A Techno-Financial Performance Analysis of Heat Pumps and Recovery Systems in Future Energy Markets

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Abstract

This research investigates the financial suitability of high-efficiency air-to-air heat pump and heat recovery systems in comparison to their standard unit equivalents in a variety of future energy market conditions. A notional thermal model for commercial workplaces was created to estimate the yearly energy usage and equipment quantities for each unit. The required financial and performance inputs for this research was sourced from various manufacturers and suppliers for heat pump and heat recovery units. The financial assessment model was developed to ascertain the operational and capital cost implications between the high-efficiency and standard systems. The model estimates the effect on payback and analyses the cost-benefit of high-efficiency systems while accounting for different yearly changes in energy prices. The financial aspect forms a key element of this study, with the outcomes indicating the suitability of high-efficiency units. The financial analysis only considered the outdoor unit, as the other system components would be the same as the units are designed for the same delivery capacity. This investigation determined out high-efficiency units achieved payback in most scenarios, providing savings in both cost and carbon emissions and are a suitable investment providing the required capital is available.

Introduction

A heat pump is a system that utilises the refrigeration cycle to transfer energy between an energy source and an occupied space. This system provides both heating and cooling. In heating mode, energy is transferred from the source to the refrigerant, then transferred to the occupied space. This is the opposite in cooling mode, where the heat energy is removed from the occupied space and released into the source (Sauer & Howell, 1983). The primary energy sources for heat pumps are water, ground, and air. Water-source heat pumps require an adjacent source of water, most often rivers or other natural means. As a result, they can only be specified in certain locations and are not widely applicable as they can also affect the ecological conditions of natural sources (Wojciech Stanek, 2019). Ground-source utilise subterranean energy, either through aquifers or residual energy from sunlight passing through from surface level. For these systems to operate, considerable excavation works are required which require either deep boreholes or an expanse of open space to allow for the long runs of pipework to allow for sufficient heat exchange (Omer, 2008).

Air-to-water systems operate through transferring heat into water which is circulated within the building for either heating or cooling. Air-to-air systems directly distribute refrigerant to internal units that heat and cool the space via air. The quantity of energy distributed is controlled by modulating the amount of refrigerant in each space, referred to as Variable Refrigerant Flow (VRF) or Variable Refrigerant Volume (VRV) (Aynur, 2010). These air-to-air systems are the primary focus of this research as they are highly applicable to commercial settings due to their flexibility and ability to provide heating and cooling to different spaces simultaneously (Afify, 2008), which an air-to-water system would be unable to achieve as multiple circuits would be required, increasing energy usage and limiting energy recovery. Alongside these air-to-air heat pumps (referred to as 2-pipe systems) are air-to-air heat recovery systems (referred to as 3-pipe systems). The primary difference between these systems is where the phase separation occurs within the cycle. For heat pump systems the phase separation occurs within the main branch controller, whereas this occurs within the indoor unit for heat recovery systems as the controllers are located on each branch (J. Xia, 2002).

Several studies have investigated the efficiency of heat pumps in varying scenarios and conditions. An experiment investigated the performance of an air source heat pump within an environmental chamber, with the generated data used to inform a thermal model that replicated a commercial office in each location (Dongwon Han, 2016). This understanding was reinforced by another study, which measured the efficiency of an air source heat pump at varying relative humidity and external temperature (Kutbay Sezen, 2022). This investigation utilised a mathematical model to determine that an increase in temperature from -10°C to 18°C can increase COP by 70-95%. Heat pump technology efficiency has greatly increased over recent decades. Several innovations have led to these improvements including the incorporation of heat-driven ejectors and compressor technology (K.J.Chua, 2010). The development of multistage, or cascading cycles also improves efficiency. An investigation was conducted where the compressor speed of a heat pump was varied at several operating modes to determine its impact on delivery capacity (Youngju Joo, 2011). Incorporating a night-time setback control feature within a UK heat pump would decrease electrical consumption by 11-15%, improving its efficiency (Loïc Cabrol, 2021). A research report highlights that the integration of an inverter within the operation of the compressor greatly increases the efficiency of both types of refrigerant systems (Duggin, 2018). An inverter allows for increased efficiencies at both full and part loads as the compressor can operate at consistent and controlled speeds (Shuangquan Shao, 2004).

Another design improvement available to manufacturers of refrigeration cycle outdoor units are Variable Path Heat Exchangers (VPHE).

An economic feasibility investigation was conducted between a VRF and mini-split refrigeration conditioning system. Financial factors such as initial capital, maintenance and operating costs were included to determine the net present worth of each system (A. T. Layeni, 2019). The investigation determined that the mini-split system offered higher value. However, it was noted that the part load operation of the VRF system was omitted. This is significant as VRF systems are considered to operate at high efficiency at part load when compared to other conditioning systems (Duggin, 2018). A key aspect of the techno-economic assessment of any conditioning equipment are the assumptions regarding future energy prices. As payback is assessed by offsetting the savings in operating costs against the initial capital investment, this value can have a considerable impact on the outcome of these assessments (Awomewe Alaba Femi, 2008). An economic comparison was conducted for the installation and operation of a VRF system and highlighted that in the scenario tested the VRF system would be 44% less over its lifespan than the conventional system (Emrah Özahi, 2017).

There appear to be several research gaps present within the literature on the performance and economic assessment of air-to-air heat pumps within commercial settings. There are significant improvements that can be made within the outdoor unit of VRF systems that provide greater operational efficiency in both part and full load conditions. However, this performance research makes little usage of techno-economic assessments, and whether the additional costs in research and components are compensated by the increase in efficiency and subsequent reduction in operating costs. This is a key research gap, as the units need to be economically sustainable to be appealing to

clients. In addition, the techno-economic assessment of multiple system types, and need for an investigation to expand the research knowledge of the economic systems compared to their standard alternatives, and the impact of future energy prices on those assessments. This would contribute considerably to the wider future energy price changes should be taken into account. As a result, there is a clear feasibility of high-efficiency refrigeration cycle
understanding of the literature surrounding the efficiency of air-to-air refrigeration system equipment and their economical suitability within commercial settings.

Methodology

Thermal and Energy Model Development

The software utilised for the thermal and energy modelling aspect of this research was Integrated Environmental Systems: Integrated Solutions (IES:VE) 2022. This is an advanced thermal modelling software that can model both steady-state (equipment sizing) and dynamic (energy consumption) simulations. To increase the comparative aspect of this study, a standard office building would be more suitable as it would improve its replicability. The IES standard template 'Medium Office' was selected for the energy modelling, with its dimensions indicated in Table 1.

Table 1 - Thermal Model - Geometry

Stories	3
Length	50 (m)
Width	33 (m)
Height	11.9 (m)
Internal Ceiling Height (per floor)	2.7 (m)
Internal Floor Area (per floor)	16661.6 (m^2)
Glazing Ratio	33 (%)

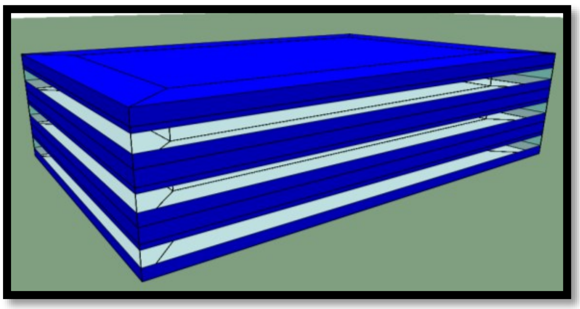

Figure 1 - Thermal Model - Medium Office

UK Part L 2022 values and air infiltration rates were applied which are presented within Table 2 (UK Building Regulations, 2021). Standard fabric constructions have been utilised with performance values matching those within Part L. The NCM templates for an open office was applied (UK NCM, 2021). The internal heat gains are presented within Table 2, while the internal gains are presented in Table 3.

Table 2 - Thermal Model - Fabric Constructions

Construction	**U-Value ($W/m^2.K$)**
Roof (flat)	0.18
Wall	0.26
Floor	0.18
Windows	1.60
Air Permeability	$8m^3/(h.m^2)$ @ 80Pa

Table 3 - Thermal Model - Internal Gains

Internal Gain	**Concentration**	**Sensible Gain**	**Latent Gain**
People	10 m^2/person (158 people)	73 W/person	50 W/person
Lighting	-	15 W/m^2	0 W/m^2
Equipment	-	12.09 W/m^2	0.09 W/m^2

A central London Weather file was utilised for the energy modelling Medium - 2030_Islington_a1fi_50_percentile_TRY to simulate a dense urban UK setting (University of Exeter, 2022). A future weather file (2030) was utilised for the energy modelling as the specified equipment will operate during these environmental conditions for most of its projected lifespan. The 'high emissions' option was selected, but as all models will be simulated with this weather file it would not impact the comparative assessment. Fresh air is provided to the offices by Mechanical Ventilation Heat Recovery Units (MVHRS) which is conditioned via an in-duct coil served from the Heat Pump/Heat Recovery system, which will be supplied at the setpoint of the room. This is detailed through developed schematics within Figures 2 and 3.

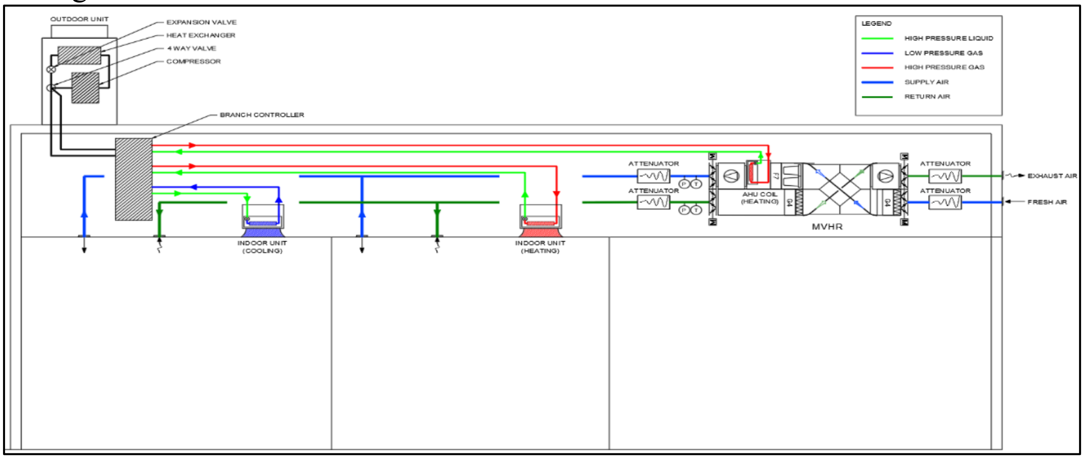

Figure 2 - 2-Pipe Heat Pump System Ventilation Schematic

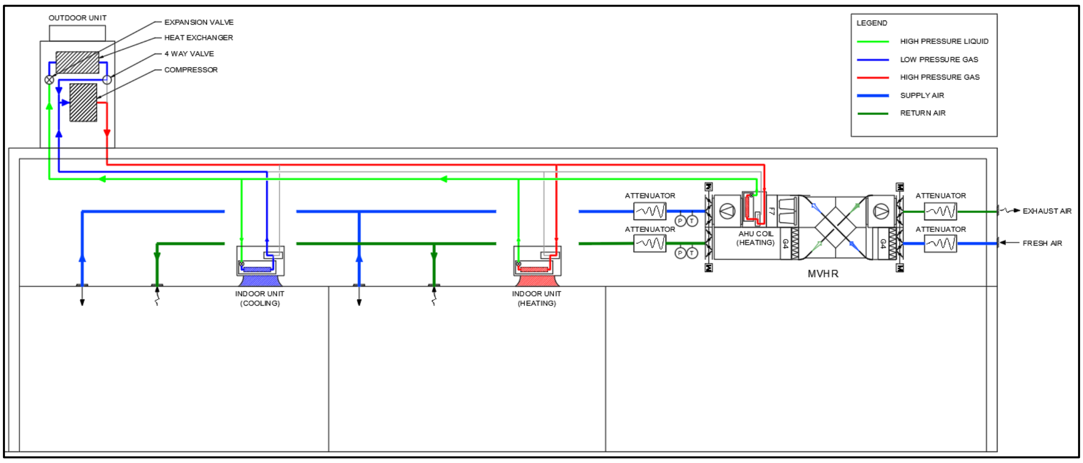

Figure 3 - 3-Pipe Heat Recovery System Ventilation Schematic

As the specified unit will condition the air within the ventilation system, this load will be included within the total heating and cooling loads and will impact the energy consumption. The MVHRs will serve each floor by providing 10 (l/s/person) of fresh air (CIBSE, 2016) and will utilise heat recovery. The model input data is displayed in Table 4 overleaf.

Table 1 - Thermal Model - Ventilation

Flow Rate	Specific Fan Power	Heat Recovery Efficiency
1580 l/s, (CIBSE, 2016)	2.0 W/(l.s)), (UK Building Regulations, 2021)	80%, (VentAxia, 2022)

Equipment Sizing and Selection

The steady-state model within the thermal modelling software was used to determine the required capacity of the equipment. The temperature extremes of the weather files were used to size the equipment presented in Table 5. These design limits were -5.0°C for winter and 31.9°C for summer.

Table 5 - Thermal Model – Equipment Loads

	Heating Load	Cooling Load
Ground	82.0kW	102.6kW
1st Floor	76.1kW	103.0kW
2nd Floor	81.9kW	104.8kW
Average	**80.0kW**	**103.5kW**

Following the calculation of the required equipment size, units were selected from all several heat pump suppliers. Utilising the projected equipment size was important, as cycle efficiency often decreases as system capacity increases, requiring a representative size to increase the suitability of the study. The performance information was extracted from datasheets and catalogues available on each manufacturer's website. In some instances where data wasn't available, the company was contacted directly to provide the missing information. Some manufacturers do not provide both standard (often referred to as space-saving) and high-efficiency models were not included within the study. The names of manufacturers and their respective units have been omitted.

Table 6 presents the naming convention used for each of the units within the investigation. These were determined by distinguishing the manufacturer, unit type, and efficiency class. These reference codes were used to identify each system during the modelling activities and to simplify the comparison analysis.

Table 6 - Equipment Reference Codes

Manufacturer	Class	Name
Air to Air Heat Pumps		
B	High Eff	B-HP-HE
B	Standard	B-HP-ST
C	High Eff	C-HP-HE
C	Standard	C-HP-ST
D	High Eff	D-HP-HE
D	Standard	D-HP-ST
E	High Eff	E-HP-HE
E	Standard	E-HP-ST
F	High Eff	F-HP-HE
F	Standard	F-HP-ST
Air to Air Heat Recovery Units		
A	High Eff	A-HR-HE
A	Standard	A-HR-ST
B	High Eff	B-HR-HE
B	Standard	B-HR-ST
D	High Eff	D-HR-HE
D	Standard	D-HR-ST
E	High Eff	E-HR-HE
E	Standard	E-HR-ST

Financial Modelling

The second element of the modelling of this research is the financial assessment. This activity measured whether the high-efficiency models would provide sufficient operational savings to offset the higher initial capital investment. This was done through the use of a payback period model created within a Microsoft Excel spreadsheet. There are five user inputs in the model:

- Standard Unit Energy Consumption;
- High-Efficiency Unit Energy Consumption;
- Standard Unit Capital Cost;
- High-Efficiency Unit Capital Cost;
- Annual Increase in Energy Tariff.

The annual energy consumption of both units (standard and high-efficiency units) being compared are inputted into the financial model, with the difference in consumption being determined. This difference in energy is converted into a monetary value using the UK grid electricity tariff (DBEIS 2022) and provides the annual savings as a result of the increase in efficiency. An annual change in energy tariff is applied to this saving, which is applied to each year. A key aspect of this investigation is the resultant magnitude of increasing energy tariffs on each unit's payback period. It was hypothesised before the modelling that the more energy prices increased annually, the more financially attractive the high-efficiency models would become as the future cost savings would be higher.

In parallel to this, the capital costs of each unit are also input into the model and that difference is also calculated. This value is the subsequent required increased capital required for the higher efficiency unit and is only applied in the first year. This model assumed that the client can purchase these units instantaneously and negate the need for financing. This also omits the need for the interest rates to be considered, as there is no requirement for the borrowing of capital. This was deemed as appropriate as these are a relatively low percentage of the total cost of a commercial office. For each year within the model, the operational savings are classified as revenue and are subtracted from the initial difference in capital. This means that over time the capital is incrementally reduced by the savings until a payback is achieved by the efficiency savings. This period is recorded and is used to determine the strength of the investment, with a 'sufficient' investment being determined as a payback achieved within the lifespan of the equipment. This period was defined as 20 years, the typical operational life of a heat pump unit (Simona Marinelli, 2019). As the research question is focused on the efficiency of the outdoor heat pump and heat recovery devices, certain elements of the wider system cost have been omitted. This includes the costs associated with installation, commissioning, maintenance, and the internal pipework and terminal devices. The reasoning for this was despite the specification of a high efficiency or standard unit, the system it would connect to would be identical. This eliminates the need for comparative cost exercise for these cost elements as the result would be a difference of zero.

Results

Manufacturers Data Results

Before energy modelling, an initial comparison was conducted to determine the difference in cost and efficiency ratios within the selected models based on the manufacturer's data. Table 9 below indicates the difference in performance and cost data between the two efficiency classes (Standard to High Efficiency). Figures 4 and 5 present this data in a graphical format. The percentage increases were used within the graphical representations as they better demonstrate the relationship between differences in efficiency and cost as they share the same unit with this method.

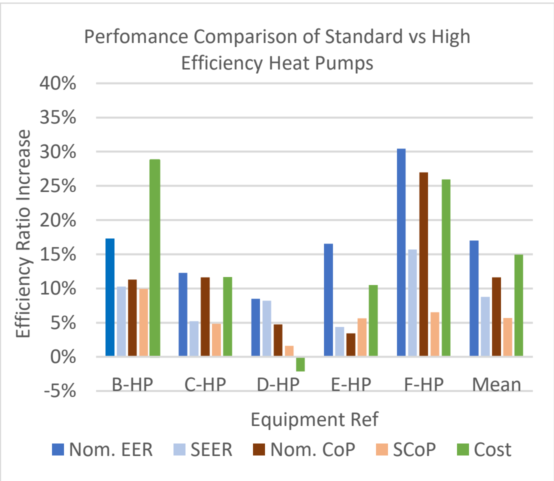

Figure 4 - Performance Comparison of Standard vs. High-Efficiency Heat Pumps

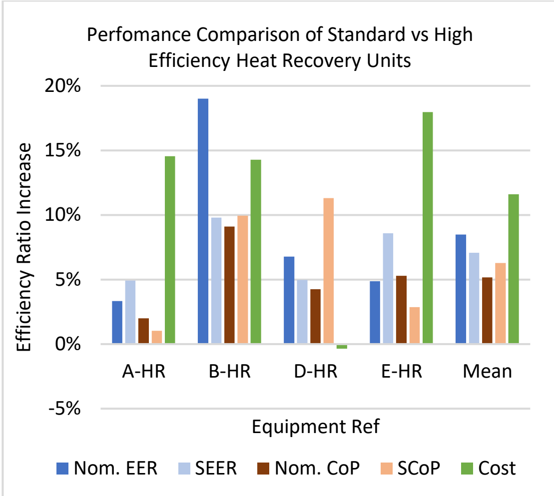

Figure 5 - Cost Comparison of Standard vs. High-Efficiency Heat Recovery Units

Figures 4 and 5 provide evidence that the comparative assessment B-HP is shown to have the highest cost increase among the system types but does not have the highest increase in efficiency ratios. Opposed to this, F-HP also had a relatively high increase in cost but is responsible for the highest increase in performance across the heat pump systems. There is also a similar situation within the heat recovery systems. Both A-HR and E-HR have high-cost increases with relatively low increases in performance, whereas B-HR also shares a high-cost increase but with the best improvements within the dataset. This would indicate that whilst the literature would suggest that there is a correlation between cost and performance, these results show it is not always the case. The heat pump system results show that the nominal EER percentage increase is consistently higher than the SEER value in all 5 cases. The nominal COP is also higher than the SCoP within the system class, except the E-HP. It was also observed that two cases (D-HP and D-HR) have negative cost increases, indicating that the cost of the high-efficiency units is lower than the comparative standard unit. This was an unexpected result, as the literature suggested that high efficiency would have a higher cost as a result of their increased development and production costs.

Thermal Model Analysis

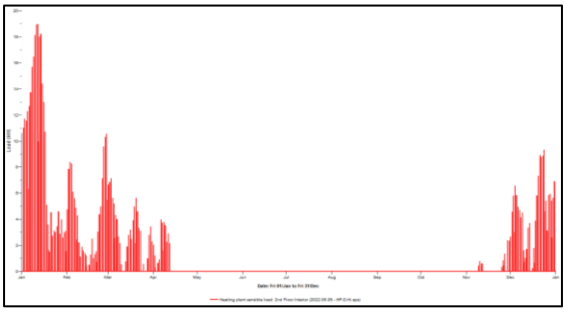

Figure 6 - Thermal Model - Heating Load

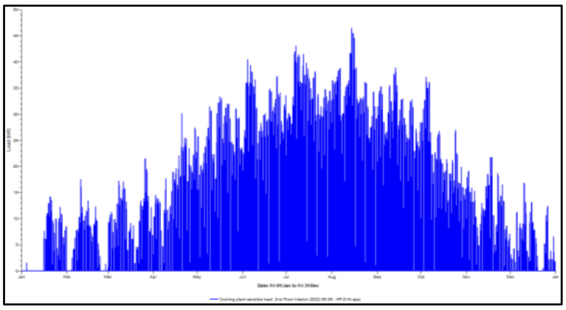

Figure 7 - Thermal Model - Cooling Load

Figures 6 and 7 highlight this system usage further, by indicating the conditioning requirement for the space. These results show that there is heating demand at the start and end of the year where the external temperature is the lowest, with a demand for cooling throughout most of the year. This was surprising for a temperature climate such as the UK, where external temperatures are below the comfortable internal temperatures for most of the year, indicating the internal gains were impacting the space more so than environmental factors such as infiltration and conduction losses.

Energy Performance Results

The results were extracted as a total building load and then divided by three (number of floors) to provide the energy consumption of an individual unit. The key output from this dataset is the Space Conditioning Total (MWh), which is indicated in bold font. This is the energy consumed by the system and was used to determine the respective operating costs. The energy usage for other systems (domestic water heating) and total system electricity have been included to demonstrate that other systems were unchanged through the simulations, and therefore did not affect the financial modelling.

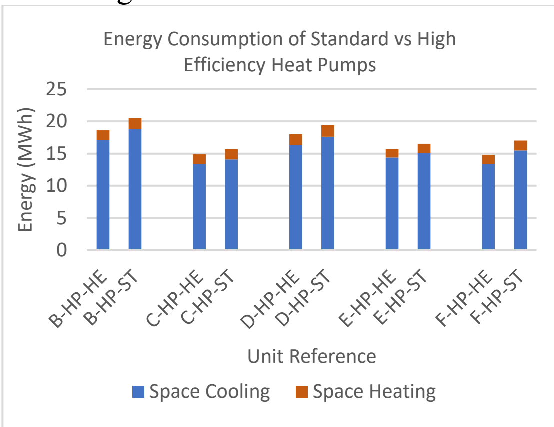

Figure 6 - Energy Consumption of Standard vs. High-Efficiency Heat Pumps

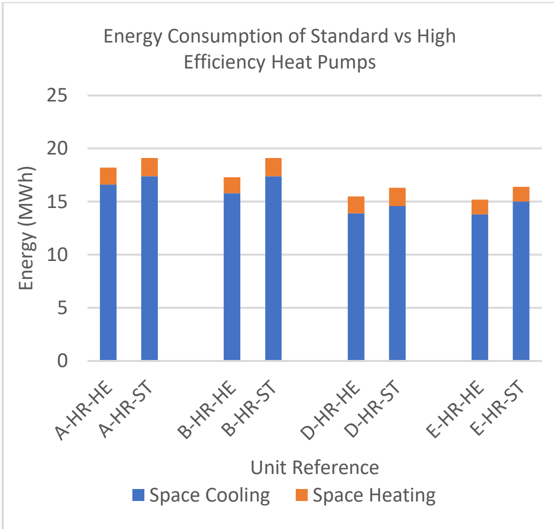

Figure 7 - Energy Consumption of Standard vs. High-Efficiency Heat Recovery Units

Figures 8 and 9 present the energy consumption for each unit, with their respective high efficiency and standard unit paring. These results align with the literature and indicate that higher efficiency devices consume less electricity for the same duty and operation. This consumption is defined within the boundaries of the conditioning system. The primary driver for the energy consumption of the systems is the electrical input required for the operation of the compressor located within the external unit. It can also be seen that there is a considerably higher energy usage in cooling mode than heating for all units, approximately eightfold. This is due to the discussed results within the thermal modelling section, noted particularly by Figures 6 and 7 which demonstrate the considerable requirement or cooling within the environment as a result of the internal gains, thermal envelope, and future weather file. The higher demand for cooling would suggest that effort should be focused on the cooling performance of the units, as this would have the most impact on reducing energy consumption.

Table 7 presents the payback periods for the additional capital required with respect to the projected cost savings due to the reduction in energy consumption of the equipment lifespan (20 years). This has been done for varying annual energy increase projections to illustrate the impact of future energy prices on equipment selections.

- Green shading – Payback achieved within system lifespan
- Red shading – Payback period exceeds system lifespan

Financial Modelling Results

Table 7 - Financial Modelling Results

	Low (2% Annual Increase)	Medium (5% Annual Increase)	High (8% Annual Increase)	Energy % Break-Even Point
Air to Air Heat Pumps				
B-HP	10 yrs	9 yrs	8 yrs	-7.4%[2]
C-HP	<20 yrs	17 yrs	15 yrs	2.3%
D-HP[1]	0 yrs	0 yrs	0 yrs	N/A
E-HP	15 yrs	13 yrs	11 yrs	-2.3%[2]
F-HP	<20 yrs	<20 yrs	19 yrs	6.9%
Air to Air Heat Recovery Units				
A-HR	<20 yrs	20 yrs	17 yrs	4.5%
B-HR	11 yrs	10 yrs	9 yrs	-5.1%[2]
D-HR[1]	0 yrs	0 yrs	0 yrs	N/A
E-HR	<20 yrs	18 yrs	15 yrs	2.6%

Footnotes
1. The high-efficiency model had a lower cost than the standard unit, creating an instant payback.
2. Energy prices remaining constant would provide a payback.

Table 7 presents the payback period for each unit pairing, indicating how long it would take for the operational savings of the high-efficiency units to offset their additional capital investment. As hypothesised, the gradual increase in energy prices increases the commercial viability of the high-efficiency units. The low annual increase shows that 55% of units would achieve payback, with the medium increase projecting 78% and high increases showing all units would be a sufficient investment. This aligns with the research gap involving whether energy price increases should be included, as their inclusion shows that several units become financially viable with higher energy prices. The 'energy % price break-even point' variable indicates the value of energy prices would need to be to achieve the payback within the lifespan of the equipment. This provides a reference of what the energy price would need to be, with a projected energy price higher than this variable indicating the unit will not reach payback. Several units have negative values, which would indicate that energy prices would need to decrease for the high-efficiency unit to be a poor investment. As stated previously, the D-HP and D-HR high-efficiency units are lower in cost than their standard unit equivalents despite offering higher operational efficiencies. As a result of this irregularity and misalignment with the literature, the devices achieve instantaneous payback.

Discussion and Analysis

The results indicate some alignment with the literature, primarily concerning the impact of energy prices on economic feasibility and the relationship between efficiency and overall energy consumption of conditioning systems. However, it was also observed some results indicate some discrepancies with the literature. The main element of this was the relationship between efficiency and price. The literature suggested that as efficiency would increase, so would the price as it the capital cost to the manufacturer to design the equipment would be higher. A research point where the results produced are reflective of the literature is the impact of the change in energy prices. This research area was highlighted as a gap in the knowledge of economic assessments of heat pumps, as fluctuating energy prices were not consistently modelled within the observed literature. As highlighted, the change in energy prices increases the payback feasibility from 55% of the units at an energy increase of 2%, up to 100% of units at an increase of 8%. This shows that the selection of a high-efficiency model is dependent upon the assumed increases in energy prices.

Energy projections are highly volatile and their association with geopolitical events leads to unpredictability. As a result, there is little defined knowledge of future energy prices as indicated within the literature review. This would require the specifier to apply their personal opinions and whether they are optimistic or pessimistic on energy prices. Therefore, it could be hypothesised that individuals who believe that energy prices will increase considerably over the equipment's lifespan would be more likely to specify a high-efficiency unit, and the opposite with one who believes energy prices will remain low. The exception to this would be scenarios such as D-HP, where a payback is achieved irrespective of very low energy prices. A specifier would have to provide sufficient references to support their opinions on future energy price projections for clients, as this area is responsible for the most uncertainty in the economic assessment. Future regulations within the UK are likely to set further efficiency limits which may make the high-efficiency units the standard. This is exemplified by the recent changes to Part L of the UK Building Regulations, where the SEER of VRF systems was increased from 4.5 to 5.0 between the 2013 (UK Building Regulations, 2013) and 2022 editions (UK Building Regulations, 2021). This would mean that either there would be an even 'higher efficiency' model to allow for flexibility during equipment specification, or that the performance would peak and mean that consumers can only select one type of unit. This would be dependent on the cost analysis relationship that has been investigated within this project. The higher the increase in performance (measured by efficiency), the higher the capital costs. As the literature suggests, this would be due to research and development, higher-quality materials, better-designed components, and more intelligent software and operating procedures. The relationship between efficiency and the required investment costs is not an indefinite linear relationship, with a limit on the efficiency of heat pumps being present. As the efficiency increases in the class of heat pumps, the scale of improvement between models would reduce as the hypothetical limit becomes closer. This would then alter the cost-benefit of the high-efficiency units, as the capital costs would increase but the operating cost reduction would decrease in magnitude. This would make the high-efficiency units less commercially appealing by extending the payback period, and in some cases not providing sufficient savings to offset the increased investment. In terms of the implications of this on designers and clients, this would then lead to a focus away from efficiency between units as the performance ceiling limit is encroached upon. This would lead to other factors becoming the differentiators, such as conditioning accuracy, control speed, design flexibility, and other cost elements such as maintenance and installation costs.

Conclusions

This research process has highlighted that, as hypothesised, increased energy prices make high-efficiency units more desirable from a financial standpoint. This is because as energy prices increase, the savings made in reduced energy consumption become larger. Each step of energy increase (+3%) reduces the payback period by approximately 2 years. The results indicate that a projected annual increase from 2% to 8%, increases the percentage of equipment pairs that reach payback from 55% to 100%. On a wider scale, this has highlighted that the lack of a defined relationship with regard to the suitability of high-efficiency units in commercial settings would indicate that each scenario should be modelled on a case-by-case basis due to the high variability in manufacturers' performance and cost values. However, this research has provided a template that allows others to follow and apply to their respective circumstances. This would allow for an optimised equipment selection process, benefiting both clients and designers. In addition, it has been demonstrated that high-efficiency systems are more financially appropriate by providing sufficient payback in most cases in all energy scenarios. This has clear environmental benefits, as less energy would be consumed and reducing carbon emissions from the national grid.

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