economic	Technical	Environment
A	a_1	b_1	c_1
B	a_2	b_2	c_2
C	a_3	b_3	c_3
$\boldsymbol{Sum^2}$	$a_1^2 + a_2^2 + a_3^2 = EC$	$b_1^2 + b_2^2 + b_3^2 = TE$	$c_1^2 + c_2^2 + c_3^2 = EN$

After the completion of the evaluation matrix, the next step is to normalise the performance value of each HRES combination in the specific evaluation criterion. Table 3-16 shows the normalised evaluation matrix.

Table 3-16. Normalisation of the evaluation matrix

Potential HRES Combination	Economic	Technical	Environment
A	$\overline{a_1} = {a_1}/{\sqrt{EC}}$	$\overline{b_1} = {b_1}/{\sqrt{TE}}$	$\overline{c_1} = {c_1}/{\sqrt{EN}}$
B	$\overline{a_2} = {a_2}/{\sqrt{EC}}$	$\overline{b_2} = {b_2}/{\sqrt{TE}}$	$\overline{c_2} = {c_2}/{\sqrt{EN}}$
C	$\overline{a_3} = {a_3}/{\sqrt{EC}}$	$\overline{b_3} = {b_3}/{\sqrt{TE}}$	$\overline{c_3} = {c_3}/{\sqrt{EN}}$

Once the performance value of each potential HRES combination in the specific evaluation criteria has been normalised, the idea best (v_j^+) and worst (v_j^-) value can be identified. The idea best value (v_j^+) indicates the best performed value in the specific evaluation criterion across different potential HRES combinations. For example, if HRES combination A performed the best in the economic criterion against another two HRES combinations, v_j^+ in the economic criterion would be $\overline{a_1}$.

The next stage is to calculate the best (S_i^+) and worst (S_i^-) Euclidean distance based on the identified idea best and worst value in each specific criterion across different HRES combinations. The best and worst Euclidean distance is calculated using the Eq. (23a, b).

$$S_i^+ = [\sum_{j=1}^{m} \left(v_{ij} - v_j^+\right)^2]^{1/2}$$
$$S_i^- = [\sum_{j=1}^{m} \left(v_{ij} - v_j^-\right)^2]^{1/2}$$
Eq.(23a, b)

Where, v_{ij} is the normalised performance value in the specific criterion of different HRES combinations. For example, $v_{ij} = \overline{a_{i=1}^3}, \overline{b_{i=1}^3}\ or\ \overline{c_{i=1}^3}$.

Finally, the final score (P_i) for each HRES combination in the specified evaluation criteria can be worked out based on the calculated the best and worst Euclidean distance using Eq. (24).

$$P_i = \frac{S_i^-}{S_i^+ + S_i^-}$$
Eq.(24)

4. Result

This chapter is constituted of seven sections as follows:

Section 4.1 presents the simulated energy demand and primary and secondary energy consumption of the retrofitted and as-built domestic building. The results demonstrate the achievement of research objective 1.

Section 4.2 presents the costs (product, installation and total) of the shortlisted renewable energy system, battery, hot water cylinder and solar inverters. Section 4.3 presents the technical data relevant to the shortlisted renewable energy systems which are used to support energy supply calculation and the associated performance evaluation. The data includes expected lifespan, whole lifecycle servicing costs and embodied carbon. Finally, this section shows the up-to-date energy tariff of the selected energy supplier and the generic emission factor of the electricity grid and natural gas pipeline in April 2022. This information was obtained from research articles and grey literature. Sections 4.2 and 4.3 demonstrate the achievement of the research objective 3.

Section 4.4 first presents the practical HRES combinations after the sizing process. Due to the changes in the renewable heating system incentives, this section presents practical HRES combinations separately for different incentives. Then, this section presents the economic-technical-environmental performance of the practical HRES combinations. The results in this section reflect the achievement of the research objective 2, 4 and 5 (economic-technical-environmental performance of HRES).

Section 4.5 presents responses from the surveyed householders in Cardiff and Bristol separately in three topics, 1) responses to the building stock condition. 2) perspectives of installing renewable energy systems in homes, and 3) householders' perspectives of renewable systems and climate change. The responses under the first topic reflect the basic stock condition of the surveyed homes. The responses under the second and third topics reflect research objective 5, demonstrating the viewpoints of installing the renewable system in homes from the surveyed householders to identify the optimal HRES combination. In addition, such responses are helpful to develop future research on investigating householders' perspectives in installing renewable systems in their homes along with the changing of the energy policy.

Section 4.6 presents the calculated weighting results for the selected economic-technical-environmental performance indicators. The weighting results were calculated based on the responses from Cardiff's householders as this research received sufficient responses from householders in Cardiff to process the weighting calculation. This section also presents the ranking results for the practical HRES combinations based on the calculated weighting results. This section presents the results of the final ranking of the HRES combination stated in objective 5.

Section 4.7 presents the developed spreadsheets used to support the sizing calculation for each renewable system, performance evaluation, the calculation of weighting values and the ranking process.

4.1. The simulation results of the selected representative domestic building

The representative domestic building was selected from a previous research project conducted by Dr Jo Patterson and her team at the Welsh School of Architecture, Cardiff University. The project was funded through the Wales European Regional Development Fund (ERDF) Programme and was part of the Low Carbon Research Institute (LCRI) Wales European Funding Office (WEFO) programme. The building was selected as the representative domestic building because it met the defined building indicators in section 3.1. The representative domestic building is a pre-1919 end-terraced house with a floor area of 67 m^2. The building has been retrofitted to EPC band C (EPC certificate issued in 2020.) (UK Government, 2020).

The as-built and retrofitted models of the representative domestic building were prepared and simulated in DesignBuilder and EnergyPlus following the method explained in section 3.9. Figure 4-1 shows the selected domestic building from GoogleMap and the created 3D model in DesignBuilder.

Figure 4-1. The selected representative domestic building: a) as built (Jones et al., 2017); b) rendered from Design Builder

The simulated annual energy demand of the as-built model is presented in Table 4-1. Annual natural gas and electricity consumption was simulated as this can then be against the sub-national energy consumption data to validate the effectiveness of the modelling method.

Table 4-1. The simulated energy demand of the as-built model

Annual	
Electricity (kWh)	Natural Gas (kWh)
2,930	13,733

The recorded average energy consumption for the region where the case site is located is 12,811 kWh (natural gas) and 2,834 kWh (electricity). The average energy consumption data was calculated by averaging the recorded regional energy consumption data of the specific location between 2015 and 2020 on the sub-national energy consumption database (UK Government, 2013b). The average regional energy consumption reflects the general energy consumption of the selected area. It does not give the selected retrofitted home's exact historical energy consumption data. The average regional energy consumption data provides a reasonable energy consumption range for the selected retrofitted home in the area. It then needs to evaluate if the simulated energy consumption of the selected home in the as-built condition is within the reasonable range of the average regional energy consumption data—the evaluation method described in subsection 3.8.2. The simulated energy consumption of the selected home is within the reasonable range of the average regional energy consumption data, indicating the used modelling method is effective and reliable in simulating energy consumption.

This study found that the difference between the simulated energy demand and the average regional consumption is 7.35%. The difference value indicates the simulated energy demand is within the reasonable range of the average regional energy consumption data (ASHRAE, 2002). Therefore, the proposed modelling method is effective, and the modelling method is reliable in creating the retrofitted building model. Table 4-2 shows the simulated energy demand and the historical solar radiation data of the selected representative retrofitted home in Cardiff. The reason to present the historical solar radiation data of the chosen home in Cardiff is that the radiation data is used in calculating the generated energy from solar systems. The space heating and gas consumption only presented the energy consumption in the intensive heating season (October to March).

Table 4-2. Simulated energy demand and the historical solar radiation data of the retrofitted building model

Annual				intensive heating season	
Solar radiation (kWh/m^2)	DHW (kWh)	Lighting (kWh)	Electrical appliances (kWh)	Space heating (kWh)	Natural Gas (kWh)
1379	1423	777	2091	3319	5594

The simulated energy demand feeds into the defined scenarios in section 3.8 to calculate the power rating for each renewable system in different HRES combinations. Due to the simulated energy consumption for the selected home in the as-built condition is within the reasonable range (7.35%) of the average recorded regional energy consumption data. The method is then proved effective and reliable to create the retrofitted building model. Therefore, the simulated energy demand of the retrofitted building model can reflect the energy consumption of the selected home within the reasonable energy consumption range in the retrofitted condition. This research did not directly use the sub-national energy consumption data (average regional energy consumption data) and feed it to the renewable system sizing process; the reason is:

- Sub-national energy consumption data only provides historical electricity and gas data. It is difficult to break down the electricity and gas data to the different energy consumption end-users—for example, domestic hot water demand, lighting demand, space heating and electrical appliance demand.

4.2. Renewable system – capital cost analysis

This section presents the collected capital cost of the shortlisted renewable systems and battery. The capital cost includes the product cost and the relevant installation cost. The cost data of the systems is collected following the method explained in subsection 3.3.1. The capital cost of renewable systems is used in the economic performance evaluation of the potential HRES combinations explained in sections 3.9 and 3.10. This section is constituted of the following subsections:

Section 4.2.1- renewable space heating systems: it presents the product and capital cost of ASHP and GSHP from the MCS-recognised brands, and the systems are used to cover the space heating demand of the selected representative domestic building.

Section 4.2.2 – renewable DHW systems: it presents the product and capital cost of STC and hot water cylinders from the identified brands. The STC and hot water cylinders cover the DHW demand of the selected representative domestic building.

Section 4.2.3 – Solar PV: it presents the capital cost of solar PV between 2015 and 2019 from the PV installation cost database created by BEIS (BEIS, 2021). This section also presents the product cost of solar inverters from six different manufacturers.

Section 4.2.4. – Battery: it presents the product and installation cost of the chosen battery brand – Tesla Powerwall 3.0.

4.2.1. Renewable space heating systems

4.2.1.1. Air Source Heat Pump

This research collected product cost of air source heat pump (ASHP) from six MCS registered brands, including Daikin, Samsung Premium, Vaillant, Hitachi and LG. The collected power rating of ASHP ranges from 3.5 kW to 14 kW. The product cost of ASHP includes indoor and outdoor units, connection accessories, wiring centre, user interface and controller but excludes the cost of the hot water cylinder. Within the cost collection, some of the collected product costs of ASHP included 20% of VAT. In order to keep the consistency of the collected product cost of ASHP and to ensure identify the most applicable VAT to calculate the capital cost of ASHP. It is important to use the 60% test rule to identify if the calculated average capital cost of ASHP can benefit from the reduced VAT rate of 5%. Therefore, the product cost of ASHP presented here is VAT-excluded. Figure 4-2 shows VAT-excluded product cost of ASHP from the identified manufacturers. The product cost was collected through the following sources, (Cityplumbing, 2022d, 2022b, 2022c; Direct heating supplies, 2022f, 2022d, 2022b, 2022g, 2022e, 2022c, 2022a; Electric heat warehouse, 2022h, 2022g, 2022d, 2022b, 2022a; Orionairsales, 2022a, 2022c, 2022b; Price spy, 2022; The underfloor heating store, 2022c, 2022b, 2022a; Trade sparky, 2022d, 2022c, 2022b, 2022a; Zero home bills, 2022)

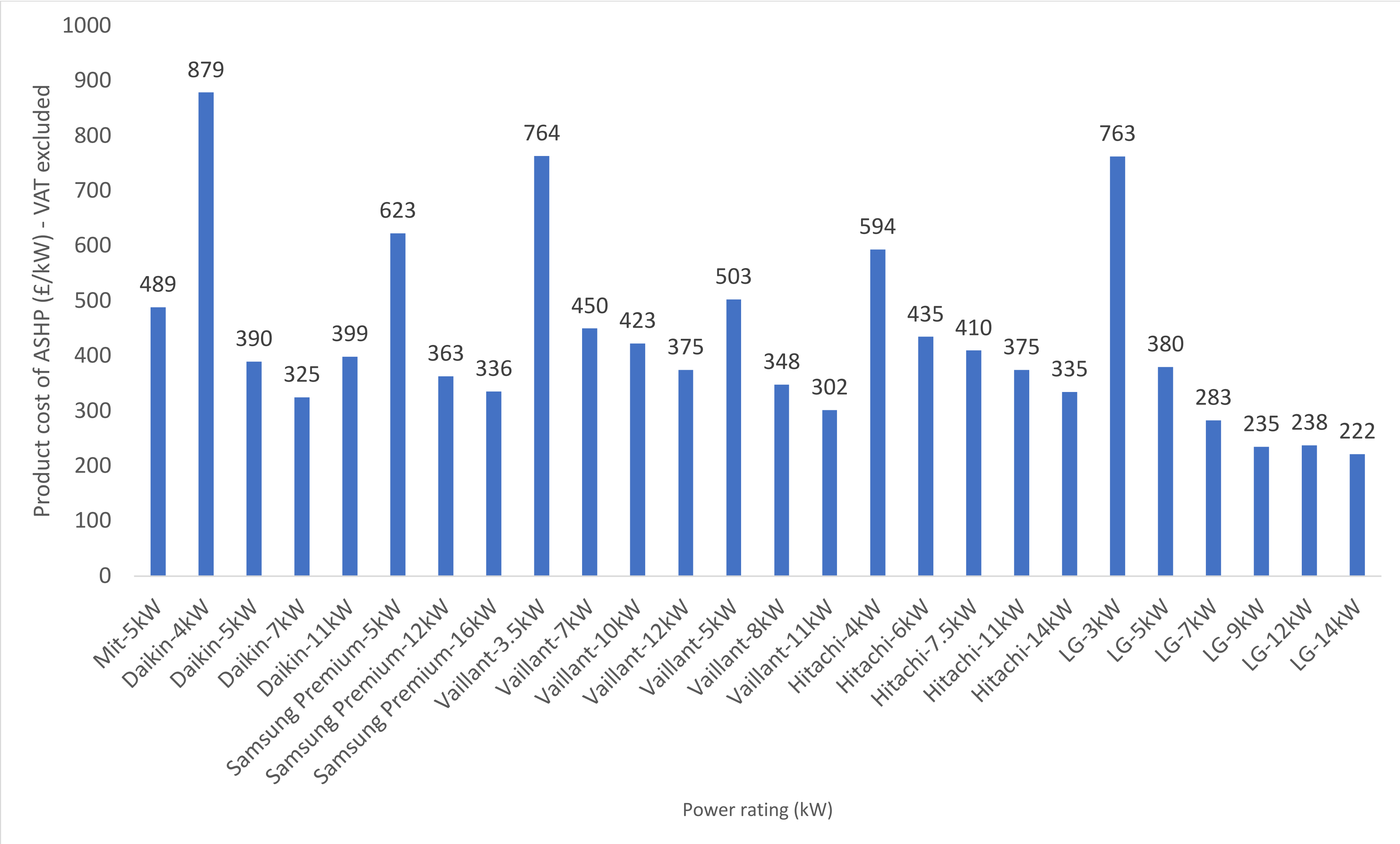


Figure 4-2. Product cost of ASHP

Based on Figure 4-2, the average product cost (VAT excluded) of the six ASHP brands is £432/kW. ASHP was considered to supply space heating load only in this research, the available commercial configurations from the selected manufactures are 3.5, 4, 5, 6, 7, 7.5, 8, 9, 11, 12, 14 and 16kW.

The installation cost of ASHP is calculated following the method explained in subsection 3.3.1.2. The calculated average installation cost can reflect the average installation cost of ASHP between 2010 and 2019 for UK homes. The average installation cost of ASHP is £506 (VAT excluded), and the average capital cost of ASHP is £938 (VAT excluded). The average product cost (£432) is less than 60% of the average capital cost (£938) of ASHP. Based on the 60% test VAT policy, ASHP is eligible to receive a reduced VAT charge at 5% in this research. Then, the average capital cost becomes £985 (including 5% VAT).

4.2.1.2. Ground Source Heat Pump

The product cost of five MCS-registered GSHP brands, including, Kensa Engineering Ltd, Viessmann, Worcester (Bosch), Vaillant and Dimplex was collected in this research. The product cost includes the cost of the indoor/outdoor unit and installation accessories (not including a hot water cylinder). The power rating of the collected GSHP brands range from 3kW to 15kW. Like the product cost of ASHP, Figure 4-3. Product cost of GSHP presents the VAT-excluded product cost of GSHP and the associated power ratings from the selected GSHP brands. The collected product cost of GSHP (£/kW) from the above-mentioned brands through the following sources, (Cityplumbing, 2022a; Dimplex, 2022; Electric heat warehouse, 2022f, 2022e, 2022c; Kensa Engineering Ltd, 2022f, 2022e, 2022d, 2022c, 2022b, 2022a; mytub.co.uk, 2022c, 2022b, 2022a; Mytub.co.uk, 2022; Trade sparky, 2022d)

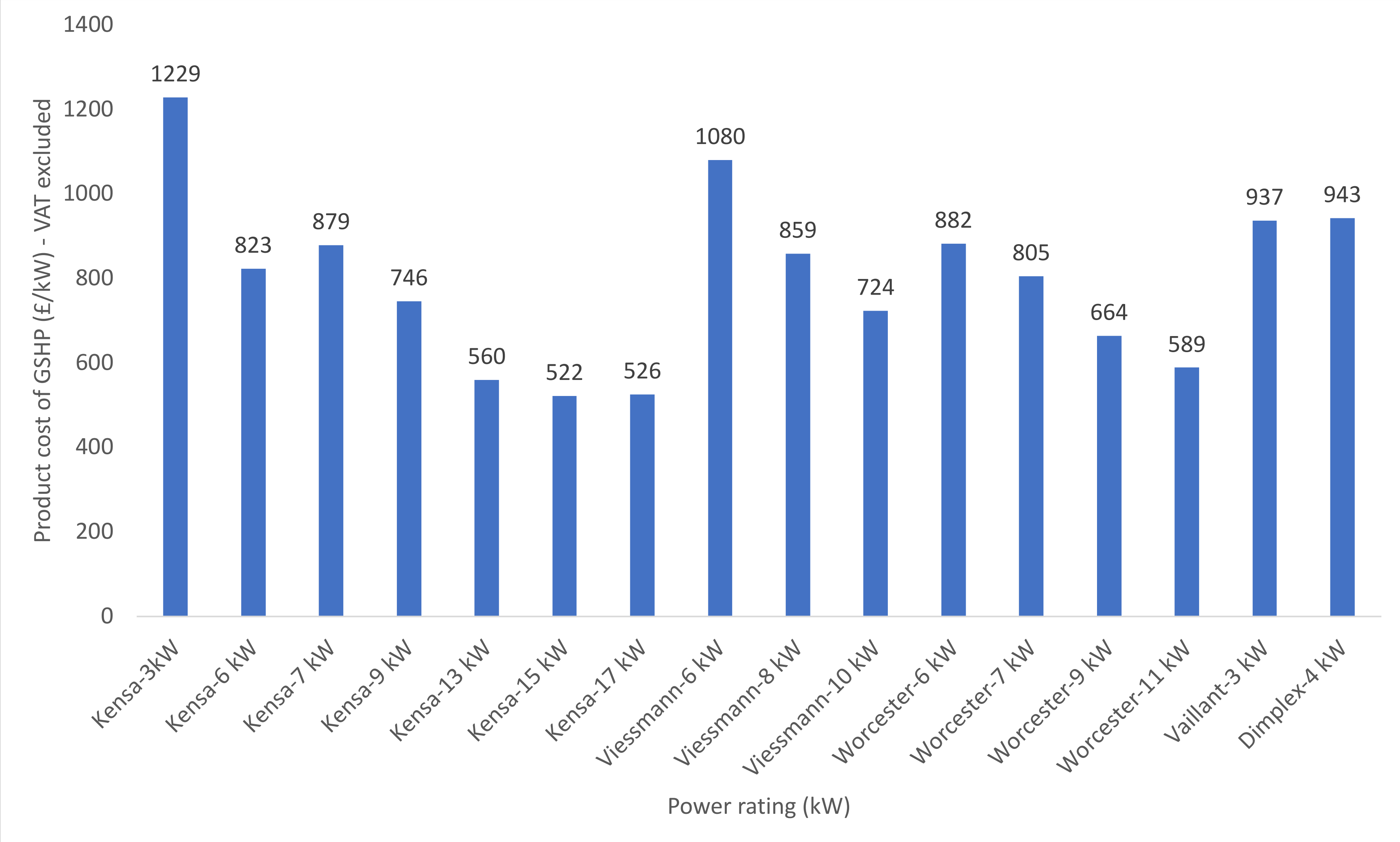


Figure 4-3. Product cost of GSHP

The average product cost of the selected five MCS registered brands is £819/kW excluding VAT. Like ASHP, GSHP was only used to cover the space heating demand of the selected representative domestic building. The commercially available GSHP configurations from the selected five MCS registered brands are 3, 4; 6, 7, 8, 9, 10, 11, 13 and 15kW.

The average installation cost (VAT excluded) of GSHP for the UK is calculated following the method explained in subsection 3.3.1.2. The average installation cost (VAT excluded) can reflect a generic installation cost (VAT excluded) of GSHP between 2010 and 2019. The calculated average installation cost of GSHP is £959/kW (VAT excluded), and the average capital cost of GSHP is £1,778/kW. However, the groundwork cost is necessary to consider in the whole GSHP installation process, and the general groundwork cost for installing a GSHP smaller than 12kW is £6,000. Then, the average product cost of GSHP is £819/kW, which is less than 60% of the average capital cost (£1,778/kW). The GSHP can also benefit from the reduced VAT rate at 5%; the capital cost (including VAT) becomes £1,867/kW (without groundwork) and £1,867/kW+£6,000 (with groundwork).

4.2.2. Solar Thermal Collector

The product cost and configurations of the solar thermal collector (STC) were collected from two MCS-registered brands, Viessmann and Worcester (Bosch). The aperture area of STC from the selected brands ranges from 2.02 to 2.25 m^2. The product cost of STC includes STC, hydraulic connection set, expansion vessel and installation/connection accessories. Figure 4-4 presents the product cost in £ (VAT excluded) of STC that can be installed on the roof from the selected brands. The collected product cost is based on the aperture area of the STC system. The collected cost of STC under the selected brands is collected from the following sources, mytub.co.uk, 2022d; Viessmann Direct, 2022b, 2022a.

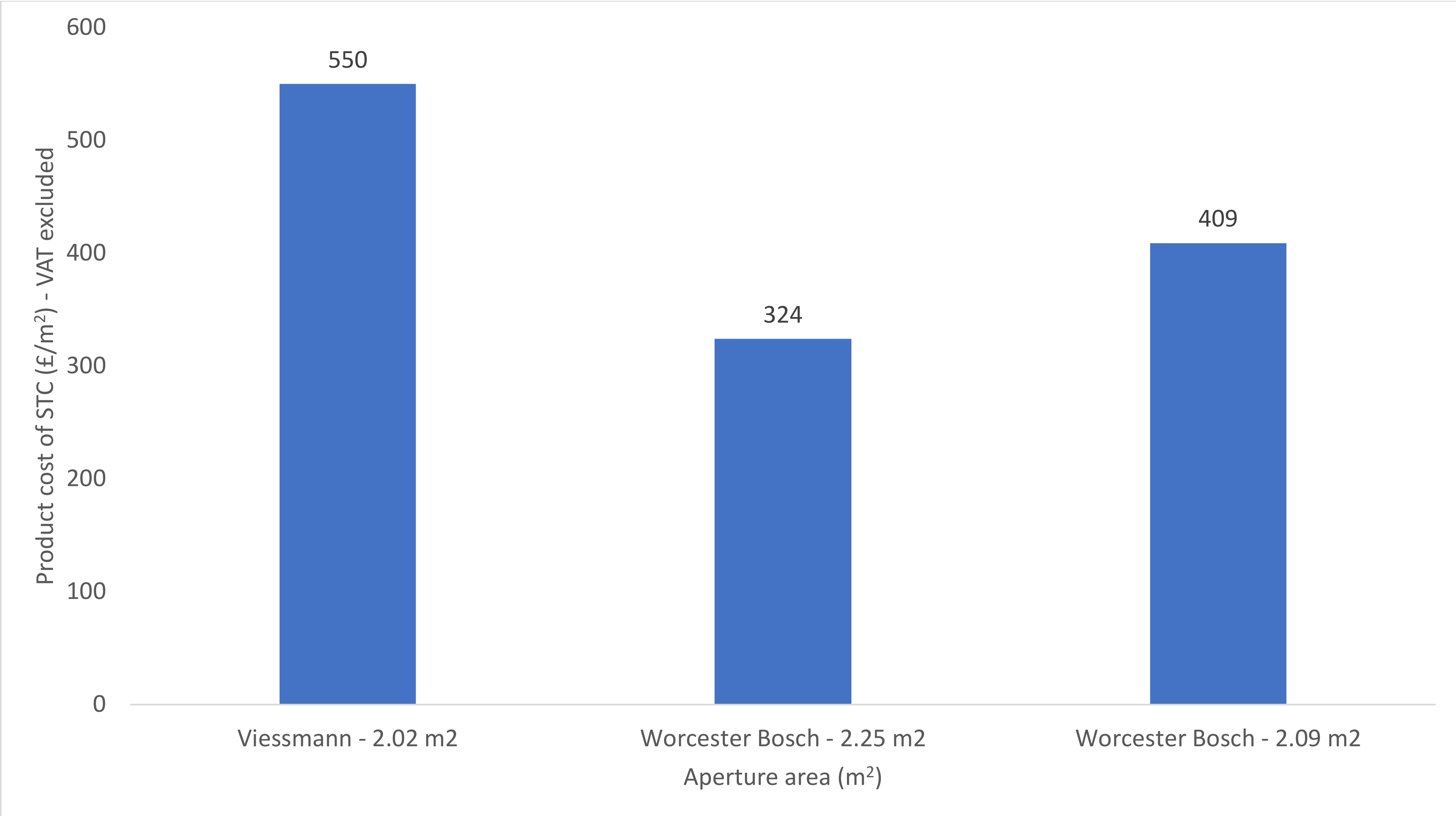


Figure 4-4. Product cost (£) of the roof top STC based on the identified aperture area (excluded VAT charge)

The average product cost of STC was calculated as £428/m^2 (VAT excluded). The average product cost for other renewable systems was calculated in £/kW. In order to use the consistent cost unit across all renewable systems, this research converted the average product cost of STC from £/m^2 to £/kW using the method created by IEA (2016). This method suggested multiplying 0.7 by the aperture area of the solar collector area to obtain the capacity (kW). Then, use the collected product cost of STC to divide by the converted capacity of STC in kW to obtain the product cost in £/kW. Finally, it works out that the converted average product cost of STC is £611/kW (VAT excluded).

Like the calculated average installation cost of ASHP and GSHP, the average installation cost of STC (£/kW) is calculated following the method described in subsection 3.3.1.2. The calculated average installation cost (VAT excluded) of STC is £847/kW, and the average capital cost (VAT excluded) is £1,458/kW. The average product cost of STC (£611/kW) is less than 60% of the average capital cost (£1,458/kW), and STC can benefit from the reduced VAT rate of 5%. Then, the capital cost of STC becomes £1,531/kW (including VAT).

The hot water cylinder is usually added to work with STC, storing the hot water when the demand is low and reusing the water for the high demand period. Based on the simulated DHW demand, the representative domestic building needs a hot water cylinder of less than 150 L. Therefore, this research collects the product cost (VAT excluded) of hot water cylinders with a size range between 100 and 150L from four different brands. The product cost of hot water cylinder from the selected brands is shown in Figure 4-5. The product cost from the selected brands is collected through the following sources, (Plumb Nation, 2022b, 2022c, 2022d, 2022e, 2022g, 2022f, 2022a; Viessman Direct, 2022; Viessmann Direct, 2022a)

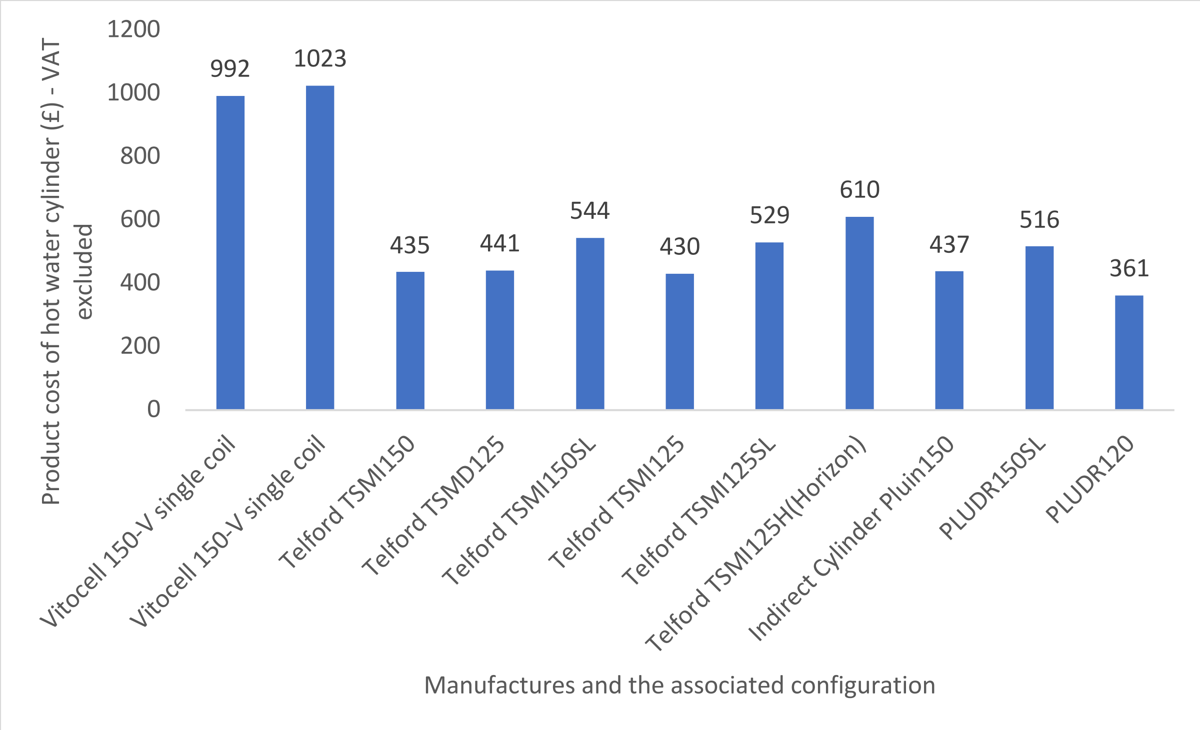


Figure 4-5. Product cost of hot water cylinder in £ (VAT excluded)

This research then calculates the average product cost of a hot water cylinder in £/L as the representative product cost in the commercial market in January 2022. The calculated average product cost is £4.5/L (VAT excluded). The hot water cylinder is not benefited from the reduced VAT charge at 5%; therefore, the average product cost of a hot water cylinder is £5.4/L with a 20% of the VAT charge. The typical installation for a new unvented hot water cylinder (120L) is £833 (excluding 20% of VAT) (The eco experts, 2023). The average installation cost in £/L (VAT excluded) is £6.9/L. The average capital cost of hot water cylinder is then becoming as £11.4/L (VAT excluded), and £13.68/L (including 20% of VAT).

4.2.3. Solar PV

The average capital cost of solar PV was calculated through the method explained in section 3.3.1.4. The average capital cost represents the average cost between 2015 and 2019 for a PV with less than 4kWp. The average capital cost of solar PV presents in the following, which includes the installation cost of a solar inverter and a VAT rate of 5%. However, the product cost of solar inverter is not included in the average capital cost of solar PV. Figure 4-6 presents the average capital cost of solar PV with and without 5% of VAT charge.

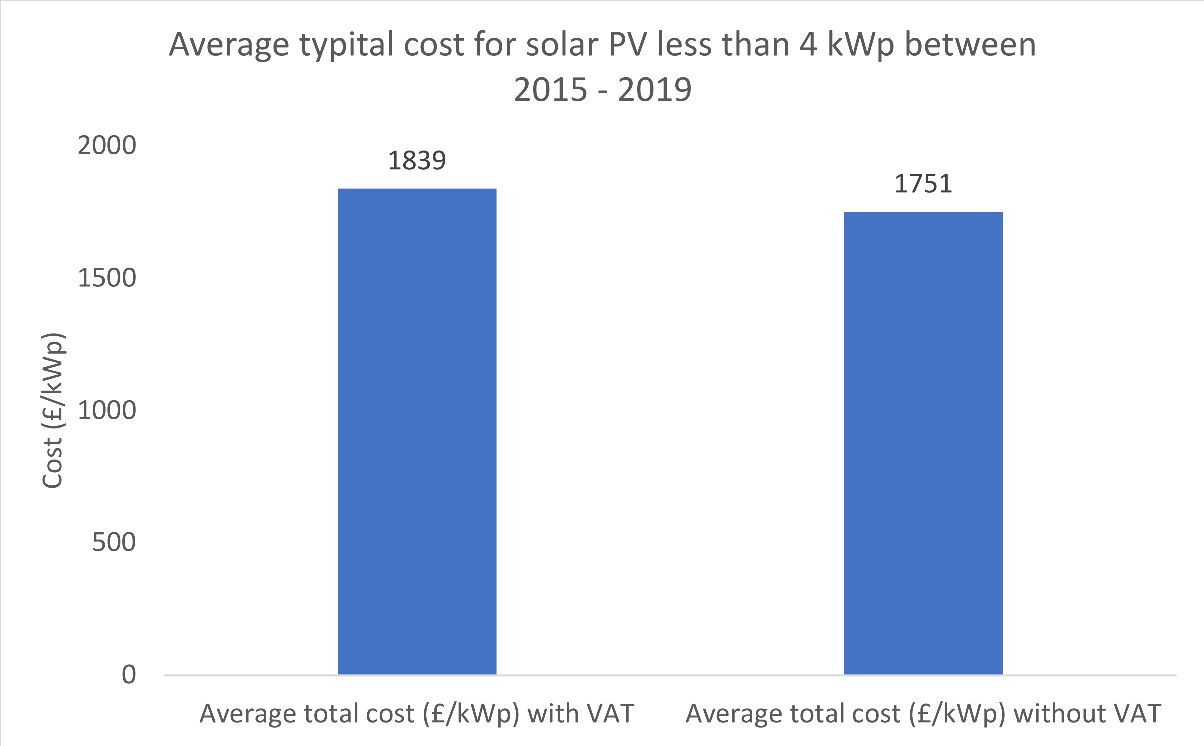


Figure 4-6. Capital cost of solar PV

This research collects the product cost (VAT excluded) of six different brands of solar inverters from the UK commercial market. The cost (VAT excluded) in £ per kW of each solar inverter is presented in Figure 4-7. The average product cost of solar inverter is carried out by averaging the collected product cost from the different brands. The average product cost of solar inverter is £138/kW. The average cost is used to represent the general product cost of solar inverter in the UK market in January 2022. The product cost of solar inverter is collected through the following sources, Renugen, 2022e, 2022d, 2022c, 2022b, 2022a; The eco supermarket, 2022h, 2022g, 2022f, 2022e, 2022d, 2022c, 2022a, 2022b.

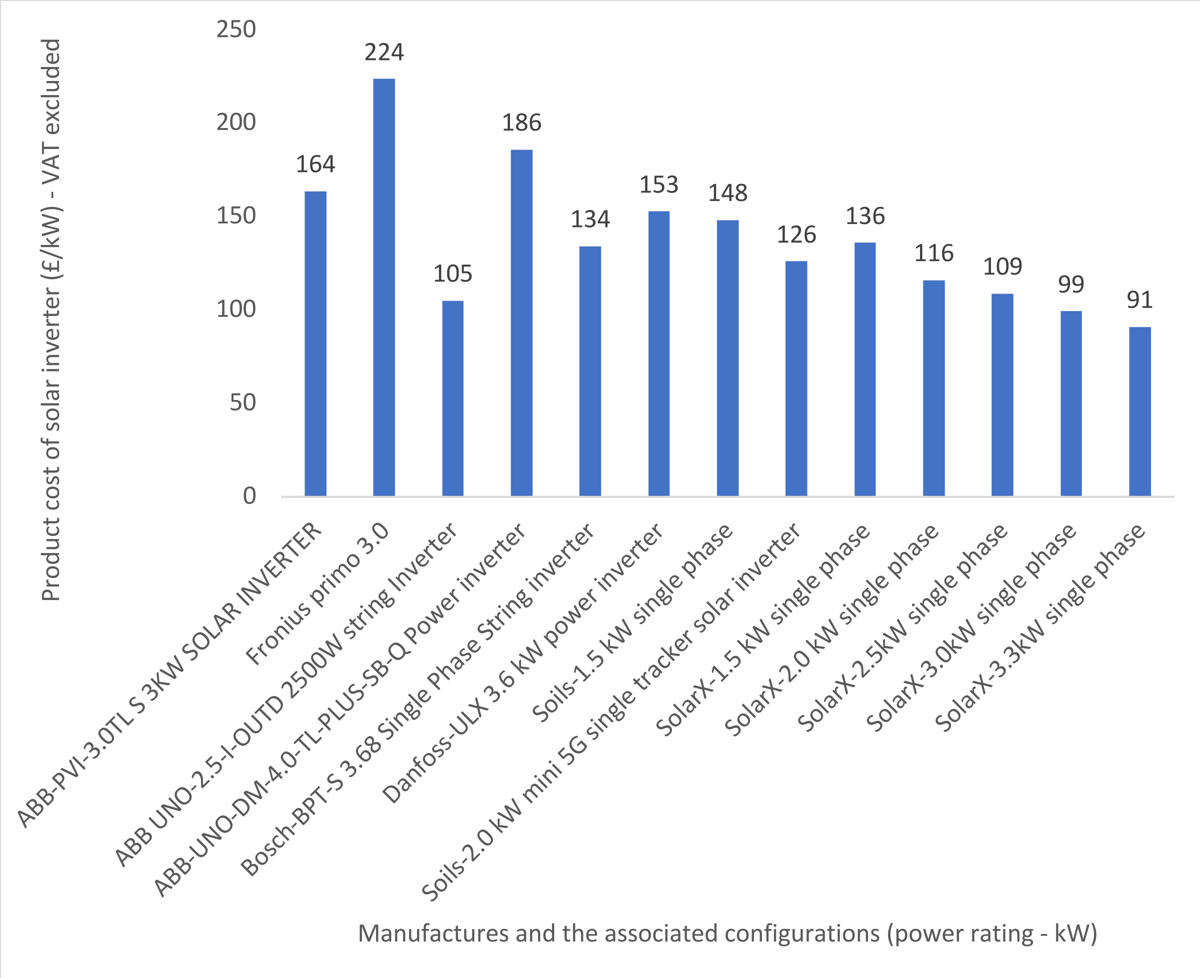


Figure 4-7. Product cost of Solar inverter

Unlike solar PV, the solar inverter does not benefit from the reduced VAT charge (5%) but a normal VAT charge (20%). Therefore, the average product cost of a solar inverter, including VAT becomes £166/kW.

4.2.4. Energy storage – Battery

The battery can improve the supply security performance of the installed onsite solar PV. In addition, the battery improves the independency of the selected representative domestic building from the national grid. This research selects the Tesla Powerwall 3.0 as the representative domestic battery for UK homes. The reasons to select Tesla Powerwall is, it has a good capacity (13.5kWh) with a more extended warranty year (up to 15 years) and a good performance (about 80% efficiency) after 15 years.

The product cost of Tesla Powerwall 3.0 in the UK market is £7825 (excluding 20% of VAT)(Tesla, 2022a). The typical installation cost for a Tesla battery in the UK is £1365 (excluding 20% of VAT)(JoJuSolar, 2017; Jojusolar, 2022; UK Alternative Energy, 2022). Thus, the capital cost of the Tesla battery is £9190 (VAT excluded), and £11028 (including 20% VAT).

4.3. Renewable system technical data and embodied carbon analysis

This section presents the technical data and embodied carbon of renewable energy system, and the energy tariff and carbon intensity data of the selected energy supplier. This data will contribute to the Economic-Technical-Environment performance analysis in Section 4.4. The structure of this section is:

Section 4.3.1: presents the technical data of renewable energy system involved in the energy supply calculation.

Section 4.3.2: presents the lifespan for each system. It then shows the general maintenance frequency and cost for the different renewable energy systems, battery, hot water cylinders and solar inverters.

Section 4.3.3: presents the embodied carbon calculated using the method explained in section 3.5.

Section 4.3.4: presents the energy tariff from the selected energy supplier for the selected representative city in Wales and England. It also presents the collected carbon intensity of the electricity grid and natural gas pipeline in 2022.

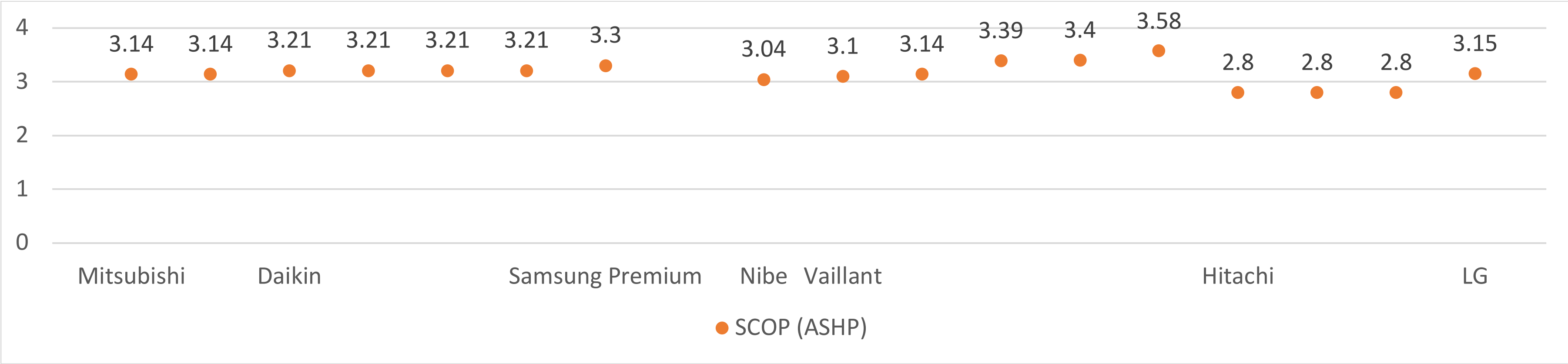
4.3.1. Technical data of renewable energy system

4.3.1.1. Photovoltaic

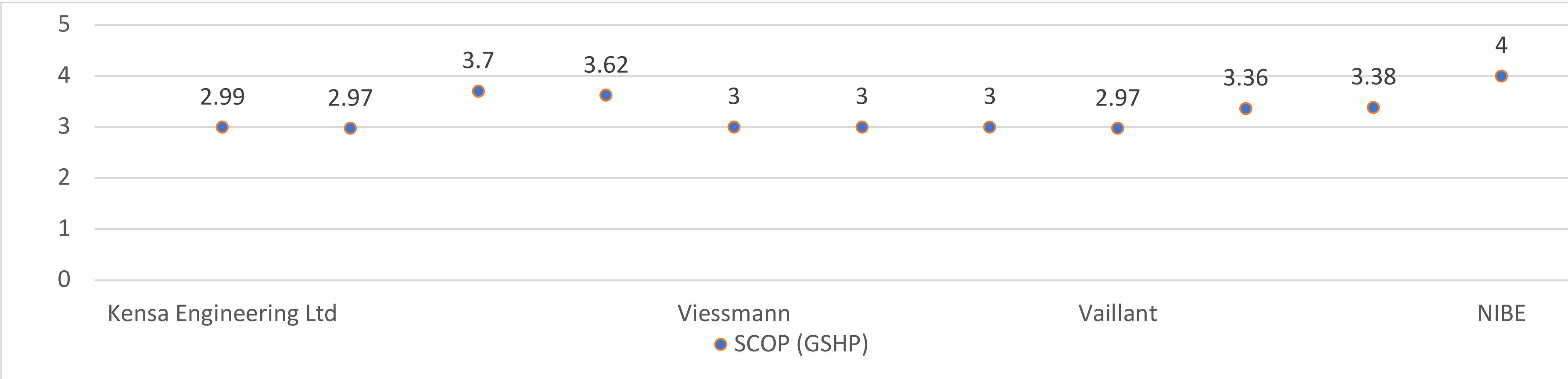
The PV panel area (in square meters) and PV efficiency are collected from commercial PV technical manuals using the method explained in section 3.4.1. The collected commercial PV panel are categorised into monocrystalline and polycrystalline solar PV panels. The model power rating for most polycrystalline solar PV ranges from 250 to 350 W. The model power rating range for most monocrystalline solar PV is 310 to 400 W (Solar Bay, 2020). The average panel area of polycrystalline solar PV based on the collected commercial technical manuals is 1.64 m^2(CCL, 2022h, 2022i; ENSOL, 2022b; Renugen, 2022f, 2022g, 2022h, 2022i, 2022j, 2022n, 2022o, 2022p; Solar Shop, 2022c). The average panel area becomes 1.67 m^2 for monocrystalline solar PV (CCL, 2022a, 2022b, 2022c, 2022d, 2022e, 2022f, 2022g, 2022j, 2022k, 2022l, 2022m; ENSOL, 2022a, 2022c; Renugen, 2022g, 2022k, 2022l, 2022m; Solar Shop, 2022a, 2022b). The identified average monocrystalline panel area and efficiency of solar PV is used to calculate the suitable size of solar PV to sufficiently cover the simulated electricity demand of the representative domestic building. Monocrystalline panels have a higher efficiency and are more cost-efficient than polycrystalline panels. This research selected 320W solar panels to carry out the relevant calculation, as this is the most common power rating for the monocrystalline panel in the existing commercial PV market.

4.3.1.2. Heat Pumps

The seasonal coefficient of performance (SCOP) is an important factor in the energy generation calculation of GSHP and ASHP. Figure 4-8 presents SCOP of the selected ASHP and GSHP brands with power ratings ranging less than 10 kW at 55^{o}C of flow temperature. The SCOP data is collected from the following sources, (Cityplumbing, 2022a, 2022c, 2022b, 2022d; Dimplex, 2022; Direct heating supplies, 2022a, 2022c, 2022b, 2022e, 2022d, 2022g, 2022f; Electric heat warehouse, 2022a, 2022b, 2022d, 2022c, 2022e, 2022f, 2022g, 2022h; Kensa Engineering Ltd, 2022a, 2022b, 2022c, 2022d, 2022e, 2022f; Mytub.co.uk, 2022; mytub.co.uk, 2022a, 2022b, 2022c; Orionairsales, 2022a, 2022b, 2022c; Price spy, 2022; The underfloor heating store, 2022a, 2022b, 2022c; Trade sparky, 2022a, 2022b, 2022c, 2022d; Zero home bills, 2022)



(a)



(b)

Figure 4-8. SCOP of GSHP and ASHP at 55°C of flow temperature. (a) shows SCOP of ASHP and (b) shows SCOP of GSHP.

The average SCOP of ASHP is 3.1, while the average SCOP of GSHP is 3.3. The average SCOP is assumed at 55^{o}C flow temperature. The calculated average SCOPs of GSHP and ASHP are used in the energy generation and the performance evaluation of HRES.

4.3.1.3. Solar Thermal Collectors

Figure 4-9 presents the zero-loss collector efficiency of STCs with the shortlisted brands. The presented zero-loss collector efficiency of STC with the aperture area ranges from 2.02m^2 to 2.25 m^2. The average zero-loss collector efficiency is calculated as 78% based on the data presented in Figure 4-9. The calculated average zero-loss collector efficiency can reflect the general zero-loss collector efficiency of the selected commercial STC brands. The calculated average zero-loss collector efficiency is then used in the energy generation and performance evaluation of HRES that contains the STC system. The relevant technical data of STC is collected from the following sources, mytub.co.uk, 2022d; Viessmann Direct, 2022c, 2022b.

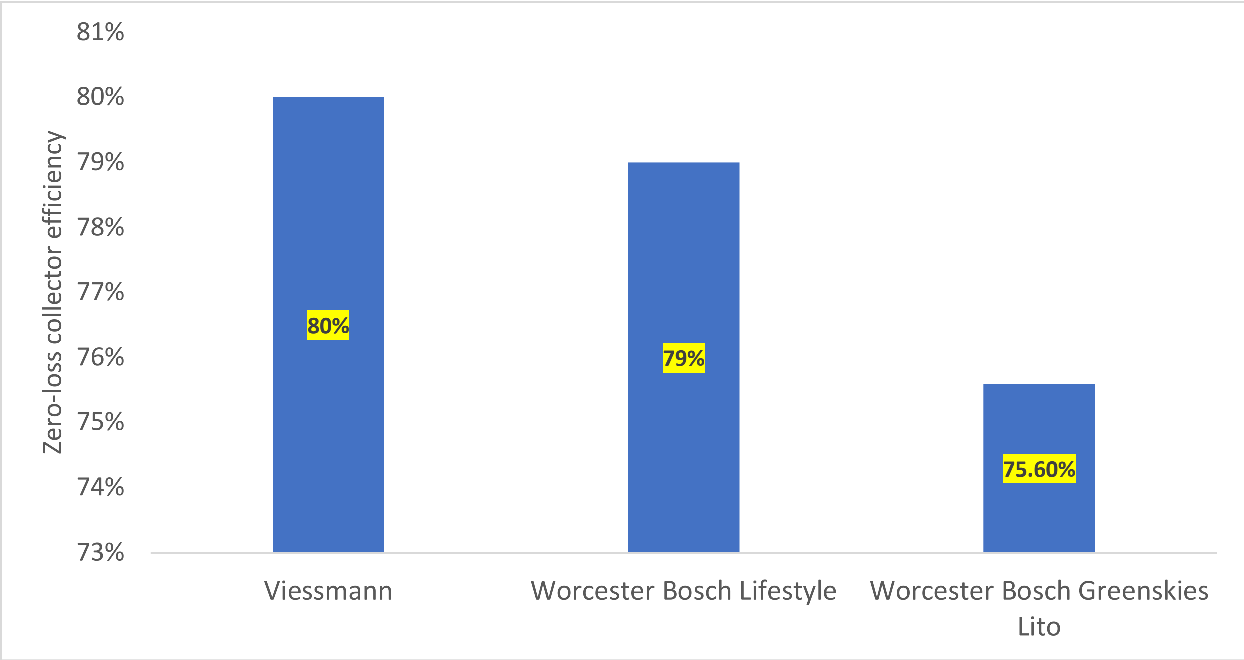


Figure 4-9. Zero-loss collector efficiency of STC

4.3.1.4. Generic lifespan, maintenance frequency and cost of renewable energy system, battery, hot water cylinder and solar inverters

The general lifespan of the existing commercial solar PV and STC is 30 years. ASHP and GSHP have a slightly shorter lifespan than solar PV and STC, the lifespan for ASHP is 20 years but 25 years for GSHP. The solar inverter normally lasts 10 to 15 years. The Tesla Powerwall 3.0 can potentially have 80% of charging capacity after 15 years. The hot water cylinder has lifespan between 20 and 30 years. Table 4-3 presents the lifespan and the source information for the above-mentioned systems.

Table 4-3. Expected lifespan for renewable energy systems, battery, hot water cylinder and solar inverters.

System	Expected lifespan (year)	Reference
Solar PV	30	(Checkatrade, 2022; GreenerGroup, 2022b; Howell, 2022)
STC	Up to 30	(The greenage, 2020; Westward energy services, 2022; Wondrausch, 2011)
ASHP	20	(Energy Saving Trust, 2022a; GreenMatch, 2022a; Heat Pump Assist, 2022)
GSHP	25	(Energy Saving Trust, 2022a; Heat Pump Assist, 2022; IMS Heat Pumps, 2022)
Hot water cylinder	20-30	(PlumbNation, 2022h)
Battery	20	(Jojusolar, 2022)
Solar inverter	10-15	(The Eco Supermarket, 2022)

In general, solar PV does not need an annual service but needs to keep panels clean to enable the expected efficiency of the electricity generation. However, some UK based renewable energy advisory websites (GreenerGroup, 2022a; the ecoexperts, 2022) suggested householders have annual service by professionals, ensuring the installed solar PV panels can work towards the expected lifespan (30 years) with the satisfactory generation efficiency. The general annual service charge for solar PV panels is £120 (including 20% of VAT) for UK homes. Energy Efficient Solutions (2022) suggested a GSHP or ASHP can be serviced by a heat pump technician every two to three years if the heat pump is only used for space heating. The general service cost is £210 per service for ASHP (including 20% of VAT), and £330 per service for GSHP (including 20% of VAT). Based on the information listed on the UK based renewable energy consultancy websites (Westward energy services, 2022; YouGen, 2022), STC needs serviced every two years at a charge of £144 (including 20% of VAT) for UK homes. The Tesla Powerwall and solar inverters do not need regular service. However, a hot water cylinder needs annual service; the calculated typical annual servicing cost (based on the method in section 3.3.2.2.) for a domestic hot water cylinder is £95 (including 20% of VAT). Table 4-4 presents the servicing frequency, cost and the associated information source of the shortlisted renewable systems and hot water cylinder.

Table 4-4. Servicing frequency and cost (excluded VAT) of the renewable energy system and hot water cylinder

System	Service frequency	Service cost (£) including 20% of VAT	Reference
Solar PV	Annual	120	(Checkatrade, 2022; GreenerGroup, 2022b; Howell, 2022)
ASHP	Every two to three years	210	(Energy Saving Trust, 2022a; GreenMatch, 2022a; Heat Pump Assist, 2022)
GSHP	Every two to three years	330	(Energy Saving Trust, 2022a; Heat Pump Assist, 2022; IMS Heat Pumps, 2022)
STC	Every two years	144	(The greenage, 2020; Westward energy services, 2022; Wondrausch, 2011)
Hot water cylinder	Annual	95	(PlumbNation, 2022h)

4.3.2. Embodied carbon data of renewable energy system, battery, and solar inverters

The embodied carbon data of renewable energy systems, batteries and solar inverters are collected using the method explained in section 3.5. The hot water cylinder's embodied carbon was not separately presented, as it was included in the embodied carbon calculation of STC based on the selected research articles. This section presents the embodied carbon of all systems within the boundary between cradle and grave to ensure the data is comparable across different systems. The presented embodied carbon of the renewable systems, battery and solar inverters can reflect the general condition of such systems globally published between 2000 and 2019. However, the data might not represent the exact embodied carbon data of renewable systems, batteries, and solar inverters in the UK context. The selected research articles investigated embodied carbon of systems manufactured in different countries between 2000 and 2019. The identified embodied carbon can present a general embodied carbon condition of such systems from a global rather than a specific country’s perspective. Figure 4-10 presents embodied carbon of the shortlisted renewable energy systems.

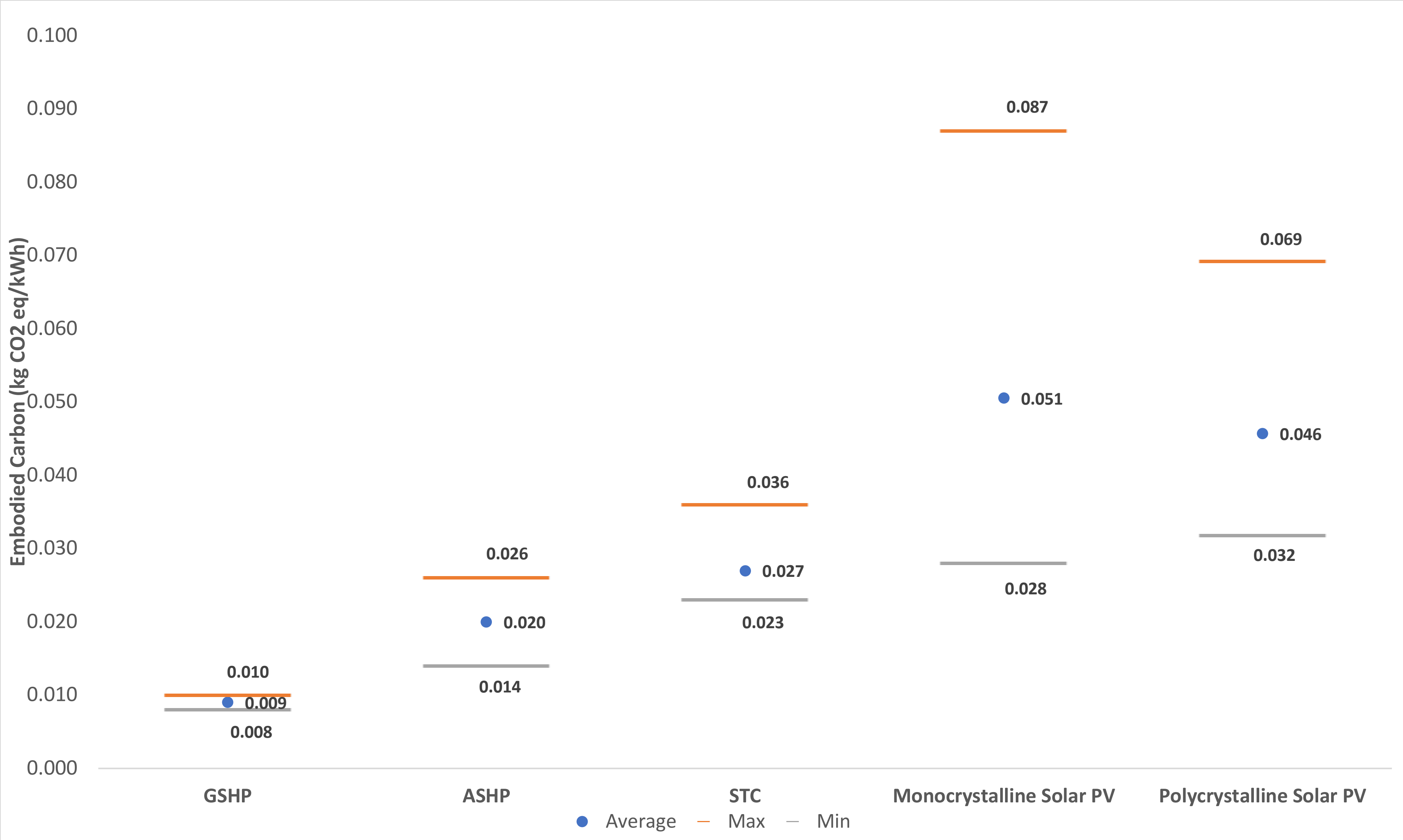


Figure 4-10. Embodied carbon of renewable systems

The average embodied carbon value is calculated based on the identified embodied carbon of such systems (Alsema, 2000; Ardente et al., 2005; Blum et al., 2010; Frischknecht et al., 2005; Fthenakis & Kim, 2011; Greening & Azapagic, 2012; Hsu et al., 2012; Johnson, 2011; Kannan et al., 2006; (Mariska) de Wild-Scholten, 2013; Milousi et al., 2019; Nawaz & Tiwari, 2006; Pacca et al., 2007; Peng et al., 2013a, 2013b; Vivas et al., 2018; Yue et al., 2014; Zhai & Williams, 2010). The maximum embodied carbon value is the identified highest embodied carbon value from the selected articles, and the minimum embodied carbon value is the identified lowest embodied carbon value. The data presented in Figure 4-10 indicates that GSHP and ASHP have lower average embodied carbon per unit (kg CO_2 eq/kWh) than solar PV and STC. Monocrystalline solar PV has the highest embodied carbon per unit (kg CO_2 eq/kWh) than the other systems.

Embodied carbon of a commercial solar inverter (Huawei solar inverter – SUN 2000-6KTL-L1) is 55.61 kg CO2/kW (Huawei, 2020). The embodied carbon of the solar inverter with the required size (2-3 kW) is about 20 times smaller than solar PV. In addition, the solar inverter has a shorter lifespan (generally about 10-15 years) than other renewable energy systems (between 20-30 years). In addition, some relevant research also considers embodied carbon of solar inverter is considerably tiny and would not have an impact on the embodied carbon calculation for the solar PV systems (Alsema, 2000; Milousi et al., 2019). Therefore, this research excludes embodied carbon of solar inverter in the overall embodied carbon of HRES combinations.

A limited number of research articles were found that investigated embodied carbon of battery. Thus, this research also collected battery embodied carbon data from the grey literature (e.g., reports from the Carbon Brief and Swedish Environmental Research Institute). This research specified embodied carbon data of battery from the cradle to the grave, enabling consistency with embodied carbon data of other systems. Figure 4-11 presents embodied carbon of the battery.

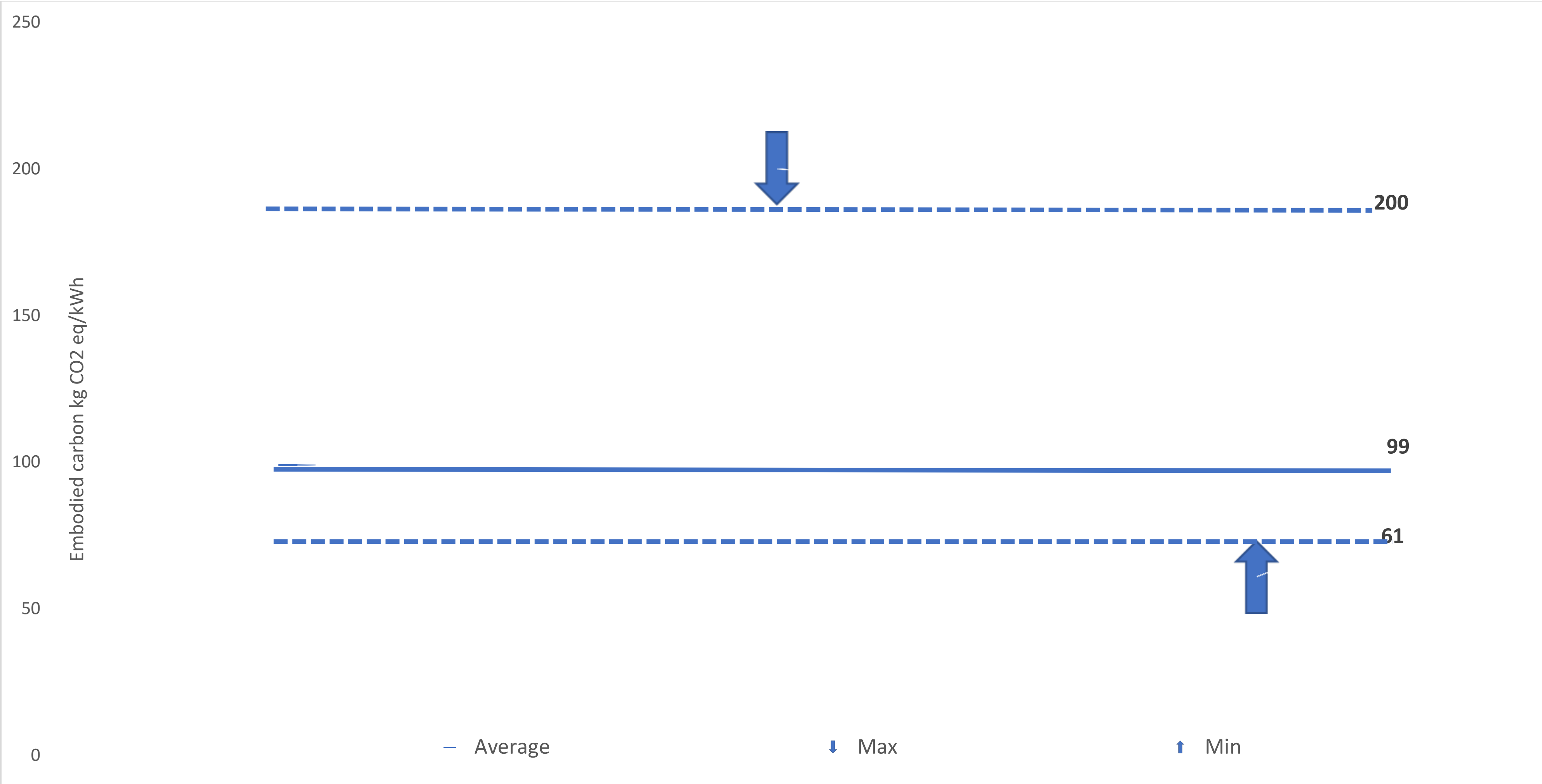


Figure 4-11. Embodied carbon of battery

The average embodied carbon of battery based on the selected articles is 99 kg CO_2 eq/kWh, with the identified highest embodied carbon 200 kg CO_2 eq/kWh and the lowest embodied carbon 61 kg CO_2 eq/kWh. The calculated average embodied carbon of battery is close to the reported average embodied carbon of 100 kg CO_2 eq/kWh on Carbon Brief (Zeke Hausfather, 2019). The report compiled 17 different lifecycle emission studies of battery manufactured in Asia, Europe, US, and other regions. The highest embodied carbon of battery is sourced from the report published by Swedish Environmental Research Institute (IVL) (Romare & Dahllöf, 2017). The report mainly compiled relevant studies from the Asia region between 2010 and 2016. Due to the limited regional coverage in the first report, IVL updated and released the revised report in 2019 (Emilsson & Dahllöf, 2019), which included embodied carbon data from relevant studies in different regions (e.g., Europe, U.S.A etc). The range of the battery embodied carbon from the IVL's revised report (2019) is lower than its first report (2017), with the maximum value of 106 kg CO_2 eq/kWh.

The calculated average embodied carbon values of renewable systems and battery are used in the environment performance evaluation of the HRES combinations. The performance evaluation results are helpful to support the discussion of the benefits and limitations of adopting the HRES combinations compared with the current energy systems (e.g., boilers). The detailed environmental performance evaluation results are shown in section 4.4.4.

4.3.3. Energy tariff and emission factor of the selected representative energy supplier

The unrestricted electricity (non-fixed electricity tariff) and standards gas tariffs from E. ON's energy plan were collected on 1st October 2021 and updated on 1st April 2022 due to the UK's energy cap being increased. The collected energy tariffs from two periods help compare the impact of the increased energy cap on the UK homes' annual energy bills. The comparison results can support the discussion of the benefits of replacing the current energy systems with the on-site renewable energy system against likeliness of the future energy bill continue to increase (section 5.1) (Ofgem, 2022a, 2022b). The energy tariff for South Wales and Southern England were considered as representative regions for England and Wales. All collected energy tariff data included 5% of VAT charge. Figure 4-12 presents the electricity tariff from E. ON for both dates and both regions.

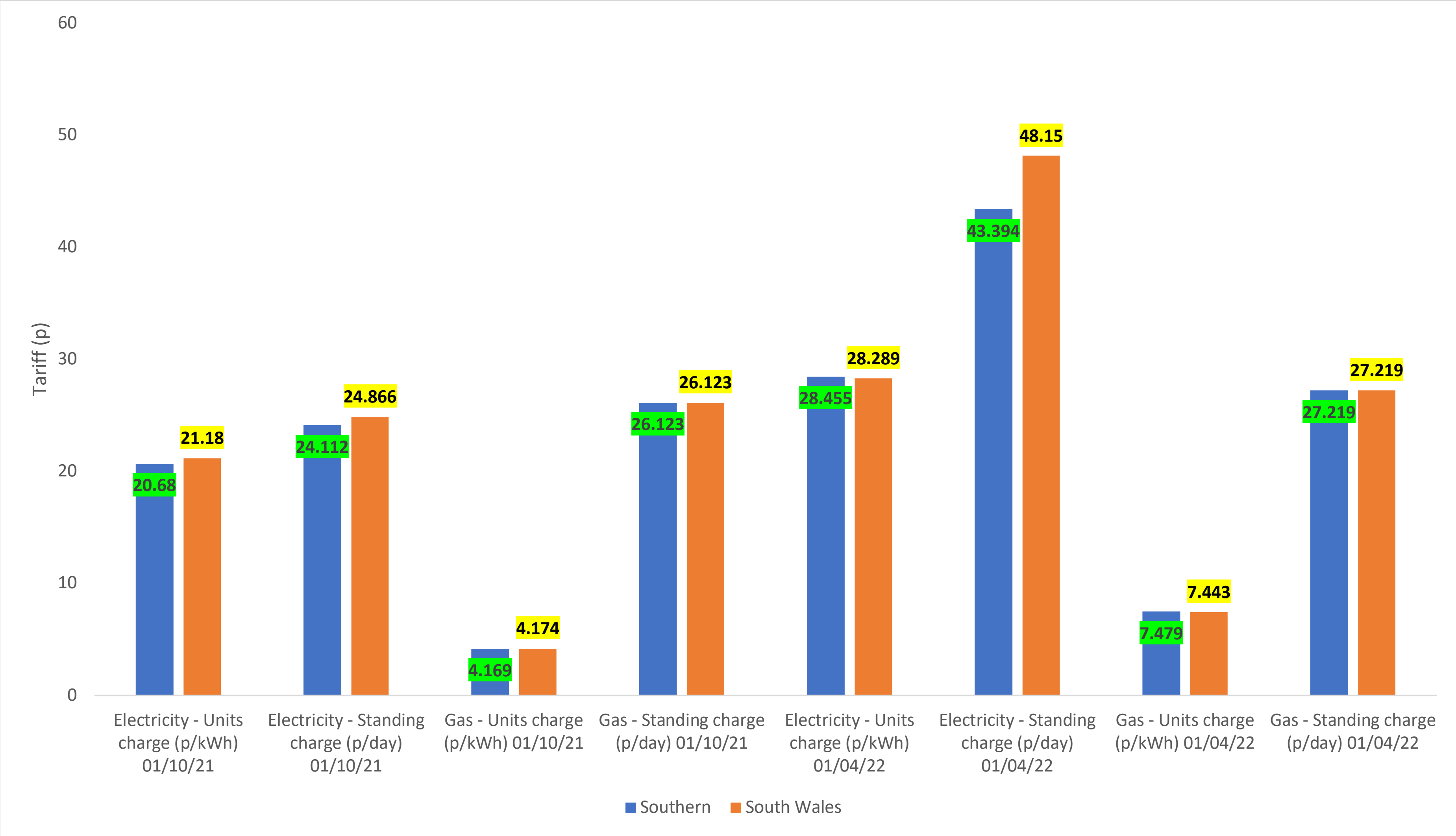


Figure 4-12. E. ON's Electricity Tariff - 1st October 2021 to 1st April 2022

After 1st April 2022 (energy cap increased), the unit charge of electricity increased by about 7p/kWh (about 35% increasing rate) in Southern England and South Wales. The unit charge of natural gas increased by about 3p/kWh in such regions. The standing charge of electricity has been increased by 22p/day in Southern England and South Wales. The standing charge of natural gas increased by about 2.5p/day. Overall, the energy (both electricity and natural gas) tariff increased about 46% in both Southern England and South Wales.

The electricity grid and natural gas pipeline emission factors were collected in February 2022, following the method explained in section 3.7. The emission factor of the electricity grid is 0.2123 kg CO_2 eq/kWh, and the gross calorific value (GCV) of the natural gas is 0.1832 kg CO_2 eq/kWh. The collected emission factor can reflect the GHG emission of the UK's electricity grid and natural gas pipeline in 2021.

4.4 Economic-Technical-Environment performance analysis of HRES configurations

This section presents the calculated HRES configurations (power ratings) considering the chosen representative domestic building and the associated energy demand (subsection 4.4.1). It then presents the economic (subsection 4.4.2), technical (subsection 4.4.3) and environment performance (subsection 4.4.4) using the identified relevant indicators of each HRES combination.

4.4.1. Practical HRES combination and the associated configurations

Based on the simulated energy of the representative retrofitted home presented in section 4.1. The space heating demand in the defined intensive heating period (from October to March) is 3,319kWh. The annual domestic hot water consumption (DHW) is 1423 kWh, and the annual lighting and electrical appliance consumption is 777 kWh and 2091 kWh, respectively. The simulated energy demand was used to calculate the configurations (same as the power ratings) for each HRES combination using the calculation method and the defined DCPs scenarios explained in sections 3.9 and 3.10. Table 4-5 presents all practical HRES combinations. Each combination with the calculated power rating was calculated automatically through the developed spreadsheet; the detail about the created spreadsheet explains in section 4.7.

Table 4-5. Practical HRES combinations

	Configuration	Electricity coverage (%)	Space Heating (SH) coverage (%)	Domestic Hot Water (DHW) coverage (%)
PV, ASHP & Battery	2.25kW\p PV+3kW ASHP	80%	100%	0
	2.5kW\p PV+3kW ASHP	90%	100%	
	2.75kWp PV+3kW ASHP	100%	100%	
	2.25kWp PV+3kW ASHP+13.5kWh Battery	80%	100%	
	2.5kWp PV+3kW ASHP+13.5kWh Battery	90%	100%	
	2.75kWp PV+3kW ASHP+13.5kWhBattery	100%	100%	
PV, GSHP & Battery	2.25kWp PV+3kW GSHP	80%	100%	
	2.5kWp PV+3kW GSHP	90%	100%	
	2.75kWp PV+3kW GSHP	100%	100%	
	2.25kWp PV+3kW GSHP+13.5kWh Battery	80%	100%	
	2.5kWp PV+3kW GSHP+13.5kWh Battery	90%	100%	
	2.75kWp PV+3kW GSHP+13.5kWhBattery	100%	100%	
PV, ASHP, STC, Battery & Hot water cylinder	2.25kWp PV+3kW ASHP+1.5kWSTC	80%	100%	100%
	2.5kWp PV+3kW ASHP+1.5kWSTC	90%	100%	
	2.75kWp PV+3kW ASHP+1.5kWSTC	100%	100%	
	2.25kWp PV+3kW ASHP+1.5kWSTC+13.5kWh Battery	80%	100%	
	2.5kWp PV+3kW ASHP+1.5kWSTC+13.5kWh Battery	90%	100%	

	2.75kWp PV+3kW ASHP+1.5kWSTC+13.5kWh Battery	100%	100%	
PV, GSHP, STC, Battery & Hot water cylinder	2.25kWp PV+3kW GSHP+1.5kW STC	80%	100%	
	2.5kWp PV+3kW GSHP+1.5kW STC	90%	100%	
	2.75kWp PV+3kW GSHP+1.5kWSTC	100%	100%	
	2.25kWp PV+3kW GSHP+1.5kW STC+13.5kWh Battery	80%	100%	
	2.5kWp PV+3kW GSHP+1.5kW STC+13.5kWh Battery	90%	100%	
	2.75kWp PV+3kW GSHP+1.5kWSTC+13.5kWh Battery	100%	100%	

The combination of PV and GSHP or ASHP can generate electricity and heat to meet the coverage percentage of electricity and space heating demand. However, such combinations are not designed to generate energy for the DHW demand. The smallest commercially available ASHP or GSHP from the MCS-recognised brands is 3kW, which generates sufficient heat to cover 100% of space heating demand in the winter. Solar PV ranged between 2.25 kWp and 2.75 kWp, the range covers 80% to 100% of the required electricity demand.

The combinations of PV, GSHP/ASHP and STC are designed to generate electricity and heat to meet the coverage percentage of electricity, space heating and DHW demand. The calculated 1.5 kW STC can supply sufficient heat to meet 100% coverage of DHW. 100-litre hot water cylinder is added to the combinations, stabilising the DHW supply in the night or less efficient solar radiation period. The advantages of using STC to supply DHW demand are:

- The HRES combination can import less electricity from the grid to power heat pumps for the DHW demand when solar PV cannot generate sufficient electricity. The current electricity from the national grid is not being entirely decarbonised (BEIS, 2022), and the electricity tariff through the national grid is likely to continue rising (Ofgem, 2022c). It is cost-effective with less GHG emission at the operational stage to consider HRES combinations to import less electricity from the national grid.
- The size of the heat pump is smaller to provide space heating only compared to providing both space heating and DHW. The smaller size of the heat pump is more practical to be installed in Welsh homes due to the permitted development requirement of installing renewable systems in Wales (Department for Communities and Local Government, 2012).

Tesla Powerwall 3.0 is added to all HRES combinations. Powerwall 3.0 is a 13.5kWh battery, and it can ensure the electricity supply stability, decrease the grid dependency, and reduce carbon emission for the whole HRES combination system in the energy supply.

The practical HRES combinations presented in Table 4-5 benefits from the following financial incentive schemes: smart export guarantee (SEG) and renewable heat incentives (RHI). RHI is due to closure for the new applicants after 31st March 2022, and the government introduced a new renewable heat incentive over 3 years from

2022 to 2025, termed boiler upgrade scheme (BUS). Unlike RHI, BUS only covers biomass and G/ASHP but not STC. In addition, BUS requires the listed renewable heating systems to cover space heating and DHW. Table 4-6 presents HRES combinations eligible for the BUS incentive.

Table 4-6. Practical HRES combinations benefit from BUS

	Configuration	Electricity coverage (%)	Space Heating (SH) coverage (%)	Domestic Hot Water (DHW) coverage (%)
PV, ASHP & Battery	2.75W\p PV+4kW ASHP	80%	100%	100%
	3.25kW\p PV+4kW ASHP	90%	100%	
	3.5kWp PV+4kW ASHP	100%	100%	
	2.75kWp PV+4kW ASHP+13.5kWh Battery	80%	100%	
	3.25kW\p PV+4kW ASHP +13.5kWh Battery	90%	100%	
	3.5kWp PV+4kW ASHP+13.5kWh Battery	100%	100%	
PV, GSHP & Battery	2.75kWp PV+4kW GSHP	80%	100%	
	3kWp PV+4kW GSHP	90%	100%	
	3.5kWp PV+4kW GSHP	100%	100%	
	2.75kWp PV+4kW GSHP +13.5kWh Battery	80%	100%	
	3kWp PV+4kW GSHP +13.5kWh Battery	90%	100%	
	3.5kWp PV+4kW GSHP+13.5kWhBattery	100%	100%	

The calculated configurations (power ratings) for GSHP and ASHP in HRES combinations are bigger than HRES combinations in Table 4-5. This is because GSHP and ASHP in Table 4-6 are designed to cover the selected representative domestic building's space heating and DHW demand. Like Table 4-5, the configuration (power ratings) for each combination was automatically calculated through the developed spreadsheet that explains in detail in section 4.7. The solar PV is used to power GSHP and ASHP to run in each HRES combination; therefore, the configuration of solar PV is bigger in Table 4-6 than in Table 4-5. In the combinations of PV+ASHP/GSHP with/without battery, PV size ranges from 2.75kWp to 3.5kWp, which can cover 80-100% of electricity demand.

The following section first presents the economic-technical-environmental performance of HRES combinations benefiting from the SEG and RHI scheme, followed by the performance of HRES combinations benefiting from the SEG and BUS scheme.

4.2. Economic performance of HRES combination

The economic performance indicators are selected following the method explained in section 3.12. The selected economic indicators are benefit-cost ratio (BCR), capital cost, discounted payback period (DPP) and lifecycle cost (LCC).

4.4.2.1. Capital cost and Life Cycle Cost (LCC)

The capital cost includes product and installation costs for ASHP, solar PV, STC and battery. The installation cost of the hot water cylinder and solar inverter is included in the installation cost of STC and solar PV, respectively. The capital cost of GSHP includes product, installation, and groundwork cost.

The lifecycle cost (LCC) is also used in the economic performance evaluation. The LCC includes capital, maintenance, and replacement cost. This study selected 20 years to calculate the lifecycle cost because of the most commercially available ASHP/GSHP, battery and solar PV and STC have at least 20 years lifespan. However, the solar inverter cannot last for more than 15 years, then LCC includes a replacement cost of solar inverter within 20 years.

The capital cost for the combination of solar PV and ASHP, and solar PV, ASHP and STC with/without battery are presented in Figure 4-13. The capital cost of the PV with ASHP ranges from £7,506 to £8,509, and the capital cost of the PV, ASHP, STC and hot water cylinder ranges from £11,170 to £12,173. The added battery brings the capital cost for the combination of PV and ASHP up to £19,537, and up to £23,201 for the combination of PV, ASHP and STC. The capital cost increased by about 50% after adding the battery to the combinations.

The capital cost of the combinations containing GSHP are more expensive than those containing ASHP due to the high groundwork cost. The capital cost of solar PV with GSHP ranges from £16,452 to £17,455, about 50-55% higher than the capital cost of solar PV with ASHP. The capital cost of the solar PV, GSHP, STC with hot water cylinder combinations ranges between £20,117 and £21,119. The capital cost increased by 42-47% compared with the solar PV, ASHP, STC with hot water cylinder combinations. The capital cost increased to £28,483 for PV+GSHP with a battery, and up to £32,147 for the combination of PV+GSHP+STC with a battery. The capital cost is about 33% higher than the combination of solar PV, GSHP, STC with hot water cylinder. Figure 4-13 presents the capital cost of the selected HRES combinations.

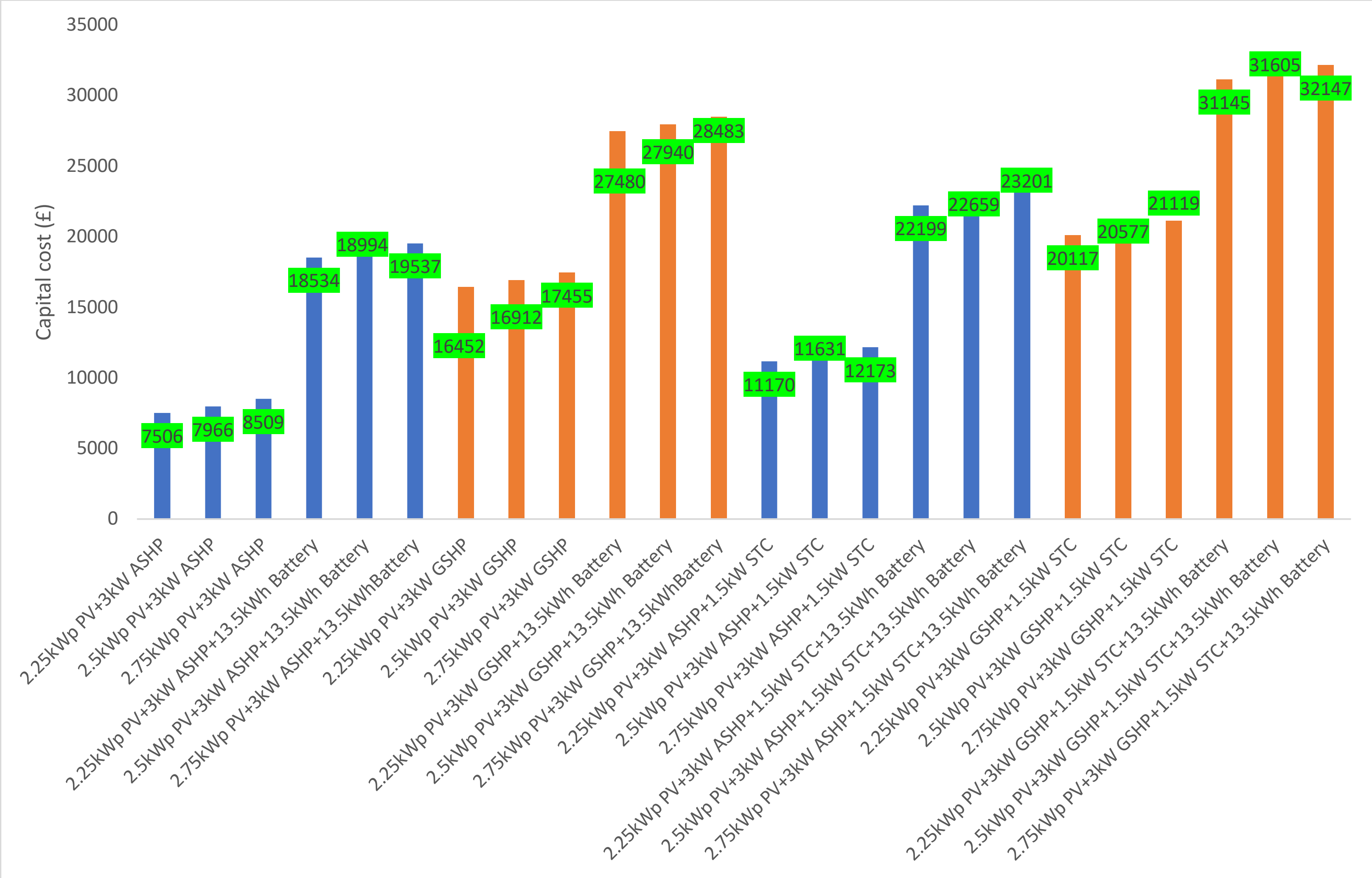


Figure 4-13. Capital cost (£) of HRES combinations with/without a battery

The energy tariffs of electricity and natural gas in South Wales are used to calculate the lifecycle cost of the energy bill. The energy tariff in South Wales is slightly higher than in Southern England; the higher energy tariff can better reflect the economic benefits of using HRES combinations. The overall energy bill for the selected representative retrofitted home is £20,982 for electricity, DHW and space heating in 20 years.

LCC for PV+ASHP supply space heating and electricity for the selected representative home is between £11,019 and £12,089 without a battery; £22,046 and £23,117 with a 13.5kWh battery. LCC for PV+ASHP+STC supply space heating, DHW and electricity for the selected representative home is between £15,689 and £16,759 without a battery; LCC is between £26,717 and 27,787 with a battery. After adding the battery to the combination, the LCC has increased by 50% for PV+ASHP and about 40% for PV+ASHP+STC. After installing PV+ASHP without a battery for the selected retrofitted home, the energy bill is between £19,615 and £19,739. The energy bill is between £13,311 and £13,596 after installing a battery to the combination of PV+ASHP. The energy bill is between £18,174 and £18,298 for PV+ASHP+STC without a battery; the energy bill is about £1,500 less than PV+ASHP in 20 years. The energy bill drops again down between £11,869 and £12,155 for adding a battery to the combination of PV+ASHP+STC. The added battery helps reduce about £6,400 compared with the same HRES combinations without the battery in energy bills.

The LCC for PV+GSHP without a battery is between £20,803 and £21,873, about £10,000 higher than the LCC of solar PV with ASHP. Adding a battery to the combination, LCC is between £31,831 and £32,901; the LCC for PV+GSHP+Battery is £11,000 higher than PV+GSHP without a battery. The LCC for PV+GSHP+STC without a battery is between £25,473 and £26,543; it is also about £10,000 higher than PV+ASHP+STC. The LCC for PV+GSHP+STC with a battery is between £36,500 and £37,571, about £11,000 higher than PV+GSHP+STC without a battery. The energy bill in 20 years for PV+GSHP and PV+GSHP+STC is between £18,000 and £19,000. The added battery reduced energy bills by about £6,400 in 20 years compared with the same combinations without a battery. Figure 4-14 presents the LCC stated above.

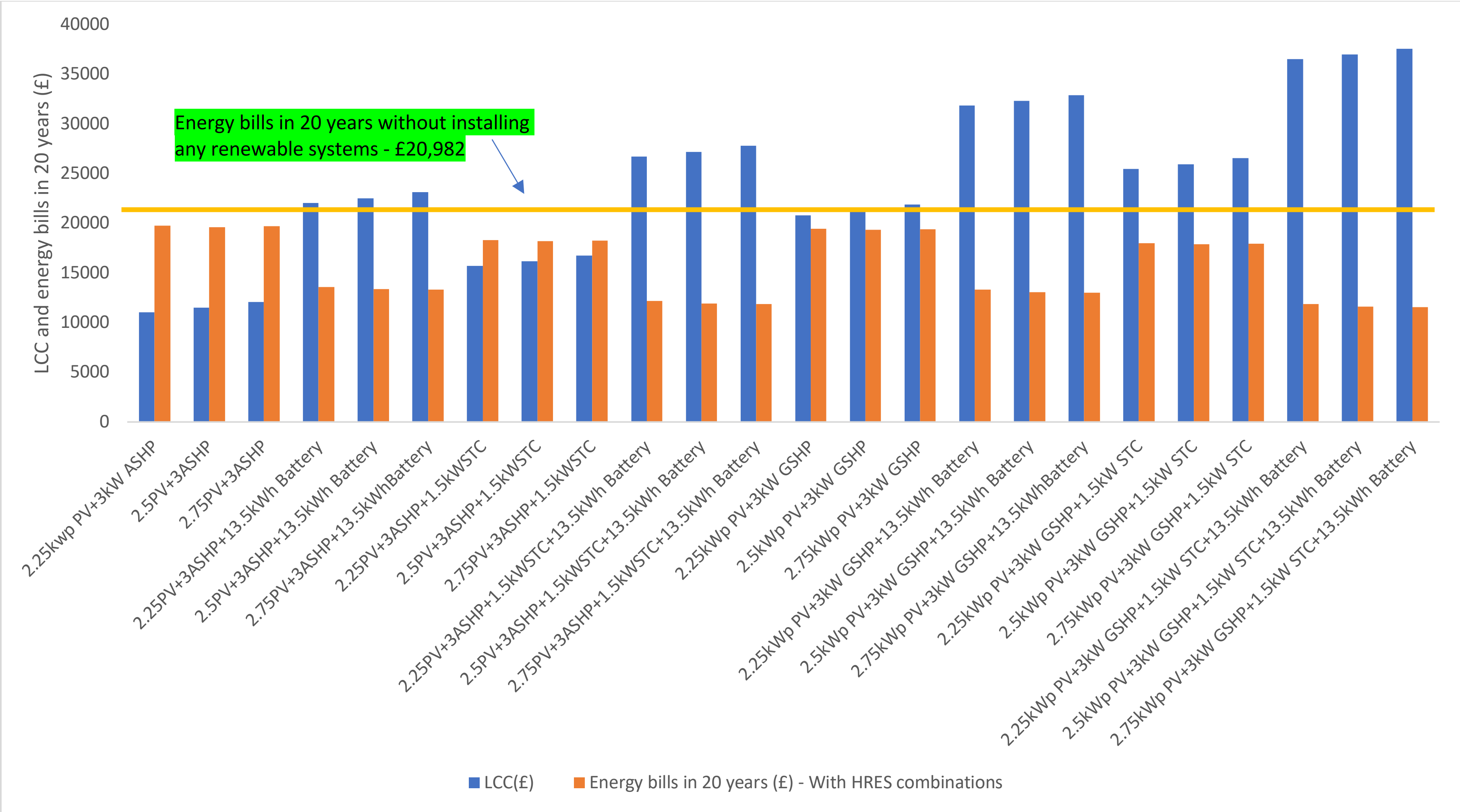


Figure 4-14. LCC and the associated energy bills of each HRES combination, and energy bills in 20 years without installing any renewable system

The BUS offers a maximum of £5,000 voucher to replace the boiler by the ASHP, and a maximum of £6,000 voucher to upgrade the boiler to the GSHP. The voucher is used to deduct the capital cost for ASHP or GSHP. In the BUS incentive, the capital cost of PV+ASHP (without a battery) is between £7,506 and £8,509. The capital cost, on average, is about 35% lower than the combination of PV+ASHP+STC (without a battery) to the same energy demand. The capital cost of PV+ASHP (with a battery) is between £18,534 and £19,537. The capital cost is about 20% lower than the combination of PV+ASHP+STC (with a battery).

The capital cost for the combinations of PV+GSHP to supply space heating, DHW and electricity demand ranges from £14,690 to £16,152 without a battery under the BUS incentive. The PV+GSHP+STC combinations (without a battery) supply the same demand under the RHI scheme, with the capital cost ranging from £20,117 to £21,119. The capital cost for the combination of PV+GSHP+STC is about 25% higher than PV+GSHP through different renewable heat incentives. The capital cost for PV+GSHP+STC (with a 13.5kWh battery) combinations is about 17% higher than PV+GSHP (with a 13.5kWh battery) to supply electricity, DHW and space heating demand. Figure 4-15 presents the capital cost stated above.

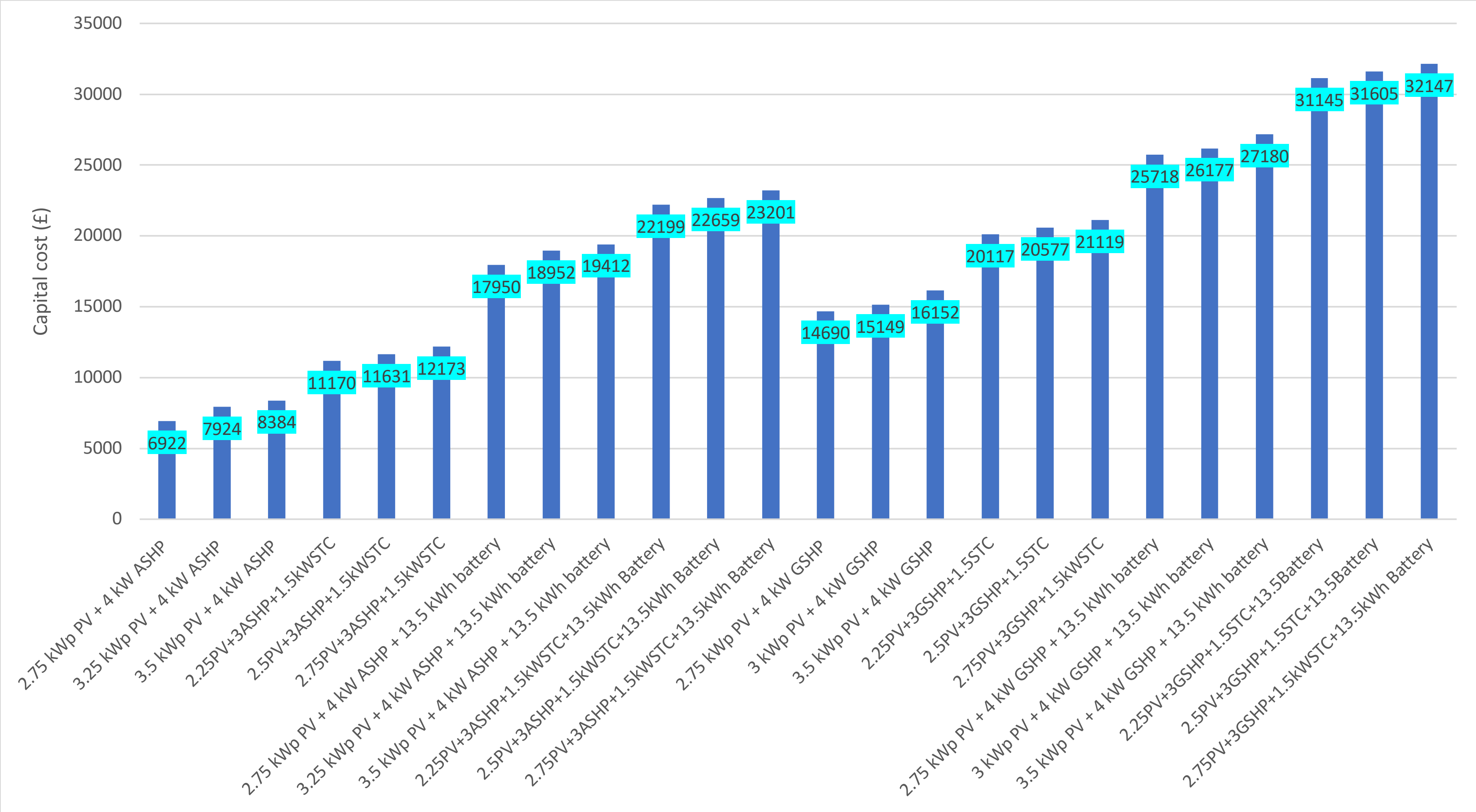


Figure 4-15 Capital cost for HRES combinations under RHI and BUS incentive

The difference in LCC between PV+ASHP under BUS and PV+ASHP+STC combinations under the RHI scheme without a battery is less than 5%. The difference in LCC between PV+GSHP under BUS and PV+GSHP+STC under the RHI scheme without a battery is about 8%. After adding a 13.5 kWh to HRES combinations, the difference of LCC is 18% between combinations under the BUS and RHI scheme. In general, the combinations under RHI scheme have a lower energy bill than those under BUS incentive in 20 years. Section 5.3 will continue to discuss the cost and gained benefits of HRES combinations under different renewable heat incentives. Figure 4-16 presents LCC and energy bills for each HRES combination under RHI and BUS incentive.

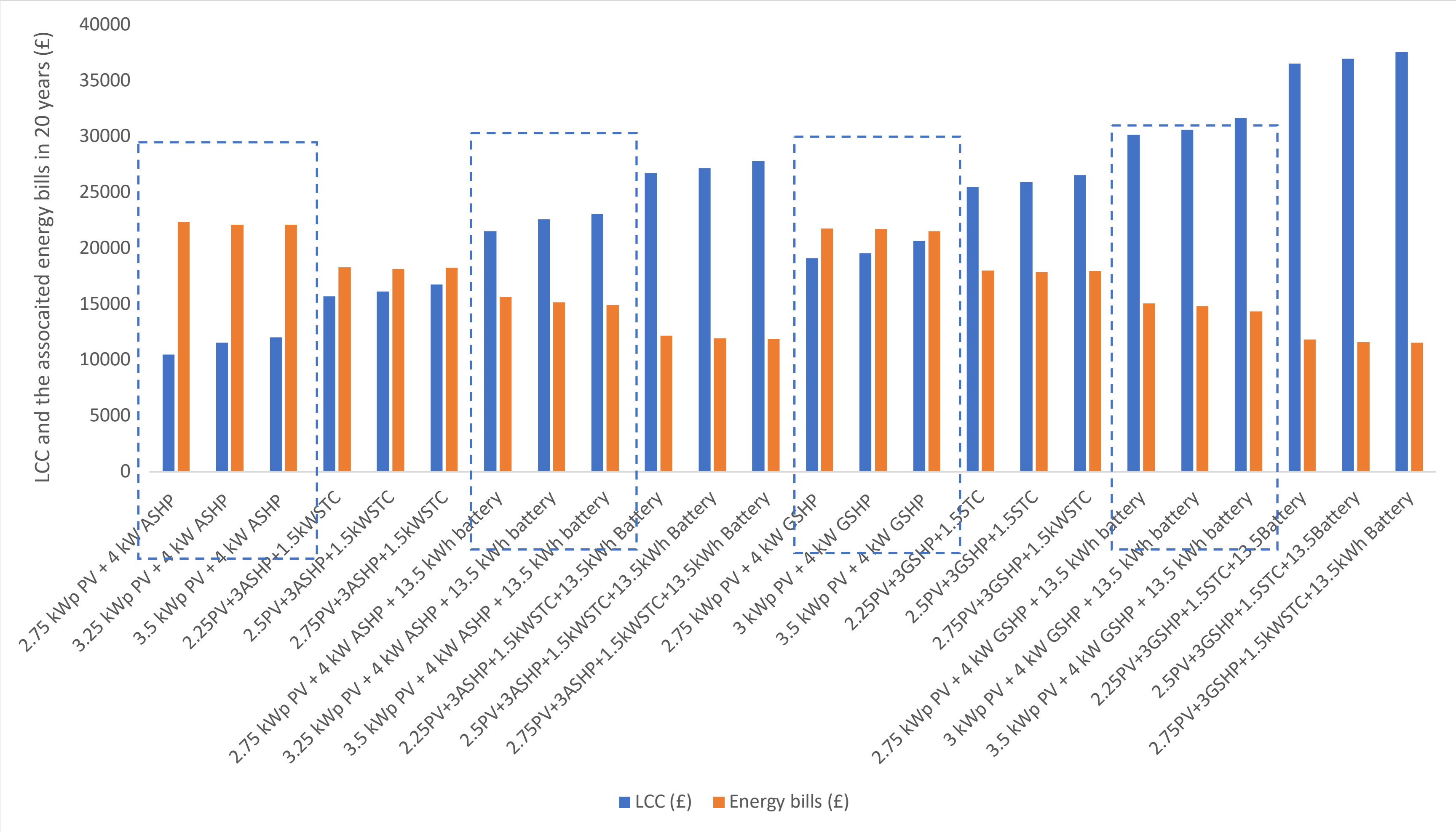


Figure 4-16. LCC and the associated energy bills in 20 years for HRES combinations under the RHI and BUS incentive. The blue dash lines included HRES combinations under the BUS incentives. The HRES combinations without blue dash lines are under the RHI scheme.

4.4.2.2. BCR

BCR is used to demonstrate the lifetime economic benefits of different HRES combinations. The BCR is calculated using the gained benefits to divide by the overall cost within the considered lifecycle (20 years in this research). The gained benefit is represented by the present value of benefits (PVB). The PVB includes the saved energy cost compared with using electricity from the grid and natural gas and the received benefits from the relevant financial incentives. The overall cost is represented by the present value of cost (PVC). It includes the capital, replacement, and servicing cost of HRES combinations. The higher BCR indicates the HRES combination has a higher economic benefit in 20 years. In addition, BCR above one indicates that the HRES combination can expect an economic payback in 20 years. However, no HRES combination has BCR above ‘1’, which means no HRES combination in this research expects an economic payback within 20 years.

The combination of PV, ASHP and STC has a slightly higher BCR value (about 0.58) than the combination of PV, GSHP and STC (about 0.46). GSHP has a higher SCOP and is more efficient than ASHP in supplying space heating demand and requires less electricity from the grid. However, in terms of the capital cost of GSHP, the groundwork cost is expensive and significantly decreases the BCR value for the combination of PV and GSHP or PV, GSHP and STC.

BCR value decreased by about 5% by comparing the combination of PV+ASHP and PV+ASHP with a battery. The small decrease in BCR indicated the added battery helps reducing the annual electricity bill by importing less electricity from the grid. However, the reduced annual electricity bill cannot compensate for the capital cost of the battery. The battery neither benefits from the reduced VAT (5%) nor financial incentive schemes.

The BCR value for PV and GSHP, and PV, battery and GSHP are different to the similar combination with ASHP. PV, battery and GSHP have a slightly higher BCR value (about 0.40) than PV and GSHP (about 0.38). Like PV, ASHP and battery, the added battery reduces the electricity bill of the imported electricity grid to compensate for the electricity demand period that the HRES combination cannot cover. The saved electricity bill compensated for the expensive groundwork cost, which caused a slightly increasing in BCR value compared with the combination of PV+GSHP.

STC can increase the economic benefits of the combination for both GSHP and ASHP by saving more natural gas for DHW. The added STC increased BCR value for ASHP and PV as well as GSHP and PV. BCR value increased by about 18% after adding STC to PV and ASHP as well as PV and GSHP. The increased BCR value indicates the positive economic benefits of adding STC to the combination. In addition, the reduced VAT (5%) and financial incentive scheme can positively impact the economic performance of installing STC to the system combinations.

The added STC increased the BCR value for PV, ASHP/GSHP and battery by about 12%. The increased BCR value indicates that STC and battery reduce the annual energy bill by importing less natural gas and electricity. The saved energy bill then compensates for the capital cost of the entire combined system. Due to the high capital cost, no available financial incentive and reduced VAT for installing a battery, the added STC to the combination with a battery demonstrates less economic benefits than the combination without a battery. The combination of STC, solar PV, A/GSHP and battery has a lower BCR (between 0.45 and 0.5) than STC, solar PV and A/GSHP (between 0.46 and 0.58). The relevant BCR value that discussed above is presented in Figure 4-17.

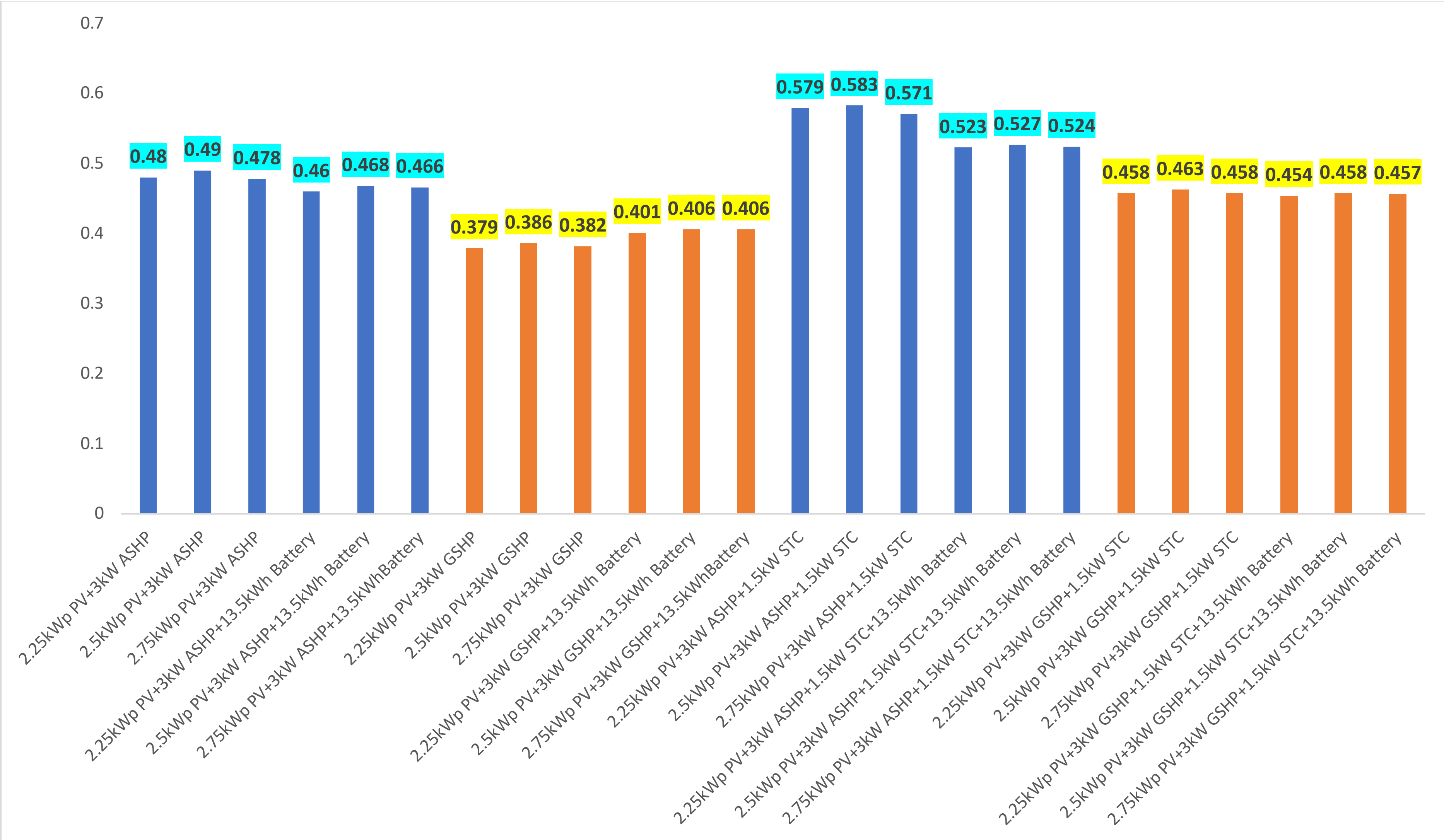


Figure 4-17. BCR value for the combination of PV+ASHP and PV+ASHP+STC with/without a battery

Whilst HRES combinations under BUS incentive have better performance in capital cost and LCC than HRES combinations under RHI to supply the electricity, DHW and space heating demand. HRES combinations under the BUS incentive have a low BCR value than combinations under the RHI scheme. The lower BCR indicates that the combinations are less economically competitive. The possible reason for the combinations under BUS incentive having a lower BCR is that the combinations import more electricity from the grid to power the heat pumps for DHW and space heating purposes. However, the combinations under the RHI scheme import electricity from the grid to power heat pumps only for space heating demand, and the STC system provided DHW. The more imported electricity led to less saved electricity cost at the operational stage. Therefore, more imported electricity causes the lower BCR for HRES combinations under the BUS incentive. Another possible reason is that RHI provides more economic benefits than BUS for renewable heating systems, and it will be discussed in section 5.3. Figure 4-18 presents BCR value for HRES combinations under BUS and RHI scheme.

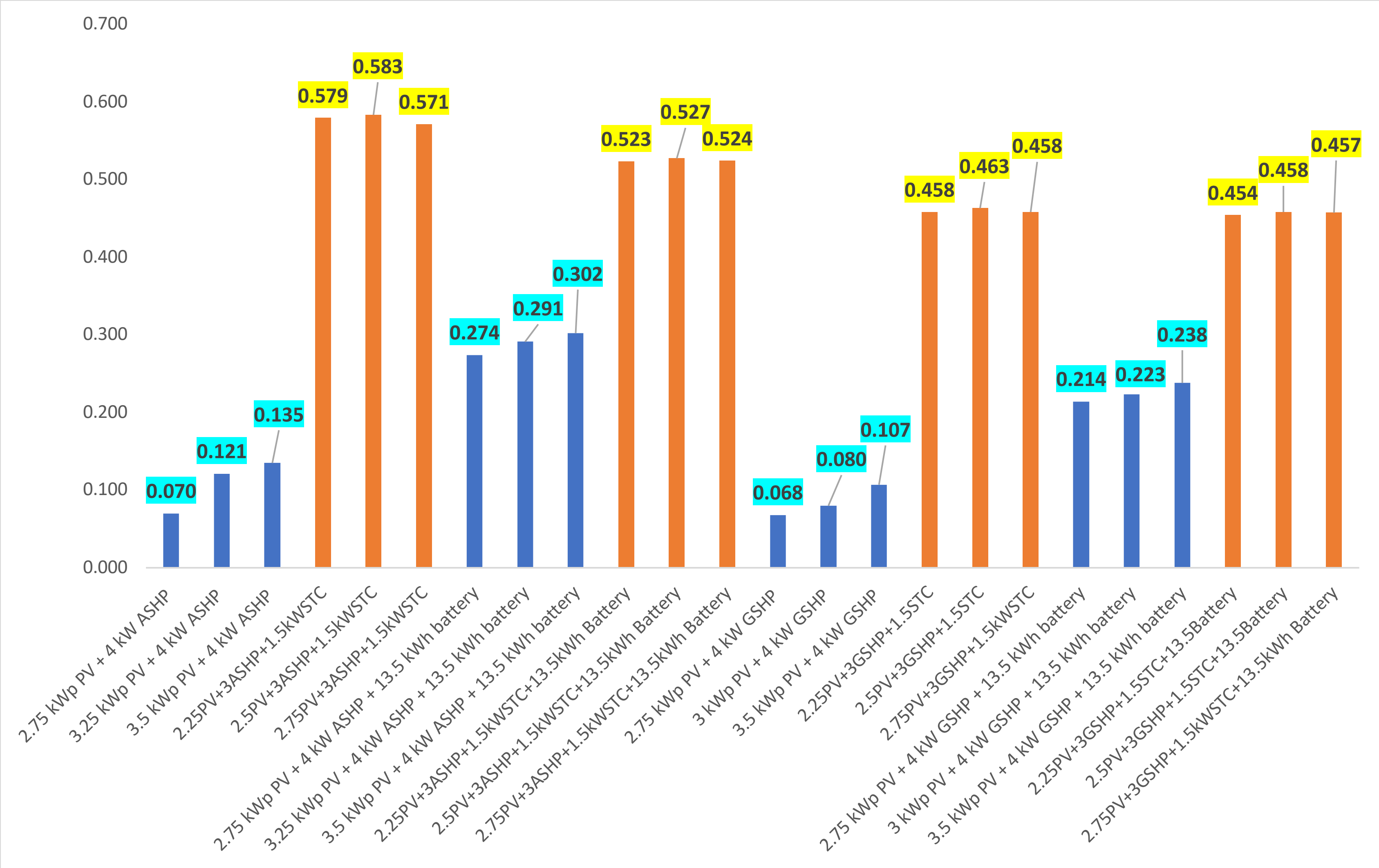


Figure 4-18 BCR value for HRES combinations under BUS and RHI scheme

4.4.3. Technical performance of HRES combinations

This section presented the grid electricity independence level (GEI) (subsection 4.4.3.1) and renewable fraction (RF) (subsection 4.4.3.2) of the practical HRES combinations.

4.4.3.1. Grid Electricity Independence level (GEI) of the practical HRES combinations

Grid electricity independence level (GEI) is an indicator to demonstrate the electricity supply stability by the on-site solar PV. GEI depends on the PV self-consumption rate and the electricity demand of the selected representative home. As explained in Chapters 2 and 3, the PV self-consumption rate describes the percentage of the generated electricity to match the electricity demand of the selected representative home. The PV self-consumption rate depends on the estimated size of solar PV, the electricity demand, the occupant's behaviour of the electricity consumption, and the usable capacity of the added battery. (MCS, 2019; National Energy Action, 2021). The battery helps increase self-consumption significantly; however, 100% of self-consumption requires a dedicated solar PV size that can match hourly electricity demand (Dual Sun, 2019). This research did not size solar PV to match the selected home's hourly but annual electricity demand. Therefore, adding a battery to HRES combinations is designed to cover 100% of the annual energy demand. The self-consumption rate of such combinations is not 100%, then no HRES combinations in this research achieved 100% of GEI.

The combinations of PV and GSHP have a slightly higher average GEI (about 2% higher) than PV and ASHP. This is because GSHP has a slightly higher SCOP than ASHP (SCOP = 3.3 for GSHP and SCOP = 3.1 for ASHP). The higher SCOP of GSHP needs less electricity to generate the required heating load than ASHP, which then boosted about 2% of GEI. The battery can significantly increase GEI, the GEI of HRES combinations with a battery are about 80% higher than the combinations without a battery. Figure 4-19 presents the GEI results that discussed above.

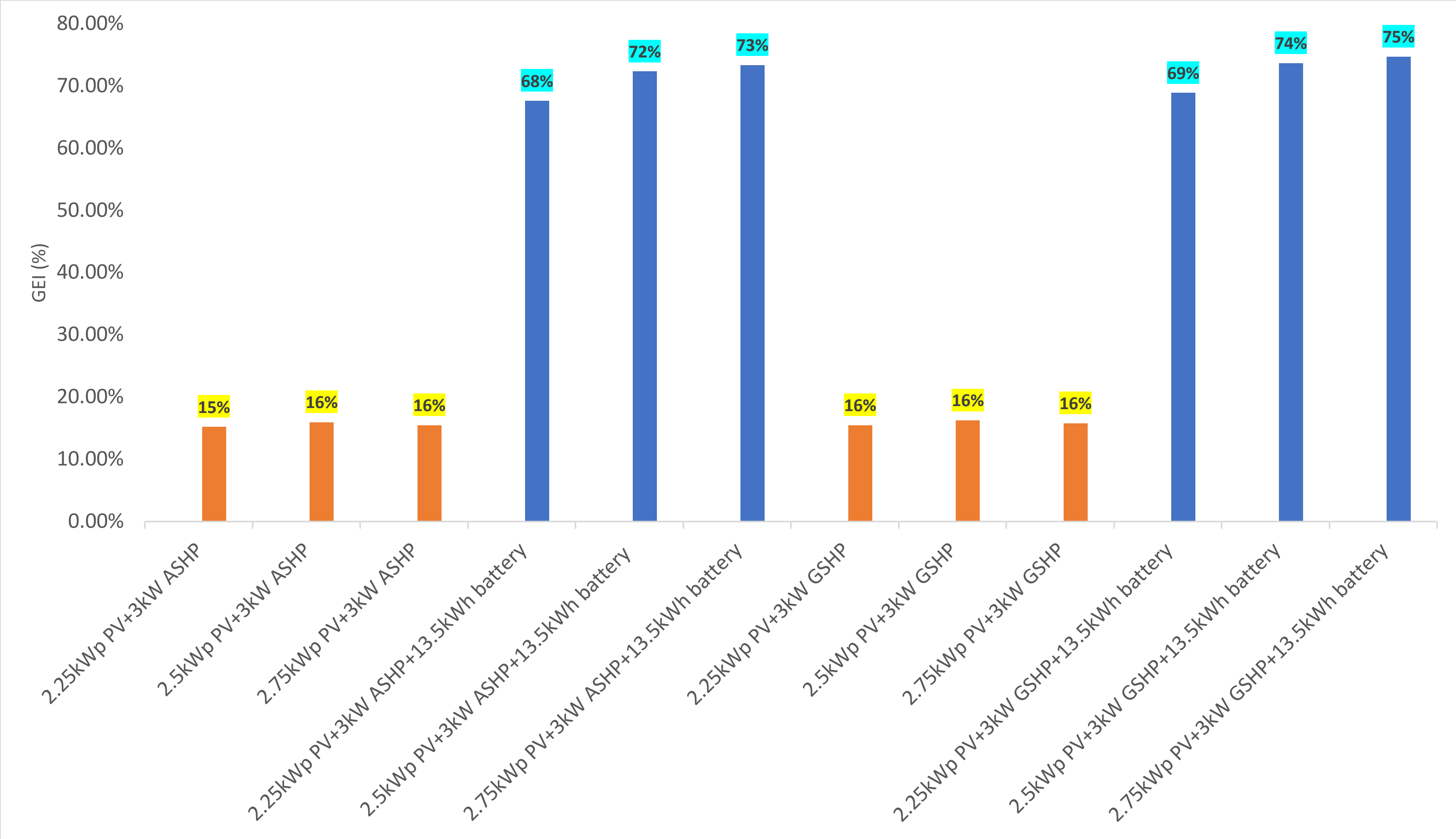


Figure 4-19. GEI (%) for HRES combinations

In general, the GEI of HRES combinations under the BUS incentive is about 20% lower than combinations under the RHI scheme. Based on the estimated electricity demand and the size of solar PV, the identified self-consumption rate for the HRES combination under the BUS incentive is 3%-5% lower than combinations under the RHI scheme. The lower self-consumption rate leads to a lower GEI for combinations under the BUS incentive. However, the HRES combinations that cover 100% of electricity and heat with a battery under the BUS incentive have a slightly higher GEI (about 2% higher) than the associated combinations with a battery under RHI scheme. Solar PV size in HRES combinations under the BUS is bigger than under the RHI scheme. The bigger solar PV generate more excess electricity stored in the battery under the BUS than the RHI scheme; the stored electricity can cover a bigger portion of electricity demand and need a smaller amount of electricity from the grid. Therefore, the GEI level for the combination designed to cover 100% of electricity and heat demand under the BUS incentive is higher than the associated combinations under the RHI scheme.

Figure 4-20 presents GEI performance for HRES combinations under BUS and RHI scheme.

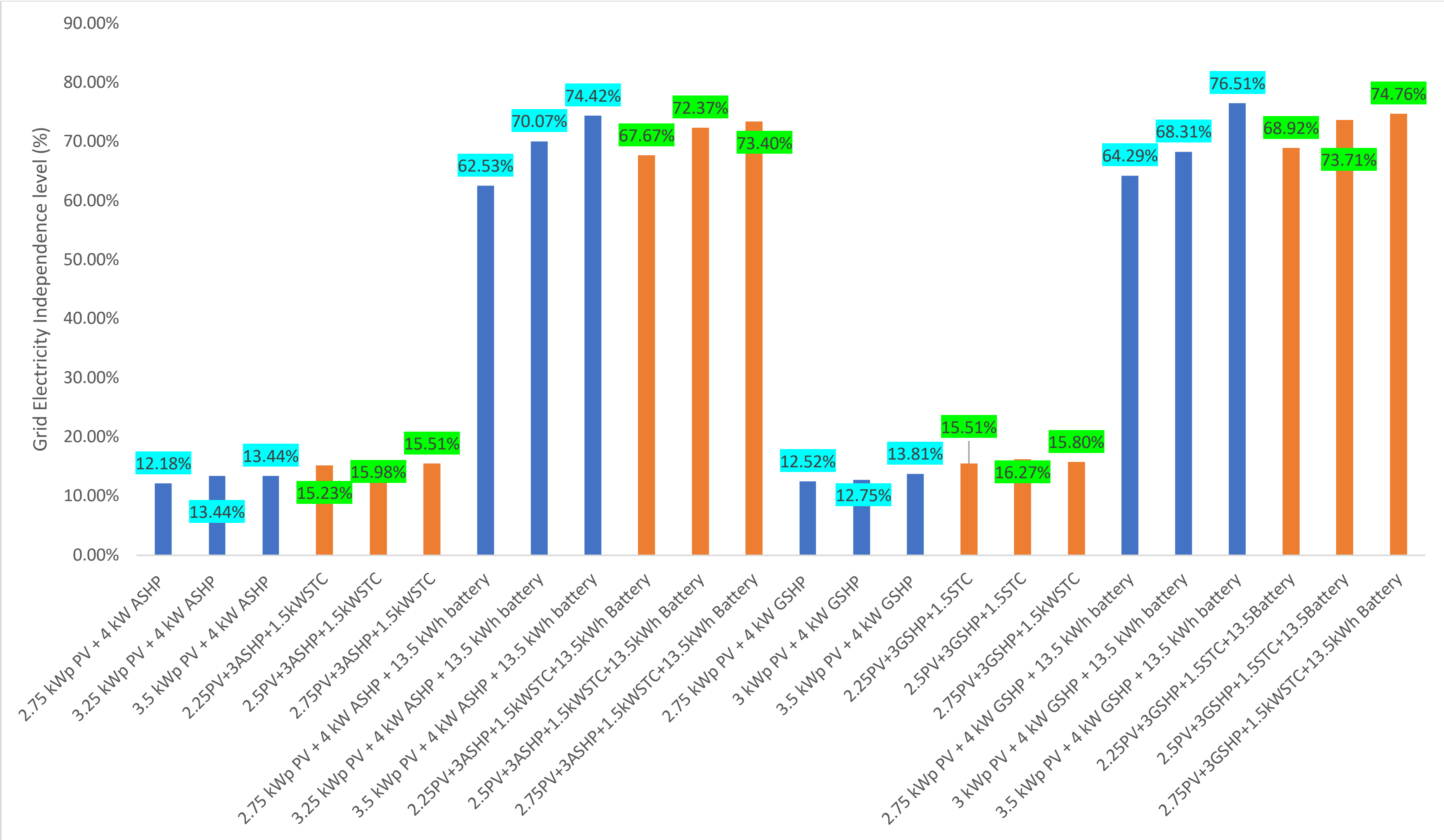


Figure 4-20 GEI for HRES combinations under BUS and RHI scheme.

4.4.3.2. Renewable fraction of the practical HRES combinations

Different from GEI that only reflects the relationship between solar PV, battery, and electricity demand. The renewable fraction (RF) reflects the proportion of the electricity and heat demand that supplied by HRES combinations. The higher RF indicates that more energy demand of the selected home is supplied by relevant HRES combinations.

PV+ASHP or PV+GSHP without a battery has RF between 51% and 57%. The RF of PV+GSHP combinations is generally 2% higher than PV+ASHP combinations. The higher RF of PV+GSHP with/without battery is because of the higher SCOP of GSHP. Then, GSHP needs to import less electricity from the grid than ASHP when the solar PV cannot generate sufficient electricity to power it.

RF has been increased by approximately 20% after adding the battery for those combinations. The battery enables more generated electricity from the solar PV to power heat pumps rather than importing electricity from the grid. The less imported electricity from the grid then contributes to increasing RF.

STC also increases the RF of each HRES combination by using less natural to cover DHW demand. STC increased RF by about 12% for PV+ASHP and PV+GSHP combinations. The combination of STC and battery help to achieve the maximum RF value for both PV+ASHP and PV+GSHP combinations. STC and battery increased RF by up to 31% for PV+ASHP and PV+GSHP combinations, helping PV+ASHP achieved the maximum RF of 77.14%, PV+GSHP achieved the maximum RF of 77.89%. The result indicates that the combination of PV+ASHP/GSHP with battery and STC can minimise importing energy from the electricity grid and natural gas pipeline, helping the domestic building effectively toward net-zero target. No HRES combination has RF value of 100%, although the combination like 2.75 kWp PV + 3 kW ASHP/GSHP + 13.5 kWh battery is designed to cover 100% of electricity demand (defined in section 3.10.1). It then needs to explain the differences between the demand coverage percentages (DCPs in section 3.10) and RF. The DCPs calculate suitable renewable systems with the capacity to generate sufficient energy to cover the required energy demand by using the annual average meteorological data (e.g., solar radiation). However, RF demonstrates the percentage of the energy demand covered by the renewable systems with the calculated capacity. Renewable systems with the calculated suitable capacity sometimes need help generating the expected energy to cover the energy demand in specific months throughout the year due to the uncertainty of the meteorological condition. Then, the electricity from the grid and natural gas would cover the mismatched energy demand and supply. Therefore, RF cannot achieve 100%; although the capacity of such renewable systems is designed to cover 100% of the energy demand. Figure 4-21 presents RF value for the combinations of PV+ASHP/GSHP and PV+ASHP/GSHP+STC with/without a battery.

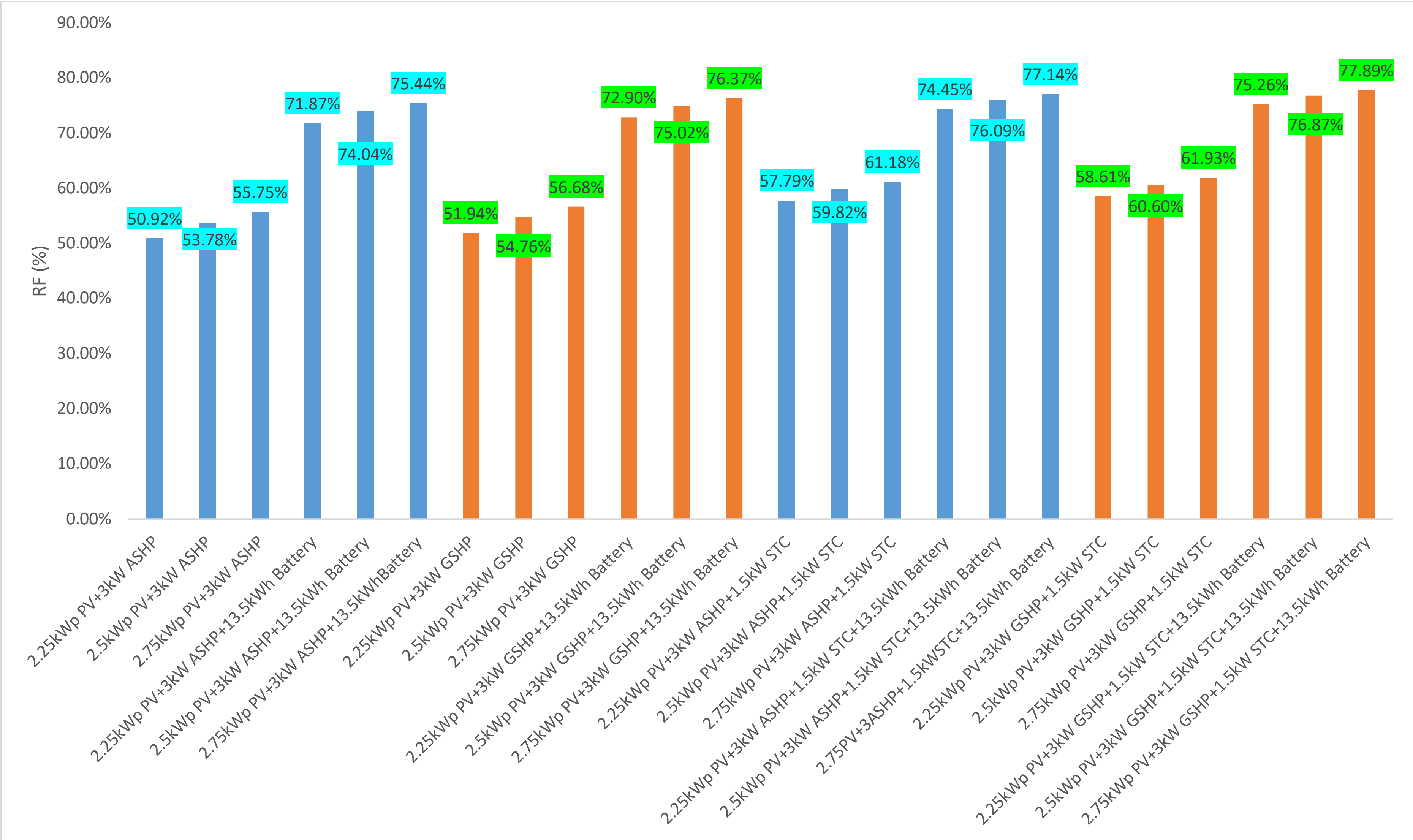


Figure 4-21. RF (%) for the combination of PV+ASHP/GSHP and PV+ASHP/GSHP+STC with/without a battery

HRES combinations under the BUS incentive have a lower RF than those under the RHI scheme. The reason is that the designed heat pumps in HRES combinations under the BUS incentive save more natural gas for covering DHW demand than combinations under the RHI. However, those heat pumps under the BUS incentive need more electricity due to their bigger size. More electricity from the grid is then used to compensate when solar PV cannot generate sufficient electricity to power such heat pumps. The consumed amount of electricity from the grid to power the heat pumps under the BUS scheme is more than the saved natural gas compared with combinations under the RHI scheme. Figure 4-22 presents RF of HRES combinations under the RHI and BUS incentive.

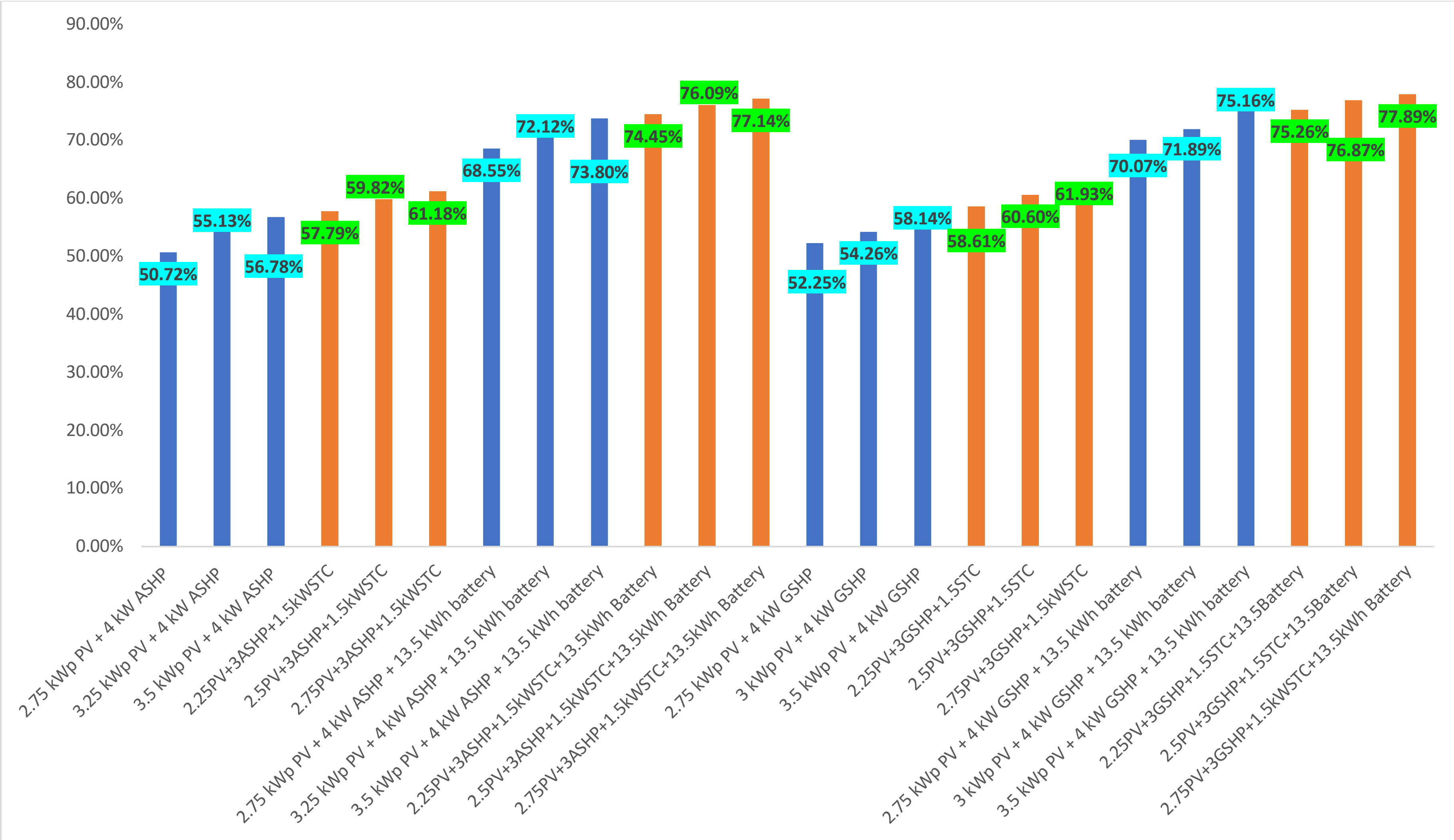


Figure 4-22 RF performance of HRES combinations under BUS and RHI scheme

4.4.4. Environment performance of HRES combinations

This section calculates the operational carbon emissions for each of the HRES combinations. The calculated operational carbon emission is then compared with the UK norm of using a gas boiler for space heating and DHW and grid electricity for lighting and electrical appliances. The comparison results demonstrate the potential environmental advantages of replacing the UK norm of using a gas boiler and grid electricity with HRES combinations. The potential advantages are becoming significant while HRES combinations work together with battery.

This section also presents the relevant results to show whether the embodied carbon of HRES combinations can payback within the lifespan (assumed an average lifespan of 20 years in this research). The results are important to show that such HRES combinations are competitive compared with the current energy supply strategy from the upfront and operational carbon perspectives. The results also show that the added battery brings in extra embodied carbon. However, the embodied carbon of the HRES combinations with a battery can pay back more quickly than those combinations without a battery by more saved electricity from the grid because of the added battery.

4.4.4.1. Operational carbon

The operational carbon of HRES combinations calculated based on the imported energy from the grid and natural gas for the demand that cannot be covered by HRES combinations. Then, the imported energy to multiply the corresponding carbon emission factor (0.212 kg CO_2 eq/kWh for grid electricity; 0.183 kg CO2 eq/kWh for natural gas) (BEIS, 2022a) to obtain the overall operational carbon emission value.

The operational carbon of PV+ASHP ranges from 750 kg CO_2 eq/year to 757 kg CO_2 eq/year; PV+GSHP has a slightly lower operational carbon that ranges from 734 kg CO_2 eq/year to 741 kg CO_2 eq/year. The operational carbon for HRES combinations mentioned above only considered the emission from space heating and electricity for the selected representative domestic building. The difference in operational carbon between PV+ASHP and PV+GSHP is due to GSHP having a higher SCOP than ASHP. Therefore, GSHP needs less electricity from the grid than ASHP to supply the same amount of space heating load. The added battery helps reduce about 60% of operational carbon for PV+ASHP and PV+GSHP. The annual operational carbon of the space heating and electricity in the selected representative domestic building is 1255 kg CO_2 eq/year. PV+ASHP can save up to 40% of annual operational carbon, and PV+GSHP save up to 42% of annual operational carbon compared with the current energy supply strategy. The added battery in PV+ASHP or PV+GSHP can save 68% of operational carbon compared with the current energy supply strategy; the battery contributes about 20% towards saving operational carbon.

The operational carbon of PV+ASHP+STC and PV+GSHP+STC consider the carbon emission from space heating, electricity and DHW. The operational carbon of PV+ASHP+STC ranges from 804 kg CO_2 eq/year to 810 kg CO_2 eq/year, and for PV+GSHP+STC ranges from 788 kg CO_2 eq/year to 795 kg CO_2 eq/year. The annual operational carbon of the current energy supply strategy in the selected representative domestic building is 1568 kg CO_2 eq/year (including the carbon emission from space heating, electricity and DHW). Compared with the current energy supply strategy, PV+ASHP+STC saved up to 49% of operational carbon, and PV+GSHP+STC saved up to 50% of operational carbon. The battery contributes another 20% of saved operational carbon to PV+ASHP+STC and PV+GSHP+STC, reducing up to 70% of operational carbon compared with the current energy supply strategy. Figure 4-23 presents the operational carbon emission for the HRES combinations discussed above.

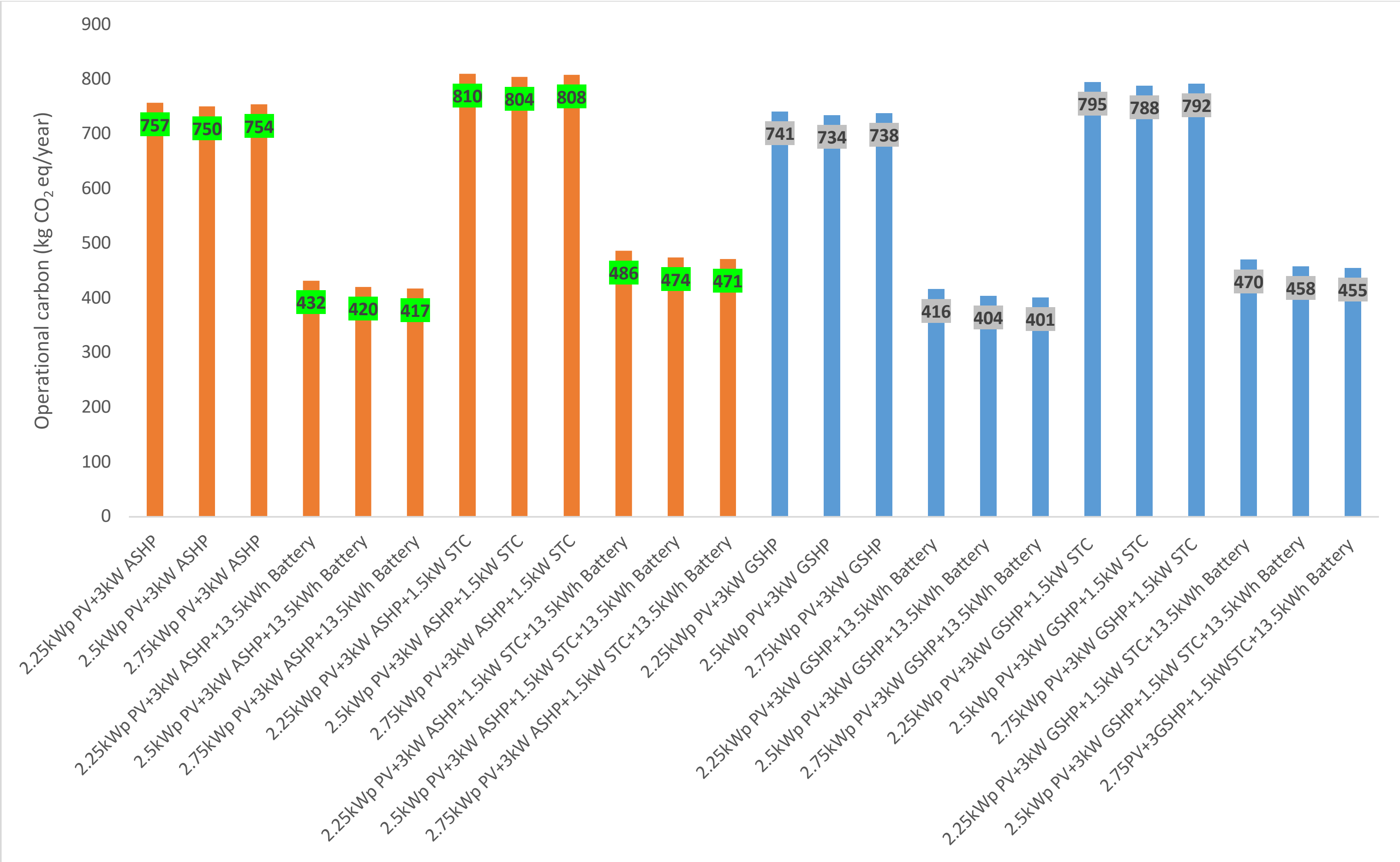


Figure 4-23. Operational carbon for the combinations of PV+ASHP/GSHP and PV+ASHP/GSHP+STC with/without a battery

4.4.4.2. Embodied carbon payback period

The embodied carbon payback period is calculated by the saved kilogram (kg) of equivalent CO_2 from the grid and natural gas divided by the overall embodied carbon of HRES combinations (with/without a battery) (Stevenson, 2022). The embodied carbon payback period for PV+ASHP combinations has been calculated as 13 to 16 years. The added STC reduced, on average, 2.5 years for the embodied carbon payback period, the payback period becomes between 11 and 13 years. The battery enables higher GEI and RF that leads to more saved operational carbon and then contributes to paying back quickly the embodied carbon of the added battery and HRES combinations. The added battery reduced, on average, 3 years of the embodied carbon payback period compared with those combinations without a battery. The embodied carbon payback period for HRES combinations then becomes between 10 and 11 years.

PV+GSHP has an average 2-year shorter embodied carbon payback period than PV+ASHP, between 12 and 14 years. The shorter embodied carbon payback period of PV+GSHP is because of a slightly higher efficiency of GSHP compared with ASHP, which leads to more saved operational carbon from the grid. Embodied carbon of PV+GSHP+STC can pay back on average 2 years early than PV+GSHP, between 10 and 12 years. The battery can reduce payback by up to 4 years for PV+GSHP and up to 3 years for PV+GSHP+STC. After adding a battery to the combinations, the embodied carbon payback period for PV+GSHP is between 9 and 11 years; and the payback period is between 9 and 10 years for PV+GSHP+STC combinations. Figure 4-24 presents the embodied carbon explained above.

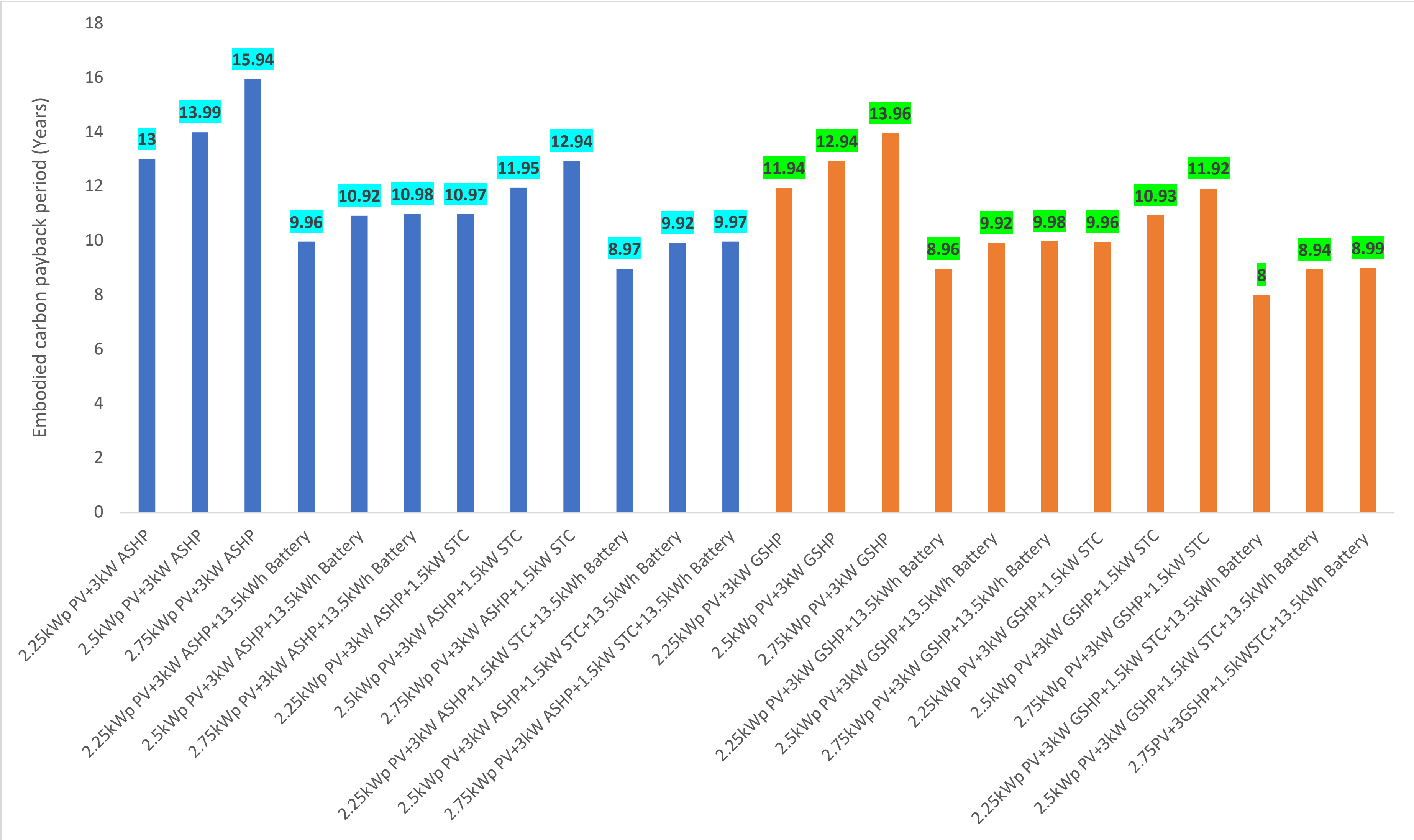


Figure 4-24 Embodied carbon payback period for PV+ASHP/GSHP, PV+ASHP/GSHP+STC with/without a battery

The HRES combinations under the BUS incentive have a higher operational carbon emission than those under the RHI scheme. It is because the combinations under BUS incentive need to import more electricity to power heat pumps to supply both space heating and DHW demand when solar PV cannot cover the electricity demand. Whilst the combinations under the RHI scheme are expected to consume more natural gas than the combinations under the BUS incentive to compensate for DHW demand when STC cannot heat enough water. The current UK's national electricity grid has a higher carbon emission factor (0.212 kg CO_2 eq/kWh) than natural gas (0.183 kg CO_2 eq/kWh) (BEIS, 2022). Therefore, the combinations under the BUS incentive have a higher operational carbon emission than the combinations under the RHI scheme. In addition, the higher operational carbon emission for those combinations under the BUS incentive led to less saved carbon emission than those under the RHI scheme. The embodied carbon payback period for the combinations under the BUS incentive then becomes longer (on average 4-5 years) than for the RHI scheme. Figure 4-25 presents operational carbon emission and embodied carbon payback period for HRES combinations under different renewable heat incentives.

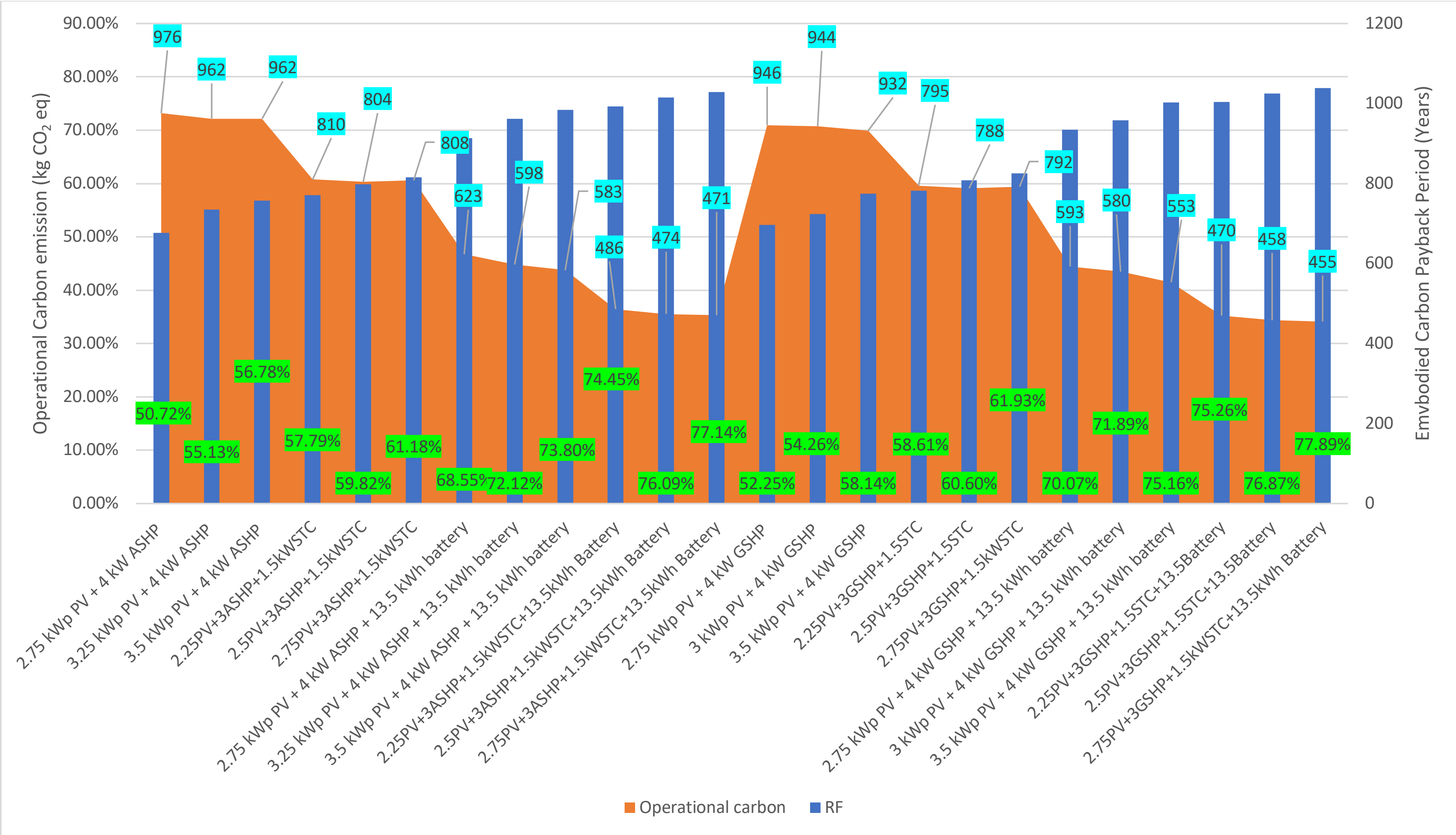


Figure 4-25 Operational carbon emission and embodied carbon payback period for HRES combinations under BUS and RHI scheme

4.5. Questionnaire responses analysis

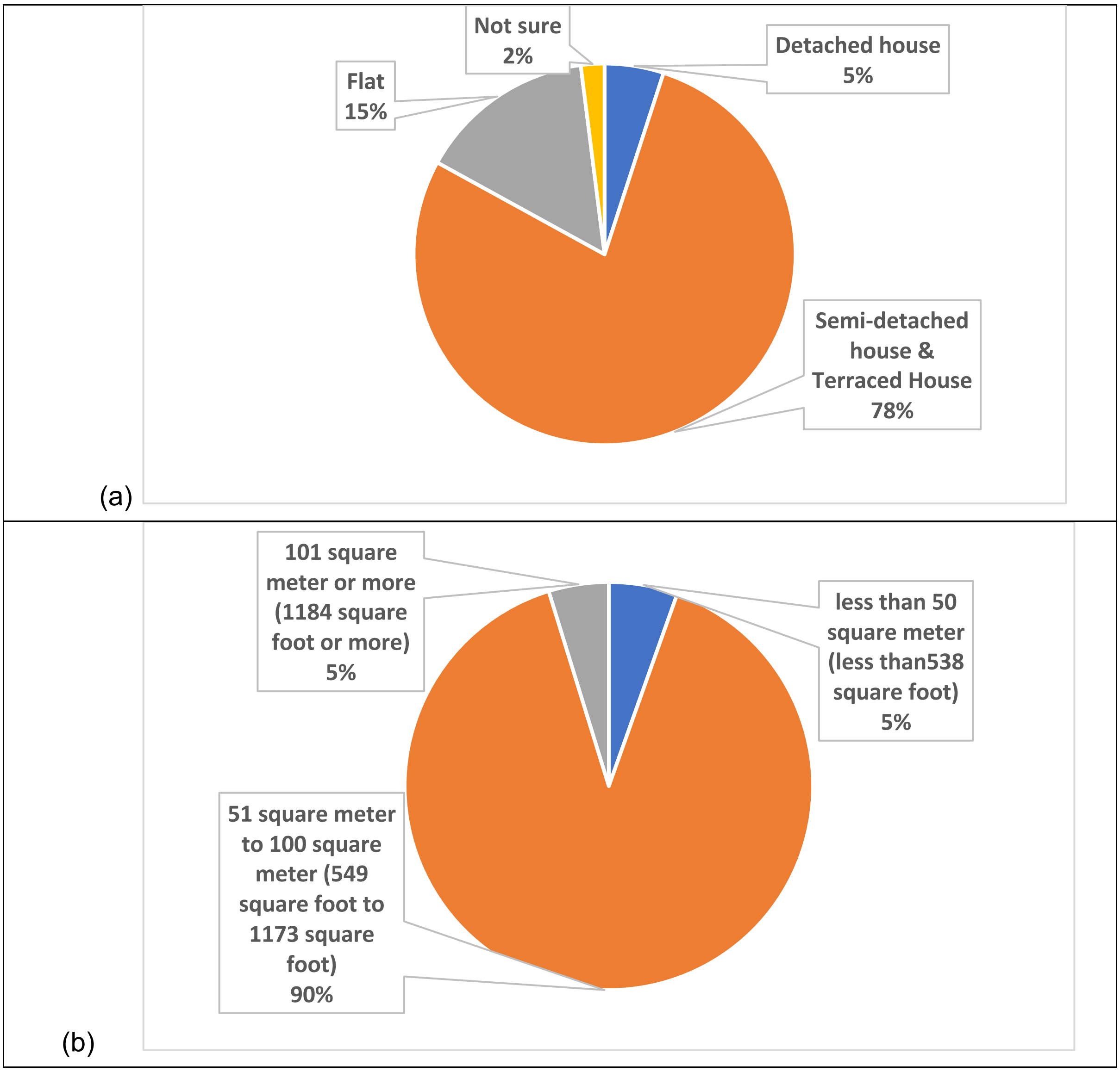
The section presents responses from Cardiff and Bristol; overall, 171 householders who live in Cardiff and Bristol responded to the questions related to the following topics:

- The building stock conditions (Subsection 4.5.1): this subsection briefly summarised the surveyed housing condition, the major roof orientation, and the associated tilt angle.
- Perspectives of installing renewable energy systems (Subsection 4.5.2): This subsection presents the potential reason householders are unwilling to install renewable systems and the main reasons that motivate householders to install renewable systems.
- The information accessibility for householders to know renewable systems (Subsection 4.5.3): this subsection presents householders' understanding of the existing renewable systems that can be installed in renewable systems. In addition, this subsection demonstrates householder-preferred sources to gain information on the renewable system.

The results in subsections 4.5.2 and 4.5.3 are helpful in understanding the allocated preference values in the created weighting system (subsection 4.6.1) based on householders' perspectives.

4.5.1. Response analysis of building stock conditions

Based on the 171 responses received from householders in Cardiff and Bristol, the results show that 77.8% of the surveyed householders live in semi-detached or terraced houses. 5% of the surveyed householders live in a detached house, 15% live in a flat, and only 2% live in a bungalow. 77% of householders live in a house with an accumulated floor area between 51 and 100 m^2. About 5% of householders live in less than 50 m^2, and 4% live in an accumulated floor area above 101 m^2. 24% of householders were uncertain about the floor area of their homes. The most surveyed homes with a major roof facing Northeast and Southwest (29.24%) or East and West (25.73%). About 36% of householders were uncertain about the tilt angle of the major roof, and more than half of householders (51%) live in a home with the tilt angle of the major roof between 30 and 34 degrees. 4% of householders live in a home with the tilt angle of the major roof between 20 and 24 or 40 and 44 degrees. Only 2% of householders live in a home with a tilt angle of the major roof between 45 and 49 degrees. Whilst this research received limited responses from householders in Cardiff and Bristol. The received basic building stock conditions help future research to explore the installation of suitable renewable systems to achieve the maximum energy generation performance. Figure 4-26 presents the building stock condition of the surveyed homes in Cardiff and Bristol. (a) The surveyed building types. (b) The accumulated floor area of the surveyed homes. (c) The main roof orientation of the surveyed homes. (d) The tilt angle of the main roof.



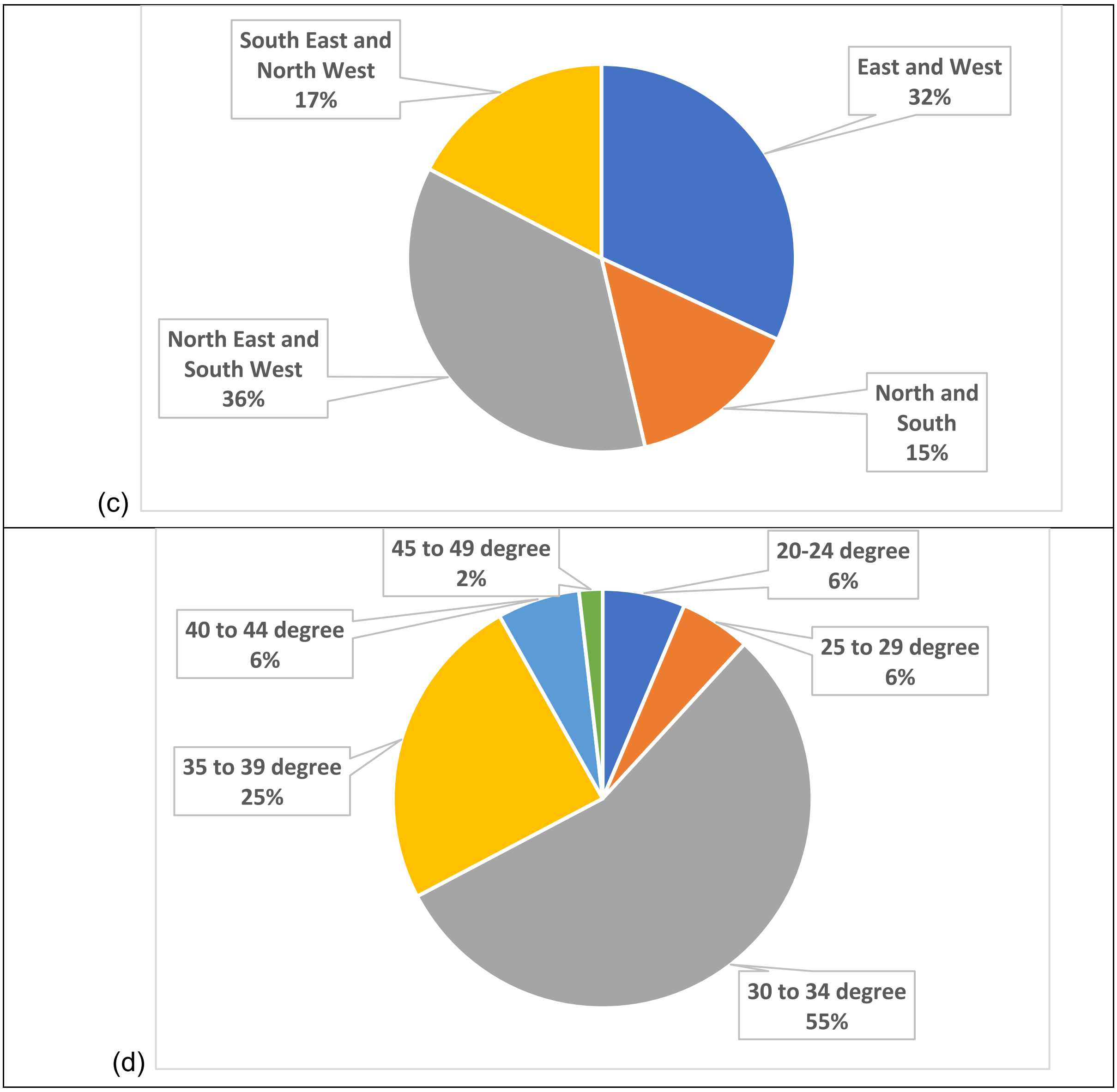


Figure 4-26 Building stock condition. (a) The surveyed building types. (b) The accumulated floor area of the surveyed homes. (c) The main roof orientation of the surveyed homes. (d) The tilt angle of the main roof.

4.5.2. Perspectives of installing renewable energy systems

This section presents the two main findings of survey results:

- The reasons for not installing renewable systems from householders who have not installed renewable energy systems in their homes.
- The reasons of installing renewable systems based on the responses from householders who have installed renewable energy systems in their homes.

Within the collected responses from 171 householders, 132 householders said they had not installed renewable systems, and 26 householders said they had installed at least one renewable system.

The survey then continues to investigate the potential reasons stopping 132 householders who have not installed the renewable system in their homes. Each householder was allowed to select multi reasons to answer why they had not considered renewable systems in their homes. The top two reasons are that householders need more knowledge of existing renewable energy systems (67%), and installing such renewable systems would be too expensive (72%). Therefore, the capital cost is the main concern of installing the renewable system, and the response aligns with the calculated high-weighting value of the capital cost that is presented in subsection 4.6.1. The surveyed potential reasons that stopping householders to install renewable system in their homes are presented in Figure 4-27.

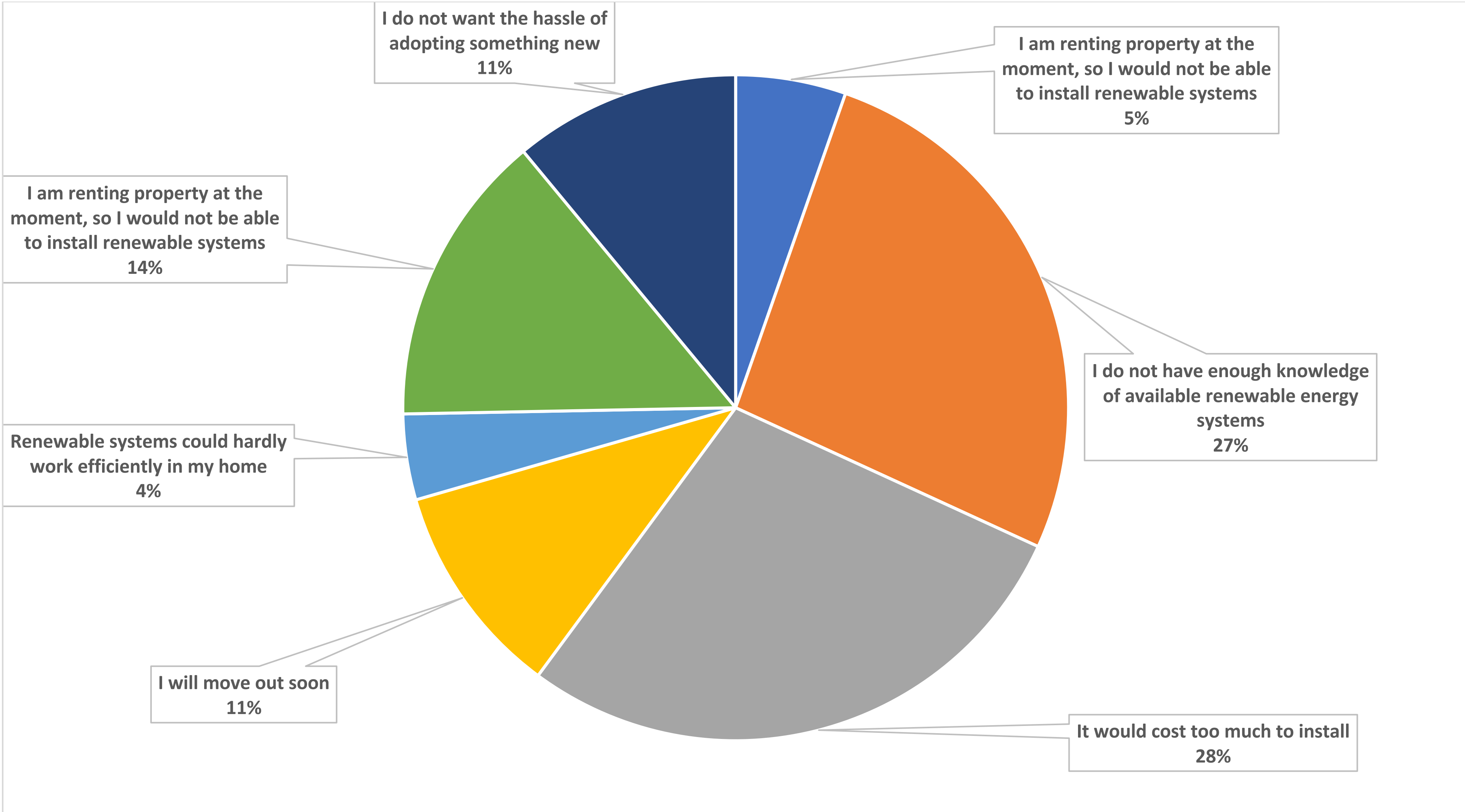


Figure 4-27 Reasons stop householders considering installing renewable systems

While asking about the motivations that encouraged 26 householders already install renewable systems in their homes. 30% of householders believe that the installed renewable systems can reduce energy bills. 24% of householders believe renewable energy systems are more environmentally friendly. 11% of householders stated that their interest in trying advanced renewable technology is the main reason for installing renewable systems. Figure 4-28 presented the selected reasons for installing renewable systems in homes by 16 householders.

Based on the findings presented in Figure 4-27 and Figure 4-28, the economic performance like the capital cost or lower energy bills is the main reason to stop or encourage householders to install renewable energy system. Besides reducing energy bills, better environmental performance after installing renewable systems is another reason that motivated householders to install renewable energy systems. The responses are consistent with the calculated weighting values based on householders' preference values that are shown in subsection 4.6.1.

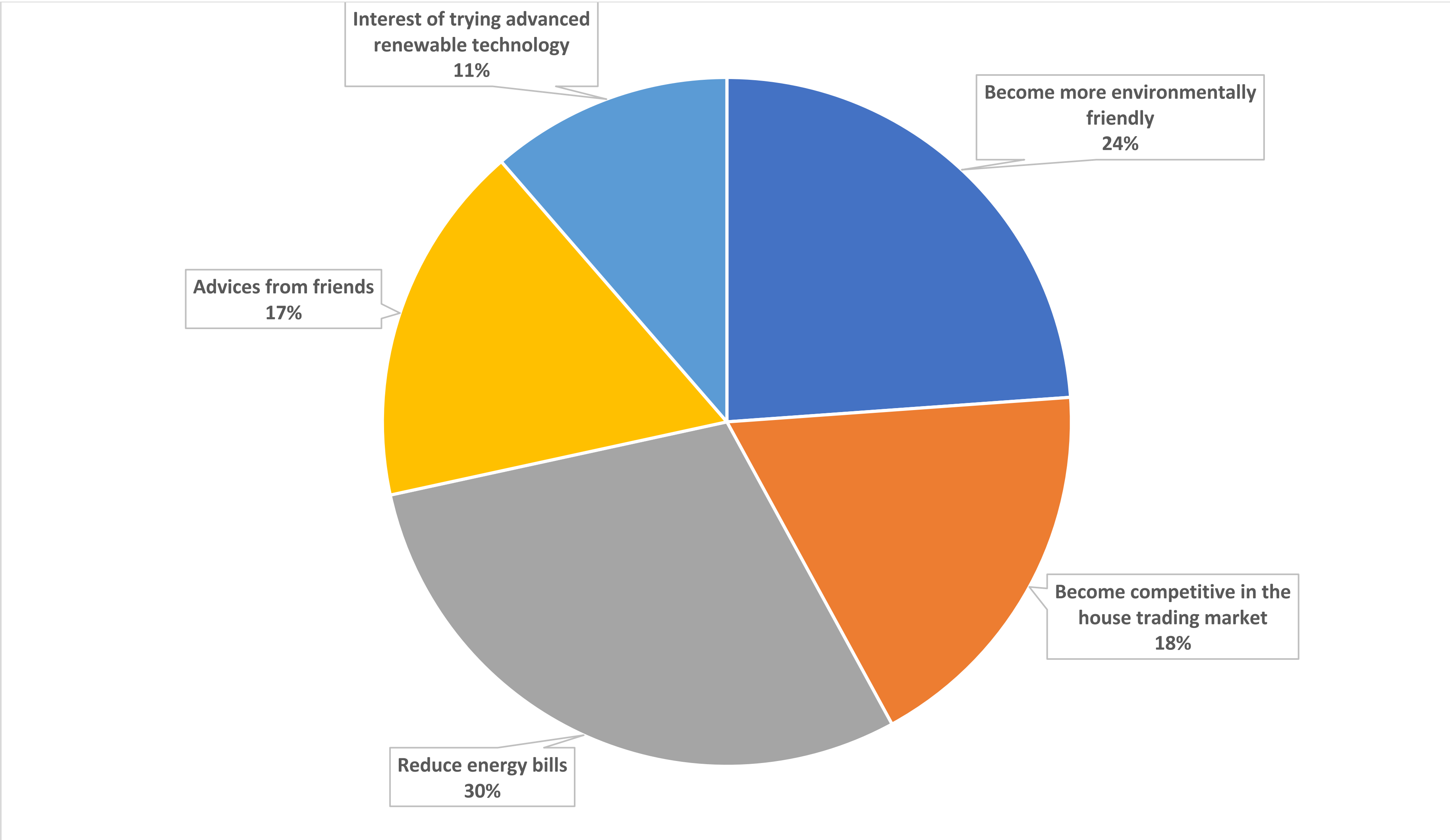


Figure 4-28 Potential reasons motivated householders to install renewable energy system

4.5.3. Householders' perspectives on renewable energy systems and climate change

This subsection first presents the number of householders familiar with solar PV, STC, ASHP and GSHP. This subsection then presents the potential sources that the surveyed householders tend to obtain information on renewable energy systems. In the last, this subsection presents the comparison results between the installed/not installed householders' perspectives on easily accessing relevant information on renewable energy systems.

The householders can select multi-renewable energy systems they are familiar with in the questionnaire. Most householders are familiar with solar products, 159 are familiar with solar PV, and 134 are familiar with solar thermal collectors. Whilst the ASHP might be easier to be installed on most surveyed homes; more householders are familiar with ground-source heat pumps (95) than air-source heat pumps (74). Figure 4-29 presents the survey result stated above.

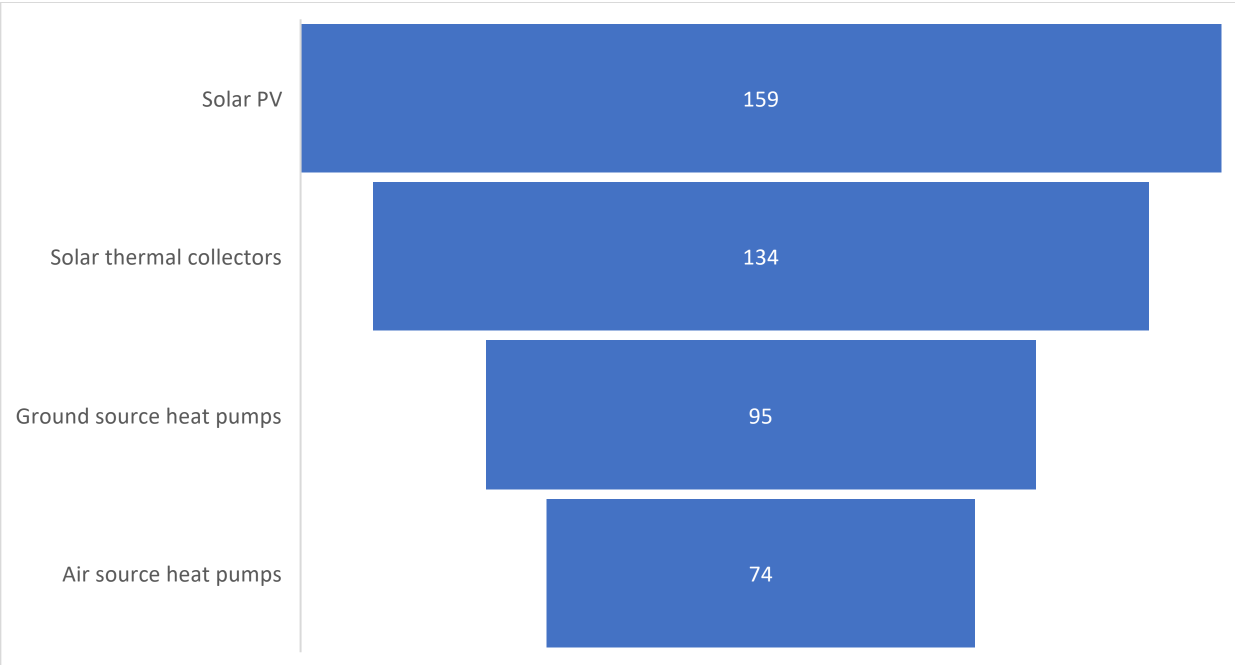


Figure 4-29 The number of householders familiar with solar PV, STC, GSHP and ASHP

While asking householders about the source to obtain the reliable renewable system information, 30% of householders stated it is more reliable to obtain the information from the professional energy efficient adviser or consultant. 26% of householders believe the UK government provide more reliable information of renewable energy system than other sources. The social media (4%), TV and radio documentaries (5%), newspaper or news on websites (3%) are the least preferred sources from the surveyed householders' viewpoints to obtain the reliable information of renewable energy systems. Figure 4-30 presents the sources that the surveyed householders gain the reliable information of renewable energy systems.

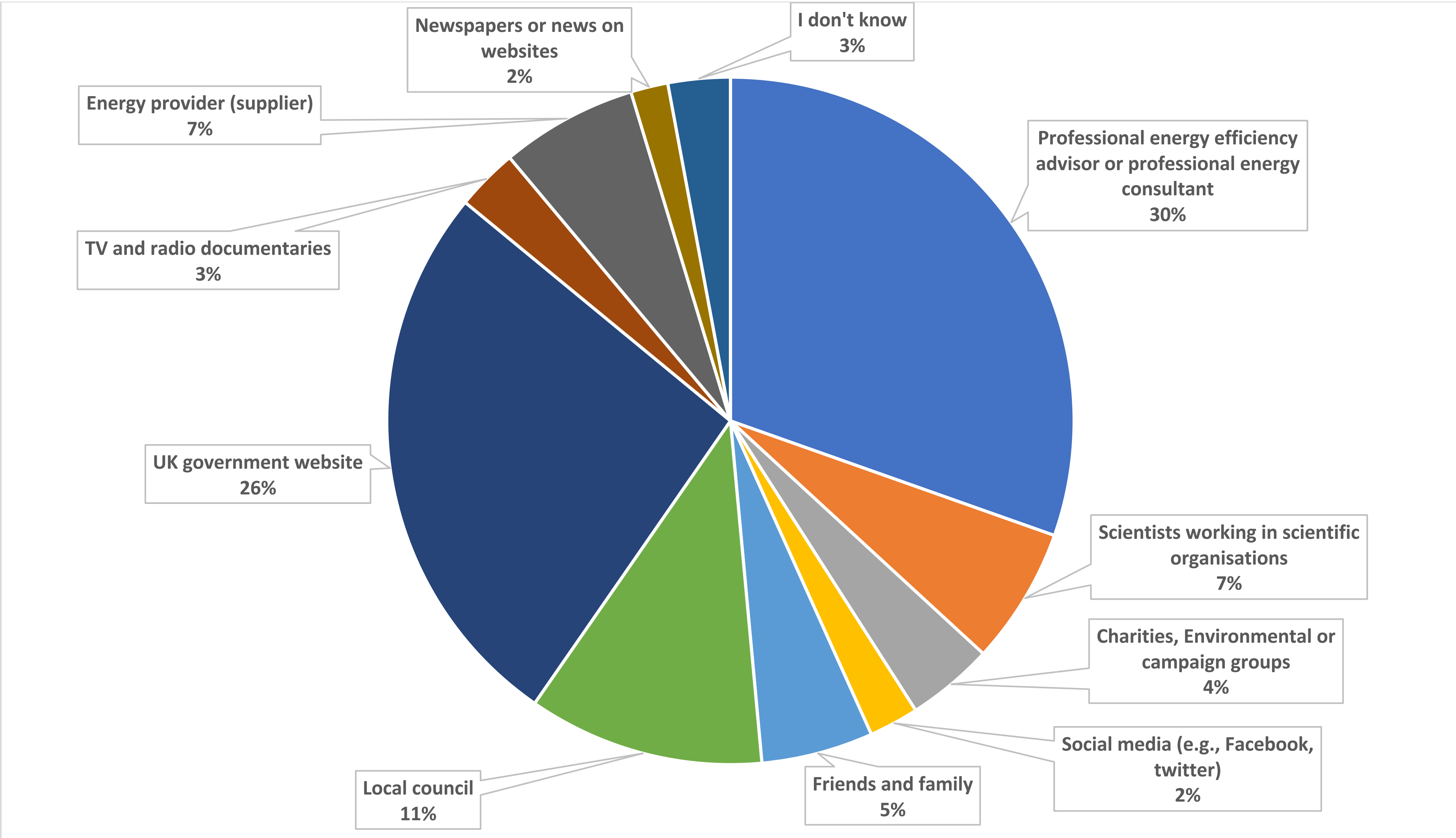
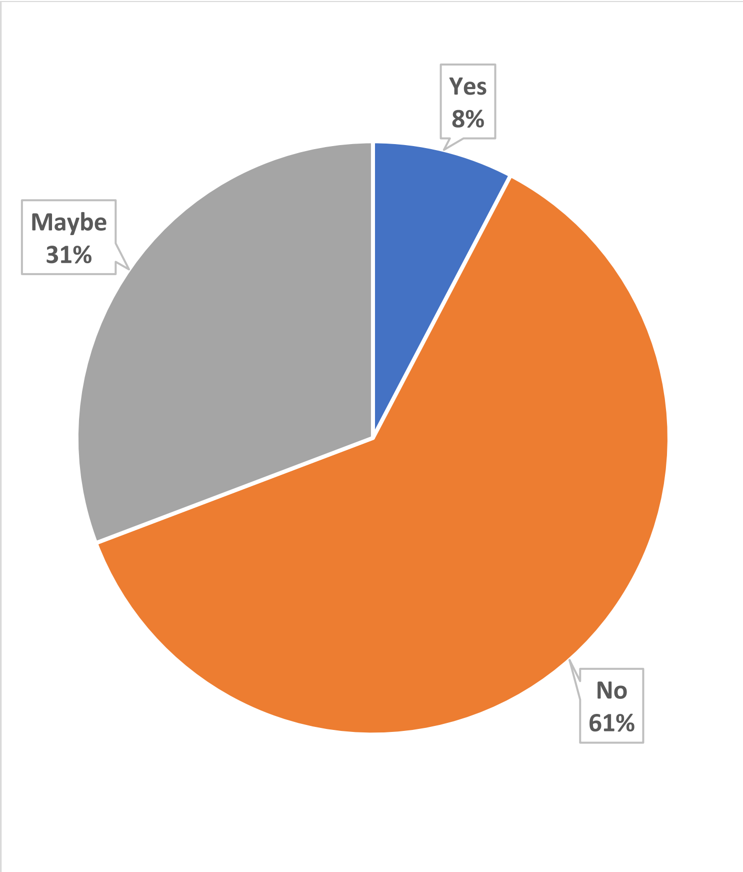


Figure 4-30. The sources that the surveyed householders most trust to obtain the information of renewable system

This section continues to analyse the results after categorising the responses received from householders already installed/have not installed renewable systems. For the group of householders who already installed renewable systems (26 responses overall), 26% of respondents stated that maybe it is difficult to access reliable information. 55% of respondents stated it is not difficult to access reliable information, and 7% of respondents stated it is difficult to access reliable information.

For the group of householders who have yet to install renewable systems (145 responses), 31% of respondents stated that maybe it is difficult to access reliable information. 11% of respondents stated they could easily access reliable information. 58% of respondents stated it is difficult to access reliable information. In addition, three householders selected ‘other’ and provided a detailed reason. One householder stated ‘They have only started investigating alternative systems in their homes. They have found sufficient information to provide high-level detail of the available products’. Another householder stated, ‘they have not looked it up’. The last householder stated, ‘they have not searched information as they are renting at the moment’. Figure 4-31 (a) and (b) presents the results stated above.

More householders selected that 'it is not difficult to access reliable information on renewable systems' in the group of householders who have installed renewable systems. Most householders in the group of householders who have not installed renewable systems selected ‘it is difficult to access reliable information of renewable systems. It is understandable for most householders who have already installed renewable systems believe it is not difficult to obtain the reliable information, as they have searched for relevant information before their installations. However, it is important to investigate the reasons householders who have not installed renewable systems about why it is difficult to access reliable information in the future.

(a) 

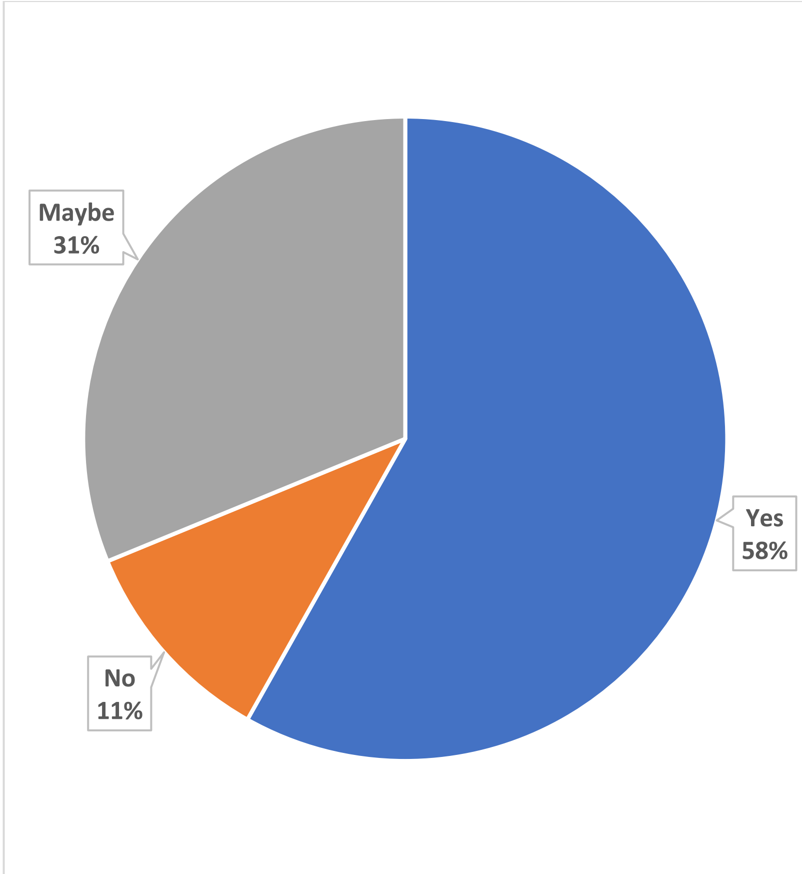
(b) 

Figure 4-31. Perspectives of difficulties in accessing reliable information in the investment of renewable energy systems. (a) presents the results from the group of householders installed renewable systems. (b) presents the results from the group of householders who have not installed renewable systems

4.6. Ranking result

This section consists of two subsections:

Subsection 4.6.1 presents the calculated weighting values on the selected decision-making indicators from 96 Cardiff householders' preference viewpoints. The received Bristol householders' viewpoints were not used to calculate weighting values due to the collected responses were statistically insufficient to represent Bristol householders' preferences value on the selected indicators.

Subsection 4.6.2 first presents the ranking results of HRES combinations under the calculated weighting values from 96 Cardiff householders' preference viewpoints. This subsection then presents the comparison ranking results of HRES combinations with and without householders' preference viewpoints.

4.6.1. Weighting values

In the questionnaire, each householder was asked to allocate the preference value from '1-5' to the economic-technical-environment criteria and the selected associated indicators. The preference value was then converted to the weights of each criterion and indicator via the AHP method explained in subsection 3.12.3. After converting each householder's preference value to the criteria and the associated indicators as the weighting values. It then averages all the calculated weights that are later used to rank HRES combinations.

The preference values from 96 Cardiff's householders are used to calculate the average weights for criteria and indicators. The average weights are later used for ranking HRES combinations. The calculated average weights for criteria and indicators based on 96 Cardiff householders' preferences are presented in Table 4-7.

Table 4-7. Weighting values

Criteria	**Economic**			**Technical**			**Environmental**	
Criteria weighting value	0.3676			0.2863			0.3462	
Indicators	**Capital cost**	**BCR**	**economic benefit ratio from the existing financial incentive scheme**	**GEI**	**Lifespan**	**RF**	**Embodied carbon payback**	**GHG emission at operational stage**
Indicator weighting value	0.1385	0.1300	0.1303	0.1100	0.1313	0.1232	0.1025	0.1343

The economic criterion is the most preferred one, with a weighting value of 0.3676. The economic criterion is followed by the environmental criterion, with a weighting value of 0.3462. The least preferred is the technical criterion, with a weighting value of 0.2863. The possible reason for the lowest weighting value for the technical criterion against the other two criteria is that most surveyed householders did not understand the technical criterion and the associated indicators, which led them to allocate the least preference value to such criterion and the relevant indicators.

The economic indicators have the highest values against other indicators. Within the economic indicators, the capital cost indicator holds the highest weighting value (0.1385) over the other two indicators, BCR (0.1300) and economic benefit ratio from the existing financial incentive scheme (0.1303). The results reflect that householders are familiar with the capital cost indicator, and the indicator has been prioritised to consider investing in the renewable system. The GHG emission at the operational stage indicator has the second highest weight (0.1343) only after the capital cost indicator. The weighting value of the GHG emission at the operational stage indicator indicates that householders tend to consider the carbon footprint at the operational stage in parallel to the economic indicators while investing in renewable systems. The lifespan indicator holds the highest weighting value (0.1313) under the technical criterion compared with another two technical indicators, GEI (0.1100) and RF (0.1232). Whilst the questionnaire briefly explains each indicator, the householders might still be unfamiliar with GEI or RF; then some householders allocated a lower preference value to the indicators that they are not familiar with. It might be the same reason for a low weighting value for the embodied carbon payback indicator (0.1025). Householders are familiar with the GHG emission at the operational stage indicator; However, they were not as familiar with the GHG emission at the operational stage indicator as the embodied carbon payback period indicator.

4.6.2. Ranking results

4.6.2.1. Ranking results based on householders' perspectives

The calculated weighting values for the criteria and indicators in subsection 4.6.1 are then used to calculate the overall economic-technical-environmental performance score. Then the overall scores are used to rank HRES combinations. The performance score for each HRES combination is calculated based on the distance between the idea best and worst under the specific criterion or indicator. The idea best value indicates the expected best performance value in the specific criterion or indicator. The worst value indicates the worst performance value in the specific criterion or indicator. The clarification of the expected idea best and worst values is presented in Table 4-8. The distance between the idea best and worst under the specific criterion or indicator can then be worked out through equations 23a, and 23b, explained in section 3.13.

Table 4-8. The expected best and worst value on each indicator

	Expected value	Best	Worst
Economic	Capital cost	Lower value in HRES combinations	Higher value in HRES combinations
	BCR	Higher value in HRES combinations	Lower value in HRES combinations
	economic benefit ratio from the existing financial incentive scheme	Higher value in HRES combinations	Lower value in HRES combinations
Technical	GEI	Higher value in HRES combinations	Lower value in HRES combinations
	Lifespan	Higher value in HRES combinations	Lower value in HRES combinations
	RF	Higher value in HRES combinations	Lower value in HRES combinations
Environmental	Embodied carbon payback period	Lower value in HRES combinations	Higher value in HRES combinations
	GHG emission at operational stage	Lower value in HRES combinations	Higher value in HRES combinations

Once the expected idea best and worst value for each selected criterion and indicator are calculated. The final performance score for each HRES combination under all selected criteria and indicators can then be calculated through equation 24 explained in section 3.13. The calculated final performance scores for the identified 24 HRES combinations are presented in Table 4-9.

Table 4-9. HRES combinations ranking result based on householders' perspectives

HRES combinations	Overall economic-technical-environmental performance score	Ranking results based on the performance score
2.25kWp PV+3kW ASHP+1.5kW STC	0.9260	1
2.5kWp PV+3kW ASHP+1.5kW STC	0.9252	2
2.25kWp PV+3kW ASHP	0.9238	3
2.5kWp PV+3kW ASHP	0.9233	4
2.75kWp PV+3kW ASHP+1.5kW STC	0.9223	5
2.75kWp PV+3kW ASHP	0.9182	6
2.25kWp PV+3kW ASHP+1.5kW STC+13.5kWh Battery	0.9006	7
2.5kWp PV+3kW ASHP+1.5kW STC+13.5kWh Battery	0.9003	8
2.75kWp PV+3kW ASHP+1.5kW STC+13.5kWh Battery	0.8996	9
2.75kWp PV+3kW ASHP+13.5kWhBattery	0.8937	10
2.5kWp PV+3kW ASHP+13.5kWh Battery	0.8937	10
2.25kWp PV+3kW ASHP+13.5kWh Battery	0.8933	11
2.25kWp PV+3kW GSHP+1.5kW STC	0.8927	12
2.5kWp PV+3kW GSHP+1.5kW STC	0.8911	13
2.25kWp PV+3kW GSHP	0.8900	14
2.5kWp PV+3kW GSHP	0.8888	15
2.75kWp PV+3kW GSHP+1.5kW STC	0.8871	16
2.75kWp PV+3kW GSHP	0.8850	17
2.5kWp PV+3kW GSHP+13.5kWh Battery	0.8741	18
2.75kWp PV+3kW GSHP+13.5kWhBattery	0.8738	19
2.5kWp PV+3kW GSHP+1.5kW STC+13.5kWh Battery	0.8738	19
2.25kWp PV+3kW GSHP+13.5kWh Battery	0.8737	20
2.25kWp PV+3kW GSHP+1.5kW STC+13.5kWh Battery	0.8735	21
2.75kWp PV+3kW GSHP+1.5kW STC+13.5kWh Battery	0.8731	22

The combinations like PV+ASHP+STC or PV+ASHP are ranked higher than PV+GSHP+STC or PV+GSHP. The main reason is that the surveyed householders highly weigh the economic indicators, particularly the capital cost indicator. The combinations of PV+ASHP+STC and PV+ASHP have lower capital costs than PV+GSHP+STC and PV+GSHP. In addition, PV+ASHP+STC ranked higher than PV+ASHP. The former combinations have a higher capital cost, but they have a better performance in GHG emission at the operational stage and BCR, such indicators have a higher weighting value. It is the same reason for PV+ASHP+STC+battery ranked higher than the PV+GSHP combinations. Whilst the later combinations have a lower capital cost, the former combinations have better performance in other performance indicators, particularly in GHG emission at the operational stage, which holds the second highest weighting value.

4.6.2.2. Ranking results based on equal weights

This section presents the ranking results of 24 HRES combinations in terms of economic-technical-environmental performance using the equal weight value to the criteria and indicators. The equal weight value to each criterion is 0.3333, and the value of each indicator is 0.125. Table 4-10 presents the ranking results of 24 HRES combinations using equal weights for the economic-technical-environment criteria and indicators. Table 4-10 also presents the comparison results of the ranking using equal weights and weights based on householders' preferences.

Table 4-10. HRES combinations ranking result based on equal weights

HRES combinations	Overall economic-technical-environmental performance score	Ranking results based on the performance score (equal weights)	Ranking results based on the performance score (householders' perspective)
2.5kWp PV+3kW ASHP+1.5kW STC+13.5kWh Battery	0.9173	1	8
2.75kWp PV+3kW ASHP+1.5kW STC+13.5kWh Battery	0.9170	2	9
2.25kWp PV+3kW ASHP+1.5kW STC+13.5kWh Battery	0.9170	2	7
2.25kWp PV+3kW ASHP+1.5kW STC	0.9095	3	1
2.75kWp PV+3kW ASHP+13.5kWhBattery	0.9094	4	10
2.5kWp PV+3kW ASHP+13.5kWh Battery	0.9090	5	10
2.5kWp PV+3kW ASHP+1.5kW STC	0.9085	6	2
2.25kWp PV+3kW ASHP+13.5kWh Battery	0.9081	7	11
2.75kWp PV+3kW ASHP+1.5kW STC	0.9051	8	5
2.25kWp PV+3kW ASHP	0.9049	9	3
2.5kWp PV+3kW ASHP	0.9039	10	4
2.5kWp PV+3kW GSHP+1.5kW STC+13.5kWh Battery	0.8990	11	19
2.75kWp PV+3kW GSHP+1.5kW STC+13.5kWh Battery	0.8986	12	22
2.25kWp PV+3kW GSHP+1.5kW STC+13.5kWh Battery	0.8983	13	21
2.75kWp PV+3kW ASHP	0.8979	14	6
2.5kWp PV+3kW GSHP+13.5kWh Battery	0.8976	15	18
2.75kWp PV+3kW GSHP+13.5kWhBattery	0.8975	16	19
2.25kWp PV+3kW GSHP+13.5kWh Battery	0.8967	17	20
2.25kWp PV+3kW GSHP+1.5kW STC	0.8824	18	12
2.5kWp PV+3kW GSHP+1.5kW STC	0.8805	19	13
2.75kWp PV+3kW GSHP+1.5kW STC	0.8759	20	16
2.25kWp PV+3kW GSHP	0.8756	21	14
2.5kWp PV+3kW GSHP	0.8738	22	15
2.75kWp PV+3kW GSHP	0.8693	23	17

After removing the highest weighting values for the capital cost, the combinations of PV+ASHP+STC+battery ranked in the top 3 positions. Compared with the ranking results considering householders' perspectives, the combinations with battery ranked in the higher positions under the equal weights. The new ranking result indicates that the combinations with a battery have a better overall performance than those combinations without a battery while equally considering the weights for each performance indicator. PV+GSHP+STC or PV+GSHP with or without a battery generally ranked lower than PV+ASHP+STC/PV+ASHP combinations. Within the ranking considering equal weights, the combinations like PV+GSHP+STC+battery, ranked in the lowest positions under the weights considering householders' perspectives, jumped in the top 15 positions.

In both rankings, the combinations with ASHP ranked higher than the combination with GSHP. The reason is that the combinations with ASHP have better economic performance (e.g., lower capital cost and higher BCR) than those with GSHP. Although GSHP has a slightly higher SCOP than ASHP, the combinations with GSHP only have a similar technical and environmental performance as the combinations with ASHP. Then, the combinations with ASHP have a higher final performance score than those combinations with GSHP and are then ranked in front positions. In addition, the ranking results indicate that PV+ASHP+STC is the preferable option while mainly considering capital cost and GHG emission at the operational stage prior to the investment. However, if the householders not only focus on the capital cost but equally consider the economic-technical-environmental performance prior to the investment. Then, PV+ASHP+STC with a suitable battery is the preferable option. Lastly, for a home in an urban area like the selected representative retrofitted home in this research. The PV+ASHP+STC combination with or without a battery is always preferable over PV+GSHP+STC with or without a battery.

4.7 The developed decision-making spreadsheet

This section presents the developed spreadsheet that support the entire calculation for the decision-making framework. The developed spreadsheet can be categorised to three groups:

- Renewable Energy sizing and demand-supply balance spreadsheet (subsection 4.7.1)
- Economic-Technical-Environmental performance evaluation spreadsheet (subsection 4.7.2)
- Weighting and decision-making spreadsheet (subsection 4.7.3)

The guidance of the decision-making framework and the whole spreadsheet were submitted separately as the appendix of the thesis. Householders can follow the guidance to practically use the developed spreadsheet to obtain the economic-technical-environmental performance of the selected renewable systems.

4.7.1 Renewable energy system sizing and demand-supply balance spreadsheet

The renewable energy system sizing spreadsheet is used to automatically work out the configurations (power ratings) for the associated renewable system (e.g., solar PV, STC, G/ASHP) in the defined scenarios (explained in section 3.9). The spreadsheet needs the following inputs to run the calculation:

- The orientation of the major roof
- Local average annual solar radiation (kWh/m^2).
- Annual space heating demand (kWh).
- Annual space heating demand in the intensive heating period (e.g., October to March) (kWh).
- Annual DHW demand (kWh).
- Annual lighting consumption (kWh).
- Annual electrical appliances consumption (kWh)

The inputs should be recorded in the sheet shows in Figure 4-32.

Location	Orientation (PV installation facing)	Building Orientation	Annual Solar Radiation (kWh/m^2)	Space Heating (kWh)	Space Heating (kWh) winter-only	DHW (kWh)	Lighting (kWh)	Electrical Appliance (kWh)	Gas consumption (kWh)	Gas consumption (Winter) kWh	Weather data source
Cardiff	N	S	731.96	6204.058	3825.842	1353	1016.507	2091.04	6375.798	3969.928	PVGIS
Cardiff	N	S		6106.876	4048.311	1353	1016.507	2091.04	6323.873	4215.153	OneBuilding
Cardiff	S	N	1680.821	6111.718	3789.271	1353	1016.507	2091.04	6363.209	3949.097	PVGIS
Cardiff	S	N		6074.486	4022.181	1353	1016.507	2091.04	6295.951	4187.46	OneBuilding
Cardiff	SE	NW	1562.13	6122.439	3860.237	1353	1016.507	2091.04	6281.248	3976.134	PVGIS
Cardiff	SE	NW		6129.829	4094.196	1353	1016.507	2091.04	6302.909	4241.246	OneBuilding
Cardiff	SW	NE	1593.76	6001.596	3847.429	1353	1016.507	2091.04	6323.786	4052.485	PVGIS
Cardiff	SW	NE		6015.967	4064.424	1353	1016.507	2091.04	6288.728	4251.989	OneBuilding

Figure 4-32 Energy consumption condition and local annual solar radiation for the specified home

Once inputs have been recorded in the spreadsheet in Figure 4-32, it first needs to calculate the configurations (power ratings) for the heat pumps. Heat pumps use electricity to power, it is economically viable to use electricity generated on-site through solar PV as much as possible. In the defined sizing scenarios (explained in section 3.9.1), the heat pumps should cover 100% of annual space heating. Then, the whole annual space heating is used to carry out the sizing calculation for the ASHP and GSHP; the calculation process explained in subsection 3.10.3. Figure 4-33 shows the developed spreadsheet for GSHP, the calculation spreadsheet for ASHP is similar to GSHP; the only difference is the COP value.

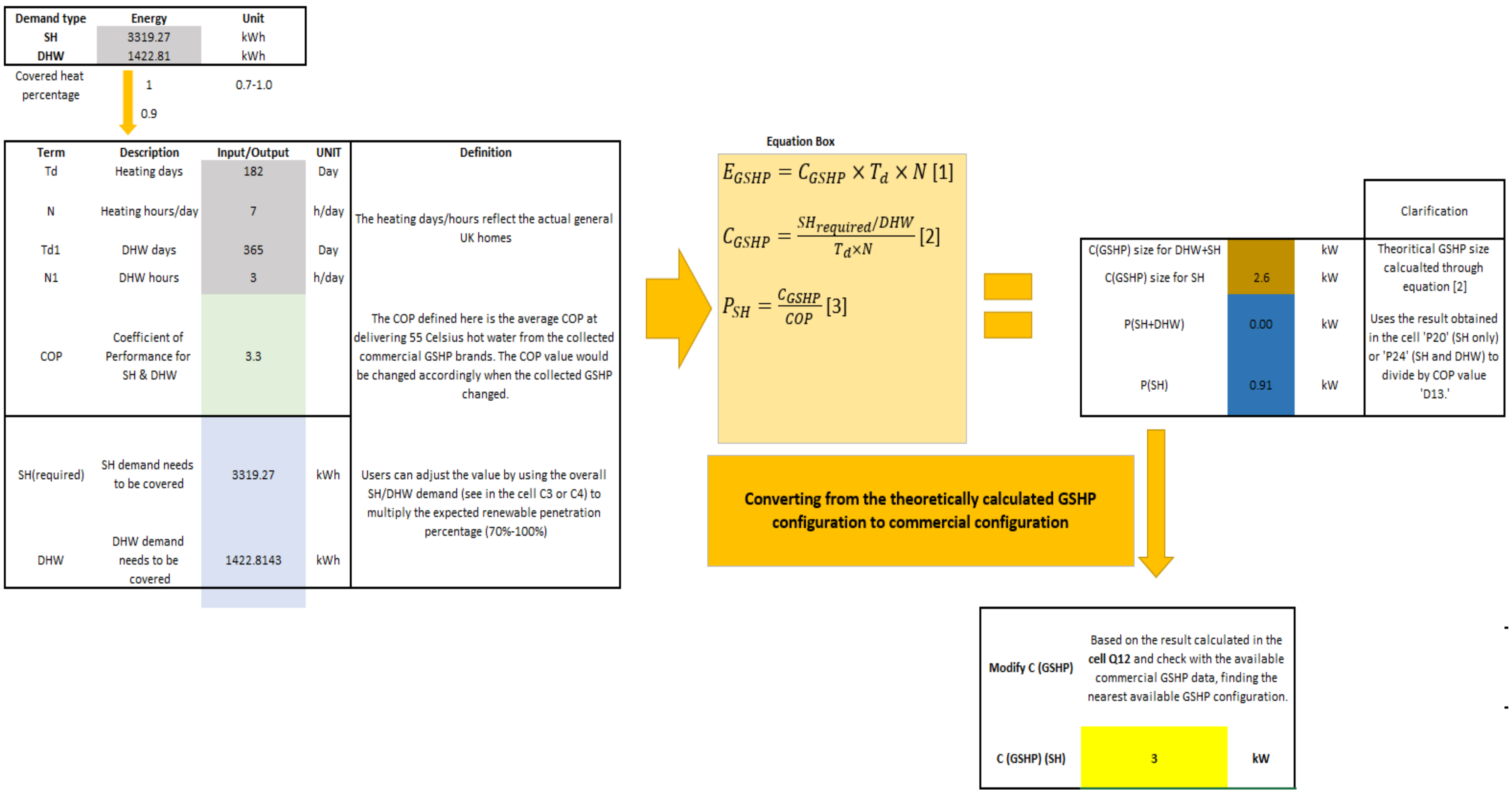


Figure 4-33 Sizing spreadsheet for GSHP or ASHP

In Figure 4-33, the calculated size for GSHP is 2.6 kW based on the required space heating demand of 3319.27 kWh. However, 2.6 kW GSHP is not existing in the current GSHP market; it then needs to convert to the nearest commercially available GSHP size (in yellow arrow).

After identifying the size for ASHP or GSHP, the spreadsheet would calculate the associated electricity consumption to generate the required space heating demand through the systems. Then, the calculated electricity consumption will add the lighting and electrical appliances to obtain the overall electricity consumption. Table 4-11 presents the example of the overall electricity consumption calculation after adding a 3kW GSHP.

Table 4-11 Example of electricity consumption data for the specified home

Electricity		
Lighting (data typed by users)	776.84	**kWh**
Appliance (data typed by users)	2091.04	**kWh**
Electric heating (data calculated based on the selected heat pumps)	1158.17	**kWh**
Electric DHW (data calculated based on the selected heat pumps)	0	**kWh**
In total	4026.06	**kWh**

The calculated overall electricity consumption with the input of the local annual average solar radiation to carry out the sizing process for solar PV. The sizing calculation followed the method explained in subsection 3.10.1, Figure 4-34 presents the developed spreadsheet.

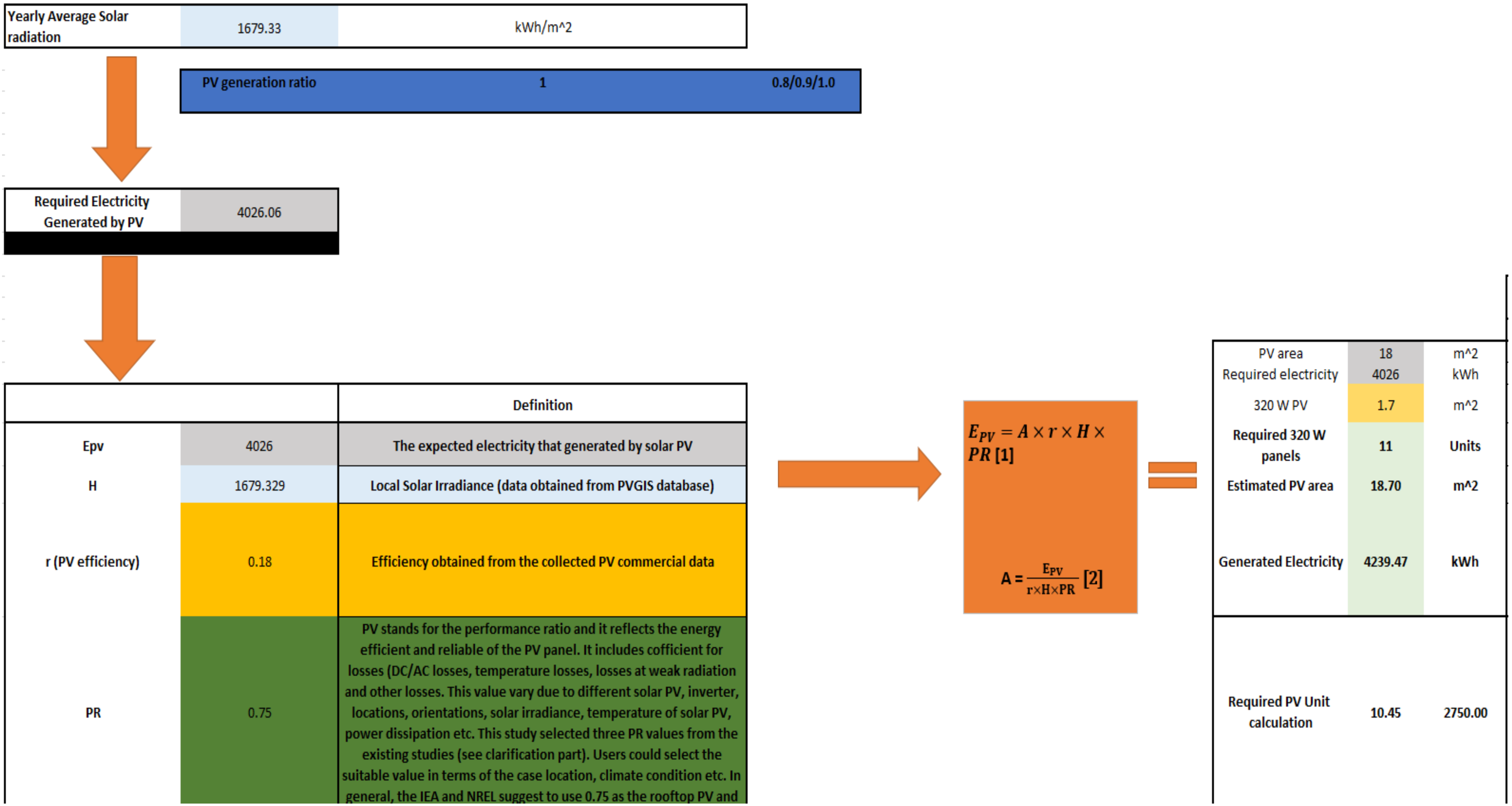


Figure 4-34 Sizing spreadsheet for solar PV

The sizing scenarios defined using solar PV to cover 80-100% of electricity demand (3.9.2). Therefore, the developed spreadsheet has a place to put the different required coverage ratios (in blue). In this case, the calculated number of PV panels is shown in the cell ‘Required PV Unit Calculation’ as ’10.45’. The figure should be rounded to the nearest whole number and filled in the cell ‘Required 320W panels’. Therefore, in this case, the cell shows ‘11’ units.

STC is used to cover the DHW demand in this research. It then needs the DHW demand of the selected home and the local annual average solar radiation as the inputs to carry out the sizing process for STC. The calculation explained in subsection 3.10.2, Figure 4-35 presents the developed sizing spreadsheet for STC. The estimated STC aperture area should first convert to the gross area; the converted gross area then compares with the available commercial data to identify the nearest commercially available STC product.

Yearly Average Solar radiation	1679.33	kWh/m^2

DHW demand	1422.81	kWh
collector performance ratio	8	a* = 6; efficiency = 75%

ε (storage volume factor)f2	99.98%	
STC zero-loss efficiency -	75%	(SAP, 2012) - Flat plate and glazed
H (Solar radiation)	1679.33	kWh/m^2
Collector performance factor (f1)	0.7148	
Overshading	1.00	No shading considered

$$E_{STC} = \varepsilon_{performance\ factor} \times A_{SC} \times \eta \times H$$

$$A_{SC} = \frac{E_{STC}}{\varepsilon_{storag} \times \eta \times H}$$

Estimated STC aperture area	1.58	m^2
STC gross area	1.76	m^2
Available commerical STC gross area	2.09	m^2
Generated DHW without annual solar radiation	1.12	kWh

			Reference
Average commercial Dedicated solar storage volume in Litres (based on SAP)	58.5L	m^2	Calculation process described in the methodology.
Average volume ratio (dedicated solar storage volume/daily average hot water demand)	0.68		SAP 2012; MCS 024; Page 1 of 9 Guidance on the selection and installation of storage cylinders for solar thermal hot water systems (2009)
Solar storage volume factor	0.9998		

Figure 4-35 Sizing spreadsheet for STC

After working out the sizing for each renewable system, it then needs to work out the amount of energy from the national grid and natural gas to compensate the demand where the renewable system could not cover. The demand-supply balance spreadsheet is developed to conduct the process mentioned above, the calculation method explained in subsection 3.10.5. This research considers a natural gas boiler to cover the space heating and DHW demand that the relevant renewable systems cannot cover. The efficiency of the natural gas boiler used in this research is 92%; then, the calculated space heating and DHW demand delivered by the gas boiler should divide by 92% to obtain the consumed overall natural gas (highlighted in yellow cells).

The generated electricity for the on-site usage (MCS, 2019) is used to illustrate the percentage of the generated electricity from solar PV for the on-site electricity consumption. This percentage is helpful to reflect a more reliable demand-supply balance between solar PV and the national grid. Therefore, the generated electricity for the on-site usage is considered in the demand-supply balance spreadsheet. The selection of the suitable value for the generated electricity for the on-site usage is explained in subsection 3.10.5.1. Detailed information on the demand-supply balance spreadsheet can be found on the submitted guidance of the decision-making framework and the whole spreadsheet.

4.7.2 Economic-Technical-Environmental performance evaluation spreadsheet

The calculated configurations (power ratings) and demand-supply balance calculation results are then used as the inputs for the economic-technical-environmental performance evaluation. The economic performance evaluation spreadsheet first needs to type the calculated configurations (power ratings) of each renewable system that were calculated from the sizing spreadsheet (subsection 4.7.1) in the 'input' column. The spreadsheet (shown in Figure 4-36) can then work out the overall cost (including the associated VAT charge) for the combination. Figure 4-36 shows an example of the capital cost of the 2.75kWp + 3kW ASHP with/without 13.5kWh battery. Figure 4-37 presents the economic performance of the 2.75kWp + 3kW ASHP in the selected indicators. The spreadsheet presents the economic performance of the HRES combination within 20 years lifespan. The discounted rate is considered in the cash flow calculation within 20 years; the calculation method of each economic performance indicator is explained in Table 3-8, section 3.11.

The technical and environmental evaluation performance spreadsheet are also supported by the renewable energy system sizing and demand-supply balance spreadsheet. The calculation detail in the spreadsheet development is explained in section 3.11. For the environmental performance evaluation spreadsheet, the results from the renewable energy system sizing spreadsheet are used to carry out the embodied carbon calculation for the HRES combination. For example, Figure 4-38 presents embodied carbon calculation for 2.75kWp PV + 3 kW ASHP + 13.5kWh Battery. The calculated embodied carbon calculation of the combination is then used to calculate the embodied carbon payback period indicator in the environmental performance evaluation spreadsheet.

PV	2.75
STC	0
ASHP	3
Inverter	3
GSHP	0

	Product cost (£/kW) inc VAT	Product cost (£/kW) exc VAT	Installation cost (£/kW) (inc. VAT)	Maintenance cost (£/kW)	Maintenance period (month/year)	Expected Lifespan	Overall cost inc. VAT	
PV		4816.428571			1	25	5057.25	5% VAT
							The 60% test	

	Product cost (£/kW) inc VAT	Product cost (£/kW) exc VAT	Installation cost (£/kW)	Installation cost (£/kW) (inc. VAT)	Maintenance cost (£/kW)	Maintenance period (month/year)	Expected Lifespan	Overall cost inc. VAT	
STC			0			1	25	0	5% VAT
								The 60% test	

	Product cost (£/kW) inc VAT	Installation (£/kW) exc VAT	Installation cost (£/kW) (inc. VAT)	Maintenance cost (£/kW)	Maintenance period (month/year)	Expected Lifespan	Overall cost inc. VAT	
ASHP		2814			2-3	20	2954.7	5% VAT
							The 60% test	

	Product cost (£/kW) inc VAT	Product cost (£/kW) exc VAT	Installation cost (£/kW) (inc. VAT)	Maintenance cost (£/kW)	Maintenance period (month/year)	Expected Lifespan	Overall cost inc. VAT	
GSHP		0			2-3	25	0	5% VAT

	Product cost (£/kW) inc VAT	Product cost (£/kW) exc VAT	Installation cost (£/kW)	Installation cost (£/kW) (inc. VAT)	Maintenance cost (£/kW)	Maintenance period (month/year)	Expected Lifespan	Overall cost inc. VAT	
3.0 kW solar PV inverter	496.8	414	covered by the solar PV installation		NA	Replace every ten years	10		60% test as a part of PV installation

	Product cost (£/kW) inc VAT	Product cost (£/kW) exc VAT	Installation cost exc. VAT (£/kW)	Installation cost (£/kW) (inc. VAT)	Maintenance cost (£/kW)	Maintenance period (month/year)	Expected Lifespan	Overall cost inc. VAT	
Battery (13.5kWh)	9390	7825	1365	1638		assume 20 years			20% VAT

Overall Cost			
exc VAT	8044.43	9190.00	17234.43
With VAT	8508.75	11028.00	19536.75

Figure 4-36 Capital cost calculation spreadsheet for HRES combination

Year	Capital cost (£)	Maintenance cost (£)	Lifecycle cost (Capital+ maintenance)	Discounted RE cost (£)	Mixed Energy bills (electricity) (discounted)	Energy bills (gas) (discounted) (mixed)	Mixed-Saved electricity from the grid (£)	Mixed-Saved gas from the gas pipe (£)	NPV	Benefits (£)	PVB/PVC	Operation and investment cost (£)	RHI	SEG
2020	8508.75	0	8508.75	8508.75	NA	NA	0.00	0.00	-8508.75		0	-8508.75	0	0
2021	0	100	120	115.94	1116.17	103.50	-162.50	258.02	481.51	597.45	5.15	115.94	359.19	142.75
2022	0	275	330	308.06	1078.42	100.00	-157.01	249.29	269.19	577.25	1.87	308.06	347.04	137.92
2023	0	100	120	108.23	1041.96	96.62	-151.70	240.86	449.49	557.72	5.15	108.23	335.31	133.26
2024	0	275	330	287.58	1006.72	93.35	-146.57	232.72	251.29	538.86	1.87	287.58	323.97	128.75
2025	0	100	120	101.04	972.68	90.19	-141.61	224.85	419.61	520.64	5.15	101.04	313.01	124.40
2026	0	275	330	268.46	939.78	87.14	-136.82	217.24	234.58	503.04	1.87	268.46	302.43	120.19
2027	0	100	120	94.32	908.00	84.20	-132.20	209.90	391.71	486.02	5.15	94.32	292.20	116.13
2028	0	275	330	250.61	877.30	81.35	-127.73	202.80	-63.34	187.27	0.75	250.61		112.20
2029	0	100	120	88.05	847.63	78.60	-123.41	195.94	92.89	180.94	2.05	88.05		108.41
2030	0	275	330	233.94	818.97	75.94	-119.23	189.31	-59.12	174.82	0.75	233.94		104.74
2031	496.8	100	716.16	490.53	791.27	73.37	-115.20	182.91	-321.62	168.91	0.34	490.53		101.20
2032	0	275	330	218.39	764.52	70.89	-111.31	176.73	-55.19	163.20	0.75	218.39		97.78
2033	0	100	120	76.73	738.66	68.49	-107.54	170.75	80.95	157.68	2.05	76.73		94.47
2034	0	275	330	203.87	713.68	66.18	-103.91	164.98	-51.52	152.34	0.75	203.87		91.27
2035	0	100	120	71.63	689.55	63.94	-100.39	159.40	75.57	147.19	2.05	71.63		88.19
2036	0	275	330	190.31	666.23	61.78	-97.00	154.01	-48.10	142.22	0.75	190.31		85.21
2037	0	100	120	66.86	643.70	59.69	-93.72	148.80	70.54	137.41	2.05	66.86		82.32
2038	0	275	330	177.66	621.93	57.67	-90.55	143.77	-44.90	132.76	0.75	177.66		79.54
2039	0	100	120	62.42	600.90	55.72	-87.49	138.91	65.85	128.27	2.05	62.42		76.85
2040	0	275	330	165.85	580.58	53.84	-84.53	134.21	-41.91	123.93	0.75	165.85		74.25

Figure 4-37 Economic performance evaluation spreadsheet

Renewable technology	Annual kWh	Expected Lifespan	EC (kg CO2e)		LifeSpan EC (kg CO2eq)
PV	3468.65	30	5307.04	sum(GSHP)	5307.04
GSHP	0.00	25	0.00	sum(ASHP)	6835.84
ASHP	3822.00	20	1528.80	sum(GSHP+Battery)	6643.54
STC			0.00	sum(ASHP+Battery)	8172.34
battery	13.5	assumed 20	1336.5		

Figure 4-38 Embodied carbon calculation spreadsheet

4.7.3 Weighting and decision-making spreadsheet

The developed AHP-model spreadsheet converts surveyed Cardiff householders' preferences on the economic-technical-environmental criteria and indicators prior to investing in the renewable system to the associated weighting values. The weighting values are then used to support the final ranking for all potential HRES combinations. The developed spreadsheet then automatically calculates the associated weighting values to reflect the preferences expressed by the householder. Figure 4-39 presents an example to show the calculation process using the AHP method, and the results in the 'normalisation' column are the calculated weighting results based on the collected householders' preference values. In this research, the AHP-model spreadsheet was used to convert preference values from all surveyed Cardiff householders.

	Indicator-1	Indicator-2	Indicator-3	Indicator-4	Indicator-5	Indicator-6	Indicator-7	Indicator-8	Average Criteria	Normalisation
Indicator-1	0.114285714	0.114285714	0.114285714	0.114285714	0.114285714	0.114285714	0.114285714	0.114285714	0.114285714	0.114285714
Indicator-2	0.142857143	0.142857143	0.142857143	0.142857143	0.142857143	0.142857143	0.142857143	0.142857143	0.142857143	0.142857143
Indicator-3	0.085714286	0.085714286	0.085714286	0.085714286	0.085714286	0.085714286	0.085714286	0.085714286	0.085714286	0.085714286
Indicator-4	0.114285714	0.114285714	0.114285714	0.114285714	0.114285714	0.114285714	0.114285714	0.114285714	0.114285714	0.114285714
Indicator-5	0.142857143	0.142857143	0.142857143	0.142857143	0.142857143	0.142857143	0.142857143	0.142857143	0.142857143	0.142857143
Indicator-6	0.114285714	0.114285714	0.114285714	0.114285714	0.114285714	0.114285714	0.114285714	0.114285714	0.114285714	0.114285714
Indicator-7	0.142857143	0.142857143	0.142857143	0.142857143	0.142857143	0.142857143	0.142857143	0.142857143	0.142857143	0.142857143
Indicator-8	0.142857143	0.142857143	0.142857143	0.142857143	0.142857143	0.142857143	0.142857143	0.142857143	0.142857143	0.142857143

Figure 4-39 AHP-model spreadsheet

The TOPSIS-model spreadsheet is used to rank potential HRES combinations by using the weighting values. This research used two groups of weighting values in the TOPSIS-model spreadsheet. One group of weighting values are from the surveyed Cardiff householders that were converted through the developed AHP-model spreadsheet, and another group is equal weighting values. In order to proceed with the ranking calculation, the spreadsheet needs to enter the evaluation performance results (shown in subsection 4.7.2) of the HRES combinations. Figure 4-40 presents the performance results of 24 to-be-ranked HRES combinations. After typing the weighting values, the spreadsheet will automatically rank the 24 HRES combinations and present the final ranking results. Figure 4-41 shows an example of the ranking results.

D	E	F	G	H	I	J	K	L	M
	Capital Cost (£)	BCR	Economic benefits ratio from financial incentive schemes	Grid electricity independence level	Lifespan (Year)	Renewable fraction	ECPBP (Years)	GHG emission (kg CO2 eq)	HRES combinations
Alternative -1	7506	0.48	0.5236	0.1523	25	0.5092	13	757	2.25PV+3ASHP
Alternative -2	7966	0.49	0.5193	0.1598	25	0.5378	13.99	750	2.5PV+3ASHP
Alternative -3	8509	0.478	0.5139	0.1551	25	0.5575	15.94	754	2.75PV+3ASHP
Alternative -4	18534	0.46	0.1445	0.6767	23.3	0.7187	39.98	432	2.25PV+3ASHP+13.5kWh Battery
Alternative -5	18994	0.468	0.1469	0.7237	23.3	0.7404	40.96	420	2.5PV+3ASHP+13.5kWh Battery
Alternative -6	19537	0.466	0.1530	0.7340	23.3	0.7544	41.95	417	2.75PV+3ASHP+13.5kWhBattery
Alternative -7	16452	0.379	0.3780	0.1551	27.5	0.5194	11.94	741	2.25PV+3GSHP
Alternative -8	16912	0.386	0.3799	0.1627	27.5	0.5476	12.94	734	2.5PV+3GSHP
Alternative -9	17455	0.382	0.3816	0.1580	27.5	0.5668	13.96	738	2.75PV+3GSHP
Alternative -10	27480	0.401	0.1807	0.6892	25	0.7290	38	416	2.25PV+3GSHP+13.5kWh Battery
Alternative -11	27940	0.406	0.1817	0.7371	25	0.7502	38.97	404	2.5PV+3GSHP+13.5kWh Battery
Alternative -12	28483	0.406	0.1853	0.7476	25	0.7637	38.99	401	2.75PV+3GSHP+13.5kWhBattery
Alternative -13	11170	0.579	0.5732	15.23%	26.7	57.79%	10.97	810	2.25PV+3ASHP+1.5kWSTC
Alternative -14	11631	0.583	0.5683	15.98%	26.7	59.82%	11.95	804	2.5PV+3ASHP+1.5kWSTC
Alternative -15	12173	0.571	0.5623	15.51%	26.7	61.18%	12.94	808	2.75PV+3ASHP+1.5kWSTC
Alternative -16	22199	0.523	0.2320	67.67%	25	74.45%	32.98	486	2.25PV+3ASHP+1.5kWSTC+13.5kWh Battery
Alternative -17	22659	0.527	0.2322	72.37%	25	76.09%	32.98	474	2.5PV+3ASHP+1.5kWSTC+13.5kWh Battery
Alternative -18	23201	0.524	0.2354	73.40%	25	77.14%	32.99	471	2.75PV+3ASHP+1.5kWSTC+13.5kWh Battery
Alternative -19	20117	0.458	0.4320	15.51%	28.3	58.61%	9.96	795	2.25PV+3GSHP+1.5STC
Alternative -20	20577	0.463	0.4324	16.27%	28.3	60.60%	10.93	788	2.5PV+3GSHP+1.5STC
Alternative -21	21119	0.458	0.4324	15.80%	28.3	61.93%	11.92	792	2.75PV+3GSHP+1.5kWSTC
Alternative -22	31145	0.454	0.2388	68.92%	26.25	75.26%	31	470	2.25PV+3GSHP+1.5STC+13.5Battery
Alternative -23	31605	0.458	0.2389	73.71%	26.25	76.87%	31.98	458	2.5PV+3GSHP+1.5STC+13.5Battery
Alternative -24	32147	0.457	0.2411	74.76%	26.25	77.89%	31.99	455	2.75PV+3GSHP+1.5kWSTC+13.5kWh Battery

Figure 4-40 Inputs of the economic-technical-environmental performance of HRES combinations in the TOPSIS-model spreadsheet

Step 4

S+' + 'S-'	P	Rank based on 'P' Value	HRES Combinations
0.138779187	0.915830392	5	2.25PV+3ASHP
0.137326818	0.916614096	3	2.5PV+3ASHP
0.13525544	0.914165438	6	2.75PV+3ASHP
0.123291927	0.880986283	21	2.25PV+3ASHP+13.5kWh Battery
0.126278389	0.882678594	18	2.5PV+3ASHP+13.5kWh Battery
0.126859477	0.881813974	20	2.75PV+3ASHP+13.5kWhBattery
0.12560637	0.895299261	14	2.25PV+3GSHP
0.124136304	0.895585146	13	2.5PV+3GSHP
0.122820431	0.893481114	15	2.75PV+3GSHP
0.119920027	0.871697906	24	2.25PV+3GSHP+13.5kWh Battery
0.123558518	0.873849055	23	2.5PV+3GSHP+13.5kWh Battery
0.124468928	0.874217567	22	2.75PV+3GSHP+13.5kWhBattery
0.140703103	0.917626656	2	2.25PV+3ASHP+1.5kWSTC
0.13935282	0.917962616	1	2.5PV+3ASHP+1.5kWSTC
0.137876724	0.91624515	4	2.75PV+3ASHP+1.5kWSTC
0.120521578	0.897064305	11	2.25PV+3ASHP+1.5kWSTC+13.5kWh Battery
0.123470669	0.899423036	7	2.5PV+3ASHP+1.5kWSTC+13.5kWh Battery
0.124038102	0.899398801	8	2.75PV+3ASHP+1.5kWSTC+13.5kWh Battery
0.127769522	0.898083404	9	2.25PV+3GSHP+1.5STC
0.126522416	0.897998755	10	2.5PV+3GSHP+1.5STC
0.12534291	0.895704852	12	2.75PV+3GSHP+1.5kWSTC
0.1203628	0.882213129	19	2.25PV+3GSHP+1.5STC+13.5Battery
0.123630439	0.883604231	16	2.5PV+3GSHP+1.5STC+13.5Battery
0.12463869	0.883566544	17	2.75PV+3GSHP+1.5kWSTC+13.5kWh Battery

Figure 4-41 Ranking results presented in the developed TOPSIS-model spreadsheet

4.7.4. Validation and future application

Subsections 4.7.1 and 4.7.3 explained the application of using the developed spreadsheet to identify the suitably sized renewable systems and energy storage for the specified home with the associated demand. The previous three sections also explained using the developed spreadsheet to evaluate the economic-technical-environmental performance of the suitably sized systems for the specified home. The results are helpful for householders to decide on the long-term benefits of investing in such systems. In addition, the results help policymakers to develop future energy policies and relevant incentives. Therefore, it is necessary to clarify the validity of the developed spreadsheet, meanwhile, to acknowledge the updates to be made in the future application to improve the accuracy of the results.

The spreadsheets were developed based on the SAP, BREEAM technical manual, MCS standards, technical report, and relevant peer-reviewed research articles. Therefore, the equations used in the spreadsheet are reliable for working out the size of the renewable energy systems and accurate in assessing the associated economic-technical-environmental performance. The results can reflect certain theoretical accuracy of the scoped systems. However, several datasets are used in the spreadsheet calculation process; the datasets like cost, technical and environmental performance of renewable and storage will change along with time. Therefore, in future applications, such datasets should maintain the update, reflecting the accurate renewable system market from the economic-technical-environmental perspective.

5. Discussion

This section discusses the results presented in chapter 4 to explain how the results answer the research questions and help to strengthen the future energy policy in UK homes. The discussion results help to understand the following topics:

- It analyses the advantages and limitations of using HRES combinations compared with using electricity from the grid and natural gas in UK homes. The comparison results help policymakers to enhance the future renewable energy policy in UK's domestic building sector. (Section 5.1)
- The advantages and disadvantages of using the battery in HRES combinations at the individual domestic building level. (Section 5.2)
- The economic analysis of HRES combinations and the associated individual renewable system(s) that benefits from different financial incentive schemes. The economic analysis is used as evidence to support the future renewable financial incentive development. (Section 5.3)

5.1. Advantages and limitations of using HRES combinations compared with using electricity from the grid and natural gas in UK homes

This subsection analyses the advantages and limitations between HRES combinations and using electricity from the national grid and natural gas to meet the energy demand for a representative home in England and Wales from the economic-technical-environmental perspectives. The discussion results demonstrate the advantages of using HRES combinations to meet the energy demand for homes in England and Wales in a 20-year timescale. In addition, the limitations of using HRES combinations are helpful to consider making the future energy policy align with the agreed climate change target in UK's domestic building sector.

5.1.1. The applied data in the discussion

The electricity and natural gas tariff used in the discussion are from E. ON in Cardiff after the increased energy cap in April 2022. The electricity tariff is 28.29p/kWh with a standing charge of 48.15/day. The natural gas tariff is 7.44p/kWh with a standing charge of 27.22p/day. The used energy tariffs include a 5% VAT charge. The carbon emission factor for electricity from the UK national grid in 2022 is 0.2123 kg CO_2 eq/kWh, and the factor for natural gas is 0.1832 kg CO_2 eq/kWh (BEIS, 2022a). The smart export guarantee (SEG) and renewable heat incentive (RHI) are considered in discussing the advantages and disadvantages of using HRES combinations compared with using electricity from the national grid and natural gas for UK homes. The selected HRES combinations in the discussions are:

- 2.75kWp + 3kW ASHP
- 2.75kWp + 3kW ASHP + 13.5kWh Battery
- 2.75kWp + 3kW GSHP
- 2.75kWp + 3kW GSHP + 13.5kWh Battery
- 2.75kWp + 3kW ASHP + 1.5kW STC
- 2.75kWp + 3kW ASHP + 1.5kW STC + 13.5kWh Battery
- 2.75kWp + 3kW GSHP + 1.5kW STC
- 2.75kWp + 3kW GSHP + 1.5kW STC + 13.5kWh Battery

According to the defined scenarios in section 3.9, the combinations listed above can cover 100% of electricity and heat demand. However, section 4.4 presents that such combinations still need electricity from the grid and natural gas to compensate for the part of the demand that the generated energy cannot cover from those combinations. The electricity from the grid and natural gas help to rebalance the supply and demand between the combinations and the associated energy demand of the selected home.

5.1.2. Discussion of using HRES combinations compared with using electricity from the national grid and natural gas in UK homes

This subsection first discusses the saved energy bills in 20 years after installing the combinations of PV+ASHP/GSHP and PV+ASHP/GSHP+STC compared with only relying on electricity from the grid and natural gas to cover the associated demand. The saved energy bill is a good indicator to demonstrate the economic benefits of installing the listed HRES combinations in subsection 5.1.1.

The simulated electricity consumption (including lighting and electrical appliances) is 2,868kWh; the natural gas consumption for DHW is 1,547 kWh/year, and the natural gas consumption for space heating is 3,692 kWh between October and March every year of the selected representative home (the detailed information can be found in section 4.1). Based on the simulated energy demand of the selected home, the considered 20 years lifecycle costs for the selected representative retrofitted home are:

- the electricity bill is £14,028;
- the natural gas bill for DHW and space heating is £6,954

In 20 years, the overall energy bills for electricity, space heating, and DHW are £20,982. After installing the selected HRES combinations with the specified configurations (power ratings), within 20 years, the energy bill for the combination of PV+ASHP is £19,692 and £19,392 for the combination of PV+GSHP. The HRES combinations saved up to £1,590 compared with only using electricity from the national grid and natural gas to supply energy in 20 years. Although the estimated combinations can cover 100% of electricity and space heating demand. Solar PV cannot provide sufficient electricity in the defined heating period (subsection 3.10.3) due to insufficient solar radiation and lack of energy storage. Thus, those combinations largely rely on importing electricity from the grid to power the heat pumps in the defined heating period. In addition, the heat pumps in those combinations are not designed to cover DHW demand; thus, the DHW demand is still supplied by natural gas. Based on the discussion above, PV+ASHP and PV+GSHP can only save up to £80 (up to £1,590 in 20 years) per year.

The present value of benefits (PVB) and lifecycle cost (LCC) are two values to describe the received benefits and costs of installing HRES combinations in 20 years. The PVB includes the selected financial incentives and saved energy bills, and LCC consists of the capital, replacement and servicing costs in 20 years. The higher proportion value between the received benefits and cost indicating the combination has a better economic performance, and then the combination is worth for householders to consider investing in.

The LCC for the combination of PV+ASHP is £12,089, and £21,873 for PV+GSHP in 20 years. The LCC difference between the PV+ASHP and PV+GSHP is due to the expensive groundwork of installing GSHP. The combination of PV+GSHP has a slightly higher PVB (£8,366) than PV+ASHP (£5,778). However, the proportion value between PVB and LCC in PV+GSHP (0.382) is lower than in PV+ASHP (0.478). The proportion value suggests householders should consider investing in PV+ASHP instead of PV+GSHP to gain a better economic performance.

The energy bills for the combinations of PV+ASHP+STC and PV+GSHP+STC in 20 years are £18,251 and £17,950, respectively. Compared with using electricity from the national grid and natural gas, the selected HRES combinations saved energy bills up to £152 per year (up to £3,032 in 20 years) to supply electricity, space heating and DHW demand.

The PVB for PV+ASHP+STC is £9,576 and £12,164 for PV+GSHP+STC. The LCC for PV+GSHP+STC (£26,543) is about £10,000 higher than PV+ASHP+STC (£16,759). PV+GSHP+STC has a higher LCC than PV+ASHP+STC still due to the expensive groundwork cost.

The combination of PV+ASHP+STC and PV+GSHP+STC has a lower energy bill than PV+ASHP or PV+GSHP in 20 years. As PV+ASHP/GSHP+STC covers DHW demand, however, the DHW demand was covered only by natural gas in PV+ASHP/GSHP. The natural gas consumption is then reduced in supplying DHW in PV+ASHP/GSHP+STC; thus, the energy bill of PV+ASHP/GSHP+STC is lower than PV+ASHP/GSHP. LCC for PV+ASHP+STC or PV+GSHP+STC is higher than PV+ASHP or PV+GSHP, as the former LCC includes the capital cost of STC. The proportion between PVB and LCC for PV+ASHP+STC is 0.571 and it is higher than PV+ASHP (proportion value is 0.478). In addition, the proportion between PVB and LCC for PV+GSHP+STC is 0.458 and it is higher than PV+GSHP (proportion value is 0.382).

A 13.5kWh Tesla battery is considered to add to the selected HRES combinations. The added battery improves PV self-consumption performance, prioritising the generated electricity to cover the demand and then exports the excess portion of the generated electricity to the grid. The battery function minimises importing electricity from the national grid, reducing energy bills, and improving the electricity independence of the selected home from the national grid. After adding the battery, the energy bills in 20 years for PV+ASHP were reduced to £13,311 and £13,010 for PV+GSHP. The energy bills for PV+ASHP+STC are £11,869 and £11,569 for PV+GSHP+STC after adding a 13.5kWh battery in 20 years. The added battery helps to reduce energy bills by up to £6,400 compared with the combinations without a battery. After adding a battery, PV+ASHP saved £384 (£7,671 in 20 years) of energy bill per year; PV+GSHP saved £399 (£7,972 in 20 years) of energy bill per year. PV+ASHP+STC saved £456 (£9,113 in 20 years) of energy bill per year; PV+GSHP+STC saved £471 (£9,413 in 20 years) of energy bill per year.

The PVB for PV+ASHP and PV+GSHP with a battery is £10,776 and £13,364, respectively; and the PVB for PV+ASHP+STC and PV+GSHP+STC with a battery is £14,574 and £17,162, respectively. The added battery increased PVB for HRES combinations up to £5,000 and it is due to the saved electricity bills. The LCC for HRES combinations with a battery has been increased up to about £11,000 compared with combinations have no batteries. The increased LCC is largely due to the added installation cost of the battery. The proportion between PVB and PVC for PV+ASHP+Battery (0.466) is slightly lower than PV+ASHP (0.478), PV+ASHP+STC+Battery (0.524) is also slightly lower than PV+ASHP+STC (0.571). The possible reasons are that the energy bills reduced by adding the battery cannot balance the installation cost of the battery, and there are no available financial incentives for installing a battery for homes. Differently, the proportion between PVB and PVC for PV+GSHP+Battery (0.406) is slightly higher than PV+GSHP (0.382). The potential reason is the saved energy bills subject to adding the battery balanced a larger part of PVC than PV+GSHP. Figure 5-1presents the results discussed above.

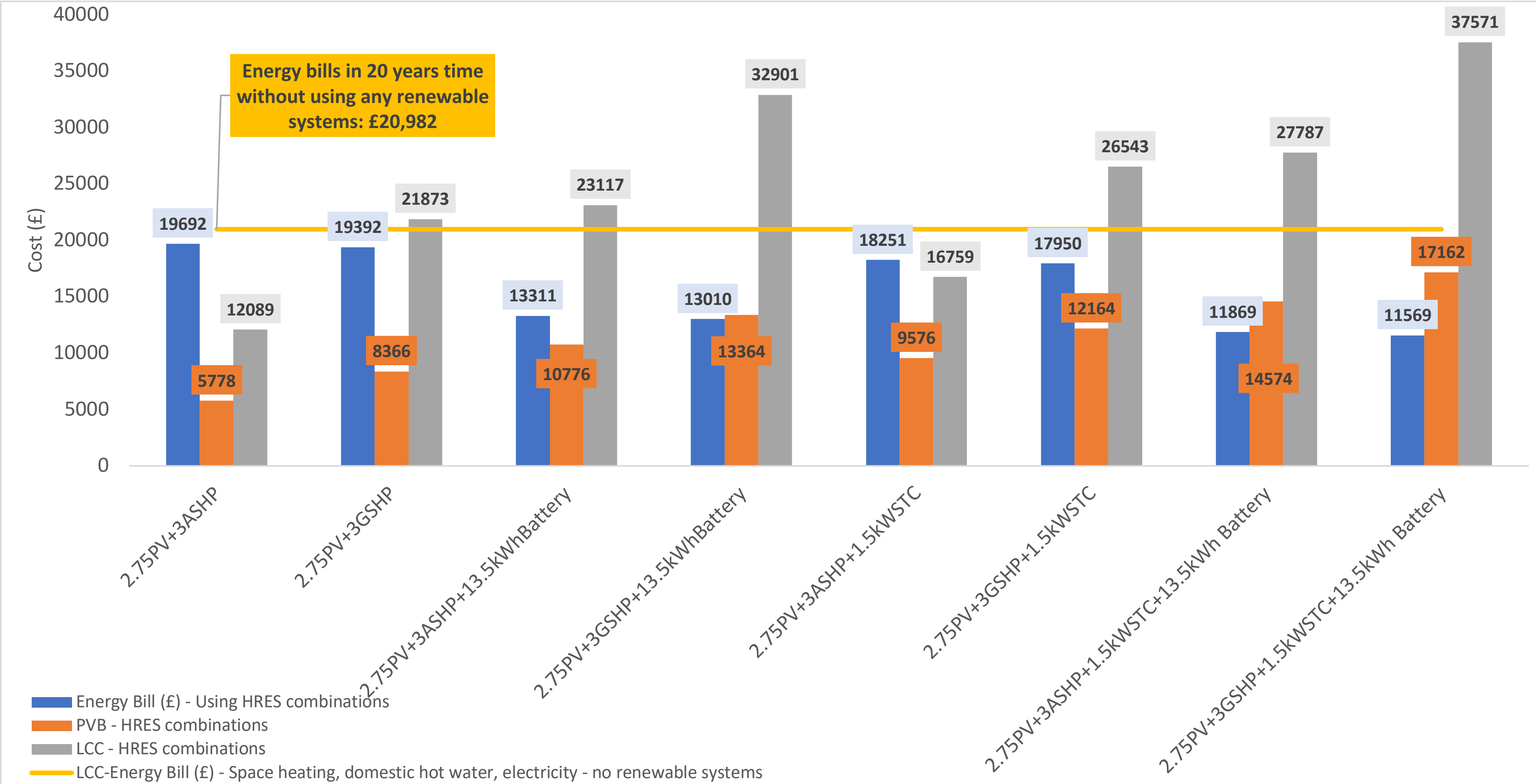


Figure 5-1 LCC, lifecycle benefits and the associated energy bills of HRES combinations against energy bills of using no renewable systems in 20 years.

HRES combinations bring economic benefits through the financial incentive schemes and the saved energy bills compared to using energy from the national grid and natural gas. However, the LCC of each HRES combination is still higher than the gained benefits (PVB), indicating HRES combinations cannot expect an economic pay back within 20 years. The reasons are summarised in the following:

1) Although the capital cost of renewable systems has been reduced in the past ten years. Especially like solar PV, the capital cost has decreased by about 30%. The capital costs of renewable systems are still more expensive than conventional energy supply strategies (Renaldi et al., 2021a).
2) The received lifecycle benefits (PVB) from the financial incentive schemes and the saved energy bill from the national grid and natural gas only compensate less than 60% of the LCC in HRES combinations. Although the combinations are designed to cover 100% of the electricity and heat demand of the selected home, the combinations still largely rely on using electricity from the grid and natural gas to balance the generated energy from the combinations and demand. Particularly, the combinations like PV+ASHP/GSHP without a battery saved less than £2,000 in energy bills in 20 years compared with only using electricity from the grid and natural gas to cover the relevant demand. Then, the saved small amount of energy bill is difficult to cover the expensive installation cost of renewable systems. The combinations with a battery like PV+ASHP/GSHP+STC saved more than £9,000 in energy bills compared with only using electricity from the grid and natural gas to cover the associated demand. However, the saved energy bills cannot pay back the high installation cost of the battery, and there are no available financial incentives to reduce the installation cost of the battery. Thus, based on the calculation mentioned above, using energy from the national grid and natural gas is cheaper than installing HRES combinations in UK homes. However, the energy tariff is continuing to increase year by year (Ofgem, 2022c, 2022b). The energy tariff in 10 years' time might be much higher than the considered energy tariff in the calculation; the economic benefits of using HRES combinations will be higher than the figure calculated above. In addition, the policymakers worth considering the relevant strategy or incentives to reduce further the capital cost of renewable systems (especially for the battery) and amplify the saved energy from the fossil energy of using HRES combinations (Renaldi et al., 2021a).

Besides adding economic benefits to householders who adopt HRES combinations with a suitable battery, the added battery can also bring technical and environmental benefits. The added battery can significantly improve grid electricity independence level (GEI); the higher GEI enables the home to cover a large portion of demand through on-site solar PV. The battery increases GEI to around 75% for the PV+ASHP/PV+ASHP+STC/PV+GSHP/PV+GSHP+STC combinations. The added battery increased the GEI performance of HRES combinations by about 58% compared with the HRES combinations without a battery. The increased high level of GEI indicates that the HRES combinations would generate enough electricity to cover about 73-75% of the electricity demand. Figure 5-2 presents GEI discussed above.

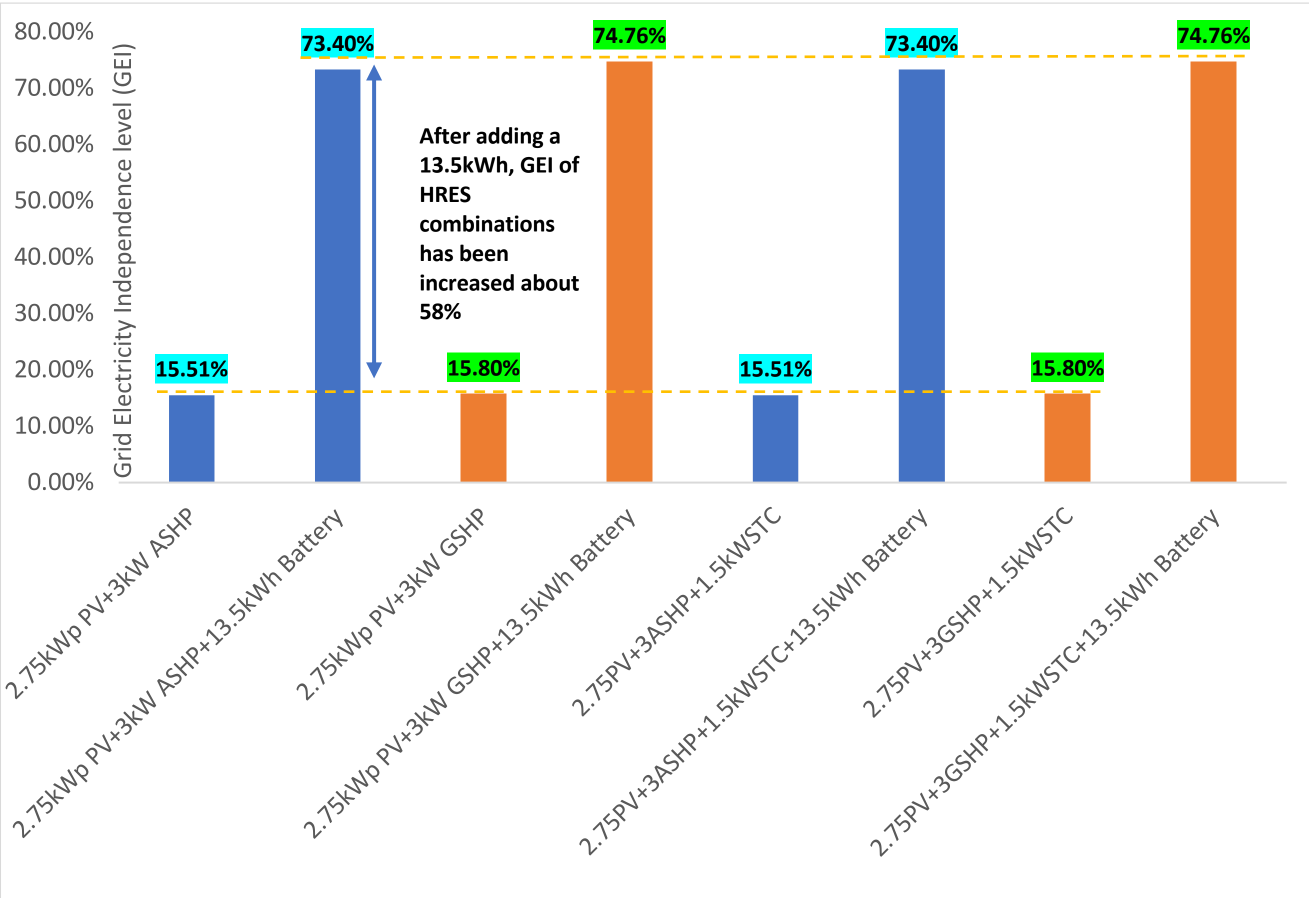


Figure 5-2. GEI comparison

The home with a higher GEI have two distinct advantages, 1) the imported electricity from the national grid would be dramatically cut (Green Square, 2021) and householders will be less affected by power outages (Westech Solar, 2022). 2) it helps to further reduce carbon emission by importing electricity from the national grid (Green

Square, 2021). From a national level, the home with a higher GEI can reduce the corresponding proportion of electricity supply by the national grid annually. In addition, the home with a higher GEI could reduce electricity lost in the grid within the transmission and distribution networks. Currently, 1.7% of electricity is lost in the transmission and 5-8% of electricity is lost in the distribution networks (Green Square, 2021).

The home-installed solar PV and a suitable battery can gain the benefits discussed above. However, some limitations have remained; the most significant barrier that stops householders from installing batteries is the highest capital cost of battery and no available financial incentive schemes for installing the battery in homes. The two alternative solutions like the grid-scale battery and community battery storage help shifting the high capital cost of battery from the individual householder to other stakeholders. Section 5.3 discusses the alternative solutions and home-installed battery in detail.

Renewable fraction (RF) is another important technical indicator; it demonstrates the percentage of the demand (both electricity and heat demand) that is covered by the on-site renewable systems. The high RF indicates that the on-site renewable system covers more energy demand. Then those combinations with a high RF would have a low energy bill and less GHG emission. PV+ASHP+STC or PV+GSHP+STC has a higher RF than PV+ASHP or PV+GSHP, as the former combinations cover electricity, space heating and DHW; the later ones only cover the electricity and space heating. The added battery can also increase RF of HRES combinations, as the battery stores excess generated electricity from the solar PV and is then used later for the energy demand. The added battery increases about 20% of RF for PV+ASHP or PV+GSHP, and it increases about 16% of RF for PV+ASHP+STC or PV+GSHP+STC. Figure 5-3 presents RF value of HRES combinations discussed above.

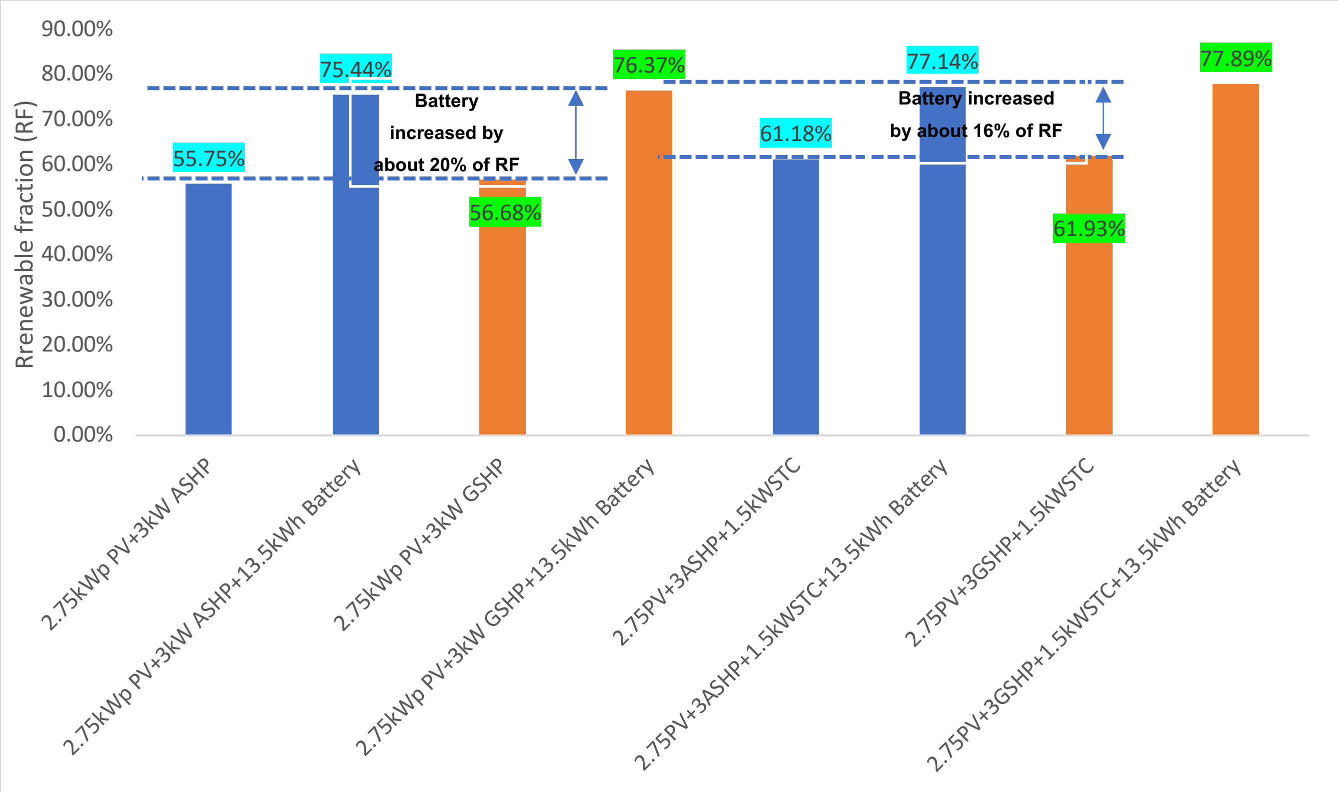


Figure 5-3 Renewable fraction (RF) of HRES combinations

Based on the collected carbon emission factor explained in subsection 5.1.1, the simulated space heating and electricity would release 1,285kg CO_2 eq per year. In addition, the home would release 1,569kg CO_2 eq per year for the consumed energy, including space heating, electricity and DHW.Click or tap here to enter text.

The HRES combinations with a high RF and GEI value, like PV+ASHP+STC or PV+GSHP+STC, with a 13.5kWh battery. They can save up to 1,114kg CO2 eq per year compared with using energy from the grid and natural gas to supply space heating, DHW and electricity. Without adding a 13.5kWh battery to the combinations, those combinations save up to 777kg CO2 eq per year compared with using energy from the grid and natural gas to supply the associated energy.

The HRES combinations like PV+ASHP/GSHP with a 13.5kWh battery can save up to 884 kg CO2 eq per year compared with using energy from the grid and natural gas to supply space heating and electricity. Without adding a 13.5kWh battery, these combinations then save up to 547kg CO2 eq per year compared with using energy from the grid and natural gas to supply the associated energy. Figure 5-4 presents the saved operational carbon discussed above.

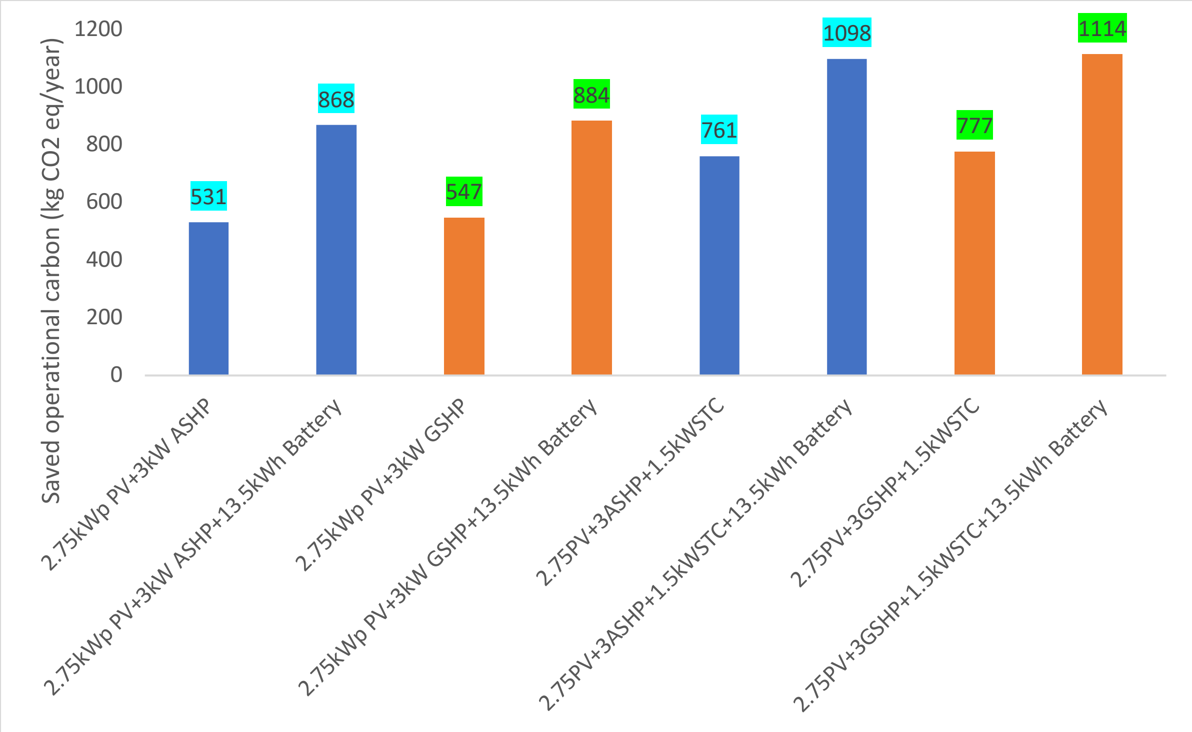


Figure 5-4 Saved operational carbon of replacing national grid and natural gas by HRES combinations

After comparing the above combinations with/without a battery, the added battery helps combinations to save about 340kg CO2 eq more per year and 6,800 kg CO2 eq more in 20 years compared with using energy from the grid and natural gas. Whilst the embodied carbon of battery is still at a high level (about 99kg CO_2 eq/kWh, (Carbon Brief, 2020)). In the research conducted by Rapier (2020), the embodied carbon of HRES combinations in per unit is 3.8 times higher than the combinations without a battery followed by Rapier's calculation method. However, the HRES combinations with a battery can still expect an embodied carbon payback period within 20 years. More than that, the added battery helps HRES combination to pay back embodied carbon at least 3 years quicker than those combinations without a battery.

The combinations without a battery save less operational carbon through using energy from the grid and natural gas. The embodied carbon of those combinations can expect a payback period between 11 and 15 years. On average, PV+ASHP/GSHP+STC can pay back the associated embodied carbon about 3 years quicker than PV+ASHP/GSHP. As the former combinations saved more operational carbon than later combinations. Figure 5-5 presents embodied carbon payback period of the HRES combinations discussed above.

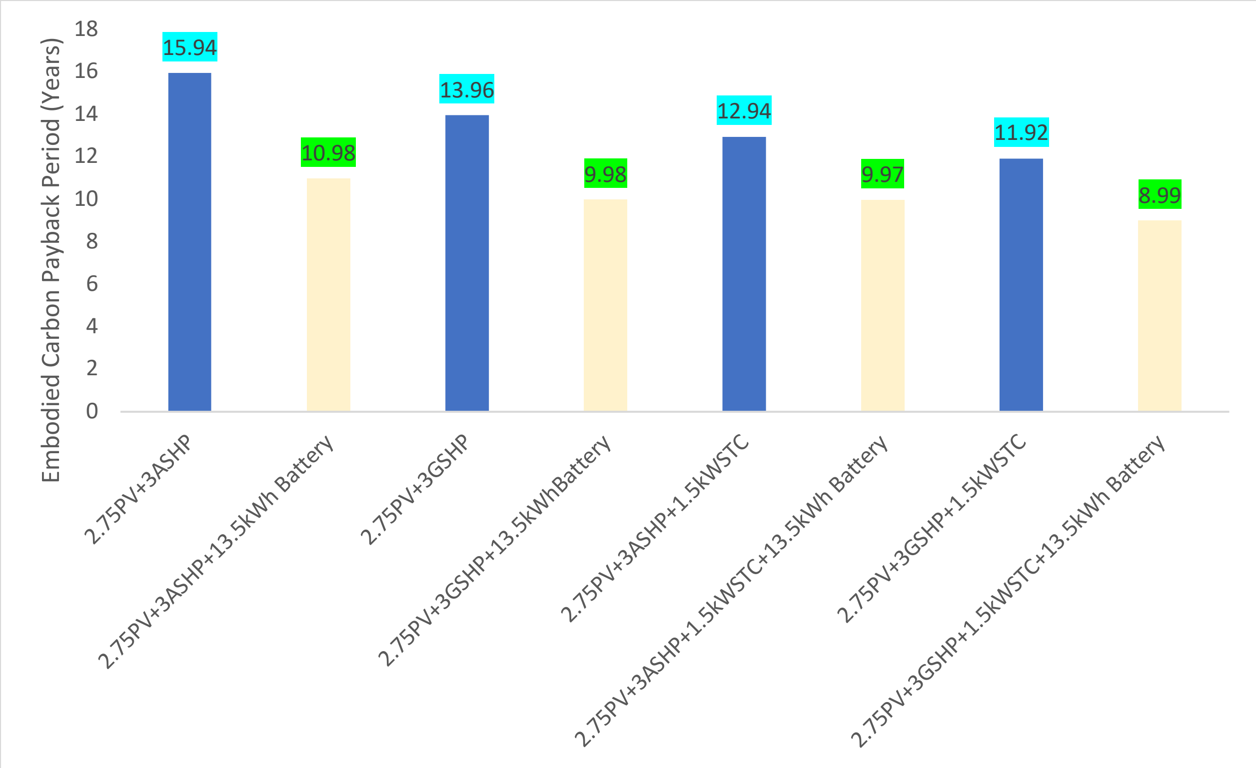


Figure 5-5 Embodied carbon payback period of HRES combinations

5.1.3. Summary

Replacing the energy supply from the national grid and natural gas by the HRES combinations that discussed in this section supply the associated energy for the selected representative retrofitted home. HRES combinations can bring the following benefits:

- Save energy bills.
- Improve the dependence from the national grid, helping home to become more energy dependent.
- Save operational carbon subject to using less energy from the national grid and natural gas.
- Accelerate the process to become a low-carbon home, helping UK to achieve the agreed climate change target by 2050 from the domestic building sector.

The added battery adds more benefits in the energy bills saving, strengthening the energy dependence from the national grid and natural gas to save more operational carbons. However, the high capital cost of the battery is still the main barrier that stops individual householders from investing battery in their homes. In addition, the embodied carbon of the battery is still at a high level, and it cannot pay back within the battery's expected lifespan. Section 5.3 will continue to discuss the advantages and disadvantages of using the battery at different scales.

Some economic limitations of using HRES combinations than the national grid and natural gas are explained earlier in this subsection. The HRES combinations also face some technical issues in the installation practice:

- some retrofitted houses cannot install an ASHP/GSHP due to the limited space and strict planning permit. Particularly in Wales, some old terraced-houses might difficult to meet 3 meters installation rule to fit in an ASHP (Welsh Government, 2022).
- Heat pumps need a longer time to heat the home to the required temperature than the boiler. As heat pumps are right-sized to meet the required demand, the boiler generally is oversized (Thermal earth, 2023). The householders might need to change their usage behaviour to leave heat pumps working longer than boilers.
- Some householders might not allow installing the sized solar PV to meet 100% of the energy demand. The Distribution Network Operator (DNO) might not approve the installation work due to the consideration of the national grid's capacity. As the exceed electricity that generated from the installed solar PV would be exported back to the grid, and DNO needs to ensure the exported electricity is within the maximum capacity of the national grid. Therefore, adding a battery, sharing solar PV with neighbours(Soutar & Devine-Wright, 2022) (Soutar & Devine-Wright, 2022) could be the potential solutions to deal with the issue.
- The existing grid or the distribution networks were not designed to handle importing electricity from solar PV or micro wind turbines installed in UK homes. The grid or the distribution networks were built based on the larger coal and nuclear power stations (Helm, 2023). The existing power networks then face a significant change subject to the increasing demand of replacing natural gas boilers by heat pumps (Ofgem, 2022a), and those heat pumps are expected to be powered by on-site renewable systems (e.g., solar PV) in homes. The existing power networks should be upgraded to a capability that can manage that generated excess electricity from such homes installed renewable systems.

5.2. An in-depth discussion of installing battery in UK homes

Subsection 5.1.2 discussed the benefits of adding a battery to the HRES combinations. The added battery can improve the PV self-consumption performance, prioritising the generated electricity to cover the demand and then exporting the excess portion of the generated electricity to the grid. In addition, subsection 5.1.2 pointed out that the high capital cost is the main barrier that stops householders from considering investing in batteries. It then introduced two alternative solutions, grid-scale battery and community battery storage, that can shift the high capital cost from the individual householders to other stakeholders. This section first discussed the differences between home-based, grid-scale, and community batteries. It then summarised the advantages and disadvantages of each battery application strategy and the issues in the current UK power supply regulation.

The grid-scale battery is an alternative solution to shift the high capital cost of battery directly from the householders to the government. The householders can then benefit from greener electricity via the national grid because most electricity is generated by renewable systems and stored in those large-scale batteries. UK government planned 760MW of grid-scale battery energy storage projects to be delivered by the end of 2026, including 90MW is already energised and another 150MW under construction (SMS, 2022). The grid-scale battery maximises the supplied electricity from renewable resources, helping the national grid meet the agreed decarbonisation plan by 2050. However, the grid-scale battery has the following limitations:

- The grid-scale battery requires a large installation space. For example, a typical 40MWh battery will need approximately a quarter acre of land to install (EcoDevGroup, 2023). The planned 760MW/1520MWh (assumed 2-hour configuration) battery then needs 9.5-acre of land to install.
- Battery has a short lifespan and a high embodied carbon value. The general lifespan for battery is between 10 and 15 years (BEIS, 2020a; Solar Reviews, 2022). However, embodied carbon of the battery is relatively high in per function unit(about 99kg CO_2 eq/kWh) (Carbon Brief, 2020) compared to the other available renewable systems. Then, the grid-scale battery that stores the excess electricity from renewable energy systems can expect a longer embodied carbon payback period than renewable systems alone (Rapier,

2020). Therefore, the grid-scale battery could lead to a high embodied carbon issue from a life cycle carbon perspective.

- There are also labour and materials shortages due to the speed of scaling up batteries. The raw material – lithium, the main component in the battery manufacturing process, is struggling to meet the fast-increasing demand of the battery globally (Mckinsey and Company, 2022).

The community-battery storage is another alternative solution to share the high capital cost between the individual householders and their neighbours. The community batteries are energy storage units based in local neighbourhoods. Householders who live in the same area with solar PV in their homes can then use those batteries to store the excess electricity at a lower demand. Householders can then use the stored electricity at a peak demand (World Economic Forum, 2022). In Western Australia, the local utilities are piloting a community-battery scheme that includes 119 homes. In the UK, S&C electric company collaborated with Scottish and Southern Energy Power Distribution to start a community-battery storage project. The project aims to achieve ‘zero-carbon homes’ in Slough. The project consists of 325kWh lithium-ion batteries connected to the homes in Slough to stabilise electricity supply (Energy Storage World Forum, 2022). The community-battery storage can help save installation space compared with installing the battery in an individual home. It can also reduce the high capital cost of installing a battery faced by individual householders. However, some limitations cannot be ignored in using the community-battery storage (Clean Energy, 2021):

- Existing regulations must be updated to cover how the DNO trades electricity between householders, community-battery, and the grid.
- The homes shared the community-battery storage would use less electricity from the grid. Therefore, DNO needs negotiate with the electricity operator for a lower daily maintenance charge for such homes .
- The battery will degrade in the usage time, and the battery's expected lifespan is short. Therefore, it is important to clarify the maintenance responsibility and the share of the replacement cost between the householders.

After compared with the grid-scale and community battery, the home-battery has advantages in:

- Smaller embodied carbon of battery compared with grid-scale and community battery.
- Flexible to manage the mismatch between the energy demand and the electricity supply by the on-site renewable systems.
- It is easier to get approval from DNO and make a trading deal between the individual householder and operator.
- Smaller installation space than the grid-scale battery.

Whilst the home-based, community and grid scale has its own pros and cons, there are some common issues in the battery application strategies discussed above.

- Energy storage will be a key technology that helps the UK to achieve the climate change targets by 2050. However, the technology readiness level (TRL) also known as the technology maturity level of batteries in the UK is still at an early stage (testing stage) (IEA, 2022a). The early stage of TRL indicates the battery is still at a relatively lower manufacturing level and has expensive capital costs.
- The expensive capital cost of the battery is also due to the limited raw material and labour (EcoDevGroup, 2023). The battery is an important technology that helps the UK to achieve the agreed climate change target. However, it is difficult to encourage more potential investments in the battery without any incentives to reduce the capital cost of the battery.
- The grid operator and electricity regulator need to upgrade existing regulations to align with the energy generation resources from fossil energy to renewable energy and battery (Helm, 2023).
- The electricity trading regulation between the grid and householders might need to change when most homes become electricity independent. The daily standing charge should be negotiable once most homes are electricity dependent, only importing a small portion of electricity but mainly exporting electricity to the grid (Clean Energy, 2021).

5.3. Economic differences between HRES combinations and individual renewable systems through different financial incentive schemes

Subsections 5.3.1 and 5.3.2 discuss the economic performance of individual renewable power and heat systems separately in different financial incentive schemes. Subsection 5.3.3 summarises the discussion results in subsections 5.3.1 and 5.3.2, suggesting the future energy policy and financial incentive schemes for encouraging large groups of householders to adopt renewable systems in their homes.

5.3.1. The economic performance of solar PV

This subsection discusses influence of different financial incentives on the economic viability of solar PV to reduce electricity usage from the grid to cover electricity demand of the selected home. Two financial incentive schemes, Feed-in-Tariff (FiT) and Smart Export Guarantee (SEG) are used to discuss the economic performance of solar PV. The electricity demand of 2,868 kWh/year was simulated for the selected home in Section 5.1.2. Based on the simulated electricity demand, the estimated size of solar PV to cover 100% of the demand is 2kWp.

The economic performance indicator, present value of benefits (PVB), the received benefits from the financial incentive schemes, and the energy bills in the defined time scale, are used in the discussion. The defined time scale in this subsection is 30 years, as solar PV expects a lifespan up to 30 years in the current solar PV market (Berg, 2018; Energysage, 2022). PVB includes the annually saved electricity bill and the gained benefits from the financial incentive schemes during the operational stage. Energy bills demonstrate the imported electricity from the grid to compensate for the electricity demand when solar PV cannot generate sufficient electricity. This subsection used the FiT scheme's average tariff between 2015 and 2019 to calculate the benefits of using 2kWp solar PV for the selected home. The reason to use the average tariff between 2015 and 2019 is that the capital cost of solar PV used in this research is derived from the same period. The FiT scheme pays the generated and exported electricity by the installed solar PV with £0.032/kWh for generation and £0.056/kWh for export. Most homes under the FiT scheme benefit from a deemed payment for 50% of exported electricity. The deemed payment would only pay 50% of the generated electricity regardless of how much electricity that export to the grid (Energy Saving Trust, 2022b). Unlike the FiT scheme, the SEG scheme only pays for the electricity exported to the grid. This subsection uses SEG export tariff of £0.041/kWh (Ofgem, 2020). The selection of the SEG export tariff used in the discussion is explained in subsection 4.4.1. The economic performance with the above-mentioned indicators of 2 kWp solar PV under the FiT and SEG scheme is presented in Table 5-1.

Table 5-1 Economic performance of 2kWp solar PV under FiT and SEG scheme

Renewable system	Capital cost (£)	PVB (£) – SEG	SEG (£)	PVB (£) – FiT	FiT (£)	Energy Bills (£)
2kWp solar PV	4,009	4,521	1,941	5,962	3,383	15,574

The economic support received from the FiT scheme is about 1.7 times higher than SEG for the selected 2kWp solar PV. In the FiT scheme, 50% of the generated electricity was exported to the grid and was considered in the calculation. Whilst 84% of the generated electricity was exported to the grid and considered in the calculation under the SEG scheme. The export tariff in FiT (£0.032/kWh) is lower than SEG (£0.041), and 34% more of the generated electricity was exported to the grid in SEG than in FiT. However, the 2kWp received less economic support (£1,941) in SEG than the FiT scheme (£3,383). In addition, under the FiT scheme, the selected 2kWp solar PV gained benefits (PVB) of £5,962 in 30 years. However, under the SEG scheme, the same solar PV gained benefits (PVB) of £4,520 in 30 years and it is about £1,440 less than the benefits gained in FiT scheme. The gained benefits through both the FiT and SEG scheme can pay back the selected 2kWp solar PV and 2kW solar inverter, as well as twice the replacement cost of the 2kW solar inverter. Such systems can expect a quicker payback period in FiT than the SEG scheme. Based on the above discussion results, the FiT scheme brings more economic support than the SEG scheme for householders to consider investing in solar PV.

The energy bills in 30 years after installing 2kWp solar PV is £15,574, with a reduction of £2,580 (a 14% reduction) compared with using electricity only from the grid (£18,154 in 30 years). This following discussion then considers adding a 13.5kWh battery to increase the self-consumption rate of solar PV based on the discussion in subsection 4.4.3.1. Table 5-2 presents economic performance of 2kWp solar PV and 13.5 kWh battery under SEG and FiT scheme.

Table 5-2 Economic performance of solar PV and battery under SEG and FiT scheme

Renewable system	Capital cost (£)	PVB (£) – SEG	SEG (£)	PVB (£) – FiT	FiT (£)	Energy Bills (£)
2kWp solar PV + 13.5kWh	4,009 + 11,028	10,767	763	13387	3,383	8,149

After adding a battery, the energy bills in 30 years were reduced by 55% compared with only using 2kWp solar PV alone to supply electricity. A suitable battery can effectively increase the self-consumption rate of solar PV, significantly reducing energy bills. In addition, the battery also increases the benefits gained by importing less electricity from the grid to compensate for electricity demand. The deemed FiT payment is considered in calculating the received benefits for the exported electricity. Thus, the benefits gained from the FiT scheme remain the same as £3,383 in 30 years. However, under the SEG scheme, less generated electricity was exported to the grid after adding a battery. The received benefits are £763 in 30 years in the SEG scheme. After adding 13.5kWh to 2kWp solar PV, in 30 years, the whole system (Solar PV, inverter and battery) received £10,767 (PVB) under the SEG scheme, and it received £13,387 (PVB) under the FiT scheme. The system received £2,620 more benefits in the FiT than the SEG scheme in 30 years. The received overall benefits in 30 years (PVB) from both financial incentives can pay back 2kWp solar PV and 2kW solar inverter, and two replacement costs of 2kW solar inverter. However, the received overall benefits cannot pay back the solar PV and battery at the same time.

5.3.2. The economic performance of A/GSHP and STC

This subsection discusses the economic performance of A/GSHP and STC to reduce natural gas usage for DHW and space heating demand of the selected home. The selected home's simulated DHW and space heating (within the intensive heating period) demand is 5,239 kWh. Renewable system(s) like 4kW A/GSHP alone (under the BUS) or 3kW A/GSHP and 1.5kW STC (under the RHI scheme) are selected to supply the required heat demand. It also compares the economic benefits of using such renewable systems received from renewable heat incentives (RHI) and boiler upgrade schemes (BUS).

The economic performance indicators, including the PVB; capital cost; the benefits gained from RHI and BUS; and the energy bills in the defined time scale after installing such renewable systems. Such indicators are used to discuss the differences between RHI and BUS. The defined time scale in this subsection is 20 years, as most commercially available ASHP expect a lifespan of up to 20 years. However, the GSHP has a slightly longer lifespan (25 years) than ASHP. This subsection uses 20 years in the discussion to ensure the consistency of the economic performance comparison.

The energy bills in 20 years account for the increased electricity demand and the reduced natural gas demand after installing heat pumps.

The capital cost includes the cost of renewable systems and a 100L hot water cylinder. For GSHP, the capital cost also includes the groundwork cost of £6,000 (VAT excluded). In the RHI scheme, the PVB includes the saved natural gas bill by using the installed renewable systems and the gained benefits from the RHI in 7 years. The tariff in the RHI scheme is £0.1085/kWh for ASHP, £0.2116/kWh for GSHP and £0.2149/kWh for STC. The used tariff is the average tariff for the associated system between 2014 and 2022 in the domestic RHI scheme. The BUS incentive offers a one-off voucher to deduct the capital cost of the installed renewable system. Therefore, the PVB only includes the saved natural gas bill in 20 years under the BUS incentive. Table 5-3 presents the economic performance of the systems mentioned above.

Table 5-3 Economic performance of A/GSHP+STC and A/GSHP under the RHI and BUS

Renewable system	Capital cost (£)	PVB (£) – RHI	RHI (£)	PVB (£) – BUS	BUS (£)	Increased electricity bill for running heat pumps (£)	Natural gas Bill (£)
3kW ASHP + 1.5kW STC	6,619	9,867	4,745	NA		4,957	1,832
4kW ASHP	1,368	NA		5,522	3,940	9,456	1,431
3kW GSHP + 1.5kW STC	15,565	11,851	7,033	NA		4,656	1,832
4kW GSHP	9,136	NA		5,522	6,000	8,885	1,431

The installed renewable system under the BUS incentive has a lower capital cost than the same systems under the RHI scheme. The BUS offered a voucher for the capital cost of up to £5,000 for ASHP or up to £6,000 for GSHP. Thus, under the BUS incentive, the capital cost only includes the cost of 100L hot water cylinder. The natural gas bill is £400 lower under the BUS than the RHI scheme after installing the associated renewable systems. In the RHI scheme, STC is used to supply DHW demand; however, the heat generation of STC is impacted mainly by solar radiation. The solar radiation is insufficient in winter; the STC cannot generate enough heat to cover the DHW demand. Therefore, the renewable systems under the RHI need more natural gas to compensate for the DHW demand that STC cannot cover. Differently, in the BUS incentive, the external environment has a limited impact on A/GSHP, as heat pumps are powered by electricity. Therefore, only a tiny amount of natural gas (about 20kWh) is needed to compensate for DHW and space heating demand that A/GSHP cannot cover under the BUS incentive.

The installed system under the BUS incentive can save more natural gas than systems under the RHI scheme. The installed systems under the BUS incentive increased electricity demand to power heat pumps more than those under the RHI scheme. The increased electricity bill for running the heat pump in the BUS incentive is more than £4,000 higher than the RHI scheme. In addition, the overall energy bill in 20 years, by adding the increased electricity bill for running heat pumps and the natural gas bill for the renewable systems under the RHI scheme, is less than £6,800. The overall energy bill of the renewable systems under the RHI scheme is lower than only using natural gas to supply space heating and DHW demand of the selected home in 20 years (£6,954, explained in subsection 5.1.2). However, the overall energy bills of the renewable systems under the BUS scheme are 1.5 times higher than only using natural gas to supply the relevant demand of the selected home in 20 years. Thus, from the lower energy bill perspective, like the installed systems under the RHI scheme, it is more economically viable to use STC to supply DHW demand, and heat pumps to supply space heating demand. In addition, it is better to use an on-site renewable power system to run heat pumps to supply the associated demand.

The RHI scheme offers more economic support than the BUS incentive. 3kW ASHP + 1.5kW STC received £4,715 of economic support from RHI in 7 years, and the BUS incentive only covers the capital cost of a 4kW ASHP (£3,940). 3kW GSHP + 1.5kW STC received £7,033 from RHI in 7 years, 4kW GSHP only received maximum of £6,000 to cover the capital cost of GSHP.

The overall received benefits (PVB) under the RHI scheme can pay back the capital cost of 3kW ASHP + 1.5 kW STC + 100L hot water cylinder. Under the BUS scheme, the received overall benefits (PVB) can also pay back the capital cost of 4kW ASHP and a 100L hot water cylinder in 20 years. However, the received overall benefits (PVB), either in the RHI or BUS incentive, cannot pay back the capital cost of 3kW GSHP + 1.5 kW STC + 100 L hot water cylinder or 4kW GSHP. The main reason is that the received overall benefits cannot balance off the expensive groundwork cost of GSHP.

ASHP has a better economic performance in the BUS than RHI due to the lower capital cost. The offered voucher from the BUS incentive can fully cover the capital cost of

ASHP in this subsection. In addition, ASHP, under the BUS incentive, saved more natural gas than the systems under the RHI. Therefore, 4kW ASHP can pay back quicker than 3kW ASHP+1.5kW STC. The product and installation cost of GSHP is expensive, and the voucher offered by the BUS incentive cannot cover the capital cost of GSHP. In addition, the benefits received from the BUS are less than the RHI, the saved natural gas bill under the BUS needs to be higher to balance the reduced benefits in the RHI scheme. Therefore, 3kW GSHP+1.5STC under the RHI scheme performs better than 4kW GSHP under the BUS to supply the same DHW and space heating demand.

5.3.3. Summary

This subsection summarises the economic comparison results relating to renewable electricity and heat generation.

- Solar PV economic benefits from the FiT were more than double the benefits from SEG, as FiT rewarded the electricity generation and export by solar PV.
- Using solar PV alone does not significantly reduce the electricity usage from the grid due to a lower self-consumption rate (McKenna et al., 2018; MCS, 2019). The installed 2kWp solar PV only saved £1,993 in electricity bills in 20 years; which only pays back half of the capital cost. However, adding a 13.5kWh battery significantly increased the self-consumption of solar PV. The combined 2kWp solar PV and battery, saved £7,731 in electricity bill in 20 years. Although the saved electricity bill can pay back the capital cost of the 2kWp solar PV it does not cover the additional capital cost of the battery.
- Either under the BUS or RHI scheme, the capital cost of the installed ASHP or ASHP+STC can expect a payback in 20 years. The BUS incentive offers a better economic performance of installing ASHP to supply DHW and space heating demand than RHI scheme. However, HRES combinations (in subsection 4.4.2.2) have a poorer economic performance under the BUS incentive than under the RHI scheme. The reason is that under the BUS incentive, it needs more electricity to power heat pumps to supply DHW and space heating demand. The increased electricity bill for running heat pumps under the BUS incentive is more than £9,000 in 20 years. The saved natural gas bill cannot balance off the increased electricity bill for running heat pumps. The increased electricity bill is even higher than using natural gas to supply

DHW and space heating demand based on the selected energy tariff in 2021. However, under the RHI scheme, the increased electricity bill for running heat pumps and natural gas is still lower than only using natural gas to supply DHW and space heating demand. Using heat pumps to supply space heating and STC to supply DHW demand is more economically viable under the selected energy tariff. Therefore, HRES combinations have a better economic performance under the RHI than the BUS incentive.

- The installed GSHP or GSHP+STC cannot pay back in 20 years under the BUS or RHI scheme to supply DHW and space heating demand. The main reason is the expensive product and installation cost of GSHP, particularly the borehole installation approach. The received benefits from the BUS or RHI and the saved natural gas bill cannot balance the capital cost of GSHP.
- The BUS and RHI schemes are effective financial incentives to encourage householders to replace gas boilers with A/GSHP or STC. The BUS incentive is more suitable for householders willing to change to renewable systems but struggling to pay the capital cost front. The RHI scheme fits householders who have sufficient money to pay off the capital cost of the renewable system and then benefit from the invested systems in the operation period. The RHI scheme could offer more economic support for householders installing the relevant renewable systems from a long-term perspective.

Based on the analysis of financial incentive schemes applied to HRES, the following two suggestions can be made:

- Electricity storage plays a vital role to increase the self-consumption rate of solar PV, then significantly reduce the electricity bill. Solar PV alone cannot effectively reduce the electricity bill due to a lower self-consumption rate. Battery is the most likely form to store electricity in UK homes. However, the product cost of battery in the UK is still high due to the lack of raw materials, labour and lower technology maturity level (Clean Energy, 2021; IEA, 2022a). In addition, no financial incentive schemes or reduced VAT are available for installing a battery in UK homes. Therefore, the future energy policy and financial incentives would benefit from considering the provision of financial support to encourage householders to install the battery in their homes.

- The BUS incentive is effective financial support when it can fully cover the capital cost of the installed renewable system. However, the BUS incentive becomes less effective when the capital cost of the renewable system is much higher than the offered voucher value. The less effective financial incentives lead to the poor economic performance of installing the renewable system, and householders would be discouraged from buying such systems. It is worth considering the available budget allocation to ensure that the ratio between the financial support and the capital cost of the renewable system remains the same. Then, the householders who need a bigger size of A/GSHP (the current BUS incentive cannot cover the capital cost) have the opportunity to consider switching to renewable systems.

6. Conclusion and recommendations

This research aims to create a multi-criteria decision-making framework and a supporting weighing system to evaluate the on-site HRES (hybrid renewable energy system) for the representative retrofitted house in Wales and England. The developed weighting system reflects householders' perspectives on economic-technical-environmental factors. It was embedded in the decision-making framework to determine the optimal HRES combination. Five research objectives are defined to achieve the research aim; Section 6.1 describes how each objective was met to achieve the research aim.

6.1. Achievement of the research objectives

Objective – 1: Review the English Housing Survey (EHS) and Welsh Housing Condition Survey (WHCS) to define the key indicators used to select the building case in this research. Then, design a modelling method based on the BRE domestic energy model (BREDEM) and standard assessment procedure (SAP) to simulate the energy demand of the selected building case.

Achievement: After reviewing the English Housing Survey (EHS) and Welsh Housing Condition Survey (WHCS), this research defined four building characteristics to be considered when choosing the typical retrofitted home case. The defined characteristics are:

- The house is located in an urban area and connected with natural gas and the national grid.
- The built age is between pre-1919 and 1980.
- The building type is either a terraced or semi-detached house.
- The floor area is between 50 and 100m^2.
- EPC band of C.

Based on the defined characteristics, the selected representative building is an end-terraced house built in pre-1919 with a floor area of 67m^2. The as-built energy performance of the selected home was poor but retrofitted to the EPC band of C (UK Government, 2022b).

The model of the selected home was created in DesignBuilder and the lighting and space heating demand was simulated in EnergyPlus using the historical meteorological data from PVGIS (EU Science Hub, 2020). The energy consumption of the selected home's electrical appliances and DHW were calculated using the SAP method (UK Government, 2013a). The simulated space heating demand in the defined heating-intensive period (between October and March) is 3,319kWh, and the annual lighting demand is 777kWh. The estimated annual electrical appliance and DHW consumption are 1,423 and 2,091 kWh, respectively.

Objective – 2: Analyse the findings from the permitted development requirement and existing financial incentives for installing government-recognised microgeneration systems in English and Welsh homes. The analysis results are used to form the potential HRES that can be practically installed in the selected building case.

Achievement: This research analysed the permitted development requirements and the available financial incentives for installing government-recognised renewable systems in the selected representative home. The potential renewable systems are solar PV, solar thermal collector (STC), and air or ground source heat pump (ASHP). Six HRES combinations were defined that:

- meet the permitted development requirement
- can benefit from the existing financial incentives
- can be practically installed in the selected representative house.

Objective – 3: Collect the economic-technical-environmental data of the scoped potential renewable system from government-recognised brands. Meanwhile, analyse different UK energy suppliers, select the most representative energy supplier, and then collect the relevant energy tariff from the supplier. In addition, collect the carbon emission factors of the electricity from the grid and natural gas.

Achievement of Economic & Technical data:

Based on the methodology described in sections 3.3 and 3.4, the average capital cost of each renewable energy technology was calculated as:

- Solar PV £1,751/kWp
- STC is £1,458/kW
- ASHP is £938/kW
- GSHP is £1,778/kW (without groundwork cost)

The vertical installation approach is usually used to install GSHP in the selected representative house in this research. Based on the findings from the existing research (subsection 3.3.1.3), the average groundwork cost of £6,000 should be added to the capital cost of GSHP smaller than 8kW.

The above-stated capital cost of the renewable system excluded the VAT charge, as the suitable VAT rate for each renewable system should be calculated through the 60% VAT test. The capital cost is used in the economic performance evaluation of HRES combinations. In addition, the collected technical data is used to calculate the generated energy by such renewable systems.

Achievement of Environmental data:

Section 3.5 explained the method used to collect the embodied carbon data of the selected renewable systems. The embodied carbon data of each renewable system is used to estimate the embodied carbon payback period for each HRES combination. The embodied carbon result for each renewable system is summarised as follows:

- The embodied carbon range for monocrystalline solar PV is between 0.028 and 0.087 kg CO_2 eq/kWh.
- The embodied carbon rage for polycrystalline solar PV is between 0.032 and 0.069 kg CO_2 eq/kWh for polycrystalline solar PV.
- The embodied carbon range for STC is between 0.023 and 0.036 kg CO_2 eq/kWh.
- The embodied carbon range for ASHP is between 0.014 and 0.026 kg CO_2 eq/kWh.
- And the embodied carbon range for GSHP is between e0.008 and 0.010 kg CO_2 eq/kWh.

Objective – 4: Analyse the findings from the report published by the UK and worldwide climate change organisations to define the demand coverage percentage (DCP) scenarios. The defined scenarios are used to size the potential HRES combinations.

Achievement of defining scenarios:

6 scenarios were created to size potential HRES combinations based on findings in reports by CCC and IEA (CCC, 2016, 2019; IEA, 2020). 3 of the developed scenarios are used to size the potential HRES combinations to supply space heating and electricity demand. Another 3 scenarios are used to size the potential HRES combinations to supply electricity, space heating and DHW demand. Such scenarios can reflect the economic-technical-environmental performance of the potential HRES combinations in different sizes to align with the achievement of the climate change targets and the current financial incentive schemes.

Combining the scenarios with each HRES combination, the size of solar PV ranges from 2.25 to 2.75kWp, the size of A/GSHP is 3kW, and 1.5kW for STC. In addition, each HRES combination is evaluated independently and with a 13.5kWh battery to store the excess generated electricity. In the potential HRES combinations, heat pumps have different energy generation functions in RHI (renewable heat incentive) and BUS (boiler upgrade scheme) incentives. Under the RHI scheme, the heat pump is defined to supply space heating only. Thus, a 100L hot water cylinder is added to the HRES combination to store STC heated water for DHW usage purposes. However, under the BUS (boiler upgrade scheme), a 100L hot water cylinder is added to the HRES combination to store the DHW demand from heat pumps.

Objective – 5: Investigate BREEAM technical manuals, MCS installation standards, SAP, and relevant research articles to select the most suitable indicators to evaluate the performance of the identified HRES combinations. In addition, investigate the preference value of the selected indicators from the representative householders' perspectives, converting such perspectives to the weights in supporting the final ranking to identify the optimal HRES combinations.

Achievement of selecting the appropriate performance indicators:

Section 3.7 introduced a method to select the appropriate economic-technical-environmental performance indicators to evaluate the performance of HRES combinations. These indicators were chosen from a thorough review of BREEAM technical manuals, MCS installation standards, SAP, and relevant research articles.

Achievement of creating weighting system:

Section 3.11 explains the method for defining the indicators as decision-making or supporting. Then, eight indicators were selected as the decision-making indicators to rank all potential HRES combinations.

Householder priorities of the eight decision-making indicators were investigated through a survey of householders who live in Cardiff and Bristol. The responses received from householders in Bristol were statistically insufficient due to the difficulty of travelling and limited time. However, the responses received from householders in Cardiff were statistically sufficient, and these responses were used to create the weighting system.

The survey indicated a higher priority (and therefore weighting value of 0.3676) for the economic criterion, followed by the environmental criterion with a weighting value of 0.3462. There was a lower priority (and therefore weighting value of 0.2863) for the technical criterion. This is potentially due to householders not being familiar with such indicators. After applying these weightings to the ranking process, the most preferred combination was found to be solar PV, ASHP and STC followed by solar PV and ASHP. This was mainly because these combinations have a better economic performance than the combinations of solar PV, GSHP and STC or the combination of solar PV and GSHP. Under the developed weighting system, the combinations with a 13.5kWh battery were ranked lower as they have a relatively poor economic performance. Although the combinations with a battery bring more technical and environmental benefits.

Objective 6: Develop a decision-making framework for householders to identify the optimal HRES combinations for their homes. The development of the framework is based on the achievements from objectives 1 to 5.

Achievement of the developed decision-making framework:

This research compiled the achievements from objective 1 to 5 to form the decision-making framework in an excel spreadsheet. The spreadsheet is free to use and help householders to identify the optimal HRES combination by entering the basic housing and energy consumption information (e.g., house location, annual electricity/gas consumption). Section 4.7 presents different functions of the developed framework through several prototypes. The detailed usage guidance and the developed spreadsheet are submitted separately as the appendix of the thesis.

6.2. Contribution to the knowledge

6.2.1. Research originality and novelty

This research created the decision-making framework for identifying the optimal HRES with the weighting system based on representative householders' perspectives for application to representative homes in England and Wales. The created framework achieved the research aim, and the contribution of the entire research work is summarised in the following.

Framework: The government encourages householders to install renewable systems in their homes. However, householders need clarification on the options to help them invest in the most suitable renewable system for their homes. Therefore, the created framework consisted of several excel spreadsheets populated with technical data to help laypersons quickly identify the possible power ratings of the HRES combination to match the required energy demand.

- The renewable generation spreadsheet: The user only needs to type in the annual electricity and heat (space heating and DHW) demand which can be found on the EPC website. If applicable, householders can also use energy bills to identify their house's relevant annual electricity and heat demand. Then, the annual electricity and heat demand is an alternative solution when householders do not have available yearly energy bills. Apart from the annual energy demand, the user also needs to select the building location; as the spreadsheet can request the local average solar radiation from the PVGIS database to carry out the demand-supply calculation.
- The energy supply-demand balance spreadsheet: Once the user types in the annual electricity, DHW and space heating demand, this spreadsheet will break down such annual demand into the monthly demand following the method explained in the SAP method. The monthly demand calculates the supply-demand balance; the balance determines the amount of energy imports from other sources (e.g., electricity from the grid and natural gas).
- Economic-Technical-Environmental spreadsheet: The spreadsheet is used to evaluate the economic-technical-environmental performance of HRES combinations. The selected indicators are included in the spreadsheet, with the collected relevant data explained in objective - 3 to run the performance evaluation process. The user needs to type the calculated size of each HRES combination based on the results in the renewable generation and energy supply-demand balance spreadsheet. Then, the economic-technical-environmental spreadsheet can automatically run the performance evaluation of the specified HRES combination.
- Weighting and decision-making spreadsheet: The spreadsheet converts the value of the collected preferences on different indicators to the weighting values using the fuzzy analytical hierarchy process (Fuzzy-AHP) method. The spreadsheet help user easily converts large amounts of perceptions to the weighting values. Then, the converted weighting values import into the decision-making spreadsheet that is created based on the technique for order preference by similarity to ideal solution (TOPSIS) method. The spreadsheet then ranks the potential options under the created weighting values.

Potential HRES combinations: Microgeneration Certification Scheme (MCS) certified a wide range of renewable systems that can be installed in UK homes. However, homes in urban areas have different available space and site conditions than homes in rural areas. Some renewable systems like biomass boilers cannot be installed in urban homes subject to the local permitted development requirements. This research analysed the permitted development in England and Wales; the findings were used to select the individual renewable system to form potential HRES combinations installed on the selected representative home.

Economic-Technical-Environmental indicators: Several UK government-recognised technical manuals, guidance and standards were used to evaluate the performance of the building and the associated on-site individual renewable system. Many existing studies investigated the performance of HRES at different application levels. However, no existing studies analysed the most suitable indicators that can better evaluate the performance of HRES in UK homes. Therefore, this research creates a method that compares the findings from the UK government-recognised technical manuals, guidelines, and standards as well as the existing relevant research. The comparison results help to select the most suitable indicators to evaluate the performance of the potential HRES combinations in the selected representative home.

Weighting system: The UK government encourages householders to switch the norm energy supply strategy (from the grid and natural gas) to renewable energy systems. It would be more effective for the government to make the future energy policy and the associated financial incentive after understanding householders' actual needs and preferences in this respect. To facilitate this, the preferences of Cardiff householders were analysed to better understand their preferred indicators.

Optimal HRES combination: PV+ASHP+STC ranked in top positions while considering surveyed householders' perceptions, as the economical criterion has been highly weighted compared with environmental and technical criteria. However, applying the same weights to economic-technical-environmental criteria, PV+ASHP+STC+Battery jumped into top positions. After removing the high weightings in economic performance, the HRES combination with a battery demonstrates a better performance than the HRES combination without a battery from the economic-technical-environmental perspective. In general, the combination containing ASHP ranked higher than the combinations containing GSHP regardless considering or not of householders' perceptions in the weighting system. Thus, the combinations containing ASHP indicate an economically and practically viable environmental solution to part replace the UK homes’ norm energy supply strategy.

The role of the battery in the HRES combination: The performance results indicate that the battery improves the technical-environmental performance of HRES combinations. Particularly, the battery ensures the stability of the supply and demand balance. Although the battery largely improves the grid-independence level, reducing the amount of imported electricity decreases the annual electricity bill. Due to the expensive capital cost of batteries and the need for a supportive energy policy and financial incentive schemes, the battery is still not an economically viable solution. The high capital cost remains one of the main barriers preventing householders from installing batteries. The findings in this research suggest that future energy policy and financial incentives should include the battery to enable a wider implementation in UK homes.

Suggestions for future energy policy and renewable systems-related financial incentives: The economic-technical-environmental performance results demonstrate that the HRES combination is economically, practically viable, and environmentally feasible to replace part of UK homes' norm energy supply strategy. However, today’s energy operational regulations and policies are not fully designed to rely on renewable systems (Helm, 2023). Therefore, it is worth creating scenarios of the energy supply mainly from renewable resources to analyse the responsibility changes of the distribution network operators (DNOs) and regulators. The analysis results in help to reshape better the future energy importing and exporting tariff and distribution regulations.

6.2.2. Research limitations and future work

The applicability of the collected data:

The product cost of the renewable system was collected in November 2020, and then it was frequently updated until final analysis in January 2022. However, the product cost of renewable systems constantly changes with time. The collected product cost can only be used to analyse a renewable system's economic performance in a general future trend rather than a specific year.

The collected energy tariff of electricity and natural gas was collected in April 2022. However, the energy tariff has changed frequently since Jan 2020 (IEA, 2022b) and it might continue to increase (Ofgem, 2022c). If the energy tariff of electricity and natural gas continue to increase, the economic benefits will become more dominant in using HRES combinations for UK homes.

In future work, such data should be updated to reflect an up-to-date and reliable economic performance of renewable systems and the economic difference between using the renewable system, the national grid, and natural gas. For example, the product cost and the energy tariff in the economic-technical-environmental should be updated to demonstrate the up-to-date economic performance.

Limited accessibility of the database:

The Microgeneration Certification Scheme (MCS) installation database is the only one that holistically stores government-recognised renewable systems' installation costs (e.g., GSHP/ASHP/STC). However, it is difficult to be granted access to the installation database. This research explained the method in subsection 3.3.1 to obtain the installation cost. However, the obtained installation cost of the renewable energy system can only reflect the period between 2015 and 2019.

Limited responses:

This research used different approaches to receive responses from householders in Cardiff and Bristol. However, the response rate is low (about 10% overall), and the potential reason is the technical content in the questionnaire which made it difficult for most householders to understand some of the questions. In future work, it can include several short, and easy-to-follow examples to explain the technical terms used in the questionnaire. The examples might help householders to understand such technical terms better, and then encourage them to complete the questionnaire.

The sensitivity of the data used in the energy-supply estimation:

The solar PV self-consumption rate used in the solar PV generation from the MCS standard (MCS, 2019)is the only available dataset. The used self-consumption rate can only represent a generic scenario of the householders who are away in the daytime and mainly use electricity at night. However, this generic scenario might differ from any specific householders' energy supply-demand balance due to various energy usage behaviours. Energy usage behaviour has a significant impact on the self-consumption rate (National Energy Action, 2021).

In future research, it is worth understanding the energy usage behaviour of the specific home and then selecting the solar PV self-consumption rate. Then, the selected self-consumption rate can better reflect the actual energy supply-demand balance of the home. In addition, the selected self-consumption rate can better reflect a more reliable economic-technical-environmental performance of solar PV installed in the home.

Future research:

- Future research should focus on updating the product and installation cost, technical and embodied carbon data of the selected renewable energy system and energy storage. The updated data can ensure that the evaluation performance matches the actual renewable and energy storage market.
- Collecting householders' perspectives from more UK regions through the developed questionnaire will be useful. Such collected perspectives can help policymakers better understand householders' preferences in investing in renewable systems and storage. Then, policymakers can develop future energy policies and incentives that can effectively encourage householders to switch conventional systems (e.g., gas boilers) to renewable systems and storage.
- This research mainly discussed the benefits of using home-based batteries as energy storage to corporate with renewable systems in individual homes. Chapter 5 briefly discussed the advantages and disadvantages of using national-scale, community, and individual home-scale batteries. Future research can explore further the economic-technical-environmental performance of using renewable systems with batteries at different scales.
- This research identified PV+ASHP+STC with/without battery as the optimal solution for the selected home. However, every home is different in England and Wales; future research could consider exploring the optimal solution for each type of representative home in terms of the geographic and building characteristics in England and Wales.
- It is a trend to use electric vehicles and charging them in homes. Future research could explore the economic-technical-environmental performance in different usage scenarios of using renewable combinations with energy storage and electric vehicle.
- The current lithium-ion battery supply chain faces challenges due to geopolitical issues. The recycling industry of the lithium-ion battery is growing; future research could explore the economic-technical-environmental performance of the on-site renewable systems with the recycled lithium-ion battery for the specified representative home in Wales and England. The results help discuss

the advantages and disadvantages of using new and recycled lithium-ion batteries in individual homes.

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Appendix A – Collected commercially available data of renewable and energy storage system

Solar Thermal Collector

Aperture area (sqr.m)	Installed capacity (kW)	Collector type	Absorption Coefficient	price (with tax) £ in m^2	price (without tax of 20%) £ in m^2	Price (without tax) £/kW	Source	Installation approach	Price including:	Last updated date
2.02	1.41	Flat-plate collector	80%	1332	1110	785.01	Viessmann Direct	On roof	Kits including: roof fixing kit, hydraulic connection set, solar expansion vessel (25L), expansion vessel connection set, Tyfocor LS 25L solar fluid	01/01/2022
2.25	1.575	Flat-plate collector	79%	874.38	728.65	462.63	http://www.gasapplianceguide.co.uk/worcester_greenskies_solar_packages.htm	On roof	With installation kit, rail, roof hooks, connection set, collector sensor.	01/01/2022
2.09	1.463	Flat-plate collector	75.60%	1026.38	855.32	584.63	https://www.mytub.co.uk/worcester-solar-lito-2-panel-on-roof-kit-product-637575	On roof		01/01/2022

GSHP

Manufacturer	Model Number	Model Configuration (kW)	Source	Flow Temperature (Max)	Flow Temperature (Min)	SCoP or CoP (low Temp)	SCoP or CoP (High Temp)	Average £/1kW (Inc. VAT)	Average £/1kW (exclude VAT)	Price including:	Last updated date
Kensa Engineering Ltd	Shoebox heat pump	3	Kensa Engineering	55	35	3.68	2.99	1474.80	1229.00	GSHP only	01/01/2022
Kensa Engineering Ltd	Shoebox heat pump	6		55	35	3.45	2.97	987.60	823.00		
Kensa Engineering Ltd	K070-S1H-Ground Source heat pump	7		55	35	4.72	3.70	1055.32	879.43		
Kensa Engineering Ltd	K070-S1H-Ground Source heat pump	9		55	35	4.64	3.62	895.20	746.00		
Kensa Engineering Ltd	K130-S1H-Ground Source heat pump	13		55	35	4.40	3.48	672.00	560.00		
Kensa Engineering Ltd	K130-S1H-Ground Source heat pump	15		55	35	4.47	3.58	626.40	522.00		
Viessmann	Vitocal 200-G	6	Electric heat warehouse	60	35	4.1	NA	1295.44	1079.53	Vitocal 200-G Ground	01/01/2022

Viessmann	Vitocal 200-G	8		60	35	4.4	NA	1030.63	858.86	Source Heat Pump Brine module with 2 ball cocks Expansion vessel 25/L 10 bar solar Heating circuit pump Wilo Stratos 25/1-7 Cylinder temperature sensor x 2	
Viessmann	Vitocal 200-G	10		60	35	4.3	NA	868.33	723.61		
Worcester (Bosch)	Greenstore LECP	6	mytub.co.uk	45	35	3.96	3.15	1057.9	881.58	No kits included	01/01/2022
Worcester (Bosch)	Greenstore LECP	7		45	35	3.82	2.97	965.44	804.53		
Worcester (Bosch)	Greenstore LECP	9		45	35	3.84	3.15	796.34	663.62		
Worcester (Bosch)	Greenstore LECP	11		45	35	3.97	3.17	707.31	589.43		
Vaillant	Geotherm Mini 3kW Ground Source Heat Pump	3	https://www.cityplumbing.co.uk/Vaillant-Geotherm-Mini-3kW-Ground-Source-Heat-Pump/p/168310	55	35	3.99	2.97	1124.31	936.925	No kits included	01/01/2022
Dimplex	SIH4ME	4kW	https://www.dimplex.co.uk/product/4kw-high-temperature-domestic-ground-source-heat-pump-sih4me	55	35	4.47	3.58	1131.28	942.73		01/01/2022

ASHP

Manufacturer	Model Number	Model Configuration (kW)	Source	Flow Temperature (Max)	Flow Temperature (Min)	SCoP or CoP (low Temp)	SCoP or CoP (High Temp)	Average £/1kW (Inc. VAT)	Average £/1kW (exclude VAT)	Price including:	Last updated date
Mitsubishi	Ecodan	5kW	https://www.cityplumbing.co.uk/Ecodan-R32-Compact-PUZ-Monobloc-Air-Source-Heat-Pump-5kw/p/304515	55	35	4.06	3.14	586.8	489.00		01/01/2022
Daikin	Altherma EHBH04D6V	4kW	https://www.orionairsales.co.uk/daikin-althermaerga04dva--ehbx04d6vair-to-water-heat-pump-low-temperature-split-4kw14000btu-hc-14298-p.asp	55	35	4.39	3.21	1054.8	879.00	HP, user interface	01/01/2022
Daikin	Monoblock	5kW	https://www.cityplumbing.co.uk/Daikin-Altherma-5kW-Small-Monobloc-Air-Source-Heat-Pump-EDLQ05CV3/p/142435	55	35	4.39	3.21	468	390.00	HP, control box.	01/01/2022
Daikin	Monobloc system	7kW	https://www.cityplumbing.co.uk/Daikin-Altherma-EDLQ07CV3-7kW-Small-Monobloc-Air-	55	35	4.39	3.21	390	325.00	HP, control box.	01/01/2022

			Source-Heat-Pump/p/142437								
Daikin	Monobloc system	11kW	https://www.orionairsales.co.uk/daikin-eblq011cv3-air-to-water-low-temperature-monoblock-heat-pump-11kw37000btu-a-240v50hz-14274-p.asp	55	35	4.39	3.21	478.8	399.00	HP, wiring centre, user interface	01/01/2022
Samsung Premium	EHS GEN6	5	https://www.theunderfloorheatingstore.com/renewable-energy/air-source-heat-pumps/samsung-premium-heat-pump	65	35	4.52	3.3	747	622.50	HP, wiring centre, user interface	01/01/2022
Samsung Premium	EHS GEN8	12	https://www.theunderfloorheatingstore.com/renewable-energy/air-source-heat-pumps/samsung-premium-heat-pump	65	35	4.52	3.3	435	362.50		
Samsung Premium	EHS GEN9	15	https://www.theunderfloorheatingstore.com/renewable-energy/air-source-heat-pumps/samsung-premium-heat-pump	65	35	4.52	3.3	403	335.83		
Vaillant	aro ThERM PLUS	3.5	https://www.directheatingsupplies.co.uk/vaillant-arotherm-plus-air-	55	35	4.41	3.1	917	764.17	HP, wiring centre, user interface	01/01/2022

			source-heat-pump-3-5kw-10037211								
Vaillant	aro ThERM PLUS	7	https://www.directheatingsupplies.co.uk/vaillant-arotherm-plus-air-source-heat-pump-7kw-10037213	55	35	4.36	3.39	540	450.00	HP, wiring centre, user interface	01/01/2022
Vaillant	aro ThERM PLUS	10	https://www.directheatingsupplies.co.uk/vaillant-arotherm-plus-air-source-heat-pump-10kw-10037214	55	35	5.03	3.58	507	422.50	HP, wiring centre, user interface	01/01/2022
Vaillant	aro ThERM PLUS	12	https://www.directheatingsupplies.co.uk/vaillant-arotherm-plus-air-source-heat-pump-12kw-10037215	55	35	4.88	3.63	450	375.00	HP, wiring centre, user interface	01/01/2022
Vaillant	aro THERM	5	https://www.directheatingsupplies.co.uk/vaillant-arotherm-air-source-heat-pump-5kw-20257346	60 (for DHW only) 50 for SH	35	4.06	3.14	603	502.50	HP, wiring centre, user interface	01/01/2022
Vaillant	aro THERM	8	https://www.directheatingsupplies.co.uk/vaillant-arotherm-air-source-heat-pump-8kw-20257347	60 (for DHW only) 50 for SH	35	4.58	3.4	418	348.33	HP, wiring centre, user interface	01/01/2022
Vaillant	aro THERM	11	https://www.directheatingsupplies.co.uk/vaillant-arotherm-11kw-air-to-water-heat-pump-11kw-20257348	60 (for DHW only) 50 for SH	35	3.46	2.6	362	301.67	HP, wiring centre, user interface	01/01/2022

Hitachi	Split ASHP (SH only)	4.3	Electric heat warehouse	55	35	4.7	2.8	712.59	593.83	x Yutaki-S Air to Water Split Heat pump - Indoor Unit 4.3kw to 16kw 1 x Yutaki-S Air to Water Split Heat Pump - Outdoor Unit 4.3kw to 16kw 1 x Pack of Anti-Vibration Feet 1 x Built in Electric Back Up Heater	01/01/2022
Hitachi	Split ASHP (SH only)	6	Electric heat warehouse	55	35	4.7	2.8	522.57	435.48		
Hitachi	Split ASHP (SH only)	7.5	Electric heat warehouse	55	35	4.7	2.8	491.79	409.83		
Hitachi	Split ASHP (SH only)	11	Electric heat warehouse	55	35	4.7	2.8	450.4	375.33		
Hitachi	Split ASHP (SH only)	14	Electric heat warehouse	55	35	4.7	2.8	401.84	334.87		
LG	Monoblock	3	https://www.zerohomebills.com/product/lg-therma-v-3kw-monobloc-atw-heat-pump/	55	35	4.45	3.15	915.60	763.00	HP, wiring centre, user interface, built-in backup	01/01/2022
LG	Monoblock	5	https://www.tradesparky.com/solarsparky/heating/air-source-heat-pumps/lg-hm051mu43-r32-	55	35	4.45	3.15	455.4	379.50		

			therma-v-air-source-heat-pump-5kw-monobloc								
LG	Monoblock	7	https://www.tradesparky.com/solarsparky/heating/air-source-heat-pumps/lg-hm071mu43-r32-therma-v-air-source-heat-pump-7kw-monobloc	55	35	4.45	3.15	339.78	283.15		
LG	Monoblock	9	https://www.tradesparky.com/solarsparky/heating/air-source-heat-pumps/lg-hm091mu43-r32-therma-v-air-source-heat-pump-9kw-monobloc	55	35	4.45	3.15	281.916	234.93		
LG	Monoblock	12	https://www.tradesparky.com/solarsparky/heating/air-source-heat-pumps/lg-hm121mu33-r32-therma-v-air-source-heat-pump-12kw-monobloc	55	35	4.45	3.15	286.056	238.38		
LG	Monoblock	14	https://www.tradesparky.com/solarsparky/heating/air-source-heat-pumps/lg-hm141mu33-r32-	55	35	4.45	3.15	266.508	222.09		

			therma-v-air-source-heat-pump-14kw-monobloc									

Hot Water Cylinder

Cost includes:	Manufacturer	Model Configuration (L)	Model size (mm)	Source	£ (Inc. VAT)	£ (exclude VAT)	£/L (Exclude VAT)	Warranty	Last updated date
G3 safety kit; 18L expansion vessel; separate sensor pocket for 4 pipe system sensor connection (sensor provided); backup 3kW immersion heater; T&P valve	Vitocell 200-V single coil	120	920*550	https://viessmanndirect.co.uk/Catalogue/Domestic-Cylinders; https://www.plumbnation.co.uk/site/viessmann-vitocell-200-v-120l-unvented-thermal-storage-cylinder/	1189.98	991.65	8.26	25.00	01/01/2022
G3 safety kit; 18L expansion vessel; separate sensor pocket for 4 pipe system	Vitocell 200-V single coil	150	1107*550	https://viessmanndirect.co.uk/Catalogue/Domestic-Cylinders	1228.07	1023.39	6.82	20-25	01/01/2022

sensor connection (sensor provided); backup 3kW immersion heater; T&P valve									
Full unvented kit, remote expansion vessel	Telford TSMI150	150	510*1060	https://www.plumbnation.co.uk/site/telford-tempest-stainless-steel-indirect-150l-unvented-cylinder/	522.2	435.17	2.90	30.00	01/01/2022
Full unvented kit, remote expansion vessel	Telford TSMD125	125	510*935	https://www.plumbnation.co.uk/site/telford-tempest-stainless-steel-direct-125l-unvented-cylinder/	528.98	440.82	3.53	30.00	01/01/2022
Full unvented kit, remote expansion vessel	Telford TSMI150SL	150	470*1200	https://www.plumbnation.co.uk/site/telford-tempest-stainless-steel-slimline-indirect-150l-unvented-cylinder/	652.63	543.86	3.63	25.00	01/01/2022
Full unvented kit, remote expansion vessel	Telford TSMI125	125	510*935	https://www.plumbnation.co.uk/site/telford-tempest-stainless-steel-indirect-125l-unvented-cylinder/	515.98	429.98	3.44	30.00	01/01/2022
Full unvented kit, remote	Telford TSMI125SL	125	470*1050	https://www.plumbnation.co.uk/site/telford-tempest-stainless-steel-slimline-indirect-125l-unvented-cylinder/	634.72	528.93	4.23	25.00	01/01/2022

expansion vessel									
Full unvented kit, remote expansion vessel	Telford TSMI125H(Horizon)	125	610*935	https://www.plumbnation.co.uk/site/telford-tempest-horizontal-stainless-steel-indirect-125l-unvented-cylinder/	731.63	609.69	4.88	25.00	01/01/2022
Full unvented kit	Indirect Cylinder Pluin150	150	550*1118	https://www.plumbnation.co.uk/site/gledhill-stainless-lite-plus-unvented-indirect-cylinder-150-litre/	524.96	437.47	2.92	25.00	01/01/2022
Full unvented kit	PLUDR150SL	150	475*1519	https://www.plumbnation.co.uk/site/gledhill-stainless-lite-plus-slimline-unvented-direct-cylinder-150-litre/	618.98	515.82	3.44	25.00	01/01/2022
Full unvented kit	PLUDR120	120	931*550	https://www.plumbnation.co.uk/site/gledhill-stainless-lite-plus-120l-unvented-direct-cylinder/	433.78	361.48	3.01	25.00	01/01/2022

Solar Inverter

Brand	Configuration	Source	Price (£) exl VAT	Price (£) inc VAT	price (£)/kW - VAT free	Price (£)/kW-VAT	Last updated date
ABB	PVI-3.0TL S 3KW SOLAR INVERTER	https://www.renugen.co.uk/abb-pvi-3-0-tl-outd-s-3kw-2mppt-single-phase-inverter/	490.67	588.8	163.6	196.3	01/01/2022
Fronius	Fronius primo 3.0	https://theecosupermarket.co.uk/product-category/solar-inverters/fronius/	670.75	804.9	223.6	268.3	01/01/2022
ABB	ABB UNO-2.5-I-OUTD 2500W string Inverter	https://www.renugen.co.uk/power-inverters/?sort=alphaasc	262.5	315	105.0	126.0	01/01/2022
ABB	UNO-DM-4.0-TL-PLUS-SB-Q Power inverter	https://www.renugen.co.uk/power-inverters/?sort=alphaasc	743.45	892.14	185.9	223.0	01/01/2022
Bosch	BPT-S 3.68 Single Phase String inverter	https://www.renugen.co.uk/power-inverters/?sort=alphaasc	482.7	579.24	134.1	160.9	01/01/2022
Danfoss	ULX 3.6 kW power inverter	https://www.renugen.co.uk/power-inverters/?sort=alphaasc	550	660	152.8	183.3	01/01/2022
Soils	1.5 kW single phase	Solis Archives - The Eco Supermarket	222	266.4	148.0	177.6	01/01/2022
Soils	Soils 2.0 kW mini 5G single tracker solar inverter	https://theecosupermarket.co.uk/product/solis-2-0kw-mini-5g-single-tracker-solar-inverter/	252	302.4	126.0	151.2	01/01/2022
SolarX	1.5 kW single phase	SolaX Archives - The Eco Supermarket	204	244.8	136.0	163.2	01/01/2022
SolarX	2.0 kW single phase	https://theecosupermarket.co.uk/product-category/solar-inverters/solax/	232	278.4	116.0	139.2	01/01/2022
SolarX	2.5kW single phase	https://theecosupermarket.co.uk/product-category/solar-inverters/solax/	272	326.4	108.8	130.6	01/01/2022

SolarX	3.0kW single phase	https://theecosupermarket.co.uk/product-category/solar-inverters/solax/	298	357.6	99.3	119.2	01/01/2022
SolarX	3.3kW single phase	SolaX Archives - The Eco Supermarket	300	360	90.9	109.1	01/01/2022

Appendix B – Embodied Carbon data

Solar PV

Resource	Embodied CO2	Efficiency	Lifespan	Configuration	Manufacturing country	EC boundary	Approach
Milousi et al 2019	0.0524	13%-18%	25-30	3kWp solar PV	Various countries	Cradle to grave	LCA method. SimaPro 8.5. Ecoinvent V 3.4
Kristjansdottir et al (2016)	0.080 (EU); 0.120 (Asian)	18.50%	30	Mono-Si-7.36kWp	Asian (Philippines) Installed in EU	Cradle to site	LCA method. Ecoinvent V2.2 and V3.1, SimaPro V8.0.5
Yue et al (2014)	0.0373 (EU) 0.0722 (China)	14.00%			Two scenarios, one produced in EU and one in China	Cradle to grave	LCI data are based on published data from Chinese plants
Peng and Lu (2013)	0.037	15.00%	20-30	Roof mounted 22kWp	PV manufactured in China (Suntech). Asian (HK) case study	Cradle to grave (transportation and disposal were not considered)	
Hsu et al (2012)	0.064 (review). 0.04 (hamonised)	14.00%	30	various configurations	Various countries	Cradle to grave	LCA method, two rounds review and screening (58 studies investigated c-SI PV) (2003-2009)
Hammond et al (2012)	0.105	NA	25	1720kWh electricity/year (building integrated roof tiles)	Applied in the UK. Manufacturered in the UK	Cradle to site	LCA method, Simapro 7.1 and Ecoinvent 2.1.
Fthenakis and Kim (2011)	0.038	14.00%	30	24kWp phoenix PV	EU application case	Cradle to grave	Review results of life-cycle inventory and relevant case studies
Ito et al (2011)	0.056 (average)	14.30%	30	10, 30, 100 kW solar PV	Application in Japan	Cradle to grave	LCA method. JEMAI-LCA software. NEDO (New Energy and Industrial Development Organisation) created a PV module LCI database
De Wild Scholten (2011)	0.035	14.40%	30		Installed in EU	Cradle to grave (transportation is not included)	ecoinvent
Ito et al (2009)	0.062	14.30%	30	1000MW	Systems are produced in Japan. Installed in Chinese Gobi.	Cradle to grave	LCA method actual project

Fthenakis et al (2008)	0.035, 0.045, 0.055	14.00%	30	US/EU company manufactured solar PV		Cradle to gate	Life-cycle inventory; commercially available solar PV
Allen et al (2008)	0.087		25	1720kWh/year; 2.1kWp roof mounted	UK application	Cradle to grave	Simapro and Ecoinvent 2.1
Kannan et al (2006)	0.0217	11.86%	25	2.7 kWp distributed solar PV	Installed in Singapore. It didn't say where the solar PV manufacturered.	Cradle to grave	Transporting data used from the report GEMIS (2002); LCA method and Life cycle inventory database.
Nawaz and Tiwari (2006)	0.028	8-11% (different application conditions)	35	1.2 kWp solar PV	SIMENSE PV and installed in India	Cradle to grave (transportation is not considered)	Input and Output analysis method
Alsema and Wild-Scholten (2006)	0.035	14.00%	30	1.25 sqr.m	11 PV manufactures (manufacturered in EU)	Cradle to site	Simapro (6.04) and Ecoinvent 2000 database
Frischknecht et al (2005)	0.037	14.00%	30	PVs are produced between 2005-2006	EU	Cradle to grave	Ecoinvent 3.1
Meier (2002)	0.039		30	8kWp solar PV roof mounted	USA	Cradle to grave	
Milousi et al 2019	0.0443	11%-16%	25-30	3kWp solar PV	Various countries	Cradle to grave	LCA method. SimaPro 8.5. Ecoinvent V 3.4
Kristjansdottir et al (2016)	0.040/0.070 (EU); 0.080/0.105 (Asia)	15.5% and 15.8%	30	Poly-Si 22.75kWp (attached), 12.48kWp (integrated)	Europe (15.5%) and Singapore (15.8%)	Cradle to site	LCA method. Ecoinvent V2.2 and V3.1, SimaPro V8.0.5
Yue et al (2014)	0.0318 (EU) 0.0692 (China)	13.20%	30		Two scenarios, one produced in EU and one in China	Cradle to grave	LCI data are based on published data from Chinese plants
Peng and Lu (2013)	0.0335	14.00%	20-30	Roof mounted 22kWp	Asian (HK) case study	Cradle to grave (transportation and disposal were not considered)	
Hsu et al (2012)	0.056 (review) 0.047 (hamonised)	13.20%	30	various configurations	Various countries	Cradle to grave	LCA method, two rounds review and screening (58 studies investigated c-SI PV) (2003-2009)
De Wild-Scholten (2011)	0.034	14.10%	30	located in South Europe	EU	Cradle to grave (transportation is not included)	ecoinvent

Ito et al (2011)	0.042	13.90%	30	600 kW poly-Si (13.9%)	Systems are produced in Japan. Installed in Chinese Gobi.	Cradle to grave	LCA method. JEMAI-LCA software. NEDO (New Energy and Industrial Development Organisation) created a PV module LCI database
Zhai and William (2010)	0.032	13.20%	30		Installed in EU	Cradle to grave	Hybrid LCA EIO method
Ito et al (2009)	0.052	NA	30	1000MW	China	Cradle to grave	LCA method
Fthenakis et al (2008)	0.032,0.042, 0.052	13.20%	30	NA	EU and USA	Cradle to gate	Life-cycle inventory; commercially available solar PV
Pacca et al (2007)	0.072	12.90%	NA		US	Cradle to grave	
Alsema and De Wild-Scholten (2006)	0.032	13.20%	30	1.25 sqr.m	USA and Western-Europe (Electricity for PV production is assumed in EU)	Cradle to site	Simapro (6.04) and Ecoinvent 2000 database
Hondo (2005)	0.053 (lifetime effects)	10.00%	30		Japan	Cradle to grave	LCA method; material production using process method and other parts using Input-Output analysis method
Tripanagnostopoules et al（2005）	0.082		30	3kWp roof mounted	Application in EU	Cradle to grave	LCA method; Simapro
Frischknecht et al (2005)	0.032	13.20%		PVs are produced between 2005-2006	EU	Cradle to grave	Ecoinvent 3.1
Alsema and Nieuwlaar (2000)	0.06(1999)/0.05(2000)	13.00%	30	Rooftop PV 1700 kWh.m^2/year (solar radiation)	EU and USA	Cradle to grave	Energy analysis
Kato et al (1998)	0.02	12.80%	20		Japan	Cradle to gate	

ASHP and GSHP

System	Resource	Embodied CO2	Lifespan	Configuration	EC boundary	Method
ASHP	Greening and Azapagic (2012)	0.014 kg CO2 eq/kWh	20		Cradle to grave	LCA method; GaBi 4.4 and CML2 Baseline 2001 methodology
	Johnson (2011)	0.026 kg CO2 eq/kWh	15	10 kW ASHP generated 59135 kWh heat	Cradle to grave	Refrigerant production footprints from UNEP RTOC; other data from Ecoinvent (2010);
GSHP	Greening and Azapagic (2012)	0.01 kg CO2 eq/kWh	20		Cradle to grave	LCA method; GaBi 4.4 and CML2 Baseline 2001 methodology
	Blum et al (2010)	0.008kg CO2 eq/kWh	20		Cradle to grave	

STC

Resource	Embodied CO2	Lifespan	Configuration	Boundary	Method
Ardente et al 2005	0.026 kg CO2 /kWh (721 kg CO2 eq)	15	Total net surface 2.13 sqr.m	Cradle to grave	LCA method; A commercial STC
Masruroh et al 2006	0.023 - 0.036 kg CO2/kWh	15	SOLARSTORE system	Cradle to grave	LCA method
Stephen et al 2018	0.023-0.036 kg CO2 eq/kWh	25			Review
Milousi et al 2019	0.0238 kg CO2/kWh	20	12.3 sqr.m	Cradle to grave	LCA method, SimaPro 8.5, Ecoinvent 3.4 database.

Battery

Resource	Year	Title	Embodied Carbon (CO2eq/kWh)	Assumed lifespan	Carbon boundary
Zeke Hausfather	2019	Factchek: How electric vehicles help to tackle climate change	[1] 150-200kg CO2 eq/kWh. [2] 61-106 kg CO2 eq/kWh [61, 146]. [3] 39-344 kg CO2 eq/kWh with average 100 kg CO2 eq/kWh.	12 years	Cradle to grave
Kurland	2019	Energy use for GWh-scale lithium-ion battery production	50-65 kWh of electricity per kWh of battery capacity	NA	Manufacturing only
Peters et al	2017	The environmental impact of Li-Ion batteries and the role of key parameters -A review	110kg/kWh [74g GHG emissions - 328 kWh energy for manufacturing]	10 years	Cradle to gate and cradle to grave
Liang et al	2017	Life cycle assessment of lithium-ion batteries for greenhouse gas emissions	127.84kg/kWh		Cradle to gate
McManus	2012	Environmental consequences of the use of batteries in low carbon systems: The impact of battery production	65-97kg/kWh (it includes Lithium water solvent and Lithium NMP(N-Methyl-2-pyrrolidone) solvent)		Cradle to grave

Appendix C – Ethical Approval

WELSH SCHOOL OF ARCHITECTURE
ETHICS APPROVAL FORM FOR STAFF AND PHD/MPHIL PROJECTS

Tick one box:	☐ STAFF	✓ PHD/MPHIL
Title of project:	Decision-making framework of identifying the optimal hybrid renewable energy system for retrofitting representative domestic buildings towards net-zero target in the UK context	
Name of researcher(s):	Zhehao Cui	
Name of principal investigator	Dr Eshrar Latif and Dr Vicki Stevenson	
Contact e-mail address:	CuiZ1@cardiff.ac.uk; LatifE@cardiff.ac.uk; Stevensonv@cardiff.ac.uk	
Date:	~~07~~20/04/21	

Participants		YES	NO	N/A
	• Children (under 16 years of age)		✓	

Does the research involve participants from any of the following groups?	• People with learning difficulties		✓	
	• Patients (NHS approval is required)		✓	
	• People in custody		✓	
	• People engaged in illegal activities		✓	
	• Vulnerable elderly people		✓	
	• Any other vulnerable group not listed here		✓	
• When working with children: I have read the University's Safeguarding Policy: https://intranet.cardiff.ac.uk/staff/policies		✓		

Consent Procedure	YES	NO	N/A
• Will you describe the research process to participants in advance, so that they are informed about what to expect?	✓		
• Will you tell participants that their participation is voluntary?	✓		
• Will you tell participants that they may withdraw from the research at any time and for any reason?	✓		
• Will you obtain valid consent from participants? (specify how consent will be obtained in Box A)[1]	✓		
• Will you give participants the option of omitting questions they do not want to answer?	✓		
• If the research is observational, will you ask participants for their consent to being observed?			✓
• If the research involves photography or other audio-visual recording, will you ask participants for their consent to being photographed / recorded and for its use/publication?			✓

Possible Harm to Participants	YES	NO	N/A
• Is there any realistic risk of any participants experiencing either physical or psychological distress or discomfort?		✓	

[1] If any non-anonymous and/or personalised data be generated or stored, *written consent* is required.

• Is there any realistic risk of any participants experience a detriment to their interests as a result of participation?		✓	

Data Protection		YES	NO	N/A
• Will any non-anonymous and/or personalised data be generated or stored?			✓	
• If the research involves non-anonymous and/or personalised data, will you:	• gain written consent from the participants	✓		
	• allow the participants the option of anonymity for all or part of the information they provide	✓		

Health and Safety	YES
Does the research meet the requirements of the University's Health & Safety policies? (https://intranet.cardiff.ac.uk/staff/supporting-your-work/manage-your-office-or-lab/health-safety-andhttps://intranet.cardiff.ac.uk/staff/supporting-your-work/manage-your-office-or-lab/health-safety-and-environmentenvironment)	✓

Research Governance	YES	NO	N/A
Does your study include the use of a drug? You need to contact Research Governance before submission (resgov@cf.ac.uk)		✓	
Does the study involve the collection or use of human tissue? You need to contact the Human Tissue Act team before submission (hta@cf.ac.uk)		✓	

Prevent Duty	YES	
Has due regard be given to the 'Prevent duty', in particular to prevent anyone being drawn into terrorism? Cardiff University Prevent Policy https://intranet.cardiff.ac.uk/staff/policies	✓	

If any of the shaded boxes have been ticked, you must explain in Box A how the ethical issues are addressed. If none of the boxes have been ticked, you must still provide the following information.

The list of ethical issues on this form is not exhaustive; if you are aware of any other ethical issues you need to make the SREC aware of them.

Box A The Project (provide all the information listed below in a separate attachment)
1. Title of Project 2. Purpose of the project and its academic rationale 3. Brief description of methods and measurements 4. Participants: recruitment methods, number, age, gender, exclusion/inclusion criteria 5. Consent and participation information arrangements - please attached consent forms if they are to be used 6. A clear and concise statement of the ethical considerations raised by the project and how is dealt with them 7. Estimated start date and duration of project All information must be submitted along with this form to the School Research Ethics Committee for consideration

Appendix D – Question sample

Investigation of households' preference prior to investing on-site renewable systems in England and Wales

* Required

Introduction

1. This survey is a part of the PhD research project. The entire PhD project is conducted by Mr Zhehao Cui (CuiZ1@cardiff.ac.uk), aiming to create a decision-making framework for identifying the optimal hybrid renewable energy system for existing domestic buildings in England and Wales. This PhD project is supervised by Dr Eshrar Latif (LatifE@cardiff.ac.uk) and Dr Vicki Stevenson (stevensonv@cardiff.ac.uk) as representatives of Cardiff University, and you can contact them via their emails if you wish to. This survey aims to understand the preference of performance indicators of the renewable system prior to households' investment in renewable systems. The data collected from the survey will be used to support the developed decision-making framework to identify the optimal hybrid renewable energy system for the selected representative existing domestic building type in Wales and England. The survey results can also support local authority and the devolved government's decision-making in wide implementation of the renewable energy systems on domestic buildings to against climate change and achieve the agreed climate change targets by 2050. The following questionnaire should take about 10-15 minutes to answer. Thank you very much in advance for your time and contribution. Your participation in this project is entirely voluntary. You can choose to proceed with this questionnaire by selecting 'Yes' or withdraw it by selecting 'No'. If you wish to receive the survey results, you can send us an email to CuiZ1@cardiff.ac.uk. The information you provide will be stored and used confidentially, and the data will be anonymous. Your personal information will not be used in the reporting or analyses in any way. The survey has been approved by the Research Ethics
Committee of the Welsh School of Architecture (ref.2116). *

Mark only one oval.

- ⬭ Yes *Skip to question 2*
- ⬭ No

General Information

2. Could you please tell us which region is your home located?

Mark only one oval.

- South Wales
- Mid Wales
- North Wales
- North-West England
- North-East England
- Eastern England
- Midlands
- Southern England
- South-West England

3. Could you please tell us the current ownership of your home?

Mark only one oval.

- You, as the owner of the home
- Rented from council/housing association
- Rented from the private
- sector Other:

____

4. Could you please indicate what type of house you (and your family) live in?

Mark only one oval.

- Flat *Skip to question 8*
- Bungalow *Skip to question 5*
- Terraced House *Skip to question 5*
- Semi-detached house *Skip to question 5*
- Detached House *Skip to question 5*
- Other:

____

Roof information

5. Could you please tell us the major roof type of your home?

Mark only one oval.

- Flat
- roof
- Pitched roof

Other:

____

6. Could you please tell us the major roof orientation of your home?

Mark only one oval.

- North and South
- North East and South West
- East and West
- South East and North
- West Other:

____

7. If you have a pitched roof, please tell us your pitched roof angle close to which group is listed in the following? If you are uncertain with your roof angle, please select I am not sure.

Mark only one oval.

- Less than 15 degree
- 15 to 19 degree
- 20 to 24 degree
- 25 to 29 degree
- 30 to 34 degree
- 35 to 39 degree
- 40 to 44 degree
- 45 to 49 degree
- 50 degree and above
- I am not
- sure Other:

____

Home total floor area and family income information

8. Could you please tell us what is your total floor area of your home? (Total floor area is the cumulative floor area of each level of your home) *Mark only one oval.*

- less than 50 square meter (538.2 square foot)
- 50 square meter to 69 square meter (538.2 square foot to 742.7 square foot)
- 70 square meter to 89 square meter (753.5 square foot to 958 square foot)
- 90 square meter to 109 square meter (969 square foot to 1173 square foot)
- 110 square meter or more (1184 square foot or more)
- I am not
- sure Other:

____

9. Could you please tell us the number of dependents in your home?

Mark only one oval.

- No dependent
- One adult with no children
- One adult with one child
- One adult with two children
- One adult with more than two children
- Two adults with no children
- Two adults with one child
- Two adults with two children
- Two adults with more than two children
- Other:

10. Could you please tell us the overall household annual income?

Mark only one oval.

- Less than £10,000
- £11,000 to £20,000
- £21,000 to £30,000
- £31,000 to £40,000
- £41,000 to £50,000
- Above
- £50,000 I
- wish not to

disclose Other:

11. Could you please tell us that have you already installed renewable systems in your home?

Mark only one oval.

- Yes *Skip to question 13*
- No *Skip to question 23*

12. Could you please tell us which type of renewable energy system you have installed in your home? (If you have selected 'No' to the previous question, please skip this question) *Mark only one oval.*

- Renewable power system only. (E.g., solar PV, micro-wind turbine) *Skip to question 13*
- Renewable heat system only. (E.g., Air source heat pump, ground source heat pump, biomass boiler) *Skip to question 15*
- Renewable power and heat system*Skip to question 17* Other:
- ____________________

Motivations of adopting renewable power system

13. Could you please tell us what are (is) motivations for you to consider installing renewable systems? (You can select multiple answers for this question if you wish to)

Check all that apply.

- [ ] Reduce energy bills
- [ ] Become more environmentally friendly (to mitigate the environmental impact)
- [ ] Advices from friends
- [ ] Interest of trying advanced renewable technology
- [ ] Become competitive in the house trading market
- [ ] Renewable heating system can work better than the existing energy systems
- [ ] Other:

____

14. Are you satisfied with the installed renewable energy system?

Mark only one oval.

- Yes *Skip to question 19*
- No *Skip to question 20*
- Other:

____

Motivations of adopting renewable heat system

15. Could you please tell us what are (is) motivations for you to consider installing renewable systems? (You can select multiple answers for this question if you wish to)

Check all that apply.

- [ ] Reduce energy bills
- [ ] Become more environmentally friendly (to mitigate the environmental impact)
- [ ] Advices from friends
- [ ] Interest of trying advanced renewable technology
- [ ] Become competitive in the house trading market
- [ ] Renewable heating system can work better than the existing energy systems
- [ ] Other: ____________________

16. Are you satisfied with the installed renewable energy system?

Mark only one oval.

- ( ) Yes *Skip to question 19*
- ( ) No *Skip to question 20*
- ( ) Other: ____________________

Skip to question 20

Motivations of adopting renewable power and heat system

17. Could you please tell us what are (is) motivations for you to consider installing renewable systems? (You can select multiple answers for this question if you wish to)

Check all that apply.

- [ ] Reduce energy bills
- [ ] Become more environmentally friendly (to mitigate the environmental impact)
- [ ] Advices from friends
- [ ] Interest of trying advanced renewable technology
- [ ] Become competitive in the house trading market
- [ ] Renewable heating system can work better than the existing energy systems
- [ ] Other:

18. Are you satisfied with the installed renewable energy system?

Mark only one oval.

- Yes *Skip to question 19*
- No *Skip to question 20*
- Other:

Renewable system satisfactory-1

19. Please tell us why you are happy with the installed renewable systems? (You can select multiple answers for this question if you wish to)

Check all that apply.

- [ ] Less annual energy bill
- [ ] Service cost is cheap
- [ ] Reduced carbon emission
- [ ] Renewable system is efficient (reliable) than existing energy systems
- [ ] Other:

Skip to question 24

Renewable system satisfactory-2

20. Please tell us why you are not happy with the installed renewable systems? (You can select multiple answers for this question if you wish to)

Check all that apply.

- [ ] Installation cost is too high
- [ ] Renewable system is not efficient (less reliable) than existing energy systems
- [ ] Renewable system is expensive to run
- [ ] Service cost is
- [ ] expensive Other:

____

Skip to question 24

Renewable system satisfactory - other

21. Please tell us why you are happy with the installed renewable systems? (You can select multiple answers for this question if you wish to)

Check all that apply.

- [ ] Less annual energy bill
- [ ] Service cost is cheap
- [ ] Reduced carbon emission
- [ ] Renewable system is efficient (reliable) than existing energy systems
- [ ] Other:

____

22. Please tell us why you are not happy with the installed renewable systems? (You can select multiple answers for this question if you wish to)

Check all that apply.

- [ ] Installation cost is too high
- [ ] Renewable system is not efficient (less reliable) than existing energy systems
- [ ] Renewable system is expensive to run
- [ ] Service cost is
- [ ] expensive Other:

____

Skip to question 24

Reasons of not adopting renewable systems

23. Could you please tell us what barriers are stopping you from adopting a renewable system in your home?

Check all that apply.

- [ ] I do not have enough knowledge of available renewable energy systems
- [ ] It would cost too much to install
- [ ] I am renting property at the moment, so I would not be able to install renewable systems
- [ ] I do not want the hassle of adopting something new
- [ ] It is not possible to install renewable systems in my home
- [ ] I am happy with my existing energy systems and the corresponding energy bills
- [ ] Renewable systems could hardly work efficiently in my home
- [ ] I will move out
- [ ] soon Other:

____

Skip to question 24

Basic question of renewable system and climate change

24. Please could you tell us which renewable systems (listed in the following) you have been aware of?

Check all that apply.

- [ ] Solar Photovoltaics (solar PV)
- [ ] Solar thermal collectors/panels (solar water heating systems)
- [ ] Ground source heat pumps
- [ ] Air source heat pumps
- [ ] Other:

____

25. Please could you tell us if you find it difficult to access reliable information in the investment of renewable systems for your home?

Mark only one oval.

Yes

No

Mayb

e

Other:

26. Please tell us the relevant information provided by who/which organisation you most trust to support your renewable system investment in your home?

Mark only one oval.

- Charities, Environmental or campaign groups
- Energy provider (supplier)
- Friends and family
- Local council
- Newspapers or news on websites
- Professional energy efficiency advisor or professional energy consultant
- Scientists working in scientific organisations
- Social media (e.g., Facebook, twitter)
- TV and radio documentaries
- UK government website
- Other:

27. From your viewpoint, do you think homes with the installed renewable systems can help UK to achieve the agreed climate change target by 2050?

Mark only one oval.

Yes

No

Maybe

I do not know

Other:

Renewable system performance criteria

You can nd the relevant de nition of each criterion through the link: https://cf-my.sharepoint.com/:b:/g/personal/cuiz1_cardiff_ac_uk/EYaajXuyxh9PkQArGSjQa7UBNpE 6Jpg8F-dzSTr3xphVw?e=Zi1lyD

28. Could you please allocate the preference value ('1' to '5')to the following performance criteria? The performance value '1' indicates least preferred. The preference value '2' indicates not preferred. The preference value '3' indicates less preferred. The preference value '4' indicates preferred. The performance value '5' indicates the most preferred. Here are some preference value allocation examples and you might wish to look at prior to allocating your preference value to each criterion: https://cfmy.sharepoint.com/:b:/g/personal/cuiz1_cardiff_ac_uk/EcG63Cxt5xOl0ZgK1ZI5UEB12GtTDY_2s2F7aP8YU55cw?e=1icHhq

Mark only one oval per row.

	1 (Least preferred)	2	3	4	5 (Most preferred)	Not sure	I do not understand
Economic							
Technical							
Environment							

Economic

You could check the de nition of each indicator through the link if you wish to: https://cfhttps://cf-my.sharepoint.com/:b:/g/personal/cuiz1_cardiff_ac_uk/EbseahWk9tBEilIwXyz-jQ8BukQQGHrX-w_z-NCjSapWIQ?e=a8OKEDmy.sharepoint.com/:b:/g/personal/cuiz1_cardiff_ac_uk/EbseahWk9tBEi

IlwXyzhttps://cf-my.sharepoint.com/:b:/g/personal/cuiz1_cardiff_ac_uk/EbseahWk9tBEilIwXyz-jQ8BukQQGHrX-w_z-NCjSapWIQ?e=a8OKEDjQ8BukQQGHrX-w_z-NCjSapWIQ?e=a8OKED

29. Could you please allocate the preference value ('1' to '5')to the following economic indicators? The performance value '1' indicates least preferred. The preference value '2' indicates not preferred. The preference value '3' indicates less preferred. The preference value '4' indicates preferred. The performance value '5' indicates the most preferred. Here are some preference value allocation examples and you might wish to look at prior to allocating your preference value to each indicator: https://cfmy.sharepoint.com/:b:/g/personal/cuiz1_cardiff_ac_uk/EcG6-3Cxt5xOl0ZgK1ZI5UEB12GtTDY_2s2F7aP8YU55cw?e=8tdXZK

Mark only one oval per row.

	1 (Least preferred)	2	3	4	5 (Most preferred)	Not sure	I do not understand
Capital cost	⬭	⬭	⬭	⬭	⬭	⬭	⬭
Discounted payback period	⬭	⬭	⬭	⬭	⬭	⬭	⬭
Cost effective indicator	⬭	⬭	⬭	⬭	⬭	⬭	⬭
Financial incentive schemes	⬭	⬭	⬭	⬭	⬭	⬭	⬭

30. Please could you specify other economic indicators that you would like to consider before investing in renewable systems (indicators not mentioned above)?

Technic

You could check the de nition of each indicator through the link if you wish to: https://cfhttps://cf-my.sharepoint.com/:b:/g/personal/cuiz1_cardiff_ac_uk/EaNSvJUXPDNGmTSFxKp52bsBa47Ctd8F5FEMAALXYapL2w?e=ZBStyOmy.sharepoint.com/:b:/g/personal/cuiz1_cardiff_ac_uk/EaNSvJUXPDNGmTSFxKp52bsBa47Ctd8F5FEMAALXYapL2w?e=ZBStyO

31. Could you please allocate the preference value ('1' to '5')to the following technical indicators? T The performance value '1' indicates least preferred. The preference value '2' indicates not preferred. The preference value '3' indicates less preferred. The preference value '4' indicates preferred. The performance value '5' indicates the most preferred. Here are some preference value allocation examples and you might wish to look at prior to allocating your preference value to each indicator: https://cfmy.sharepoint.com/:b:/g/personal/cuiz1_cardiff_ac_uk/EcG6-3Cxt5xOl0ZgK1ZI5UEB12GtTDY_2s2F7aP8YU55cw?e=TCFqIO

Mark only one oval per row.

	1 (Least preferred)	2	3	4	5 (Most preferred)	Not sure	I do not understand
Ease of installation	◯	◯	◯	◯	◯	◯	◯
Grid electricity independence level	◯	◯	◯	◯	◯	◯	◯
Lifespan	◯	◯	◯	◯	◯	◯	◯
Saved fossil energy indicators	◯	◯	◯	◯	◯	◯	◯
Renewable energy system maturity level (The acceptance level that different stakeholders decide for renewable systems)	◯	◯	◯	◯	◯	◯	◯

32. Please could you specify other technical indicators that you would like to consider before investing in renewable systems (indicators not mentioned above)?

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____

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Environment

You could check the de nition of each indicator through the link if you wish to: https://cfhttps://cf-my.sharepoint.com/:b:/g/personal/cuiz1_cardiff_ac_uk/ERVAHjtCA8RBvfYN6ffAI_kBa2iSSGKrhPYVDQyYP1lUuw?e=5vs8wkmy.sharepoint.com/:b:/g/personal/cuiz1_cardiff_ac_uk/ERVAHjtCA8RBvfYN6ffAI_kBa2iSS GKrhPYVDQyYP1lUuw?e=5vs8wk

33. Could you please allocate the preference value ('1' to '5')to the following environment indicators? The performance value '1' indicates least preferred. The preference value '2' indicates not preferred. The preference value '3' indicates less preferred. The preference value '4' indicates preferred. The performance value '5' indicates the most preferred. Here are some preference value allocation examples and you might wish to look at prior to allocating your preference value to each indicator: https://cfmy.sharepoint.com/:b:/g/personal/cuiz1_cardiff_ac_uk/EcG6-3Cxt5xOl0ZgK1ZI5UEB12GtTDY_2s2F7aP8YU55cw?e=WNQ3VJ

Mark only one oval per row.

	1 (Least preferred)	2	3	4	5 (Most preferred)	Not sure	I do not understand
Embodied Carbon Payback Period	◯	◯	◯	◯	◯	◯	◯
Greenhouse Gas emission (GHG) at operational stage	◯	◯	◯	◯	◯	◯	◯

34. Please could you specify other Environmental indicators that you would like to consider before investing in renewable systems (indicators not mentioned above)?

End of the questionnaire

You have reached the end of the questionnaire. We appreciate your help and time to complete the questionnaire. Please contact us via the email: CuiZ1@cardiff.ac.uk if you wish to receive the questionnaire results. Thanks for your help!

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