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Technical and economic assessment of a hybrid heat pump system as an energy retrofit measure in a residential building

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ABSTRACT

Air to water electric heat pumps are one technological solution to achieve energy defossilisation goals for heating of residential building stock. Nevertheless, they may not necessarily be the only solution for all residential building stock. A case in point is where extensive fabric refurbishment is impracticable or where electric heat pumps are installed where low ambient temperatures prevail and/or high water delivery temperatures must be utilised. For such instances, hybrid (gas and electric) heat pumps offer an alternative option by facilitating fuel source switching between electricity and gas, when ambient temperatures are low or high water supply temperatures are required. In the current study, the effectiveness of an air-to-water electric heat pump and hybrid heat pump are examined for different building retrofit scenarios for a residential dwelling located in Ireland. This is achieved by means of a sensitivity study of a validated building simulation model, incorporating both heat pump systems, subject to different building retrofit scenarios. Relative to a conventional oil-fired boiler, for a deep building retrofit scenario, the hybrid and electric heat pumps achieve primary energy reduction of 128 kWh/m^2/year (72%) and of 123 kWh/m^2/year (70%), respectively. Considering the associated carbon footprints, the reductions were found to be 29.7 gCO_2e/m^2/year (74%) for the hybrid heat pump, and 27.6 gCO_2e/m^2/year (68%) for the electric heat pump. Finally, the deployment of either an electric heat pump or hybrid heat pump for deep building fabric retrofit achieves approximately half of the heating system capital cost return within 20 years.

1. Introduction

Improving the energy performance of the building sector has been well established as a key energy policy goal of the European Union (EU), given that the EU has committed to developing a sustainable, secure and carbon-free overall energy scenario by 2050. To make that objective a reality, energy stakeholders throughout all member states require measures to achieve such energy efficiency and carbon emissions targets. Given the building sector accounts for about 40% of primary energy consumption and 36% of associated greenhouse gas emissions in Europe, it plays a paramount role towards achieving a carbon-neutral and competitive economy [1].

Currently, about 35% of EU buildings are over 50 years old, 75% of which do not meet the national energy performance targets according to the EU Directive 2018/844 on the energy performance of buildings [2]. Despite the stated goals of the EU Commission, the rate of building stock renovation continues to advance at a slow pace, between 0.4-1.2% of existing stock per year, depending on the EU country [3]. Therefore, a critical element to achieving 2050 energy goals is the development of long-term energy retrofit strategies providing a solid support for renovating residential and non-residential building stocks, thereby helping advance the decarbonisation of the building sector by 2050 [4]. Retrofitting of existing buildings can lead to energy savings, with the potential to decrease the EU total energy consumption by 5-6% and minimise CO_2 emissions by about 5% [5]. However, it is essential to ensure that energy efficiency measures target not only the building envelope, but also encompass all related elements and technical systems in a building for the provision of heating and/or cooling.

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Nomenclature

Acronyms

$ASHRAE$	American Society for Heating Refrigeration and Air Conditioning Engineers
$AWHP$	Air-to-Water Heat Pump
CGB	Condensing Gas Boiler
$CIBSE$	Chartered Institution of Building Services Engineers
DHW	Domestic Hot Water
EHP	Electric Heat Pump
EU	European Union
GB	Gas Boiler
HHP	Hybrid Heat Pump
HP	Heat Pump
OB	Oil Boiler
RAD	Radiator
ROI	Return of Investment
SCN	Scenario
$SEAI$	Sustainable Energy Authority of Ireland
SFI	Science Foundation Ireland

Abbreviations

$ALU-R$	Aluminium Radiator
$Elec$	Electricity
$init$	Initial Investment
$NatGas$	Natural Gas

Subscripts

$Elec$	Electricity production	
EP	Energy production	
HHP	Hybrid heat pump	
HP	Heat pump	
hs	Heating system	
i	Time step, Fuel type	-
$mode-switch$	Hybrid heat pump mode switch	
$outdoor$	Ambient/Outdoor	
pr	Per unit	
$waterflow$	Heat pump water flow	

Greek Letters

ϵ	Carbon Intensity	tonnes
η	Efficiency	

Other Symbols

$\bar{y}$	Mean Value	-
g	gram	g
m	Number of Fuels Used	-
N	Total Number of Data Points	-
p	Number of Predictor Variables	-
r	Discount Rate	%
x	Simulated Value	-
y	Experimental or Measured Value	-

Symbols

ACS	Annual Cost Saving	€
CF	Cash Flow	€
COP	Coefficient of Performance	-
$CVRMSE$	Coefficient of Variation of Root Mean Square Error	-
E	Energy Consumption	kWh
e	Energy Saved	kWh
EE	Electricity Delivered for Final or End-User Consumption	kWh
EF	Emissions Factor	-
EP	Energy Production	kWh
F	Price	€/kWh
$MAPE$	Mean Absolute Percentage Error	%
NCF	Net Cash Flow	€
NPV	Net Present Value	€
PE	Primary Energy	kWh
PEF	Primary Energy Factor	-
PES	Primary Energy Saving	%
Q	Thermal Energy Output	kWh
RC	Operating Cost	€
$RMSE$	Root Mean Square Error	
SPF	Seasonal Performance Factor	-
T	Temperature	°C
TCC	Tolerable Capital Cost	€

Deep retrofitting of buildings requires significant investment costs for building owners or stakeholders, hence, the transformation of existing energy-inefficient buildings into nearly zero-energy buildings needs to be facilitated in a cost-effective manner. A key enabling factor in meeting energy retrofit targets is the availability of financial incentive support schemes. For this, EU member countries have established policies and measures to stimulate cost-effective deep retrofit of buildings, thereby supporting energy efficiency improvements in the residential and commercial sectors. These include; grants, low-interest loans and other financial incentives [6].

Consequently, there has been an increasing amount of literature on building retrofit solutions aimed at reducing the energy consumption of buildings [7], including building fabric thermal retrofitting [8], building integrated passive systems [9], and technical system upgrades, such as heat pumps [10] and combined heat and power systems [11]. However, the latest research insights show an increasing necessity towards optimising technical system performance in combination with fabric upgrades [12]. Moreover, the integration of renewable energy resources with the power grid, which if coupled with electrification of building space heating, is one of the possible routes that many countries are considering in the pursuit of decarbonisation [13].

In this context, heat pumps can play an important role in the electrification of heat in the context of the 2050 targets. Vorushylo et al. [14], for a study carried out in Ireland, determined that heat pumps bring the most significant environmental benefits to energy markets, which have a significant renewable energy contribution such as wind. Another comprehensive study in Germany, carried out by Palzer and Henning [15], found that heat pumps can play a major role in the decarbonisation of the heating sector. Similarly, Fischer and Madani [16] concluded that heat pumps should be considered as a potential key technology to provide flexibility to the power system, while providing heating and cooling retrofit solutions. The study shows that heat pumps can be used to ease the transition towards a renewable interconnected energy system.

Nevertheless, there are also challenges associated with the electrification of heat, the foremost being the shift of residential space heating from conventional fossil fuel based technologies, such as gas or oil to electricity, which in certain scenarios can require an enhanced and expanded electricity infrastructure with consequent high investment costs. With many residential retrofits set to take place over the immediate coming decades [17], it would seem that no one solution can be optimally deployed for every instance and instead accurate preliminary techno-economic assessment of different retrofitting scenarios needs to be carried out.

One potential retrofit technology option for the residential heating sector is hybrid heat pumps (HHP). HHPs combine an electrically driven heat pump, usually as an air to water system [18], and a gas condensing boiler within a single system or unit. These systems can offer an alternative retrofitting solution in older dwellings, where high temperature heat emitters have been typically utilised in this residential building stock category. Under appropriate operating conditions, HHPs have been observed to achieve higher seasonal performance compared to Electric-only Heat Pumps (EHPs), arising from the possibility to operate in gas boiler (GB) mode for certain conditions when EHP performance is less favourable [19]. For instance, during the coldest weather periods, when greater heating loads occur together with associated poorer EHP performance, HHPs offer the possibility to switch to GB mode, which may be more favourable in such conditions. Typically, HHP systems operate in EHP mode when external ambient air temperatures exceed $3-5^oC$ and in GB mode otherwise. The use of the GB mode may also offer certain advantages over EHP mode when domestic hot water (DHW) is required, often at temperatures exceeding 50^oC [20].

Moreover, given that a hybrid heat pump incorporates a gas boiler which can be deployed to cover peaks in thermal demand, allows for a lower rating of the EHP, resulting in smaller EHP equipment and associated power demand [21]. A study carried out by Dongellini et al. [22] found that the over-sizing of heat pumps is a critical design issue that heavily influences the energy performance (and economic suitability) of heat pump systems, affecting both seasonal and annual energy performance. Park et al. [23] performed an economic analysis of a hybrid heat pump system, which was compared with conventional gas-fired water heaters for residential houses in Korea. It was found that about 4% of annual energy costs could be saved from the operation of the hybrid system. Benefits from carbon emission reductions resulting from a widespread adoption of hybrid solutions were analysed by Heinen et al. [24], who concluded that hybrid heating systems (heat pump/gas boiler or electric heat pump/resistance heater) can reduce CO_2 emissions significantly, while also reducing total power system costs, compared to single-fuel heating technologies, especially if considered from an integrated gas network/power grid perspective.

Typically, the performance of HHP systems is strongly affected by how the hybrid system is integrated, controlled and operated. Chargui and Sammouda [25] noted that electricity and natural gas prices play an important role on the HHP performance, as these can vary by region. Typically, the authors found that HHP systems are more satisfactory in residential buildings when a careful integration of the system is undertaken to optimise gas and electricity usage. Therefore, an effective operation strategy is essential for a hybrid heating system. According to Li and Du [26], the associated control strategies for a HHP system can lead to 20%-65% economic benefits compared to a non-optimised baseline.

Research work to date on HHP systems has tended to focus mainly on associated system energy and economic analysis, while little research has been carried out on the integrated analysis of building retrofitting scenarios incorporating either EHP or HHP systems, where different building fabric thermal retrofit options are evaluated. Currently, there is an emerging need to examine the efficacy of energy policy instruments on energy efficiency and energy performance improvement in residential buildings [27]. Therefore, more research is needed to identify the technical and economic potential of these retrofitting strategies with current home retrofit options and incentives [17] which is focus of the present contribution.

The current paper presents an economic and technical analysis of a hybrid heat pump, which was installed in association with a retrofit upgrade of a residential building located in Ireland, which involved retrofit of both the heating system and the building envelope. A building energy simulation model of the integrated system was developed and validated as part of this research. Using this model, further simulation analysis was carried out for different retrofit scenarios. The overall aim of the paper is to examine the effectiveness of the HHP system subject to different envelope retrofit measures and operational boundary conditions. Benchmarking of the HHP system is carried out with reference to an electric heat pump system, as well as conventional fossil gas and oil heating systems. The significance of the current study lies insofar as little investigation has been carried out to date that examines the integrated analysis of a hybrid heat pump and residential building - including different retrofit measures - such that technical and economic performance can be examined with reference to an electric heat pump and fossil fuel boiler systems.

Table 1
Characteristics of the building envelope.

	U-Value (W/m^2K)			
	External Wall	Roof	Floor	Glazing
Base Case	0.31	0.31	0.25	2.15
Minimal Retrofit	0.31	0.16	0.25	2.15
Deep Retrofit	0.18	0.16	0.18	0.8

2. Material and methods

The case study consists of a residential building, described in section 2.1.1, which was subject to staged retrofit of its fabric and energy conversion systems, as described in section 2.1.2. To provide a more comprehensive analysis, a simulation model of the building was developed (section 2.2.1) and validated against experimental data associated with the aforementioned building (section 2.2.2). The model was then used to carry out a technical analysis to determine the potential benefits of different retrofitting scenarios in terms of primary energy savings and carbon emissions reduction, with reference to various metrics as described in section 2.3.1. Finally, several economic indexes were introduced (section 2.3.2) to investigate the investment sustainability of each considered retrofit scenario. The overall methodology of the present research is summarised in Fig. 1.

2.1. Case study

2.1.1. Building description

The reference building is a residential detached house which was constructed in 1999 and is located in Ireland. The building uses a hydronic based heating system, the use of which is ubiquitous in Ireland & the UK, with a reported penetration of 95% with reference to all installed residential heating systems [28]. The building has a floor area of 160 m^2 and a south-easterly facing aspect. The ground floor consists of four communal living spaces and a bathroom, while the first floor contains four bedrooms and a bathroom. The building has ceiling to floor height of 2.5 metres and a total external wall surface area of 139 m^2. The windows are double-glazed units, with a window to wall ratio of 0.22 and a total glazed area of 30.5 m^2, with a majority of the glazing on the ground floor.

The building was retrofitted by the house owner in stages between October 2014 and April 2015. First, the original condensing gas boiler was replaced with a hybrid heat pump system (HHP). A data monitoring system was also installed and commissioned in November 2014. Next, in late February 2015, low temperature aluminium radiators were installed, replacing conventional high temperature steel radiators. Finally, in April 2015, other retrofitting measures were completed which included upgraded insulation in the dormer roof structure to reduce heat losses. Therefore for the present work, three fabric retrofit scenarios (see Table 1 for fabric details) are considered in the simulation analysis as follows:

- *Base Case Scenario*: This scenario utilises the building fabric specifications as per the original construction (1999). Therefore, for the building simulation model, the relevant building fabric components are mapped to the prevailing Irish Building Regulations at that time [29].

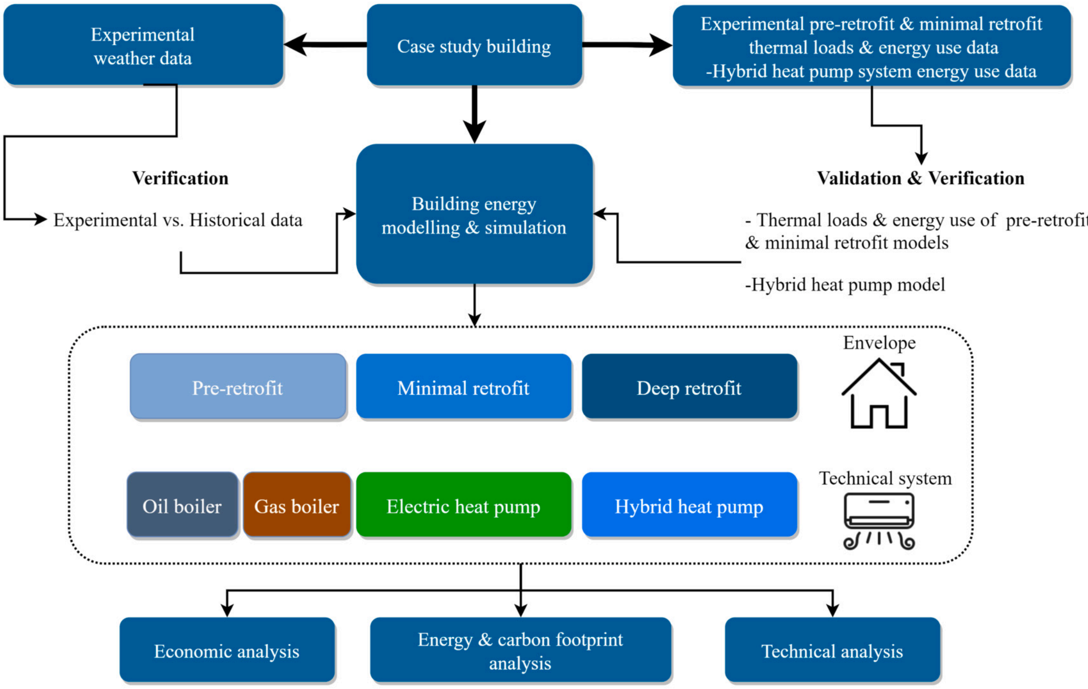

Fig. 1. Schematic diagram of the overall workflow of the study.

- *Minimal Retrofit Scenario*: This scenario is based on the retrofitted dwelling carried out in April 2015 and includes the fabric improvements at the upper floor and roof level. It is mapped to the prevailing Irish Building Regulations at the time of retrofit [30].
- *Deep Retrofit Scenario*: This scenario considers the implementation of additional retrofitting measures corresponding to contemporary Irish national guidelines [31]. They include improvements to the ground floor, the ground floor external walls and the window U-value specifications. It should be noted that as these deep retrofit measures were not carried out to the actual building fabric, instead for the current work, they are analysed by means of the building simulation model (see Section 2.1.2).

Four different heating systems are considered as follows: an oil boiler with older cast iron radiators, a condensing gas boiler with steel radiators, a hybrid heat pump with aluminium radiators and an all-electric heat pump with aluminium radiators. Further specific information on the integration of the heating systems with the aforementioned fabric scenarios is provided in Section 2.1.2. More generally, for all scenarios, the heating system was normally operated so as to maintain an average internal temperature of 20 °C with a 0.5 °C dead band at all times. A night setback period was utilised. This is in line with prevailing standards to maintain thermal comfort conditions in dwellings [32]. The building schedules are maintained and thus the HHP system was scheduled to operate over the entire year. Based on Köppen Geiger climate classification system [33], the relevant climate type is defined as a temperate oceanic climate.

The installed HHP system is a commercially available air-source HP system with a nominal output of 8 kW (rated at 35 °C water supply temperature from the HHP system) for the heat pump and 33 kW for the gas boiler. The HHP system can operate as either a hybrid system or as individual independent units. The control strategy for hybrid heat pump is based on the outdoor air temperature and the supply water flow temperature which determines the mode under which the unit operates. It can be summarised as follows:

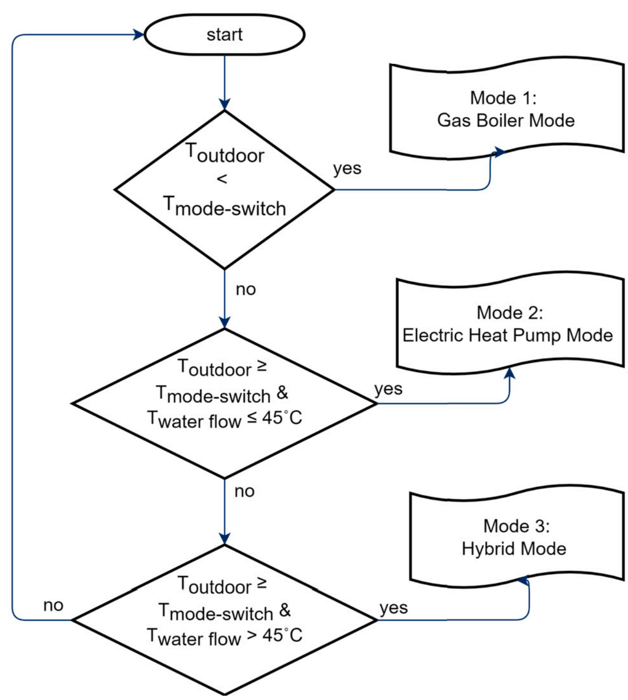

Fig. 2. Hybrid heat pump control algorithm flowchart.

- Mode 1 - Gas Boiler Mode: this mode is controlled by HHP mode-switch temperature and it was set at 2 °C as per manufacturer specifications. During periods where the external air temperature is below the mode-switch temperature, the gas boiler provides the entire thermal load (Switch to Mode 1, if $T_{outdoor} < T_{mode-switch}$).
- Mode 2 - Electric Heat Pump Mode: this mode applies when the outdoor air temperature is greater than the mode-switch temperature, and where the water supply flow temperature is equal to or less than 45 °C (Switch to Mode 2, if $T_{outdoor} \geq T_{mode-switch}$ & $T_{waterflow} \leq 45$ °C).
- Mode 3 - Hybrid Mode: this mode applies when outdoor air temperature is greater than the mode-switch temperature, and the water

Table 2
Summary of analysed scenarios.

Scenario	System	Distribution	Fuel	Water Supply Temp. (°C)	Envelope Categorisation
(a)	OB	RAD	Oil	70	Base Case
(b)	CGB	RAD	Nat. Gas	60	Base Case
(c)	HHP	ALU-R	Elec./Nat. Gas	55	Base Case
(d)	EHP	ALU-R	Elec.	55	Base Case
(e)	HHP	ALU-R	Elec./Nat. Gas	55	Minimal Retrofit
(f)	EHP	ALU-R	Elec.	55	Minimal Retrofit
(g)	HHP	ALU-R	Elec./Nat. Gas	55	2018 Building Regulations
(h)	EHP	ALU-R	Elec.	55	2018 Building Regulations

supply temperature is greater than 45 °C. In this mode, the heat pump and the gas boiler operate in series to provide the thermal load (Switch to Mode 3, if $T_{outdoor} \geq T_{mode-switch}$ & $T_{waterflow}$ > 45 °C).

In addition, a control algorithm flowchart for the hybrid heat pump is illustrated in Fig. 2.

2.1.2. Summary of the analysed scenarios

In the present study, two baseline and six retrofit scenarios incorporating different combinations of the heating system and building fabric retrofit are considered, which are outlined below and summarised in Table 2.

- Scenario (a) uses the base case building with a non-condensing oil-fired boiler with an assumed overall efficiency of 80%. A water supply temperature of 70 °C is applicable and the heating distribution system uses cast iron radiators.
- Scenario (b) is similar to scenario (a), except for a natural gas condensing boiler with an overall efficiency of 92% is deployed. A water supply temperature of 60 °C is applicable and steel radiators are utilised. Scenarios (a) and (b) were included to provide reference baselines, as both scenarios are common in Irish building stock.
- Scenario (c) uses the base case building with the hybrid heat pump and a design water supply temperature of 55 °C. In addition, the heating distribution system uses aluminium radiators which are designed to operate at lower temperatures compared to conventional steel radiators. No other retrofit measures are applied to the dwelling.
- Scenario (d) uses the base case building with an electric heat pump and a design water supply temperature of 55 °C. Aluminium radiators are utilised. No other retrofit measures are applied to the dwelling. The capacity rating of the EHP is 14 kW (55 °C), as per manufacturer specifications.
- Scenario (e) corresponds to a minimal fabric retrofit scenario which includes both aluminium radiators and additional dormer and roof insulation. The heating system is as per scenario (c).
- Scenario (f) uses the same building model as Scenario (e). The heating system is an EHP as per scenario (d).
- Scenario (g) incorporates a deep retrofit as per the 2018 Irish Building Regulations [34]. It uses the same heating system and supply flow temperatures as scenario (c).
- Scenario (h) incorporates a deep retrofit as per the 2018 Irish Building Regulations [34]. The heating system is an EHP as scenario (d).

The performance of the oil and gas boilers were based on CIBSE guide B [35] and SEAI guidelines [36]. The performance of the hybrid heat pump was based on experimental data from the installed system, which was fitted with a regression equation. The performance data of electric heat pumps were provided by the manufacturer for a range of operation points. These are shown in Fig. 3. In the simulation analysis, the experimental HHP performance curve was used for all HHP scenarios, and a standard heat pump performance curve from a manufacturer (Model RLQ014, Fig. 3) was used for all EHP scenarios.

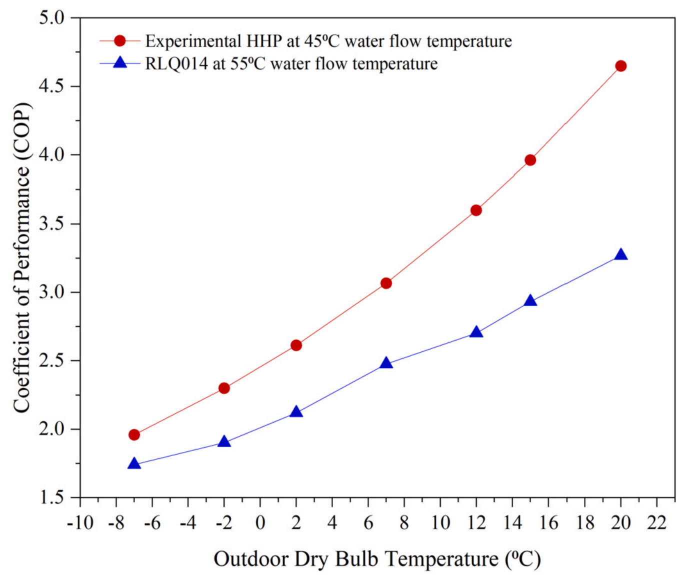

Fig. 3. Heat pumps performance curves.

2.2. Modelling and assessment procedures

2.2.1. Energy simulation model

Building energy simulation models for each of the aforementioned scenarios were created using IESVE [37]. This simulation software uses ApacheSim [38] as the internal engine to model the building heat transfer processes. A schematic of the modelled building is given in Fig. 4. A time step of 2 minutes was used for simulation and data was exported every 10 minutes to match the experimental data reporting intervals.

The simulation model uses climatic data made available by ASHRAE [39] for a location which is approximately 16 kilometres from the building test site. Ambient weather conditions were measured experimentally at the site based on 10 minute intervals and included dry-bulb temperature and solar radiation. This data was averaged on the basis of one hourly intervals to allow comparison with meteorological data and the ASHRAE climatic database. Hourly weather data was recorded by the Irish Meteorological service, Met Éireann [40], at a weather station located 10 km away from the dwelling.

2.2.2. Model validation

Verification of the building and energy system model was based on data collected for the period from December 2014 to April 2016. Three verification metrics were used: the root mean square error (RMSE), the coefficient of variation of root mean square error (CVRMSE), and the mean absolute percentage error (MAPE).

The RMSE is the standard deviation of the prediction errors (residuals) as specified in Equation (1), where N is the total number of time steps or data points in the simulation, i is the current time step, x_i is

Fig. 4. Case study residential building.

the simulated value at the current time step, and y_i is the experimental value at the current time step, and p is the number of adjustable model parameters, for calibration purposes, ASHRAE suggests $p = 1$.

$$RMSE = \sqrt{\frac{1}{N-p}\sum_{i=1}^{N}(x_i - y_i)^2} \tag{1}$$

The CVRMSE is an index determining how well a model fits the data by capturing the offset error between measured and simulated data. This error metric, recommended by ASHRAE [41], is defined by Equation (2), where $\bar{y}$ is the average value of the experimental data. Typically, a 15% acceptance criteria for the calibration of building energy models is recommended.

$$CVRMSE = \frac{100}{\bar{y}}\sqrt{\frac{\sum_{i=1}^{N}(x_i - y_i)^2}{N-p}} = \frac{RMSE}{\bar{y}} \tag{2}$$

Finally, the MAPE measures the average absolute magnitude of the errors in a set of predictions or simulations. Equation (3) shows how to calculate the MAPE.

$$MAPE = \frac{100}{N}\sum_{i=1}^{N}\left|\frac{x_i - y_i}{y_i}\right| \tag{3}$$

Data collection in the period December 2014 to February 2015 allowed predicted and measured space heating loads to be compared prior to the building envelope retrofitting as shown in Fig. 5. The simulated heating load is calculated by the IESVE software (with respect to the external ambient conditions and inside temperature at 20 °C), whereas the experimental data is based on an energy balance measurement of the building heating supply/return water temperatures. For the three months, a MAPE of 3.5%, a RMSE of 196 kWh, and a CVRMSE of 6.5% were noted. All are deemed to be within requirements as per ASHRAE specifications [41].

Regarding the minimal retrofit scenario, heating loads were compared for the period May 2015 to April 2016, as shown in Fig. 6. The basis for determining the simulated and experimental loads is similar to that outlined for Fig. 5. For this data, a RMSE of 131 kWh, a MAPE of 4.4% and a CVRMSE of 10.4% are applicable, all of which are within ASHRAE recommended tolerances [41].

Finally, the metered energy consumption (kWh) of the HHP (gas and electricity consumption) is compared with simulation predictions, as per Fig. 7, where both gas and electricity consumption were shown for 12 calendar months (Jan 2015 - Dec 2015) for the heating system. The results exhibit an average monthly RMSE of 112 kWh, a MAPE of 4.55% and a CVRMSE of 10.6%, which are all within the ASHRAE specifications [41].

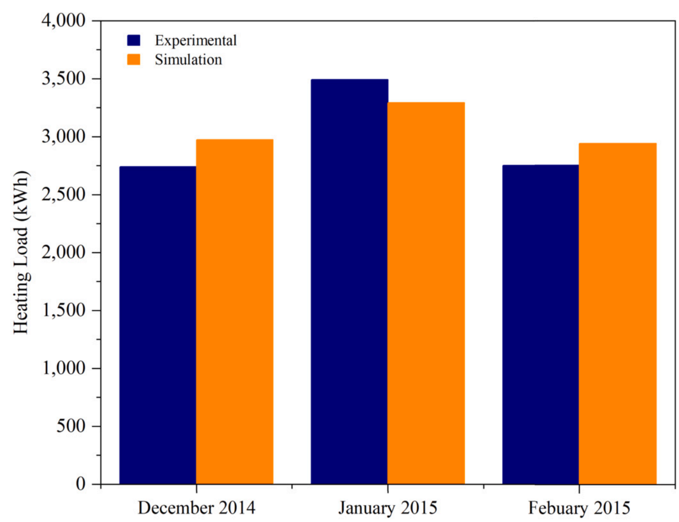

Fig. 5. Comparison of building heating loads - simulation (No retrofit model) vs. experimental data.

2.3. Techno-economic analysis

2.3.1. Energy analysis

Space heating of buildings can be supplied by different energy conversion systems and associated energy sources. For this reason, appropriate indicators are essential for analysing energy efficiency and performance of energy systems in buildings [42]. To resolve energy consumption by different energy conversion systems to a single comparable primary energy baseline, the Primary Energy Factor (PEF) is often used to take into account the production chain of the energy vector that has been used by the different systems [42]. The energy performance evaluation of technical systems in buildings is highly influenced by PEF values and therefore it is important that the PEF is applied correctly [42,43].

The PEF for the electricity used by the heat pump depends on the generation mix of the country in which it operates and it is calculated using Equation (4) [44] as follows:

$$PEF = \frac{PE_{EP}}{EE} \tag{4}$$

where PEF is the primary energy factor for electricity production, PE_{EP} is the primary energy utilised for electricity production on the network, and EE is the electricity delivered for final or end-use energy consumption. The PEF for the Irish electrical grid for this analysis was set as PEF_{elec} = 1.83 [45]. For natural gas and oil, the PEF was set as PEF_{gas} = 1.15. Conversion factors for the different energy vectors

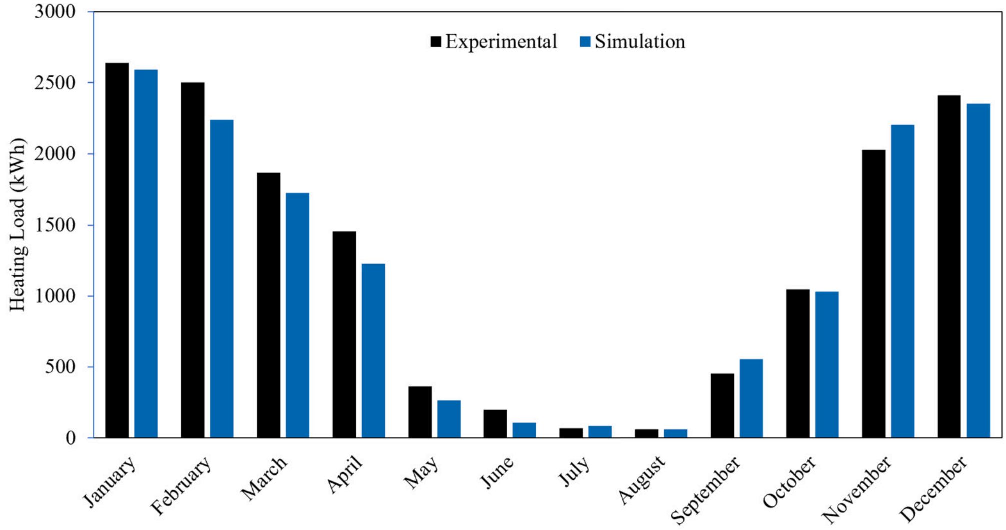

Fig. 6. Comparison of building heating loads (May 2015 - Apr 2016) - simulation (Minimal retrofit model) vs. experimental data.

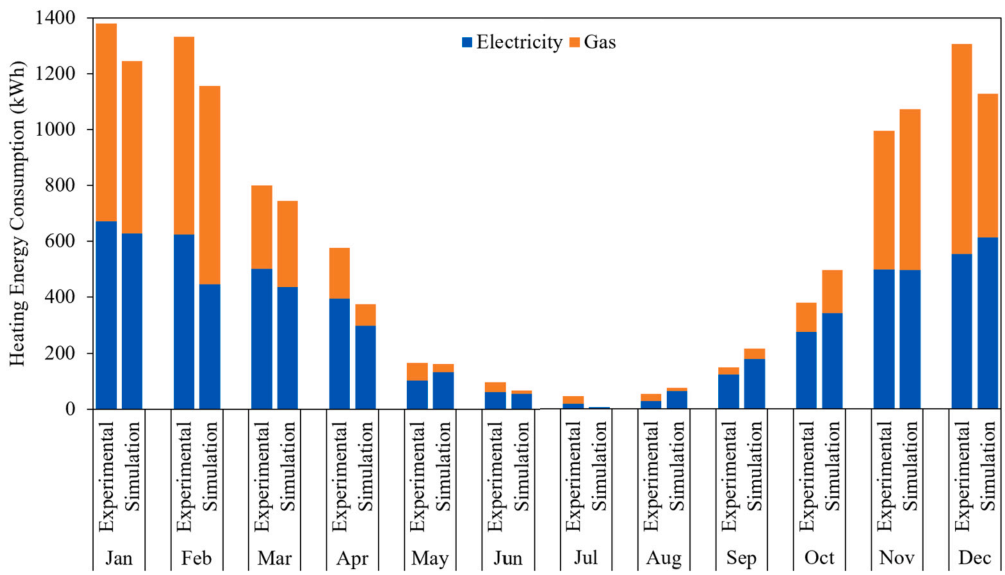

Fig. 7. Hybrid system - total energy consumption: (Jan 2015 - Dec 2015) Scenario (e).

are based on data from the Irish energy agency SEAI [46]. It should be noted that these conversion factors differ from country to country and depend on their national energy system at a specific point in time, in conjunction with the total share of renewable generation in the respective power systems [47]. The PEFs used in this study are within the range of typical primary energy conversion factors used in most EU countries [48].

The PEF for heat production in the case of the all-electric air-source HP heating system was calculated using Equation (5), where PEF_{HP} is the primary energy factor for an all-electric HP system, PEF_{elec} is the primary energy factor of electricity production, and SPF_{HP} is the seasonal performance factor of the all-electric heat pump.

$$PEF_{HP} = \frac{PEF_{elec}}{SPF_{HP}} \quad (5)$$

where the SPF of the heat pump is defined as per Equation (6):

$$SPF_{HP} = \frac{Q_{HP}}{E_{elec}} \quad (6)$$

where Q_{HP} is the heat pump thermal output, and E_{elec} is electrical consumption of the heat pump system, both on an annual basis.

The PEF for heat production in the case of the hybrid heat pump was calculated using Equation (7):

$$PEF_{HHP} = \frac{PE_{HHP}}{Q_H} = \frac{PE_{HHP}}{Q_{H,CGB} + Q_{H,HP}} \quad (7)$$

and

$$PE_{HHP} = PE_{gas} + PE_{HP} = \frac{Q_{H,CGB}}{\eta_{CGB}} \, . \, PEF_{gas} + \frac{Q_{H,HP}}{SPF_{H,HP}} \, . \, PEF_{elec} \quad (8)$$

where PE_{HHP} is the primary energy utilised for electricity and gas production, $Q_{H,CGB}$ and $Q_{H,HP}$ are the final energy (thermal) associated the hybrid condensing gas boiler and hybrid heat pump units, respectively, PEF_{gas} and PEF_{elec} are the primary energy factors of gas and electricity production, respectively; η_{CGB} is the efficiency of the condensing gas boiler and the $SPF_{H,HP}$ is determined as per Equation (6), albeit for the heat pump unit of the hybrid heat pump system.

The seasonal performance factor of the hybrid heat pump system was calculated based on a methodology similar presented in Klein et al. [21] and Lin et al. [49], as per Equation (9):

$$SPF_{HHP} = \frac{Q_{HHP}}{E_{elec}} \quad (9)$$

where SPF_{HHP} is the hybrid heat pump system seasonal performance factor, Q_{HHP} is the overall heat output, and E_{elec} is the overall electrical energy input (metered energy consumption) to the heating system, all measured in kWh.

With knowledge of the PEFs of all heating systems, the primary energy savings (PES) with respect to Scenario (a) can be calculated by using Equation (10).

$$PES = \frac{PE_{OB} - PE_{hs}}{PE_{OB}} \times 100\% \tag{10}$$

where PE_{OB} is the primary energy consumption of the oil boiler reference heating system, and PE_{hs} is the primary energy consumption of the heating systems of Scenarios (b) to (h).

The carbon intensity for each scenario is quantified using the metric (tCO_2/year), where the emission factor for each fuel vector uses the appropriate national conversion factors. Emission factors of 0.2639 kg/kWh for oil, 0.2047 kg/kWh for natural gas, and 0.4366 kg/kWh for electricity were utilised [46]. This allows the annual carbon intensity to be calculated using Equation (11) as follows:

$$\epsilon = E \times \frac{EF}{1000} \tag{11}$$

where ϵ is the carbon intensity in tonnes CO_2 per year, E is the energy use in kWh, and EF is the emissions factor for each fuel vector. It is noted that in the case of the hybrid heat pump system, the emissions of both the natural gas and the electricity energy vectors are summed.

2.3.2. Economic assessment

In order to perform a comprehensive economic assessment of the scenarios outlined in Table 2, capital costs of material and components, as well as monetary savings resulting from the implementation of the retrofitting measures were considered.

The purchase costs of materials and components for each scenario were determined using publicly available prices and estimates. The data chosen for this analysis were averaged for a number of heat pump distributors and compared to values found in the literature [12,17,50]. As this analysis is for residential buildings, prices of heat pumps do not vary widely in relation to capacity due to the relatively low variations in capacity in comparison to commercial installations. Retrofit insulation costs were based on market prices [51], while window retrofit estimates were given indicative values using Window24 [52], which provides window pricing from several window types and suppliers. Underfloor heating prices were provided per square metre in accordance with NuHeat [53], while aluminium radiators prices were calculated using the EcoRad database [54]. Labour costs are based on values provided by SEAI for typical charges per square metre of insulation installed [55] and Window24 was used for estimating window installation costs [52]. Maintenance costs are deemed to be similar for all scenarios and are therefore not included, as individuals may or not service their systems and the regularity at which it is done varies widely [56].

Several energy retrofitting grants are available from the Irish agency, SEAI [57], who are responsible for energy policy in Ireland, and these are listed in Table 3. This is part of the *Better Energy Homes* initiative that the Irish government has in place to support retrofit solutions in the residential sector. The goal of this initiative is to reduce the energy costs in Irish domestic dwellings, while simultaneously reducing carbon dioxide emissions and providing more comfortable homes.

Table 4 shows a summary of the capital costs and applicable grants for each scenario, which are inputs to the economic analysis. It is important to highlight that discount rates on energy projects in the Irish market range from 5-14% [58]. Therefore, an 8% discount rate was considered appropriate for the purposes of this analysis. Irish domestic fuel prices for oil, natural gas, and electricity were considered as €0.088/kWh, €0.069/kWh, and €0.21/kWh, respectively, according to Irish domestic fuel prices in 2021 [59]. These prices do not include consumption taxes nor utility standing charges.

Table 3
Summary of SEAI Grants [57].

Element	Grant Value
Attic Insulation	€400
Internal Insulation (Detached)	€2,400
AWHP	€3,500
Heating Controls	€700
Three Upgrade Bonus	€300

Given that Scenario (a) is the most common pre-retrofit heating system configuration in Ireland [17,60], it is used as the reference case for the economic analysis. Therefore, the cost savings (if any) will be based on assessment of each subsequent retrofit option relative to Scenario (a). These are defined based on Equation (12), where NCF is the Net Cash Flow, RC_{init} for the operating costs of the oil boiler base case (Scenario (a)) and RC_{SCN_x} are the operating costs of the scenario x as analysed.

$$NCF = RC_{init} - RC_{SCN_x} \tag{12}$$

In order to analyse the economic feasibility of heat pumps, two indicators were adopted [61]:

- *Net Present Value (NPV)*: this represents the present value of the total discounted cash flows NCF, calculated over a specified period of time (i.e., 20 years), compared to the initial investment [11]. The term r is the discount rate, assumed to be equal to 8% as mentioned earlier. The NPV can be calculated as shown in the Equation (13):

$$NPV = \sum_{i=1}^{N} \frac{NCF_i}{(1+r)^i} - CF_{init} \tag{13}$$

- *Tolerable Capital Cost (TCC)*: this evaluates the economic feasibility of a project when the initial cash flows cannot be accurately determined [62]. The TCC can be calculated as shown in Equation (14):

$$TCC = ACS \times N(1+r)^{-1} \tag{14}$$

where ACS are the net annual cost savings due to energy upgrade, N is the acceptable payback period in years, and r is the discount rate. The ACS can be calculated using Equation (15), where m is the number of fuels used in the residence, F_{pr} is the price per unit of each fuel type in €/kWh, and e is the energy saved per period i, for each fuel type, expressed in [63].

$$ACS = \sum_{i=1}^{m} (F_{pr} \times e)_i \tag{15}$$

3. Results

3.1. Primary energy savings

Fig. 8a shows the primary energy consumption associated with each retrofitting scenario, while Fig. 8b indicates the SPF, the primary energy factor of the heat source (PEF_{source}), and the primary energy factor (PEF) of the heating system for each scenario. As outlined in Section 2.3.1, when calculating PES values, all scenarios are benchmarked with respect to the oil boiler (Scenario (a)) energy conversion system.

Generally, scenarios utilising either an electric heat pump or hybrid heat pump, i.e., scenarios (c)-(h), achieve higher PES values from 45% to 70%, where PES values for the hybrid heat pump system retrofit scenarios, i.e., scenarios (c), (e) and (g) are the highest. Furthermore, compared to the fossil fuel systems (Scenarios (a) and (b)), scenarios (c)-(h) all have lower respective PEFs, which when considered in conjunction with their SPFs, result in higher PES values. Moreover, it can

Table 4
Summary of economic model inputs.

	Scenario (c)	Scenario (d)	Scenario (e)	Scenario (f)	Scenario (g)	Scenario (h)
Electric HP Heating Capacity (kW)	8	14	8	14	8	14
EHP/HHP Cost (€)	9,000	7,500	9,000	7,500	9,000	7,500
Heating Emitter System Cost (€)	8,000	8,000	8,000	8,000	8,000	8,000
Insulation Cost (€)	-	-	1,650	1,650	7,874	7,874
Window Cost (€)	-	-	-	-	23,870	23,870
Labour (€)	2,000	2,000	6,400	6,400	36,950	36,950
Grant Available (€)	700	4,200	700	4,200	3,800	7,300

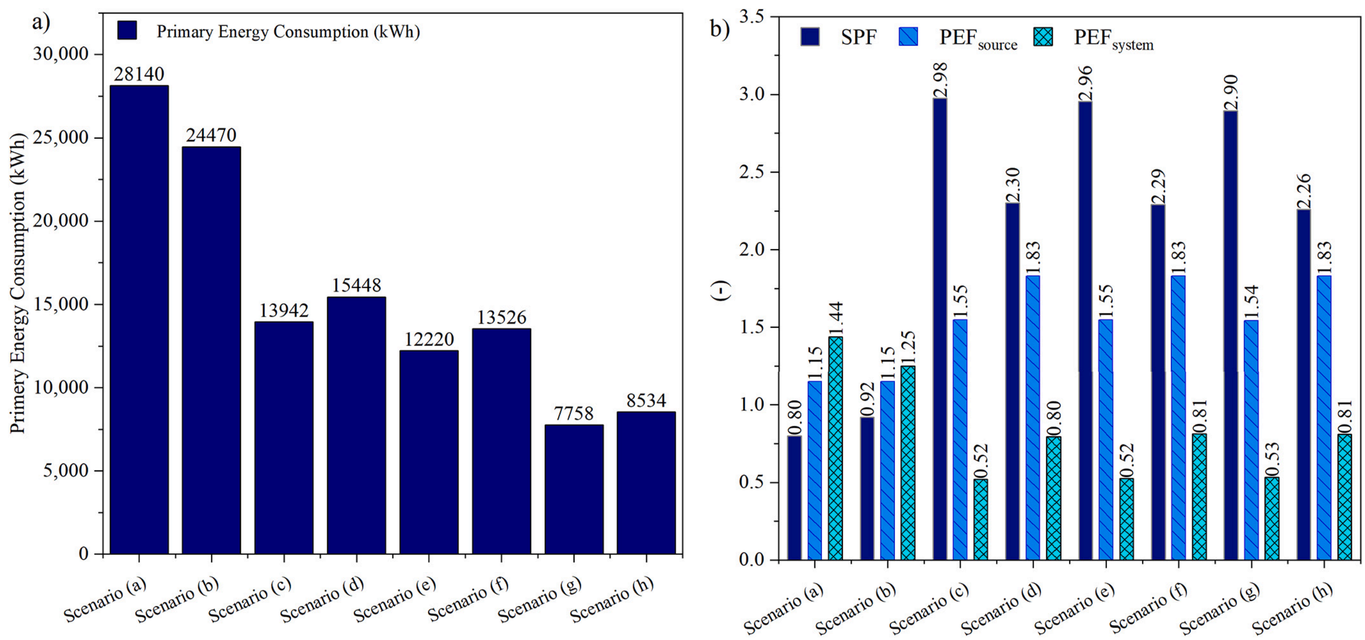

Fig. 8. Analysis of (a) Primary Energy Consumption and (b) SPF and PEF for scenarios (a) to (h).

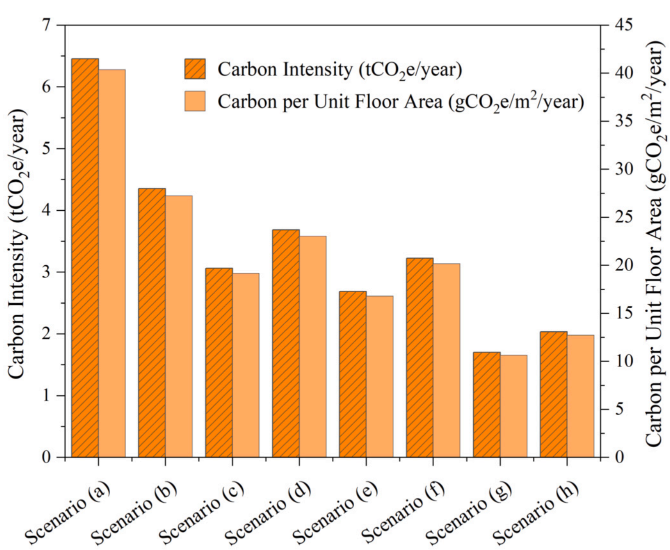

Fig. 9. Analysis of carbon emissions for each scenario.

be seen that Scenarios (e) and (g), hybrid heat pump systems with minimal and deep thermal retrofit, respectively, achieve the highest PES (56% and 72%), and lower PEF values (1.55 and 1.54). Additionally, examining Fig. 8b, it can be seen that, in general, hybrid heat pump energy systems, i.e., scenarios (c), (e), and (g), achieve higher SPF values compared to electric heat pump energy systems, i.e., scenarios (d), (f), and (h).

For the HHP systems, the ratio of gas to electricity consumption significantly impacts the overall PES, due to the use of gas as a fuel source. This is evident for scenarios (c), (e), and (g), where the gas:electricity utilisation ratios are 41.5:58.5, 41.4:58.6, and 42:58, respectively. For scenario (c), where no thermal retrofit was implemented, the actual gas consumption (4301 kWh) is higher than Scenarios (e) (3758 kWh) and (g) (2436 kWh), with minimal and full thermal retrofit, respectively. The fuel ratio and thermal retrofit play an important role and have the potential to make electric heat pumps and hybrid heat pumps, even with a higher water supply temperature, a more attractive option in terms of primary energy savings, when full thermal retrofit has taken place. This is evident from Scenarios (g) and (h). Since scenarios (d) and (f) utilise an electric-only heat pump operating with 55 °C water supply temperature but with different thermal insulation levels, both scenarios achieved almost similar SPFs, and exhibit PES of approximately 45 and 52%, respectively, compared to OB reference scenario. However, for Scenario (g), where deep thermal retrofit with a HHP is considered, a PES value of approximately 72.5% is attained which is the highest PES value.

Carbon dioxide emissions for each scenario are shown in Fig. 9. Scenarios (a) to (d) show the carbon emissions associated with each energy conversion system, where the base case (no retrofit) building envelope is assumed. With reference to the SPF data in Fig. 8b, in which Scenario (c) is observed to have a higher SPF than Scenario (d), Scenario (c) exhibits a 52% reduction in emissions compared to the OB energy system (Scenario (a)). The equivalent reduction in carbon footprint for Scenario (g) is 74% compared to the OB energy system (Scenario (a)). This shows that, at least for the boundary conditions considered in this study, the HHP system outperforms the EHP system in terms of carbons

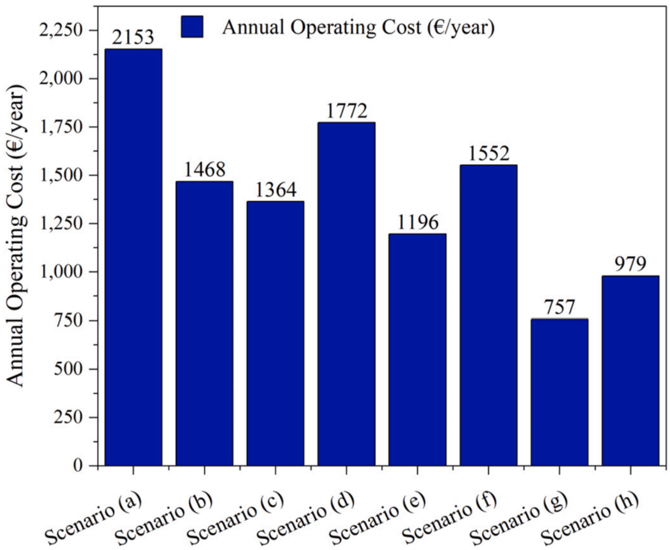

Fig. 10. System operating costs for each scenario.

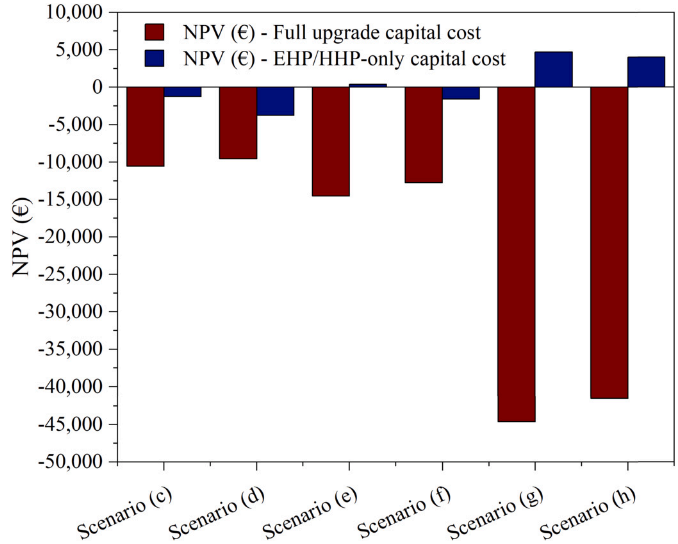

Fig. 11. Net present values (20 years) of each scenario, with reference to oil boiler (Scenario (a)).

emissions. Similar results are found in a recent study authored by Lin et al. [49]. This is because in Scenario (g), the hybrid system switches to condensing gas boiler mode when the external ambient temperature is below 2 °C, or works in series to supply water at 55 °C, thereby ensuring that the heat pump COP is not penalised and resulting in the higher performance of the HHP. Similarly, the HHP system with the minimal retrofit (Scenario (e)) achieves 4% less carbon emissions reduction compared to the electric heat pump system with minimal retrofit (Scenario (f)), indicating that, for the boundary conditions considered, the hybrid system is less carbon intensive than the EHP.

The greatest carbon reductions correspond to HHP and EHP systems with a deep retrofit (Scenario (g) and Scenario (h)), where the carbon emissions per unit floor area are 10.6 gCO_2/m^2/year and 12.7 gCO_2/m^2/year, respectively, the lowest values recorded for all scenarios. Scenario (g) achieves a 44% and 37% carbon emission reduction relative to Scenario (c) (HHP base case) and Scenario (e) (HHP with minimal retrofit), respectively. Scenario (h) (EHP with deep retrofit) achieves a 45% and 37% carbon emission reduction compared to Scenario (d) (EHP base case) and Scenario (f) (EHP with minimal retrofit), respectively.

3.2. Analysis of the investment

Fig. 10 summarises the annual running costs for each scenario. For comparable retrofit options utilising the HHP system (Scenarios (c), (e) and (g)) and the EHP system (Scenarios (d), (f), and (h)), lower annual operating costs are evident for the HHP scenarios. Comparing all HHP scenarios (c, e and g), it can be seen that Scenario (g) outperforms Scenarios (c) and (e) by achieving higher cost savings, respectively. Also, it can be seen that non-condensing oil-fired boiler (Scenario (a)) has the greatest yearly operating cost compared with other scenarios, while Scenario (g) (HHP with deep thermal retrofit) and scenario (h) (EHP with deep thermal retrofit) have the lowest annual operating costs of €757/year and €979/year, respectively.

Fig. 11 shows the Net Present Values (NPV) of all scenarios with reference to either a full upgrade capital cost investment or an EHP/HHP-only capital cost investment. The NCF values are calculated with respect to the oil boiler system (Scenario (a)). For Scenarios (c) and (d), a full upgrade includes the capital costs associated with the energy conversion system, the upgraded heat emitter distribution system, and the labour costs; for Scenarios (e) and (f), the energy conversion system, the upgraded heat emitter distribution system, the minimal fabric retrofit, and the labour costs; and for Scenarios (g) and (h), the energy conversion system, the upgraded heat emitter distribution system, the full

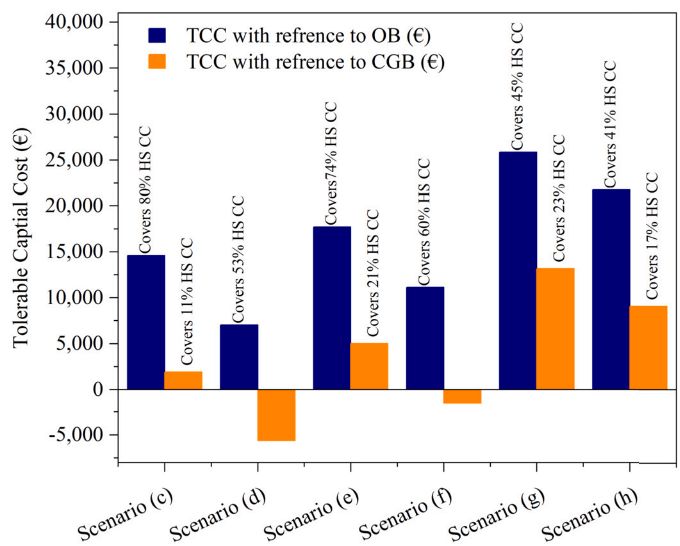

Fig. 12. Tolerable capital cost for each scenario, with reference to OB (Scenario (a)) and CGB ((Scenario (b)). (Note: HS CC = Heating System Capital Cost).

fabric retrofit, and the labour costs. Grants for the all-electric heat pump (EHP), the control systems, and the fabric thermal retrofit are taken into account. The EHP/HHP-only capital cost investment takes into account the capital costs of the EHP or HHP only, excluding grants, control systems and labour costs.

The investment analysis in the cases of retrofitting of the energy conversion system only (i.e., the EHP/HPP-only capital cost) shows positive NPVs for scenarios (e), (g), and (h), based on a 20 year assessment period. Scenario (e) with minimal retrofit has a marginal return on investment, whereas Scenarios (g) and (h) with deep thermal retrofit are observed to have a return on investment over a 20-year period of €4711, and €4028, respectively. Furthermore, the investment analysis in case of the full retrofit capital investment shows no return of investment after 20 years and the NPV values are all negative.

A key reason why householders may undertake deep retrofit measures is to achieve better levels of thermal comfort in their homes, possibly with a increase in the building market value, and thus may not necessarily expect a full payback based purely on system operation alone. With this perspective on mind, Fig. 12 depicts the economic indicators corresponding to the energy conversion system only, by con-

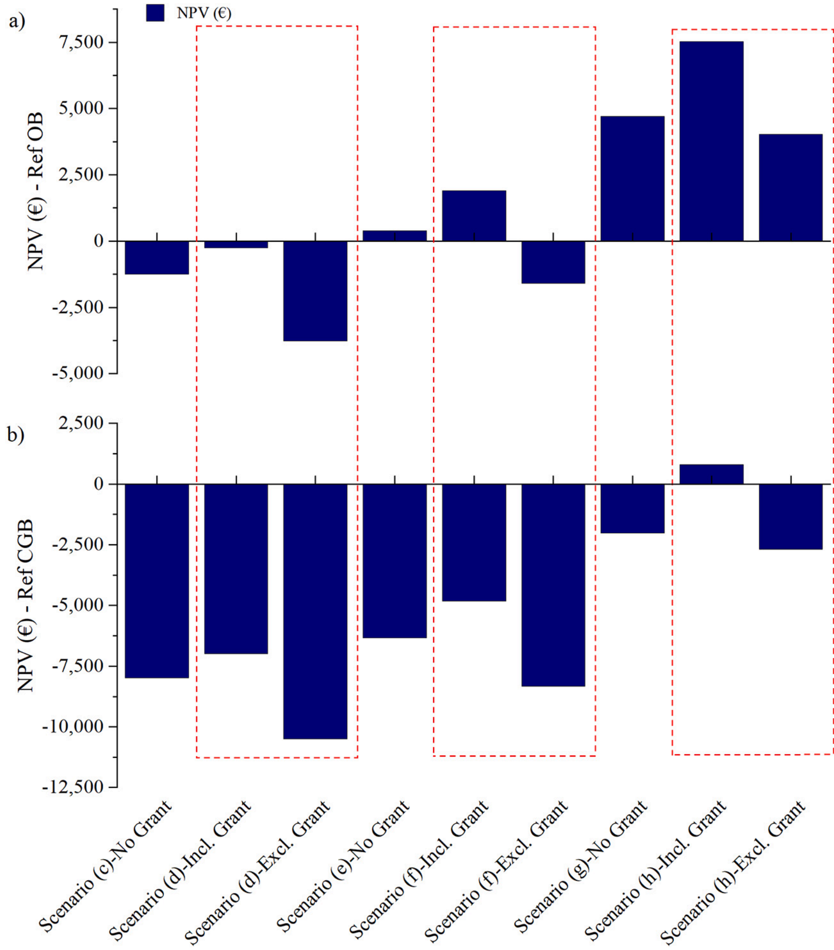

Fig. 13. Return on investment analysis with focus on HP Grant support, with reference to OB (Scenario (a) and CGB (Scenario (b)).

sidering the OB (Scenario (a)) and CGB (Scenario (b)) as reference cases. The tolerable capital cost is a useful indicator to ascertain the capital cost for an energy saving upgrade that will be recovered based on the annual energy savings, the payback period, the estimated annual interest, and fuel cost escalation rates [63]. However, savings are considerably influenced by the reference case selection. For this research, electricity prices (€0.21/kWh) in Ireland are more expensive than oil (€0.088/kWh) and natural gas (€0.069/kWh) prices, which economically favours hybrid heat pump systems. In the case of the current analysis, the period considered is 20 years. In addition, the TCC indicator is appropriated for the current analysis as installation and labour fees are challenging to determine and can vary from contractor to contractor as well as from country to country.

In Fig. 12, it can be seen that TCC values, when the OB was considered as the reference case, are higher than TCCs corresponding to scenarios with the CGB is used as the reference case. The is due to the higher efficiency of the CGB, which consumes less primary energy compared to the OB. Replacing the OB with any of the retrofitting scenarios ((c)-(h)) yields economic benefits. The HHP Scenarios (c) and (e) achieve 80% and 74%, respectively, of the heating system capital cost return, whereas the return for Scenarios (g) and (h) cover over 40% of the heating system capital cost. The TCCs for all-electric HP scenarios are also promising where in excess of 50% of the HS capital cost is expected for Scenario (d), and 60% coverage of the heating system capital cost can be expected in Scenario (f).

Considering CGB as the reference case, the TCC values are less for all scenarios. In general, it can be seen that positive returns, on the basis of the TCC indicator, are achieved for both the EHP and HHP heating systems with deep retrofit (Scenarios (g) and (h)), and HHP system with minimal retrofit or no retrofit (Scenarios (e) and (c)).

Fig. 13 shows the comparison of the return on investment for all the scenarios where Scenario (a) (Fig. 13a) and Scenario (b) (Fig. 13b) have been considered as reference cases. For Scenarios (d, (f) and (h), the NPV analysis considers each scenario subject to grant support and excluding all grant support. It should be noted that Scenarios (c), (e), and (g) do not include any grant support for energy upgrades.

The technical and economic assessment found HHP scenarios to be competitive with their EHP scenario counterparts. The analysis also shows that for the HHP scenarios with either minimal (Scenario (e)) or full thermal retrofit (Scenario (g)) achieve positive NPV values with reference to the OB system.

It can be seen that if grant support was not available, then the NPVs exhibited by the EHPs is less. For example, in Fig. 13a, EHP scenarios with minimal and deep retrofit (Scenarios (f) and (h)), and HHP with minimal and deep retrofit (Scenarios (e) and (g)) yield economic benefits after 20 years, with EHP scenarios (Scenarios (f) and (h)) having better NPVs given that they are benefiting from home energy upgrade grants. The HHP with deep retrofit (Scenario (g)) is also an attractive option even without grant support, as is the EHP with deep retrofit (Scenario (h)). Also, it can be noted that the highest NPVs are achieved when the building is deeply retrofitted and this can be seen from Scenarios (g) and (h). Deep thermal retrofit not only increases the indoor thermal comfort and energy savings, but also results in better performance of the electric heat pump and hybrid heat pump energy systems, which results in associated lower levels of carbon dioxide emissions. Notwithstanding, it is important to state that applying the same methodology and analyses under different climate zones and in countries with different fuel prices, primary energy factors or emission footprints may lead to different results.

Fig. 13b shows NPVs when CGB was considered as the reference case. It can be seen that only Scenario (h) (EHP with a deep thermal retrofit and grant support) achieves a positive NPV. Other scenarios do not show positive NPVs and are less attractive from an economic perspective.

4. Conclusions

The present paper investigated different energy system scenarios consisting of electric and hybrid heat pumps for a range of different building retrofit measures. All retrofit options were referenced with respect to an oil fired boiler system and a condensing gas boiler system. An existing residential building in Ireland, which underwent various energy conversion system and envelope thermal retrofitting steps, was used to carry out a techno-economic assessment on the impact of the different retrofitting measures. The main results of the analysis can be summarised as follows:

- The electric and hybrid heat pump systems both achieve primary energy savings compared to fossil fuel (oil or gas) heating systems. For the research carried out in this study with reference to the oil boiler system, the hybrid heat pump scenarios achieved a slightly higher range of primary energy savings (50% to 72%) compared to the respective electric heat pump scenarios (45% to 70%).
- Hybrid systems remain competitive when assessing carbon emissions per unit floor area, with values between 10 - 19 gCO_2e/m^2/year (1.7 - 3.0 tCO_2/year), whereas for the electric heat pump, values of between 12 - 23 gCO_2e/m^2/year (2.0 - 3.7 tCO_2/year) were obtained.
- The TCC analysis shows that between 41% to 80% of the heating system capital cost can be recovered for all scenarios with reference to an oil boiler system.
- It is evident from the study that electricity and gas prices have a significant impact on the results; where the high relative cost of electricity price compared with natural gas decreases net present values (NPV), and lower relative gas prices make hybrid heat pump systems marginally more economically attractive.

Finally, it is observed that while NPV valves for all retrofit scenarios are negative, this is not unexpected given the applicable tariff regimes. It is also noted that in some cases, house owners are motivated to retrofit not only to improve thermal comfort but to potentially improve the dwelling overall value.

Future work could include: (i) examination of the hybrid system subject to different climate conditions, (ii) examination of the hybrid system subject to different mode temperature switch-over settings, (iii) examination of system performance subject to different electricity tariffs regimes and electricity CO_2 grid generation footprints.

CRediT authorship contribution statement

Mohammad Saffari: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Software, Visualization, Writing – review & editing. **David Keogh:** Data curation, Formal analysis, Investigation, Methodology, Resources, Software, Validation, Writing – original draft. **Mattia De Rosa:** Conceptualization, Investigation, Methodology, Writing – review & editing. **Donal P. Finn:** Conceptualization, Funding acquisition, Project administration, Supervision, Writing – review & editing.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Donal P. Finn reports financial support was provided by Science Foundation Ireland.

Data availability

The data that has been used is confidential.

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References

[1] European Commission, Clean energy for all Europeans, Technical Report, Publications Office of the European Union, 2019.
[2] The European Union, Directive (EU) 2018/844 of the European Parliament and of the Council of 30 May 2018, Technical Report L 156/75, The European Commission, 2018.
[3] K. Qu, X. Chen, A. Ekambaram, Y. Cui, G. Gan, A. Økland, S. Riffat, A novel holistic EPC related retrofit approach for residential apartment building renovation in Norway, Sustain. Cities Soc. 54 (2020).
[4] O.Y. Edelenbosch, D.P. van Vuuren, K. Blok, K. Calvin, S. Fujimori, Mitigating energy demand sector emissions: the integrated modelling perspective, Appl. Energy 261 (2020) 114347.
[5] P. Zancanella, P. Bertoldi, B. Boza-Kiss, Energy efficiency, the value of buildings and the payment default risk, Technical Report, Publications Office of the European Union, 2018.
[6] L. Castellazzi, P. Zangheri, D. Paci, M. Economiduo, N. Labanca, T. Ribeiro Serrenho, S. Panev, P. Zancanella, J.-S. Broc, Assessment of second long-term renovation strategies under the Energy Efficiency Directive, Technical Report, European Commission, 2019.
[7] R. Lowe, L.F. Chiu, Innovation in deep housing retrofit in the United Kingdom: the role of situated creativity in transforming practice, Energy Res. Soc. Sci. 63 (2020) 101391.
[8] K. Biswas, T. Patel, S. Shrestha, D. Smith, A. Desjarlais, Whole building retrofit using vacuum insulation panels and energy performance analysis, Energy Build. 203 (2019).
[9] J.H. Park, B.Y. Yun, S.J. Chang, S. Wi, J. Jeon, S. Kim, Impact of a passive retrofit shading system on educational building to improve thermal comfort and energy consumption, Energy Build. (2020) 109930.
[10] M.F. Touchie, K.D. Pressnail, Evaluating a proposed retrofit measure for a multi-unit residential building which uses an air-source heat pump operating in an enclosed balcony space, Energy Build. 85 (2014) 107–114.
[11] M. Carragher, M. De Rosa, A. Kathirgamanathan, D.P. Finn, Investment analysis of gas-turbine combined heat and power systems for commercial buildings under different climatic and market scenarios, Energy Convers. Manag. 183 (2019) 35–49.
[12] A. Rogeau, R. Girard, Y. Abdelouadoud, M. Thorel, G. Kariniotakis, Joint optimization of building-envelope and heating-system retrofits at territory scale to enhance decision-aiding, Appl. Energy 264 (2020) 114639.
[13] P. Capros, M. Kannavou, S. Evangelopoulou, A. Petropoulos, P. Siskos, N. Tasios, G. Zazias, A. De Vita, Outlook of the EU energy system up to 2050: the case of scenarios prepared for European commission's "clean energy for all europeans" package using the PRIMES model, Energy Strat. Rev. 22 (2018) 255–263.
[14] I. Vorushylo, P. Keatley, N. Shah, R. Green, N. Hewitt, How heat pumps and thermal energy storage can be used to manage wind power: a study of Ireland, Energy 157 (2018) 539–549.
[15] A. Palzer, H.M. Henning, A comprehensive model for the German electricity and heat sector in a future energy system with a dominant contribution from renewable energy technologies - Part II: results, Renew. Sustain. Energy Rev. 30 (2014) 1019–1034.
[16] D. Fischer, H. Madani, On heat pumps in smart grids: a review, Renew. Sustain. Energy Rev. 70 (2017) 342–357.
[17] P. Moran, J. O'Connell, J. Goggins, Sustainable energy efficiency retrofits as residential buildings move towards nearly zero energy building (NZEB) standards, Energy Build. 211 (2020) 109816.
[18] M. Sun, P. Djapic, M. Aunedi, D. Pudjianto, G. Strbac, Benefits of smart control of hybrid heat pumps: an analysis of field trial data, Appl. Energy 247 (2019) 525–536.
[19] W. Xu, C. Liu, A. Li, J. Li, B. Qiao, Feasibility and performance study on hybrid air source heat pump system for ultra-low energy building in severe cold region of China, Renew. Energy 146 (2020) 2124–2133.

[20] X. Li, W. Lyu, S. Ran, B. Wang, W. Wu, Z. Yang, S. Jiang, M. Cui, P. Song, T. You, W. Shi, Combination principle of hybrid sources and three typical types of hybrid source heat pumps for year-round efficient operation, Energy 193 (2020).

[21] K. Klein, K. Huchtemann, D. Müller, Numerical study on hybrid heat pump systems in existing buildings, Energy Build. 69 (2014) 193–201.

[22] M. Dongellini, C. Naldi, G.L. Morini, Sizing effects on the energy performance of reversible air-source heat pumps for office buildings, Appl. Therm. Eng. 114 (2017) 1073–1081.

[23] H. Park, K.H. Nam, G.H. Jang, M.S. Kim, Performance investigation of heat pump-gas fired water heater hybrid system and its economic feasibility study, Energy Build. 80 (2014) 480–489.

[24] S. Heinen, D. Burke, M. O'Malley, Electricity, gas, heat integration via residential hybrid heating technologies - an investment model assessment, Energy 109 (2016) 906–919.

[25] R. Chargui, H. Sammouda, Modeling of a residential house coupled with a dual source heat pump using TRNSYS software, Energy Convers. Manag. 81 (2014) 384–399.

[26] G. Li, Y. Du, Performance integration and economic benefits of new control strategies for heat pump-gas fired water heater hybrid system, Appl. Energy 232 (2018) 101–118.

[27] A. Thonipara, P. Runst, C. Ochsner, K. Bizer, Energy efficiency of residential buildings in the European Union – an exploratory analysis of cross-country consumption patterns, Energy Policy (2019) 1156–1167.

[28] O. Faber, D. Kell, A. Wilson, in: J.R. Oughton (Ed.), Faber & Kell's Heating & Air-Conditioning of Buildings, Routledge, 2015.

[29] Ireland Department of the Environment and Local Government, Technical guidance document l - conservation of fuel and energy, https://www.housing.gov.ie/housing/building-standards/tgd-part-l-conservation-fuel-and-energy/technical-guidance-document-l-1, 1997.

[30] Department of Housing Planning and Local Government of Ireland, Building Regulations 2011 - Technical Guidance Document Part L - Conservation of Fuel & Energy - Dwellings, https://www.housing.gov.ie/file/1269, 2011.

[31] Sustainable Energy Authority of Ireland (SEAI), Deep Retrofit Pilot Programme 2019, https://www.seai.ie/resources/publications/Deep-Retrofit-Application-Guidance-Document-.pdf, 2019. (Accessed 23 July 2019).

[32] BS EN 15251:2007, Indoor environmental input parameters for design and assessment of energy performance of buildings- addressing indoor air quality, thermal environment, lighting and acoustics Contents, 2007.

[33] M. Kottek, J. Grieser, C. Beck, B. Rudolf, F. Rubel, World map of the Köppen-Geiger climate classification updated, Meteorol. Z. 15 (2006) 259–263.

[34] Department of Housing, Planning, and Local Government of Ireland, Building Regulations 2018 Technical Guidance Document Part L - Conservation of Fuel and Energy - Dwellings, 2018.

[35] CIBSE, Applications and Activities: HVAC Strategies for Common Building Types, 2016.

[36] Sustainable Energy Authority Ireland (SEAI), Home heating appliance register of performance (HARP) database, https://www.seai.ie/energy-in-business/ber-assessor-support/harp-database/, 2019. (Accessed 30 July 2019).

[37] IES, Integrated environmental solutions (IES) Ltd., https://www.iesve.com/, 2019. (Accessed 30 January 2019).

[38] Integrated Environmental Solution (IES) Ltd., ApacheSim calculation methods, www.iesve.com/downloads/help/Thermal/Reference/ApacheSimCalculationMethods.pdf, 2019. (Accessed 21 July 2019).

[39] ASHRAE, ASHRAE international weather for energy calculations 2.0, https://www.ashrae.org/technical-resources/bookstore/ashrae-international-weather-files-for-energy-calculations-2-0-iwec2, 2019. (Accessed 30 July 2019).

[40] Met Éireann, The Irish meteorological service, https://www.met.ie/, 2019. (Accessed 22 July 2019).

[41] ASHRAE Guideline, Guideline 14-2014 – Measurement of Energy, Demand, and Water Savings, ASHRAE, Atlanta, GA, 2014.

[42] S. Stinner, T. Schlösser, K. Huchtemann, D. Müller, A. Monti, Primary energy evaluation of heat pumps considering dynamic boundary conditions in the energy system, Energy 138 (2017) 60–78.

[43] M. Gustafsson, R. Thygesen, B. Karlsson, L. Ödlund, Rev-changes in primary energy use and CO2 emissions—an impact assessment for a building with focus on the Swedish proposal for nearly zero energy buildings, Energies 10 (2017) 978.

[44] M. Jarre, M. Noussan, M. Simonetti, Primary energy consumption of heat pumps in high renewable share electricity mixes, Energy Convers. Manag. 171 (2018) 1339–1351.

[45] International Energy Agency (IEA), Electricity Information 2017, https://www.oecd-ilibrary.org/content/publication/electricity-2017-en, 2019. (Accessed 30 January 2019).

[46] Sustainable Energy Authority of Ireland (SEAI), Conversion factors, https://www.seai.ie/resources/seai-statistics/conversion-factors/, 2020. (Accessed 29 April 2020).

[47] K. Saidi, A. Omri, The impact of renewable energy on carbon emissions and economic growth in 15 major renewable energy-consuming countries, Environ. Res. 186 (2020) 109567.

[48] S. Hamels, E. Himpe, J. Laverge, M. Delghust, K. Van den Brande, A. Janssens, J. Albrecht, The use of primary energy factors and CO_2 intensities for electricity in the European context - A systematic methodological review and critical evaluation of the contemporary literature, Renew. Sustain. Energy Rev. 146 (2021) 111182.

[49] H. Lin, J. Clavreul, C. Jeandaux, J. Crawley, I. Butnar, Environmental life cycle assessment of heating systems in the UK: comparative assessment of hybrid heat pumps vs. condensing gas boilers, Energy Build. 240 (2021) 110865.

[50] D. Dineen, B.P. Ó Gallachóir, Exploring the range of energy savings likely from energy efficiency retrofit measures in Ireland's residential sector, Energy 121 (2017) 126–134.

[51] eurima, European insulation manufacturers association, https://www.eurima.org/, 2020. (Accessed 29 March 2020).

[52] Window24, Windows prices, https://www.window24.ie/window-prices/, 2019. (Accessed 23 July 2019).

[53] NuHeat, How much does underfloor heating cost?, https://www.nu-heat.co.uk/underfloor-heating/costs/, 2019. (Accessed 30 January 2019).

[54] EcoRad, Ecorad Rocco aluminium radiators, https://www.theradiatorshop.ie/aluminium-radiators-ireland/437-ecorad-rocco-aluminium-radiators-ireland.html, 2019. (Accessed 23 July 2019).

[55] Sustainable Energy Authority of Ireland (SEAI), Home energy grants, https://www.seai.ie/grants/home-energy-grants/, 2020. (Accessed 30 March 2020).

[56] R.D. Muddu, D.M. Gowda, A.J. Robinson, A. Byrne, Optimisation of retrofit wall insulation: an Irish case study, Energy Build. 235 (2021) 110720.

[57] Sustainable Energy Authority of Ireland (SEAI), Better energy homes programme, applying for and claiming cash grants, version 10, https://www.seai.ie/resources/publications/Homeowner-Application-Guide.pdf, 2018. (Accessed 24 July 2019).

[58] GrantThornton, Renewable energy discount rate survey results - 2018, a grant thornton and clean energy pipeline initiative, https://www.grantthornton.co.uk/globalassets/1.-member-firms/united-kingdom/pdf/documents/renewable-energy-discount-rate-survey-results-2018.pdf, 2019. (Accessed 23 July 2019).

[59] Sustainable Energy Authority of Ireland (SEAI), Domestic Fuels Comparison of Energy Costs, 2020.

[60] F. Pallonetto, M. De Rosa, D.P. Finn, Environmental and economic benefits of building retrofit measures for the residential sector by utilizing sensor data and advanced calibrated models, Adv. Build. Energy Res. (2020) 1–29.

[61] C. Zopounidis, M. Doumpos, P.M. Pardalos, Handbook of Financial Engineering, vol. 18, Springer, New York, 2008.

[62] S.R. Asaee, V.I. Ugursal, I. Beausoleil-Morrison, Development and analysis of strategies to facilitate the conversion of Canadian houses into net zero energy buildings, Energy Policy 126 (2019) 118–130.

[63] S. Nikoofard, V. Ismet Ugursal, I. Beausoleil-Morrison, An investigation of the technoeconomic feasibility of solar domestic hot water heating for the Canadian housing stock, Sol. Energy 101 (2014) 308–320.