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

Phil Holker[1], Dr. Dashamir Marini[2]

[1]Environmental Engineering Division, Foster & Partners

[2]The Bartlett School of Environment, Energy and Resources, University College London

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 annual energy usage and associated operating costs. 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 fluctuations 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 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.

Keywords: energy; efficiency; sustainability; finance

INTRODUCTION

Variable Refrigerant Flow (VRF) 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), optimisation of compressor speed according to delivery output (Youngju Joo, 2011), optimising controls and setback regimes (Loïc Cabrol, 2021), the integration of inverters (Shuangquan Shao, 2004) and the selection of better performing materials (Maddah, Gooddarzi, & Safei, 2020).

The evolution of this technology over recent decades has allowed manufacturers and suppliers to provide the market with options to suit their needs. One of the primary variations in heat pump technologies is with regards to efficiency, with many vendors providing a *standard* or a *high efficiency* model that has the same delivery capacity but with improved heating and cooling efficiencies. As discussed, there are several methods in which a heat pump efficiency can be improved such as the optimisation of controls, components and materials which has led to an overall increase in energy efficiency across the market (Hitachi, 2022). However, there is often an increased cost associated with this additional efficiency due to additional research and development required and material costs (US Department of Energy, 2017).

The details of the quantifiable improvement resulting from each technological innovation is not public knowledge, as it would hinder manufacturers' ability to compete with others in the same market.

There is some research available on financial assessments comparing different space conditioning systems. 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). 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% lower in costs over its lifespan than a conventional air-based system supplied by a gas boiler (Emrah Özahi, 2017) . However, this research makes little usage of techno-economic assessments, and whether the difference in capital costs are compensated by the increase in efficiency and subsequent reduction in operating costs.

A key aspect of a techno-economic assessment of any conditioning equipment are the assumptions regarding future energy prices. As payback is determined by offsetting the savings in operating costs against the initial capital investment, energy prices can have a considerable impact on the outcome of the payback period (Awomewe Alaba Femi, 2008).

The performance and financial aspects of different systems is a well-researched area, however there appears to be a knowledge gap with regards to units of the same type but with differing characteristics. As a result, this study will aim to expand the research knowledge of the economic feasibility of high-efficiency VRF units compared to their standard alternatives, and the impact of future energy prices on those assessments. This would contribute considerably to the wider understanding of the literature surrounding the efficiency of VRF heat pump and recovery systems and their economical suitability within commercial settings.

METHOD

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 conduct 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	12 (m)
Internal Ceiling Height	2.7 (m)
Internal Floor Area (per floor)	16662 (m^2)
Glazing Ratio	33 (%)

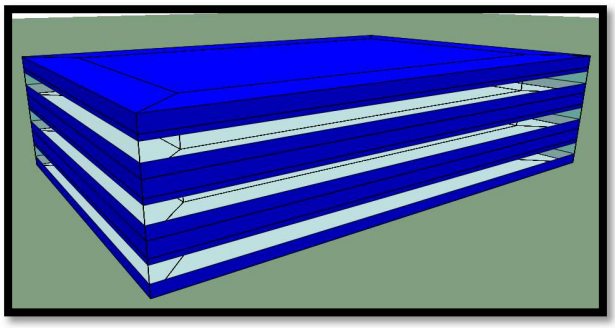

Figure 1 - Thermal Model - Medium Office

UK Part L 2022 envelope performance values were applied which are presented within Table 2 (UK Building Regulations, 2021). The National Calculation Methodology (NCM) template for an open office was applied (UK NCM, 2021).

The envelope performance is presented within Table 2, while the internal gains are presented in Table 3.

Table 2 - Thermal Model – Envelope Performance

Construction	U-Value (W/m².K)
Roof (flat)	0.18
Wall	0.26
Floor	0.18
Windows	1.60
Air Permeability	8m³/(h.m²) @ 80Pa

Table 3 - Thermal Model - Internal Gains

Internal Gain	Concentration	Sensible Gain	Latent Gain
People	10 m²/person (158 people)	73 W/person	50 W/person
Lighting	-	15 W/m²	0W/m²
Equipment	-	12.1W/m²	0.1W/m²

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. This weather file would simulate warmer conditions as temperatures are projected to rise, increasing cooling energy consumption when compared to the current climate.

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. The temperature within the zones is controlled through recirculating ceiling units, with the room air passing over coils supplied with fluid from the outdoor units (heat pump/heat recovery equipment). These are reversible systems that can provide both heating and cooling to separate spaces on the same circuit. For further detail, refer to the schematics presented within Appendices A and B.

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 10l/s/person of fresh air (CIBSE, 2016) and will utilise heat recovery. The model input data is displayed in Table 4.

Table 4 - 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 conditioning equipment. This simulates the theoretical peak delivery capacity in heating and cooling modes by altering the gains and losses for the space to reflect peak operation. The gains were maximised for cooling and removed for heating, and the external temperatures were -5.0°C for winter and 31.9°C for summer. The calculated conditioning loads are presented in Table 5.

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
Peak	**82.0kW**	**104.8kW**

Following the modelling of the required equipment load, units were selected from several heat pump suppliers. Utilising the calculated load was important. Unit efficiency decreases as system capacity increases, as demonstrated within the manufacturers literature (Daikin, 2022), 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. 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. All manufacturers were listed, and a deep dive was conducted to ensure they provided both a standard and high efficiency unit with the required delivery capacity for either the heat pump or heat recovery variant. Some manufacturers were unable to supply both, resulting in some manufacturers only appearing in one of the heat pump/recovery unit sets.

These reference codes were used to identify each system during the modelling activities and to simplify the comparison analysis. In addition, Table 7 states the efficiencies for each equipment that was used for the study. Independent test results were not available for this research. The reported values from manufacturers were deemed as sufficient to be used for modelling to carry out the intended research aims and objectives, as efficiency values were calculated to BS-EN 14825 Standards.

A simulation was conducted for each unit listed within Tables 6 and 7. After the completion of each annual simulation, the energy data was extracted, and the heating and cooling modelling input was updated with the efficiency values for the next unit. This was done to create 18 individual annual datasets which was used to determine the annual energy consumption for each unit.

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

Table 7 - Equipment Efficiencies

Name	CoP	SCoP	EER	SEER
Air to Air Heat Pumps				
B-HP-HE	4.23	4.10	3.87	6.02
B-HP-ST	3.80	3.73	3.30	5.46
C-HP-HE	4.61	4.34	3.84	7.70
C-HP-ST	4.13	4.14	3.42	7.32
D-HP-HE	4.21	3.75	3.70	6.31
D-HP-ST	4.02	3.69	3.41	5.83
E-HP-HE	3.93	5.07	3.31	7.13
E-HP-ST	3.80	4.80	2.84	6.83
F-HP-HE	4.47	4.74	3.77	7.67
F-HP-ST	3.52	4.45	2.89	6.63
Air to Air Heat Recovery Units				
A-HR-HE	3.07	3.96	4.04	6.19
A-HR-ST	3.01	3.92	3.91	5.90
B-HR-HE	4.08	4.2	3.88	6.50
B-HR-ST	3.74	3.82	3.26	5.92
D-HR-HE	4.17	4.13	3.63	7.39
D-HR-ST	4.00	3.71	3.40	7.04
E-HR-HE	3.78	4.68	3.23	7.47
E-HR-ST	3.59	4.55	3.08	6.88

Financial Modelling

The second element of the modelling for 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 using a payback period model created within a Microsoft Excel spreadsheet. This was considered an appropriate method of financial analysis that has been conducted by other researchers for assessing conditioning systems (Al-Falahat, 2022) (D'Agostino, 2020) (Ozpolat, 2021) (Sadeghi, 2022).

The annual energy consumption of each unit within a pair (standard and high efficiency) are inputted into the financial model, with the difference in consumption determined. This difference in energy is converted into a monetary value using the UK grid electricity tariff of £0.1469/kWh (Department for Business, Energy, & Industrial Strategy, 2022) and provides the annual operating cost difference, between the two units.

An annual increase 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 prior to the modelling as 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 entered into the calculation. For each year within the model, the operational savings are classified as revenue and are subtracted from the initial difference in capital. This payback period is extracted and used to determine the strength of the investment, with a 'sufficient' investment being determined as a payback achieved within the lifespan of a typical heat pump, which is 20 years (Simona Marinelli, 2019). An annual discount value of 4% was considered to incorporate the time effect of money.

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 can be omitted. This includes the costs associated with installation, commissioning and maintenance. The reasoning for this was despite the specification of a high efficiency or standard unit, the HVAC system would operate in the same manner. This eliminates the need for comparative cost exercise for these elements as the result would be a difference of zero.

RESULTS AND DISCUSSION

Manufacturers Data Results

Before the 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. Figures 4 and 5 present the difference in performance and cost data between the two efficiency classes (Standard to High Efficiency). Each reference tag is an equipment pair, e.g. *B-HP* is the standard and high efficiency heat pumps from manufacturer B compared. The key variables are:

- Nom.EER – Nominal Energy Efficiency Ratio
- SEER – Seasonal Energy Efficiency Ratio
- Nom.CoP – Nominal Coefficient of Performance
- SCoP - Seasonal Coefficient of Performance
- Cost – Capital cost difference between models

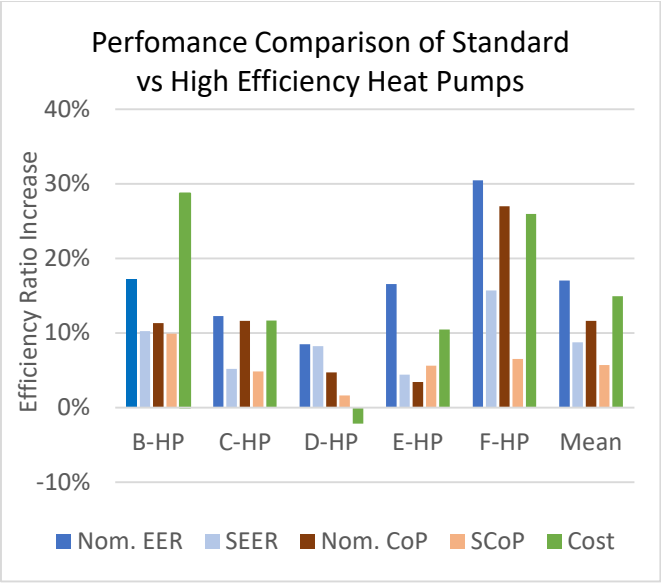

Figure 2 - Performance Comparison of Standard vs. High-Efficiency Heat Pumps

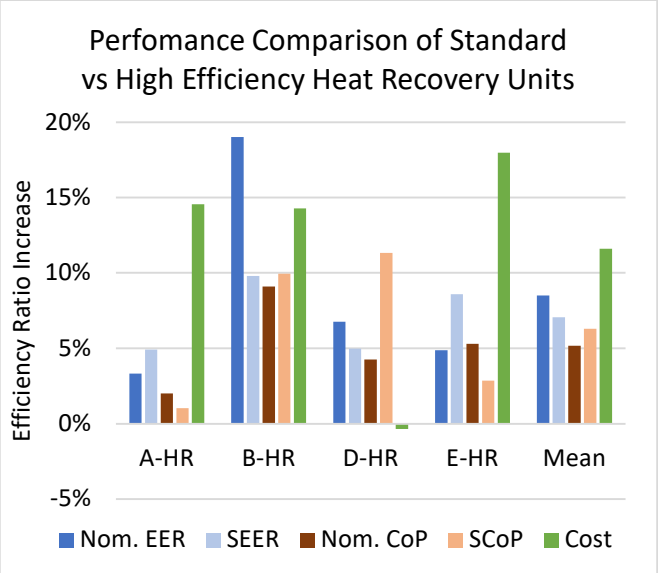

Figure 3 - Cost Comparison of Standard vs. High-Efficiency Heat Recovery Units

Figure 2 indicates the B-HP pair to have the highest cost increase among the system types but does not have the highest increase in efficiency ratios. Conversely, 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 a similar situation within the heat recovery systems in Figure 3. Both the A-HR and E-HR pairs have high-cost increases with relatively low increases in performance, whereas B-HR also shares a high-cost increase but with the biggest efficiency increase within the dataset. This would suggest within these results there is not necessarily a correlation between an increase in cost and an increase in performance.

It was also observed that two pairs (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 interesting result, as a high efficiency unit is expected to have a higher cost as a result of increased development and production costs (US Department of Energy, 2017).

Energy Performance Results

The annual energy consumption for space heating and cooling delivered by each of the heat pump/recovery units is presented in Figures 4 and 5. This is the energy consumed by the system and was used to determine the respective operating costs.

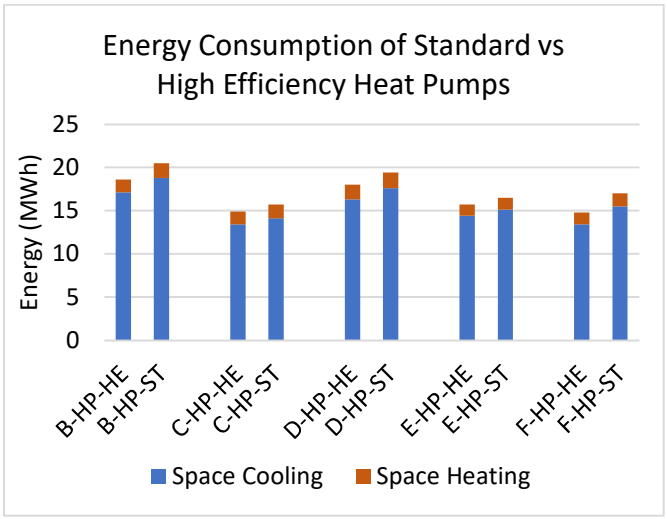

Figure 4 - Energy Consumption of Standard vs. High-Efficiency Heat Pumps

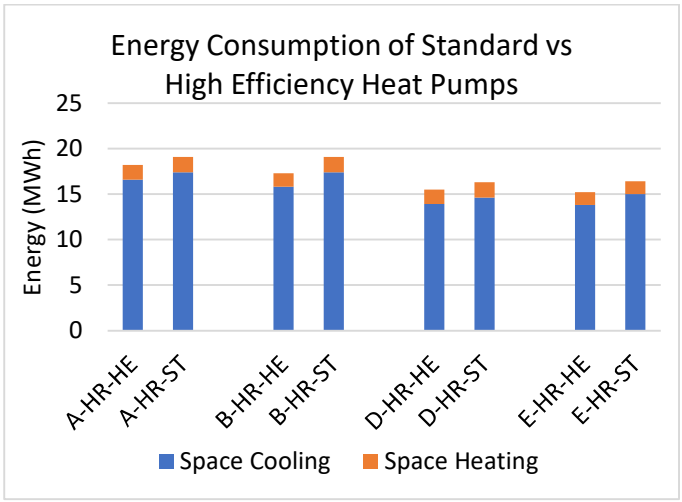

Figure 5 - Energy Consumption of Standard vs. High-Efficiency Heat Recovery Units

Figures 4 and 5 present the energy consumption for each unit, with their respective high efficiency and standard unit paring. In all cases the high efficiency units consume less energy than the standard units whilst delivering the same quantity of heating and cooling.

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. This is primarily due to the high internal gains, high window wall ratio of the glazing and usage of a future weather file. In addition, the annual heating and cooling loads are presented within Appendices C and D to demonstrate the difference in usage.

There are various methods that could be implemented such as incorporating night ventilation, improving the glazing G-value and the inclusion of an air-side economiser to reduce cooling energy consumption. However, this is not the purpose of this research study so has not been implemented.

Financial Modelling Results

Table 8 presents the payback periods for the additional capital required to offset the operating cost savings due to the reduction in energy consumption. This has been done for several energy price scenarios to illustrate the impact of future energy prices on equipment selections.

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

	Low (2% Annual Increase)	Medium (5% Annual Increase)	High (8% Annual Increase)
Air to Air Heat Pumps			
B-HP	10 yrs	9 yrs	8 yrs
C-HP	>20 yrs	17 yrs	15 yrs
D-HP[11]	0 yrs	0 yrs	0 yrs
E-HP	15 yrs	13 yrs	11 yrs
F-HP	>20 yrs	>20 yrs	19 yrs
Air to Air Heat Recovery Units			
A-HR	>20 yrs	20 yrs	17 yrs
B-HR	11 yrs	10 yrs	9 yrs
D-HR[1]	0 yrs	0 yrs	0 yrs
E-HR	>20 yrs	18 yrs	15 yrs

Table 8 - Financial Modelling Results

Table 8 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 increased 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.

	Energy % Break-Even Point
Air to Air Heat Pumps	
B-HP	-7.4%[22]
C-HP	2.3%
D-HP[1]	N/A
E-HP	-2.3%[2]
F-HP	6.9%
Air to Air Heat Recovery Units	
A-HR	4.5%
B-HR	-5.1%[2]
D-HR[1]	N/A
E-HR	2.6%

Table 9 - Financial Modelling Results

Table 9 states the '*energy % price break-even point*' which indicates the value of energy prices would need to be to achieve the payback within the lifespan of the equipment. 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, the devices achieve instantaneous payback.

Discussion and Analysis

The results indicate that energy prices have an impact on payback period. 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

[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.*

the literature review (Awomewe Alaba Femi, 2008) (Emrah Özahi, 2017).

Subsequently, to maximise accuracy, payback assessments should be conducted considering multiple energy scenarios to understand the range of payback period for the conditioning equipment. This would improve the accuracy of these assessments in with little additional work required.

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 study.

The higher the increase in performance (measured by efficiency), the higher the capital costs. This is due to research and development, higher-quality materials, increased design resources, and more intelligent software and operating procedures (US Department of Energy, 2017). 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 has highlighted increased energy prices make high-efficiency units more desirable from a financial standpoint. 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%. However, energy prices are highly volatile and are influenced by geopolitical events, indicating several price scenarios should be considered during financial planning for energy-related equipment.

In addition, a weak correlation has been found between the efficiency increase from a standard to a high-performance unit and its respective increased capital cost. This demonstrates the need for these assessments to be conducted on projects where investment value is key driver. It has also 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 thereby reducing operational carbon emissions.

It should be noted this study is for a single type of building (an office) within a single climate (UK). If the ratio of heating to cooling load were to change due to either of these factors, the relationship between the standard and high efficiency units would be altered. It would be beneficial to understand the impact on the relationship between cost and efficiency in a heating or cooling/dominant location as opposed to a moderate climate. In addition, a building type with a considerably different usage such as a domestic or a healthcare setting would also allow for greater understanding regarding capital investments and efficiency.

NOMENCLATURE

ASHP	Air Source Heat Pump
CoP	Coefficient of Performance
EER	Energy Efficiency Ratio
HE	High Efficiency
HP	Heat Pump
HR	Heat Recovery
IES:VE	Integrated Environmental Solutions: Virtual Environment
MVHR	Mechanical Ventilation Heat Recovery
NCM	National Compliance Modelling
SCoP	Seasonal Coefficient of Performance
SEER	Seasonal Energy Efficiency Ratio
ST	Standard
VRF	Variable Refrigerant Flow
VRV	Variable Refrigerant Volume

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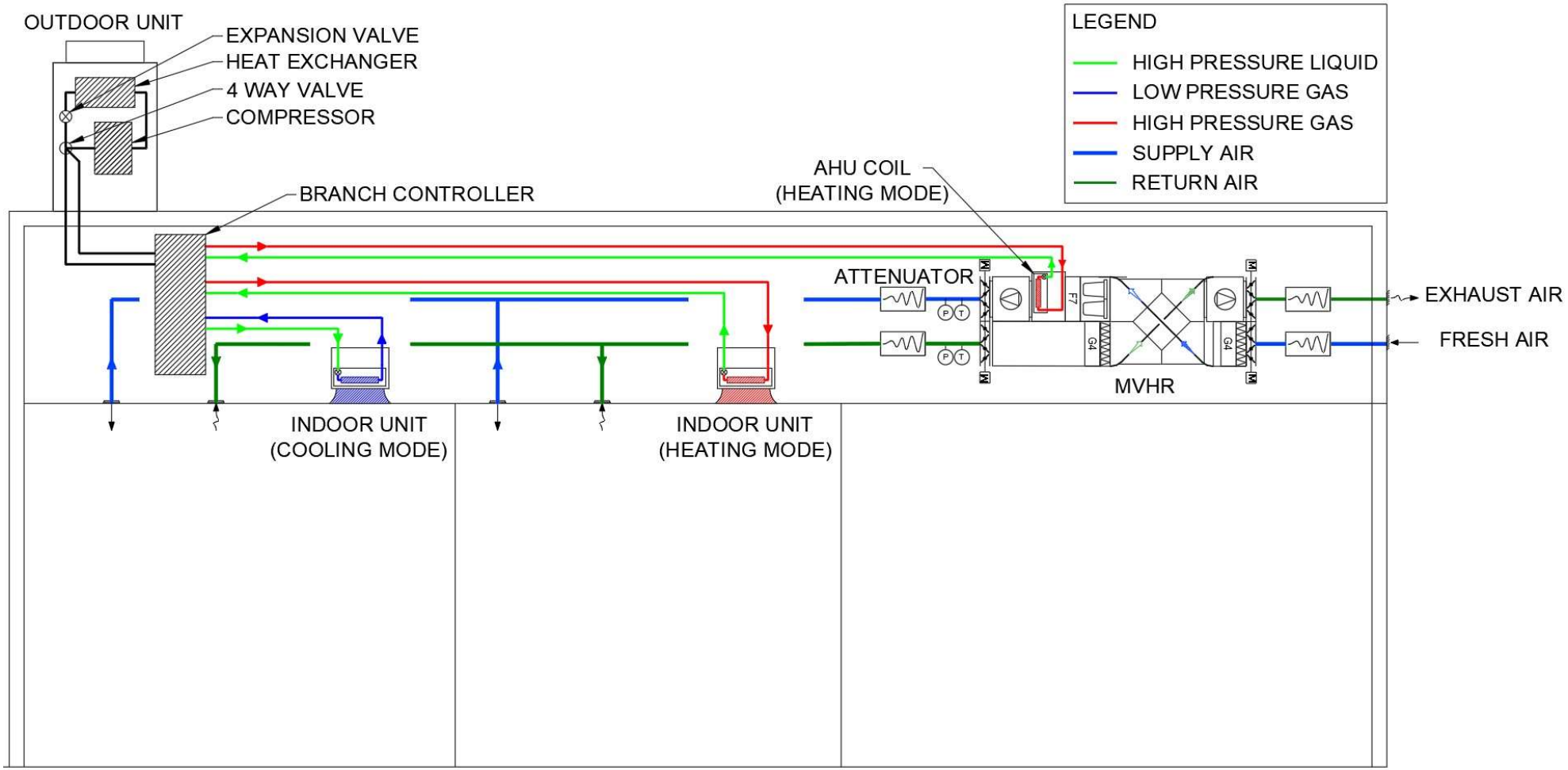
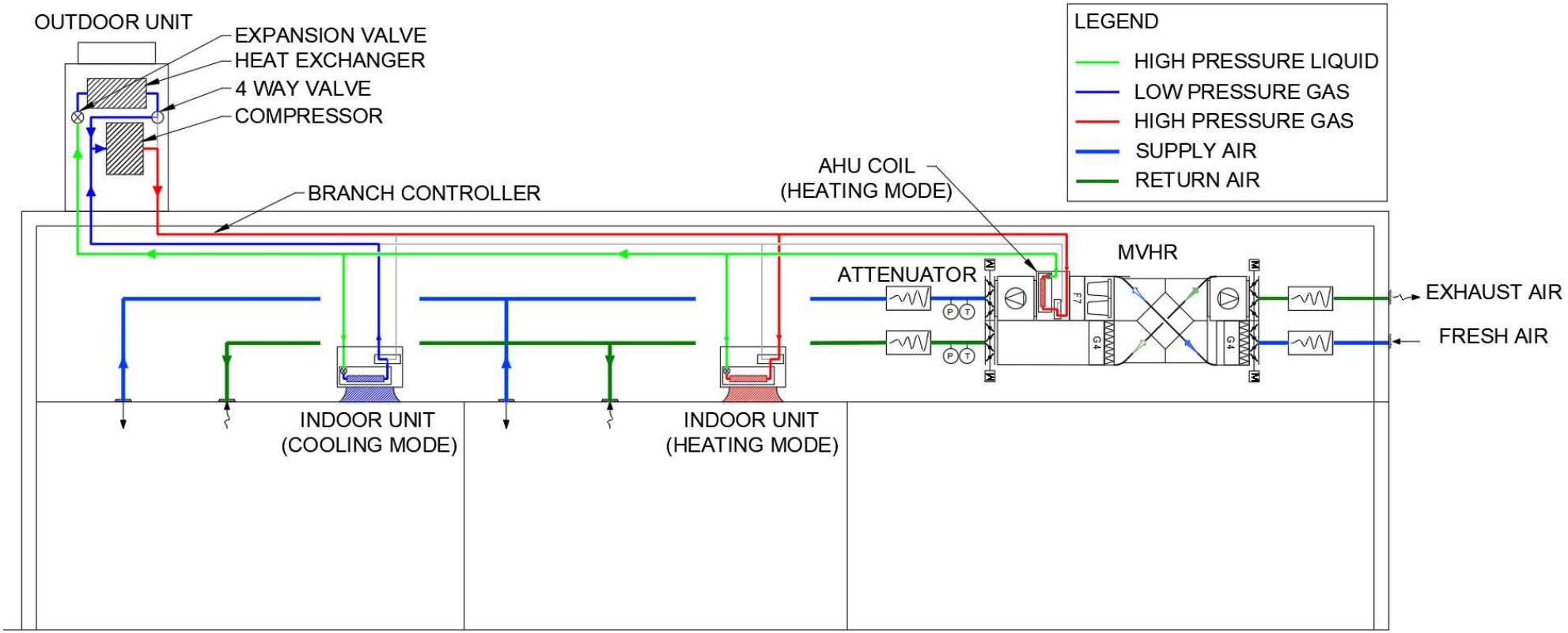
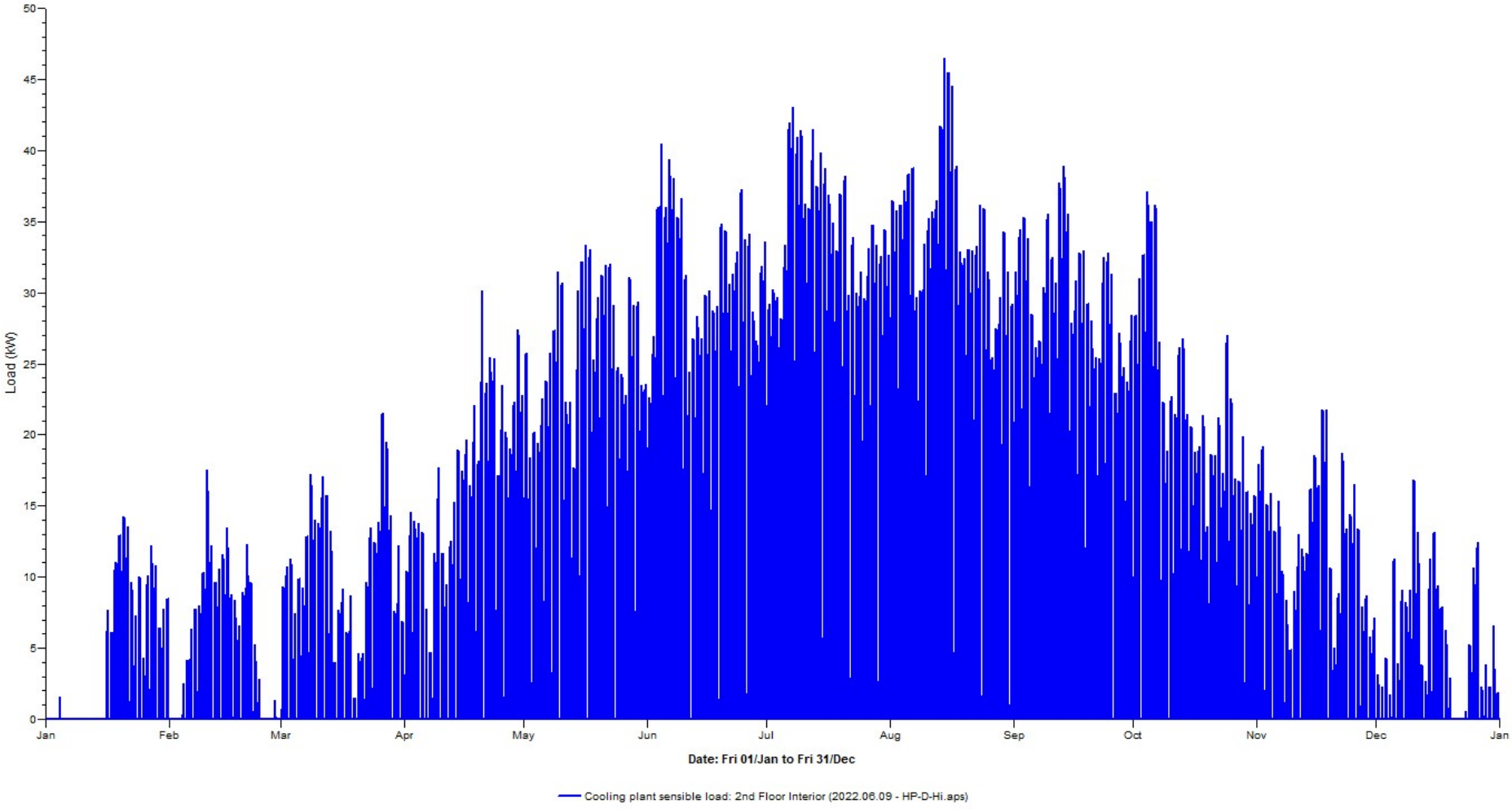
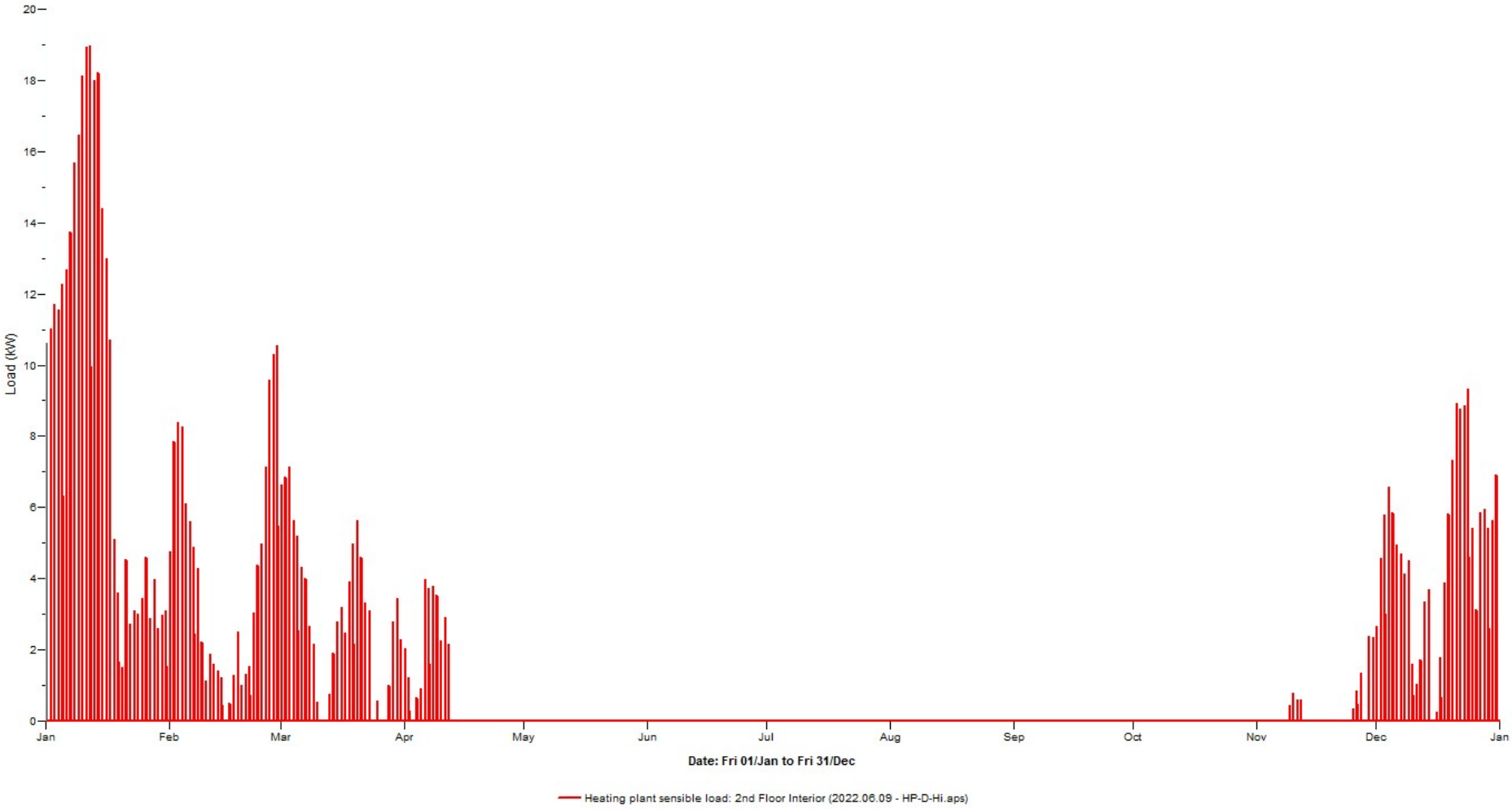
Appendix A – 2-Pipe Heat Pump System Schematic



Appendix B – 3-Pipe Heat Recovery System Schematic



Appendix C – Annual Cooling Conditioning Load



Appendix D – Annual Heating Conditioning Load