

Article

Electrical Demand Uplift and Coil Performance Constraints in Air-Source Heat Pump Retrofits for Commercial Office Buildings

Darren Kelly , Akhtar Kalam  and Shasha Wang

School of Mechanical Engineering, Engineering Institute of Technology (EIT), Perth Campus, 1031 Wellington St., West Perth, WA 6005, Australia; akhtar.kalam@eit.edu.au (A.K.); shasha.wang@eit.edu.au (S.W.)

* Correspondence: 15612@student.eit.edu.au

Abstract

Decarbonising existing commercial buildings requires replacing combustion-based heating systems with electrically driven alternatives such as air-source heat pumps (ASHPs). Although the energy and emissions benefits of heat pumps are well established, less attention has been given to the plant-level electrical demand uplift and hydronic constraints that can limit retrofit feasibility in existing buildings. This study quantifies the electrical demand uplift and air-handling unit (AHU) coil performance limitations associated with ASHP retrofitting in an existing Australian commercial office building. A peak design-load assessment was undertaken to compare the baseline gas-fired heating system with an electrified ASHP configuration under equivalent thermal load conditions. The principal electrical outcomes are derived from a specified 1900 kW Stage 3 plant-screening heating boundary. This boundary reflects the prevailing installed plant-screening condition, rather than the aggregate of scheduled AHU heating duties. First-principles energy balances and hydronic relationships were used to translate thermal demand into plant electrical demand under winter design conditions, while existing AHU heating coils were re-rated under low-temperature hydronic operation. The results show that baseline winter heating is associated with only a small auxiliary electrical load, whereas the governing baseline plant peak occurs during cooling at 399 kW. When referenced to the adopted 1900 kW Stage 3 installed-capacity screening boundary, the peak winter ASHP plant electrical demand increased to 956.66 kW, corresponding to an upper-bound electrical uplift of 557.7 kW relative to the governing baseline plant electrical demand. In parallel, low-temperature hydronic operation (55/45 °C) reduced AHU heating-coil capacity, requiring increased flow rates and, in many cases, coil modification to maintain scheduled duty. These findings indicate that, in the assessed case-study building, the principal barriers to ASHP retrofitting are not annual energy performance alone, but peak electrical infrastructure implications and hydronic system compatibility. The study therefore provides a transparent, building-scale screening methodology for assessing electrification feasibility in existing commercial buildings, while recognising that the reported numerical results are specific to the case-study building and stated design assumptions.



Academic Editor: Nassif Nabil

Received: 22 April 2026

Revised: 20 June 2026

Accepted: 23 June 2026

Published: 26 June 2026

Copyright: © 2026 by the authors.

Licensee MDPI, Basel, Switzerland.

This article is an open access article distributed under the terms and

conditions of the [Creative Commons](https://creativecommons.org/licenses/by/4.0/)

[Attribution \(CC BY\)](https://creativecommons.org/licenses/by/4.0/) license.

Keywords: air-source heat pump; building electrification; retrofit feasibility; electrical demand uplift; peak demand; hydronic systems; AHU heating coils; commercial office buildings; low-temperature heating

1. Introduction

The decarbonisation of the building sector has emerged as a central objective of global climate policy, with commercial office buildings accounting for a significant share of operational energy use and greenhouse gas (GHG) emissions. Buildings account for approximately one-third of the global final energy consumption and are responsible for a substantial share of energy-related emissions, with heating, ventilation, and air-conditioning (HVAC) systems constituting the dominant energy end-use. In existing commercial buildings, where the majority of the 2050 building stock is already constructed, achieving net-zero operational performance requires the transformation of existing systems rather than new-build optimisation [1–4].

A key component of this transition is the electrification of fossil fuel-based heating systems. Conventional office buildings typically rely on natural gas boilers for space heating, resulting in direct (scope 1) emissions. Electrification strategies aim to eliminate these emissions by replacing combustion-based systems with electrically driven technologies, most notably heat pumps. Among the available options, ASHPs are widely regarded as the most deployable solution for retrofitting applications owing to their relatively low capital cost, minimal site disruption, and compatibility with existing building configurations [5–7].

While the energy and emissions benefits of heat pump systems are well established, their integration into existing commercial buildings introduces engineering challenges that are not fully addressed in the current literature. Electrification fundamentally alters the relationship between thermal and electrical demands. Under conventional gas-fired operations, the heating demand is decoupled from the electrical infrastructure. In contrast, ASHP systems directly translate thermal demand into electrical demand through compressor operation, resulting in structural coupling between the heating load, system efficiency, and electrical peak demand [8–10].

This transformation has significant implications for the feasibility of retrofitting. The electrical infrastructure in commercial buildings is typically sized based on peak demand rather than annual energy consumption. Consequently, the transition from gas-fired systems to heat pumps can lead to substantial increases in peak electrical load, potentially exceeding the capacity of existing switchboards and distribution systems. However, most existing studies evaluate heat-pump performance primarily in terms of annual energy consumption or seasonal efficiency, with limited attention given to peak electrical demand and infrastructure constraints [3,4,7].

In parallel, heat pump adoption introduces changes in the thermal operating conditions. Conventional hydronic systems operate at 70–90 °C, whereas ASHP systems operate more efficiently at 40–55 °C. This reduction in temperature significantly affects the AHU heating coil performance, potentially requiring increased flow rates or system modification [11–14].

While previous studies have primarily evaluated heat pump systems in terms of annual energy performance and emissions reduction, the present case-study analysis indicates that the feasibility of ASHP retrofitting may be influenced more strongly by peak electrical infrastructure implications and hydronic system compatibility than by annual performance alone. By explicitly quantifying thermal-to-electrical load translation and terminal-unit derating within a single analytical framework, this study highlights the importance of treating building electrification as an infrastructure-aware engineering problem rather than solely an energy-efficiency or emissions-reduction exercise. In doing so, this study contributes to emerging research that emphasises peak load-based electrification assessment and provides a transferable workflow for evaluating electrical and hydronic constraints in existing buildings.

To the authors' knowledge, few prior studies have combined peak electrical uplift, heat-pump design-point performance, and hydronic terminal-unit compatibility within a single building-scale retrofit assessment for an existing commercial office building. The contribution of the present study is therefore not the discovery of a previously unknown physical relationship, but the quantification of these interacting constraints within a single case-study screening framework.

The objectives of this study are as follows:

- Quantify electrical uplift associated with ASHP retrofit;
- Analyse the transformation of thermal demand into electrical demand;
- Evaluate the implications of low-temperature operation on the AHU coil performance.

The remainder of this paper is structured as follows: Section 2 reviews the relevant literature, Section 3 describes the methodology, Section 4 presents the results, Section 5 discusses the implications, and Section 6 concludes.

2. Literature Review

2.1. Electrification and Infrastructure Constraints

Electrification is widely recognised as a central pathway toward net-zero buildings, driven by the need to eliminate direct emissions from fossil fuel combustion and align building energy use with an increasingly low-carbon electricity supply [3–5,7]. This transition represents a fundamental shift in building performance evaluation from a focus on annual energy consumption and emissions to an emphasis on infrastructure-based constraints. Under electrification, the thermal demand is directly coupled to the electrical demand, fundamentally altering the load profiles and increasing the peak electrical requirements [7]. Recent studies have demonstrated that large-scale building electrification can significantly increase the peak demand at the building and supply grid levels. However, much of the existing literature continues to prioritise aggregated or annual performance metrics, with limited attention to peak demand implications or building-specific electrical constraints in commercial retrofit scenarios. Consequently, the role of electrical infrastructure capacity as a limiting factor in electrification feasibility remains insufficiently developed [3–5,7].

2.2. Heat-Pump Performance and Variability

Heat pumps are widely regarded as a cornerstone technology for building decarbonisation because of their potential to deliver heating and cooling at high efficiencies. Despite this, real-world performance exhibits substantial variability, with field studies reporting operational coefficients of performance (COP) ranging from approximately 1.2 to 3.2, which are often significantly lower than laboratory-rated values [8]. This performance gap is driven by factors such as climatic conditions, control strategies, system sizing, and integration with existing building systems. The variability is particularly pronounced in cold conditions, where declining ambient temperatures increase the compressor demand and reduce efficiency. Critically, these reductions in performance tend to occur during peak heating periods, resulting in elevated electrical demand precisely when electrical infrastructure constraints are most acute [8–10,15].

2.3. Load Dependency and System Interaction

The performance of heat pump systems is strongly dependent on the building's thermal demand, with higher heating loads directly translating into increased electrical demand during electrified operation. Improvements to building envelope performance have been shown to significantly reduce heating demand and, in turn, lower the electrical loads associated with heat pump operation [16]. However, evidence of diminishing returns suggests that envelope upgrades alone may not always deliver optimal outcomes, and

that system-level optimisation can be equally impactful, or more so, in certain contexts. Despite this interdependence, the literature frequently treats building fabric performance and system electrification as distinct domains, with limited integration of their combined effects on peak electrical demand and infrastructure requirements [16,17].

2.4. Hydronic Constraints and Coil Performance

The transition from high-temperature boiler-based systems to low-temperature heat pump operations introduces significant challenges to existing hydronic distribution systems. Reduced supply temperatures decrease the temperature differential across AHU coils and other terminal units, resulting in a reduced heat transfer capacity [11,12]. To maintain an equivalent thermal output, systems must compensate for increased water flow rates, larger heat exchange surfaces, or system reconfiguration. These adaptations have implications for both energy consumption and retrofit feasibility, as increased flow rates raise pumping energy and may exceed the design limits of the existing distribution infrastructure. While previous literature has established that heat-pump electrification can reduce direct fossil-fuel use, fewer studies quantify the interactions among design-point plant electrical uplift, existing terminal-unit performance, and retrofit feasibility at the individual commercial-building scale. This is particularly important in cases where low-temperature heat delivery, existing coil geometry, and limited electrical headroom must be assessed together [11–14].

2.5. Research Gap

The existing literature provides a robust foundation for understanding heat pump technology, building electrification pathways, and energy efficiency strategies in the context of decarbonisation. However, as synthesised in Sections 2.1–2.4, several critical gaps remain, limiting the applicability of this body of work to real-world commercial retrofitting scenarios. First, despite the growing recognition that electrification fundamentally shifts buildings from energy-based to infrastructure-based constraints, peak electrical demand is rarely treated as a governing feasibility criterion. Instead, assessments continue to rely on annual or seasonal performance metrics, obscuring the infrastructure limitations that emerge under peak operating conditions. Second, there is a lack of detailed building-scale quantitative analysis of electrical load uplift associated with electrification in retrofit contexts, particularly for commercial buildings with constrained electrical capacity. Third, while the limitations of hydronic systems during low-temperature heat pump operation are acknowledged, these constraints are seldom integrated into electrification assessments in ways that capture their interactions with electrical demand and system performance. Consequently, the combined effects of electrical infrastructure capacity, heat pump operational variability, building thermal load, and hydronic system constraints remain insufficiently explored in the literature. This study addresses these gaps by providing an integrated, building-specific analysis of the electrical and hydronic implications associated with heat pump electrification in a commercial building retrofit context, with particular emphasis on peak demand and infrastructure feasibility [3,4,8,11,14,17].

Accordingly, the literature indicates a clear need for building-scale electrification assessments that go beyond annual energy metrics and explicitly evaluate peak electrical infrastructure implications, as well as hydronic and terminal-unit compatibility.

3. Materials and Methods

This section describes the case-study building, the baseline model and plant assumptions, the analytical system boundary, and the first-principles relationships used to quantify electrical uplift and terminal-unit derating under ASHP retrofit. The approach combines a fit-for-purpose baseline building model with screening-level thermodynamic and hydraulic

calculations to assess electrification feasibility under governing peak-load conditions. This analysis focuses on converting thermal demand into plant electrical demand and assessing how low-temperature hydronic operation affects the performance of existing AHU heating coils.

The analysis was undertaken using a representative multi-storey commercial office building, designated as the case-study building. The building has a gross floor area of approximately 15,000 m² and is representative of the medium-to-large segment of Australian commercial office stock. Its configuration and operational characteristics are consistent with contemporary Australian design practice and relevant regulatory requirements, including the National Construction Code (NCC) and AS 1668 for ventilation and indoor air quality [1,4].

3.1. The Case-Study Building and Baseline Definition

The case-study building is served by a centralised HVAC system comprising 13 air-handling units (AHUs) that supply open-plan office zones via hydronic heating and cooling coils. Space heating is provided by gas-fired boilers, and cooling by water-cooled chillers. Hydronic circulation is delivered through primary and secondary pumping systems within the building. This arrangement is representative of a contemporary 5-star NABERS-rated commercial office building and provides a realistic basis for evaluating heating electrification in existing commercial stock.

An IES VE-informed model was used to establish the baseline conditions. The model was developed using IES VE and informed by load checks and site-observed system information, including installed plant capacities, equipment nameplate ratings, available building documentation, and operational and commissioning data. Its purpose was to define the governing plant-level thermal loads and electrical reference conditions required for comparative retrofit screening, rather than to provide a full utility-bill calibration or formal measurement-and-verification model. The resulting model provides a suitable engineering basis for the comparative analysis of the baseline and electrified scenarios. The peak thermal loads from the baseline were 1900 kW for heating and 1813.10 kW for cooling.

Under baseline operation, the heating demand is met through gas combustion and is therefore largely decoupled from the building's electrical system. Winter heating operation is associated with only a small auxiliary electrical load of 5.54 kW, including heating plant auxiliaries and pumps. In contrast, the governing baseline plant electrical demand occurs during the cooling operation, peaking at 399 kW, including energy for the chiller, cooling tower, and pump. Accordingly, the cooling operation was adopted as the governing baseline electrical condition for infrastructure comparison.

3.2. Peak Load Derivation and Data Sources

The peak thermal loads were derived from a combination of on-site operational data and first-principles heat balance calculations. This approach was adopted to maintain transparency and reproducibility while remaining consistent with engineering design practices for electrical and hydronic infrastructure assessments.

The heating and cooling loads of the building were determined under steady-state peak design conditions. The envelope heat transfer was calculated using documented characteristics of the façade, glazing, and roof. Internal gains from occupants, lighting, and equipment were based on the observed operational data and typical high-performance office usage profiles. The ventilation and infiltration loads were derived from the design airflow rates and outdoor air requirements.

Peak conditions were assessed using long-term meteorological data from Canberra, Australia. A winter ambient temperature of −5 °C was adopted for the peak heating

analysis to represent a conservative design condition for infrastructure assessment. The cooling loads were evaluated under the corresponding summer design conditions. Using this approach, peak heating and cooling loads of 1900 kW and 1813.10 kW, respectively, were established as the governing thermal inputs for the subsequent analysis.

This study focused on steady-state peak conditions rather than time-series operations. This reflects that switchboards, transformers, and hydronic distribution systems are sized based on the maximum coincidence demand rather than on annual or average energy consumption. The resulting load set was used consistently throughout the electrical, hydraulic, and terminal-unit assessments.

The AHU schedule reproduced in Appendix A provides the basis for the terminal-unit compatibility assessment, but it does not by itself define the full governing plant-level screening boundary. The scheduled AHU heating duties sum to approximately 1046.3 kW, whereas the 1900 kW heating load used in the electrification assessment reflects the broader Stage 3 plant-screening condition adopted. The 1900 kW value should therefore be interpreted as a conservative installed-capacity retrofit screening boundary rather than the sum of scheduled AHU coil duties alone. The reported electrical uplift should accordingly be understood as an upper-bound plant-screening outcome referenced to the adopted installed heating boundary, rather than as a direct measure of the building's coincident scheduled AHU peak demand.

A summary of the principal baseline model inputs, operating assumptions, and verification basis is provided in Appendix A.

3.3. Overview of Analytical Framework

System boundary of the assessment. The present study evaluates the implications of heating electrification at the plant and terminal-unit levels rather than a full whole-building energy-system replacement. The baseline case comprises gas-fired boilers serving the existing hydronic heating network, together with the existing cooling plant, which is retained as the governing baseline electrical reference during summer operation. The reported 624.17 kW summer ASHP demand is presented as a comparative reversible-operation scenario used to test whether summer or winter operation would govern electrified plant demand; it does not replace the retained baseline cooling plant within the principal retrofit boundary. The retrofit case assesses replacing combustion-based heating with ASHP-based heating at equivalent peak thermal demand, while the existing terminal-unit network is re-evaluated for low-temperature hydronic operation. Accordingly, the principal comparison is between baseline plant electrical demand and electrified plant electrical demand under governing seasonal conditions, rather than between total annual whole-building electricity consumption. This system boundary is adopted deliberately to isolate the infrastructure consequences of heating electrification, including peak electrical uplift and terminal-unit compatibility, which are the principal focus of the study.

The analytical framework was used to evaluate the implications of replacing the baseline gas-fired heating system with an ASHP system. The method translates peak building thermal demand into electrical demand while simultaneously assessing hydronic system requirements and terminal-unit performance.

The analysis was structured in three stages:

1. Hydronic system transformation, in which the thermal demand is converted to the required water flow rates and pumping energy.
2. Heat pump electrical demand calculation, based on peak heating demand and ASHP coefficient of performance (COP).
3. Terminal-unit reassessment, in which existing AHU heating coils are re-rated under low-temperature operation.

This structure allows electrification feasibility to be assessed as a coupled plant-and-distribution problem, rather than as a simple equipment substitution [18].

3.4. Hydronic System Representation

The required hydronic mass flow rate was determined from the steady-state energy balance using Equation (1). The corresponding volumetric flow rate is calculated using Equation (2). The hydraulic pumping power is determined using Equation (3) and converted to pump electrical demand using Equation (4), where the system pressure differential and combined pump-and-motor efficiency are explicitly included. Together, these relationships define the auxiliary electrical demand associated with hydronic heat delivery under electrified operation. A 55/45 °C supply/return regime was adopted as a pragmatic low-temperature retrofit condition for the present analysis. This temperature range was selected to reflect an operating condition that is more compatible with ASHP efficiency than conventional high-temperature boiler systems while remaining within a range that existing hydronic terminal units may approach under retrofit conditions. Therefore, the chosen regime provides a suitable basis for evaluating the interaction between improved plant efficiency and reduced terminal-unit capacity.

$$\dot{m} = \frac{Q_{heat, peak}}{c_p \Delta T} \quad (1)$$

where $\dot{m}$ is the water mass flow rate (kg/s), $Q_{heat, peak}$ is the peak heating load (kW), c_p is the specific heat capacity of water, and ΔT is the temperature differential between supply and return water.

The corresponding volumetric flow rate is given by

$$\dot{V} = \frac{\dot{m}}{\rho} \quad (2)$$

where ρ is the density of water.

The hydronic pumping power was calculated from the pressure–flow relationship as follows:

$$P_{hyd} = \Delta P \cdot \dot{V} \quad (3)$$

and converted to electrical demand as follows:

$$P_{pump} = \frac{\Delta P \cdot \dot{V}}{\eta} \quad (4)$$

where ΔP is the system pressure differential and η is the combined pump-and-motor efficiency. For the present case-study calculation, the winter ASHP heating pumping demand of 6.66 kW was evaluated using the adopted 1900 kW heating load, a 55/45 °C hydronic regime, an equivalent retrofit heating-circuit pressure differential of 88 kPa, and a combined pump-and-motor efficiency of 60%. These values represent the simplified retrofit-screening pumping basis used in Equations (3) and (4), rather than the existing baseline heating-pump schedule values reported in Appendix A.

These relationships define the auxiliary electrical demand associated with hydronic heat delivery under electrified operations.

3.5. Heat Pump Electrical Demand

The electrical demand of the compressor required to meet the peak heating load was calculated using Equation (5), which relates the thermal load to the heat pump COP. For the peak demand assessment, the ASHP was evaluated at a winter design ambient temperature

of $-5\text{ }^{\circ}\text{C}$. A COP of 2.0 was adopted as a conservative lower bound representative of adverse winter operations. This COP is intended to represent a conservative winter design point for infrastructure assessment, rather than for seasonal or annual heat-pump performance. This assumption reflects adverse operating conditions associated with low ambient temperature, increased compressor lift, and peak heating operation. It was adopted to avoid understating the electrical implications of electrification under the most onerous credible winter conditions. The robustness of this assumption is examined through the sensitivity analysis presented in Section 4.2, which shows that the electrical uplift remains material across a wider range of plausible COP values. This conservative design-point assumption is also consistent with the lower end of field-reported cold-condition heat-pump performance discussed in the literature review, where real-world COP values can fall well below nominal catalogue values under adverse ambient conditions [8,9,15]. The present study does not explicitly simulate transient defrost events, auxiliary electric heating, or manufacturer-specific capacity derating curves; these effects are therefore not embedded in the base-case numerical result and, if included, would be expected to reinforce rather than reduce the winter infrastructure constraint.

The total peak ASHP plant electrical demand is then calculated using Equation (6) as the sum of the compressor and hydronic pumping demands. This value represents the electrical demand imposed by heating electrification.

$$P_{ASHP} = \frac{Q_{thermal}}{COP(T_{ambient})} \quad (5)$$

where P_{ASHP} is the compressor's electrical demand and $COP(T_{ambient})$ is the temperature-dependent performance of the heat pump.

The total plant electrical demand is then calculated as

$$P_{total} = P_{ASHP} + P_{pump} \quad (6)$$

3.6. Electrical Infrastructure Impact Assessment

The impact of electrification was assessed by comparing the peak ASHP plant demand with the governing baseline plant demand. The incremental electrical uplift is defined by Equation (7) as the difference between the peak ASHP plant electrical demand and the maximum baseline plant electrical demand.

To ensure that the electrical uplift is assessed under the most restrictive operating conditions, Equation (8) defines the governing electrical uplift as the maximum of the winter and summer uplifts. This approach reflects the practical need to consider the highest credible plant demand when screening the potential implications of electrification for existing electrical infrastructure.

$$\Delta P_{MSB} = P_{total} - P_{baseline} \quad (7)$$

where ΔP_{MSB} is the incremental plant electrical uplift relative to the governing baseline plant electrical demand, P_{total} is the total ASHP plant electrical demand under the assessed condition, and $P_{baseline}$ is the maximum baseline plant electrical demand used as the comparison reference. To account for seasonal variation, the governing electrical uplift is defined as the maximum of the winter and summer uplifts as follows:

$$\Delta P_{MSB, max} = \max(\Delta P_{winter}, \Delta P_{summer}) \quad (8)$$

This approach provides a conservative plant-level screening basis for assessing the potential electrical infrastructure implications of electrification.

3.7. Heating Coil Re-Rating and Terminal-Unit Assessment

In addition to the plant's electrical demand, heating electrification affects the thermal performance of terminal heating units because existing coils are exposed to lower entering water temperatures. To assess this effect, the AHU heating coil's performance was re-evaluated using an effectiveness–NTU formulation. For the purposes of the present screening assessment, the coil re-rating procedure was implemented using a simplified heat-exchanger representation in which the existing coil UA was inferred from the scheduled duty, entering water temperature, entering air condition, and rated flow condition of each AHU. This approach was adopted as a pragmatic engineering method for comparative retrofit screening rather than as a detailed manufacturer coil-selection exercise. The resulting UA values should therefore be interpreted as inferred effective conductances for comparing relative performance at alternative water temperatures, rather than as exact manufacturer-rated coil parameters. For screening purposes, the NTU–effectiveness formulation was implemented using a simplified counter-flow representation. This approximation is expected to provide a slightly optimistic estimate of coil performance relative to a more representative cross-flow treatment and may therefore modestly overstate the inferred UA. In addition, the coil reassessment was undertaken under equivalent airflow conditions; the present analysis therefore does not capture any VAV response in which increased airflow might partially offset coil shortfall but would also increase winter fan power.

The airside and waterside heat capacity rates are defined by Equation (9), and the corresponding capacity ratio is determined using Equation (10). The coil effectiveness is defined in Equation (11) and is related to the number of transfer units using Equation (12). The inferred overall heat transfer conductance UA is then obtained using Equation (13).

Using the inferred coil UA , the achievable heating capacity at 55 °C entering water temperature is calculated using Equation (14). The resulting reduction in coil capacity relative to the legacy high-temperature condition is given by Equation (15). Finally, Equations (16) and (17) define two uplift metrics: the required increases in water flow and heat transfer conductance to restore the original duty under low-temperature operation. The reported flow uplift factors represent the calculated increase in water flow required to recover scheduled duty under the same low-temperature condition and are therefore treated as screening-level indicators of hydronic capacity stress rather than as final design flow selections. These metrics form the basis of the AHU-by-AHU compatibility assessment reported in Section 4.5.

$$C_a = \dot{m}_a c_{p,a}, C_w = \dot{m}_w c_{p,w} \quad (9)$$

The capacity ratio is given by

$$C_r = \frac{C_{min}}{C_{max}} \quad (10)$$

where C_{min} and C_{max} are the minimum and maximum heat capacity rates.

The coil effectiveness is defined as:

$$\varepsilon = \frac{Q}{C_{min}(T_{h,in} - T_{c,in})} \quad (11)$$

and is related to the number of transfer units (NTU) as follows:

$$NTU = \frac{1}{1 - C_r} \ln \left(\frac{1 - \varepsilon C_r}{1 - \varepsilon} \right) \quad (12)$$

The overall heat transfer conductance is expressed as

$$UA = NTU \cdot C_{min} \quad (13)$$

Using the inferred UA , coil performance is re-evaluated under the reduced entering water temperature (55 °C) to determine the achievable heating capacity:

$$Q_{55} = \varepsilon_{55} C_{min}(T_{w, in, 55} - T_{a, in}) \quad (14)$$

The reduction in the heating capacity is expressed as

$$\text{Capacity Ratio} = \frac{Q_{55}}{Q_{70}} \quad (15)$$

where Q_{70} represents the scheduled heating duty under the legacy high-temperature regime.

To assess the feasibility of restoring the original performance, two uplift metrics were defined:

$$\text{Flow Uplift Factor} = \frac{\dot{V}_{required}}{\dot{V}_{existing}} \quad (16)$$

$$\text{UA Uplift Factor} = \frac{UA_{required}}{UA_{existing}} \quad (17)$$

These metrics quantify the extent to which increased water flow or heat transfer area is required to maintain the designed heating capacity under low-temperature operation.

3.8. Modelling Approach and Assumptions

The analytical framework combines first-principles thermodynamic and hydraulic relationships with simplified representations of heat-pump performance. Building thermal loads are derived from an IES VE-informed, fit-for-purpose engineering feasibility model, while plant performance is represented through reduced-order COP relationships and steady-state hydronic equations. This may be described as a hybrid white-box/grey-box approach: the building thermal behaviour is represented using physics-based modelling and design-load verification, whereas heat-pump performance, pumping demand, and hydronic operation are represented through simplified engineering relationships appropriate for screening-level assessment. The framework is intended for building-scale feasibility assessment, where the objective is to quantify electrical demand uplift and hydronic compatibility constraints rather than to simulate detailed compressor thermodynamics or full transient plant operation [18].

Although the numerical results presented in this study are specific to a single representative commercial office building, the underlying analytical methodology is transferable to a broader range of existing buildings. To support wider application, the analytical process can be expressed as a structured and repeatable workflow comprising the following steps:

- (1) Determine the peak heating and cooling loads using suitable software-based feasibility models, such as IES VE-informed models, design-day heat-balance calculations, or BMS time-series data where available.
- (2) Establish heat-pump performance under design ambient conditions, including COP degradation at low temperatures.
- (3) Convert the thermal demand to electrical demand using temperature-dependent COP relationships and hydronic pumping requirements.
- (4) Use the resulting peak electrical demand to quantify plant-level electrical uplift and assess the potential implications for existing switchboard and transformer capacity.
- (5) Re-rate existing AHU heating coils under reduced entering water temperatures (40–55 °C) using NTU–effectiveness methods to quantify capacity shortfall.
- (6) Determine enabling measures, including flow rate increases, coil modification, envelope improvements, and hybrid system configurations.

Accordingly, the principal contribution of this study lies not in the universal applicability of the reported values, but in providing a structured workflow through which electrical uplift, heat-pump performance, and hydronic compatibility can be assessed in other retrofit contexts. This workflow enables practitioners to evaluate electrification feasibility in other commercial buildings in a consistent and transparent manner. In addition to the base-case assessment, a limited parametric extension was undertaken to test the sensitivity of the principal results to variation in peak heating-load magnitude and heat-pump COP. The purpose of this analysis was not to represent full multi-building or time-series behaviour, but to determine whether the governing electrical conclusions remain materially consistent across a plausible range of retrofit conditions.

4. Results

4.1. Overview of Analytical Outputs

The results are presented in terms of peak thermal demand, the corresponding electrical demand under ASHP operation, and the resulting electrical uplift relative to baseline conditions. Additional results are provided for the distribution of electrical demand components and the impact of reduced supply temperatures on the AHU heating coil performance. Although the present results are specific to the case-study building, the analytical structure is transferable and serves as the basis for the workflow described in Section 3.8.

4.2. Peak Thermal-to-Electrical Demand and COP Sensitivity

The peak heating and cooling demand for the case-study building is 1900 kW and 1813.10 kW, respectively. For reference, the scheduled AHU heating duties reproduced in Appendix A sum to approximately 1046.3 kW, while the 1900 kW value used in the base case represents the adopted Stage 3 installed-capacity screening boundary.

Under ASHP operation with a COP of 2.0, the corresponding peak electrical demand was calculated as 956.66 kW for heating and 624.17 kW for cooling, using the governing energy balance, hydronic flow, pumping, and heat-pump performance relationships defined in Equations (1)–(6). This represents the electrical input required to meet the design heating and cooling loads, along with the corresponding pumping power under winter and summer conditions. For summer operation, a cooling COP of 3.0 was adopted for the comparative ASHP cooling case. Under the governing cooling load of 1813.10 kW, this corresponds to a compressor electrical demand of 604.37 kW, which, together with 19.80 kW of associated chilled-water pumping demand, gives the reported total summer plant electrical demand of 624.17 kW. The larger summer pumping term reflects the higher cooling-mode water flow associated with the adopted 7/14 °C chilled-water regime and the 192 kPa equivalent cooling-circuit pressure differential, compared with the 55/45 °C heating case and 88 kPa equivalent heating-circuit pressure differential.

This summer ASHP case is therefore used as a comparative electrified-operation scenario rather than as the principal adopted retrofit boundary, which retains the existing cooling plant as the baseline summer electrical reference.

Figure 1 separates the peak thermal-load basis from the corresponding plant electrical demand to avoid conflating thermal and electrical quantities. Figure 1a presents the peak heating and cooling thermal loads used as inputs to the ASHP assessment, while Figure 1b presents the resulting baseline and ASHP plant electrical demands under winter and summer operating cases.

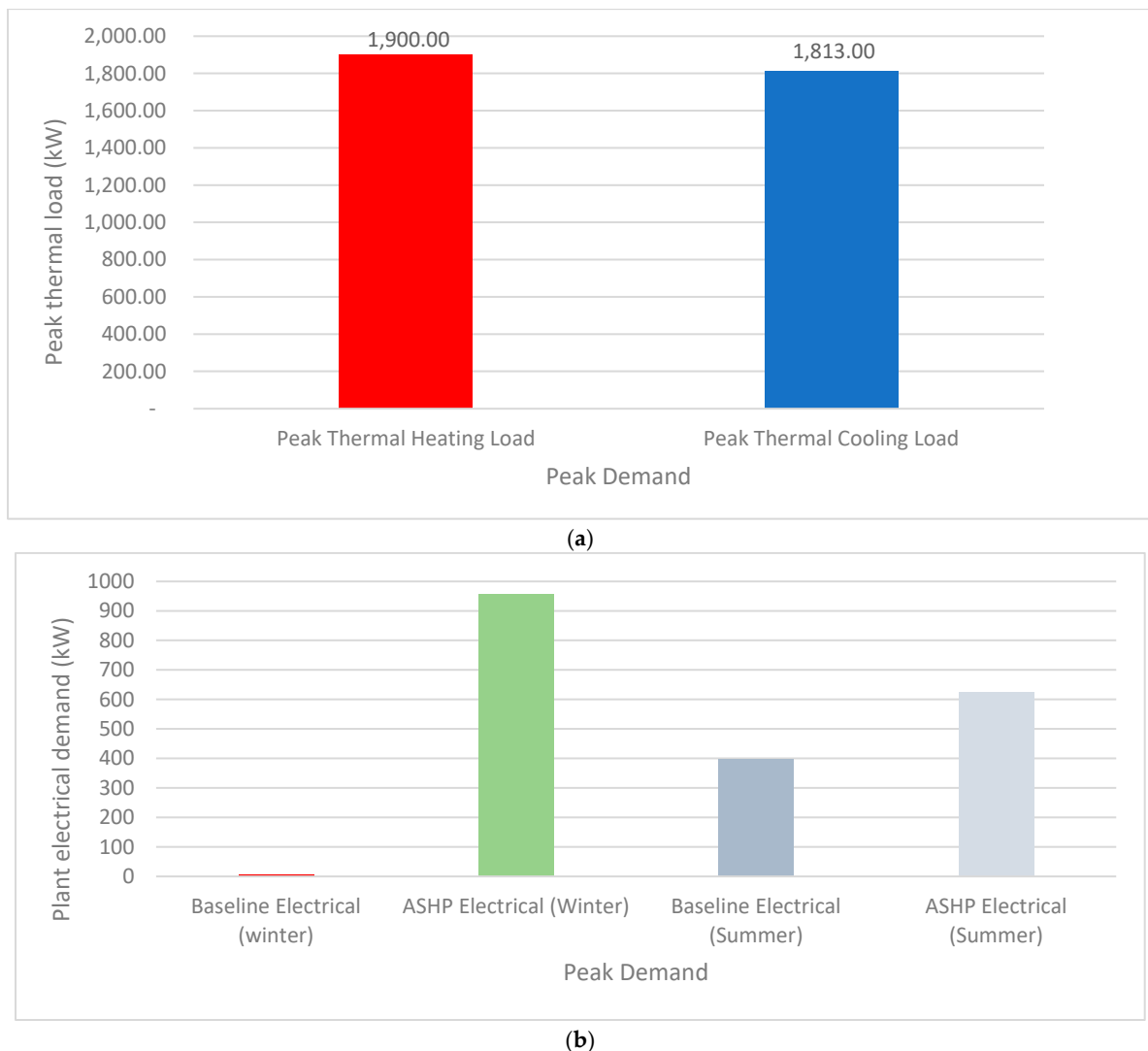


Figure 1. (a) Peak heating and cooling thermal loads used as the governing design-load inputs for the case-study building. Thermal quantities are reported in kW. (b) Baseline and ASHP plant electrical demands under winter and summer operating cases. Electrical quantities are reported in kW.

Figure 1 shows the peak thermal-to-electrical demand conversion for the base ASHP case at a design COP of 2.0. However, because the electrical demand imposed by the heat pump is highly sensitive to COP, the infrastructure implications of electrification vary significantly with plant performance under adverse operating conditions. To illustrate this dependency, Table 1 summarises the corresponding peak electrical demand and uplift across a representative range of COP values. As the COP decreases, the electrical demand required to satisfy the same 1900 kW heating load increases rapidly. In the limiting case where the COP approaches 1.0, the system offers little practical advantage over direct electric resistance heating, since nearly one unit of electrical input is required for each unit of thermal output. Under such conditions, the peak electrical demand would become prohibitively high for most retrofit applications, substantially undermining the technical and economic viability of ASHP-based electrification [8,10,15]. Table 1 summarises the sensitivity of peak ASHP plant electrical demand to variations in COP across a representative performance range.

Table 1. Sensitivity of peak ASHP plant electrical demand and electrical uplift to COP.

COP	Electrical Demand (kW)	Electrical Uplift (kW)	Relative Uplift (%)
1.5	1273	874	219.13
2	957	558	139.76
2.5	767	368	92.14
3	640	241	60.40

As shown in Table 1, lower COP values lead to a substantial increase in peak electrical demand and relative uplift, whereas higher COP values reduce, but do not eliminate, the electrical uplift relative to baseline operation. Even at a COP of 3.0, the electrified winter plant demand remains materially above the governing baseline plant demand of 399 kW.

To extend the assessment beyond one-dimensional COP testing, the same peak-demand framework was applied across a bounded range of heating-load magnitudes and design-point COP values. This additional analysis was used to test whether the main electrical findings remain materially consistent when the adopted heating-load basis and heat-pump performance assumptions are varied within a plausible retrofit screening range.

4.3. Parametric Sensitivity of Peak Electrical Uplift

To test the robustness of the base-case electrical result beyond a single COP and heating-load assumption, the peak-demand framework was extended across a bounded range of heating-load magnitudes and design-point COP values. Heating-load multipliers of 0.55, 0.80, 1.00, and 1.20 were combined with COP values of 1.5, 2.0, 2.5, and 3.0. The 0.55 multiplier corresponds closely to the scheduled AHU heating-duty total of approximately 1046.3 kW, while the 1.00 multiplier represents the adopted 1900 kW Stage 3 installed-capacity screening boundary. The 0.80 and 1.20 cases provide additional lower- and higher-load sensitivity points around the installed-capacity screening case.

For each case, the governing ASHP plant electrical demand and corresponding electrical uplift relative to the baseline peak plant demand of 399 kW were recalculated using the same thermodynamic and hydronic relationships applied in the base case. Hydronic pumping demand was scaled from the base-case winter value of 6.66 kW in proportion to the applied heating-load multiplier. Table 2 summarises the resulting peak ASHP plant electrical demand and electrical uplift across the tested parameter range. Across the sensitivity range, lower COP values and higher heating-load assumptions increase the governing winter plant demand, whereas higher COP values and lower heating-load assumptions reduce the uplift relative to the baseline plant demand.

Table 2 shows that peak ASHP plant demand and electrical uplift are strongly dependent on both the assumed heating-load basis and the design-point COP. Across all heating-load multipliers, lower COP values increase the calculated electrical demand, while higher COP values reduce the uplift relative to the governing baseline plant demand of 399 kW. The lower end of the tested load range, at approximately 0.55 of the installed-capacity case, corresponds closely to the scheduled AHU heating-duty total of 1046.3 kW reported in Appendix A. On a scheduled-duty basis, the calculated uplift is materially lower than under the adopted 1900 kW Stage 3 installed-capacity screening boundary. Conversely, the base-case 1.0 multiplier represents the conservative installed-capacity screening condition and produces the reported 557.7 kW uplift at COP = 2.0. The sensitivity results therefore confirm that the headline uplift should be interpreted as an upper-bound installed-capacity screening result, rather than as the building's coincident scheduled AHU peak-demand outcome.

Table 2. Parametric sensitivity of peak ASHP plant electrical demand and electrical uplift to heating-load magnitude and COP.

Heating-Load Multiplier	Peak Heating Load (kW)	COP	Peak ASHP Plant Demand (kW)	Electrical Uplift (kW)	Relative Uplift (%)
0.55	1046.30	1.50	701.20	302.20	75.74
0.55	1046.30	2.00	526.82	127.82	32.04
0.55	1046.30	2.50	422.19	23.19	5.81
0.55	1046.30	3.00	352.43	−46.57	−11.67
0.80	1520.00	1.50	1018.66	619.66	155.30
0.80	1520.00	2.00	765.33	366.33	91.81
0.80	1520.00	2.50	613.33	214.33	53.72
0.80	1520.00	3.00	511.99	112.99	28.32
1.00	1900.00	1.50	1273.32	874.32	219.13
1.00	1900.00	2.00	956.66	557.66	139.76
1.00	1900.00	2.50	766.66	367.66	92.14
1.00	1900.00	3.00	639.99	240.99	60.40
1.20	2280.00	1.50	1527.99	1128.99	282.95
1.20	2280.00	2.00	1147.99	748.99	187.72
1.20	2280.00	2.50	919.99	520.99	130.57
1.20	2280.00	3.00	767.99	368.99	92.48

Figure 2 shows the relationship between heating-load multiplier and peak ASHP plant electrical demand across the tested COP range. The results indicate an approximately linear increase in plant electrical demand with increasing load multiplier for each COP series. For any given load multiplier, lower COP values produce materially higher plant electrical demand, whereas higher COP values reduce, but do not eliminate, the electrification-related uplift relative to the baseline plant demand.

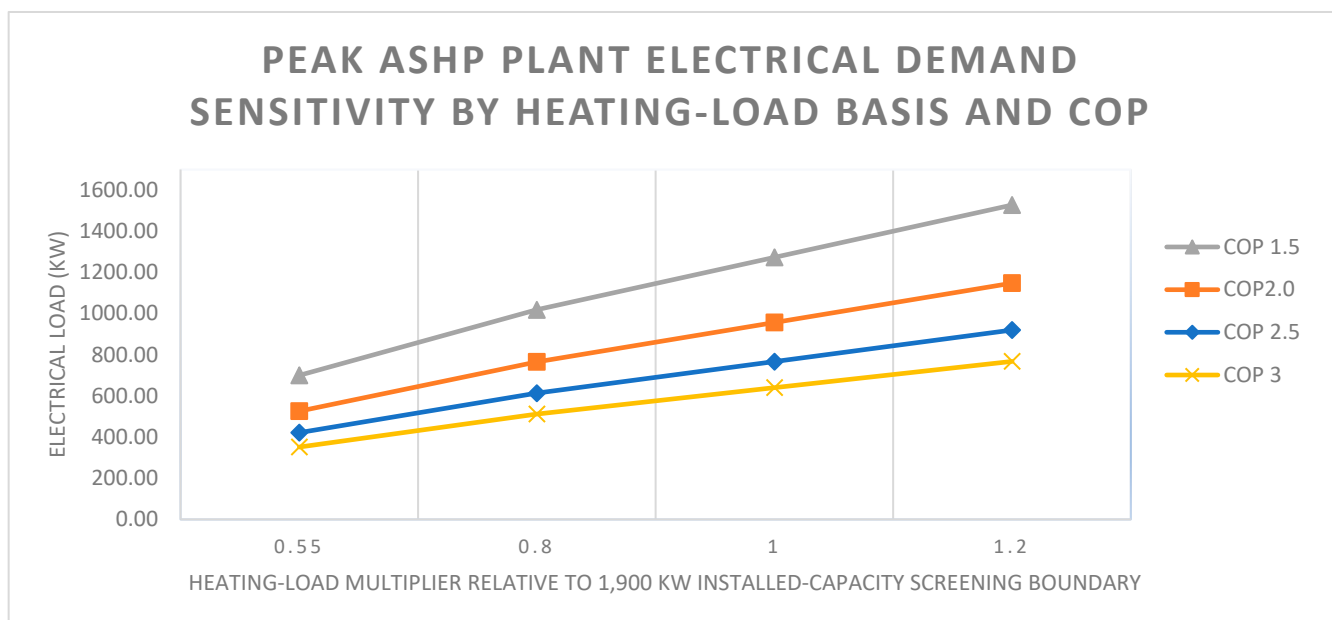


Figure 2. Sensitivity of peak ASHP plant electrical demand to heating-load basis and design-point COP. The 0.55 multiplier corresponds approximately to the scheduled AHU heating-duty basis of 1046.3 kW, while the 1.00 multiplier represents the adopted 1900 kW Stage 3 installed-capacity screening boundary.

Across the tested range, the base-case conclusion remains unchanged: ASHP electrification materially increases winter plant electrical demand relative to the baseline

cooling-governed electrical peak. Accordingly, the feasibility of heating electrification in the assessed building remains sensitive to both design-point COP and the magnitude of the governing peak heating load.

4.4. Baseline and Electrified Peak Demand Comparison

Under baseline operation, peak electrical demand was driven by the cooling system, with a maximum plant demand of 399 kW. The governing winter ASHP plant electrical demand of 956.66 kW comprises 950.00 kW of compressor demand and 6.66 kW of hydronic pumping demand. The component breakdown shown in Figure 3 therefore disaggregates this governing winter plant demand into its principal contributors rather than introducing an alternative total demand value.

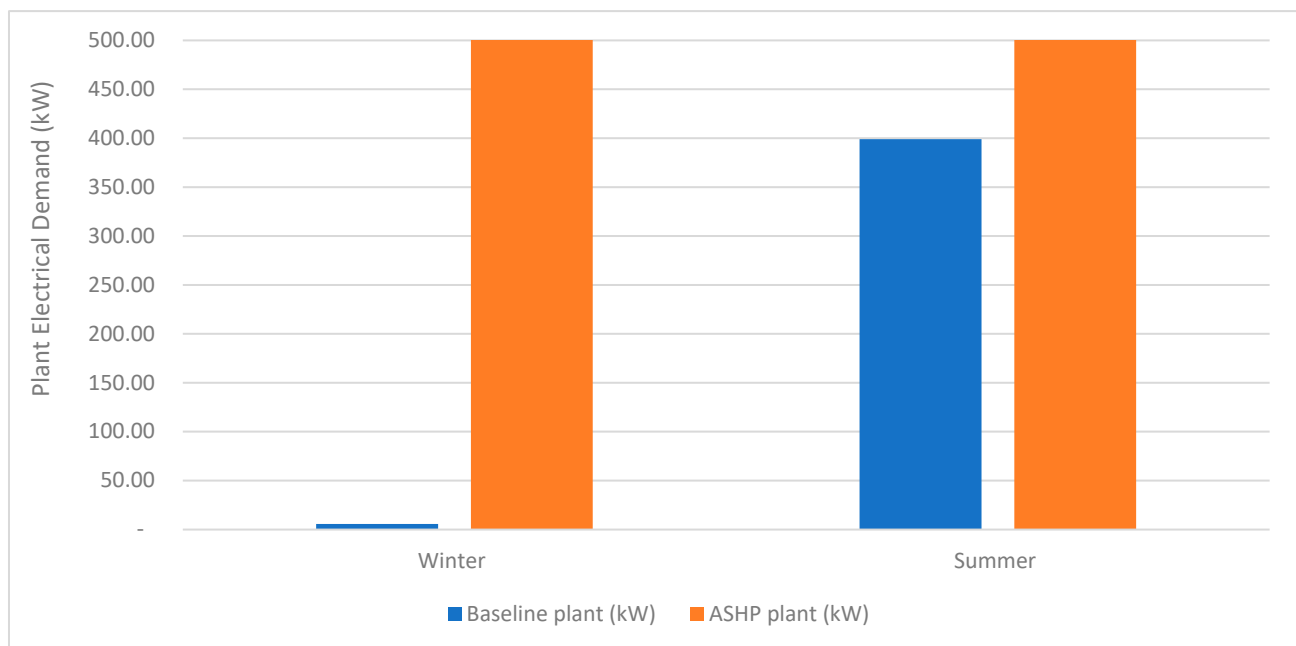


Figure 3. Comparison of baseline and ASHP peak plant electrical demand.

Importantly, the electrified winter heating peak exceeded the corresponding summer ASHP plant demand, indicating that electrification shifts the governing design condition from a cooling-dominated baseline to a heating-dominated winter operation.

4.5. Electrical Demand Breakdown

The distribution of electrical demand under ASHP operation is dominated by compressor power, which accounts for approximately 99% of the total demand. Auxiliary loads, including primary circulation pumps, contribute to a minor proportion of the total electrical load. For clarity, the peak ASHP plant electrical demand reported in this study refers to the combined winter plant demand used for infrastructure assessment, comprising heat pump compressor electrical input and associated hydronic pumping demand. The component breakdown shown in Figure 4 is therefore presented to disaggregate the governing winter plant demand into its principal contributors, rather than to introduce an alternative total demand value.

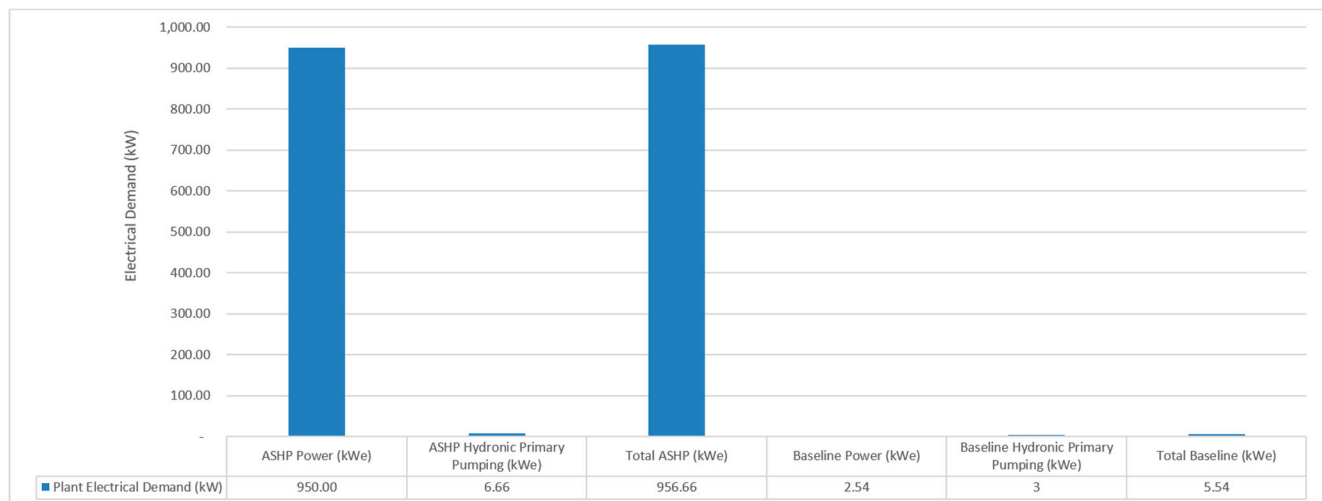


Figure 4. Component breakdown of the governing winter ASHP plant electrical demand for the case-study building, including compressor and hydronic pumping contributions.

4.6. AHU Heating Coil Performance

The transition from conventional high-temperature operation to low-temperature ASHP operation (55/45 °C) reduces the logarithmic mean temperature difference across the AHU heating coils, thereby reducing the achievable heating duty under equivalent airflow conditions. In the assessed case-study building, the resulting AHU capacity ratios generally fall in the range of approximately 0.71–0.79 of the scheduled high-temperature duty. To maintain the original heating output, increased hydronic flow rates, coil surface area augmentation, or coil replacement would be required for several units.

This increase in hydronic demand introduces additional auxiliary load and may place material stress on the hydraulic capacity of the existing pipework and pumps, particularly where system dimensions are fixed by retrofit constraints. Table 3 presents the AHU-by-AHU coil performance assessment under 55/45 °C ASHP operation.

Table 3. AHU coil performance impact under 55/45 °C ASHP operation.

Unit	Scheduled Duty (kW)	Capacity 55 °C (kW)	Capacity Ratio (Q_{55}/Q_{70})	Indicative Shortfall (%)	UA Uplift Factor (×)	Modification Required
AHU—1	46.40	32.91	0.71	29	1.82	Yes
AHU—2	15.90	11.64	0.73	27	1.65	Yes
AHU—3	4.20	3.26	0.78	22	1.36	No
AHU—4	24.10	18.38	0.76	24	1.53	Likely
AHU—5	222.10	168.71	0.76	24	1.56	Yes
AHU—6	173.10	131.49	0.76	24	1.49	Likely
AHU—7	77.10	54.60	0.71	29	1.70	Yes
AHU—8	50.10	35.81	0.71	29	1.69	Yes
AHU—9	50.10	35.81	0.71	29	1.69	Yes
AHU—10	61.80	48.96	0.79	21	1.44	Moderate
AHU—11	61.80	48.96	0.79	21	1.44	Moderate
AHU—12	184.30	133.11	0.72	28	1.70	Likely
AHU—13	75.30	53.28	0.71	29	1.69	Yes

Across the 13 AHU heating coils assessed, the reduction in entering water temperature from 70 °C to 55 °C resulted in capacity shortfalls generally in the order of approximately 21–29% relative to scheduled duty. The corresponding flow uplift factors required to restore original duty ranged from approximately 1.4 to 2.0, indicating that substantial increases

in hydronic capacity would be required in several cases. Similarly, the UA uplift factors required to maintain design heating output ranged from approximately 1.3 to 1.8, indicating that coil surface-area increases or coil replacement would be necessary for most units.

4.7. Summary of Key Results

Under the adopted 1900 kW Stage 3 installed-capacity screening boundary, the results indicate that ASHP electrification increases peak plant electrical demand from 399 kW to 956.7 kW, with compressor power representing the dominant component of the electrical load. This governing value refers to the winter plant electrical demand adopted for infrastructure comparison and is used consistently throughout the manuscript as the basis for the reported electrical uplift.

5. Discussion

The results of this study provide a building-scale demonstration of the constraints identified in the preceding literature review. They show how peak electrical demand, design-point heat-pump performance, and low-temperature terminal-unit compatibility interact to shape the feasibility of ASHP retrofit in the assessed commercial-building case.

5.1. Alignment with and Extension of Electrification Literature

Several studies have noted that electrification fundamentally alters the relationship between thermal and electrical demand, increasing peak electrical loads at both the case-study building and grid scales [7–9]. The present results substantiate these findings at the building level: when referenced to the adopted 1900 kW Stage 3 installed-capacity screening boundary, replacing gas-fired heating with ASHPs increases peak plant electrical demand by 557.7 kW, shifting the governing design condition from cooling to heating. This confirms the assertion by recent electrification research that annual energy metrics obscure critical peak load constraints [3,4] and demonstrates that these constraints are not theoretical; they appear as substantial, quantifiable electrical uplifts in the assessed building.

Accordingly, this study extends prior work by quantifying the plant-level electrical consequences of COP variability, showing that even modest reductions in COP can materially increase electrification-related demand uplift.

5.2. Hydronic and Terminal-Unit Constraints in Context

The hydronic and coil performance results also align with and deepen the literature on low-temperature operations. Prior studies have noted that reducing supply temperatures from 70 to 90 °C to 40–55 °C significantly reduces coil heat transfer capacity [11–14], but few have quantified this effect at the building scale or linked it to retrofit feasibility. The present analysis shows that AHU heating coils in the case-study building experience capacity shortfalls of 21–29%, with required flow uplift factors of 1.4–2.0 and UA uplift factors of 1.3–1.8. These findings confirm the concerns raised in prior hydronic research [11–14] and indicate that terminal-unit derating is a material retrofit constraint that should be evaluated alongside plant-level electrical uplift.

Furthermore, the results support the argument by envelope-performance studies [16,17] that reducing heating loads can mitigate the challenges of electrification. However, the diminishing returns noted in those studies are consistent with the present finding that even substantial load reductions may not eliminate hydronic or electrical constraints, particularly in buildings with high baseline heating loads.

5.3. Integrated Implications for Electrification Practice

By synthesising electrical, hydronic, and thermal performance within a single analytical framework, this study provides a more holistic understanding of electrification feasibility than is typically found in the literature. The results demonstrate that:

- Plant-level electrical demand uplift, rather than annual energy performance alone, emerges as the governing screening issue for the assessed retrofit case [3,4,7].
- Terminal-unit compatibility cannot be assumed, extending the findings of coil-performance research [11–14] by quantifying the scale of derating across an entire building.
- Heat-pump performance at design ambient conditions, rather than seasonal COP, must be used for feasibility assessment, reinforcing the concerns raised by field studies documenting COP variability [8,9,15].

These insights collectively support a shift toward peak-load-based electrification planning, in which plant-level electrical uplift, hydronic compatibility, and real-world heat-pump performance are treated as first-order design considerations. While the present study focuses on a low-temperature ASHP configuration as a representative electrification pathway, alternative retrofit strategies may modify the magnitude of the resulting uplift and terminal-unit constraint. These include higher-temperature heat pumps, hybrid or bivalent heating arrangements, staged electrification, thermal storage, and demand-reduction measures that lower the governing peak heating load. The practical significance of the present results, therefore, lies not in claiming that all electrification pathways are equivalently constrained, but in showing that under the assessed low-temperature design condition, both electrical uplift and terminal-unit compatibility require explicit evaluation. In practical terms, higher-temperature heat-pump or hybrid arrangements would be expected to reduce the coil-capacity shortfall materially relative to the 55/45 °C base case, although this would likely be offset, at least in part, by lower design-point heat-pump efficiency and a reduced electrical-performance advantage.

5.4. Policy and Industry Implications

The results also have implications for policy frameworks that promote building electrification. Current programmes often emphasise annual energy savings or emissions reductions, but the literature increasingly recognises the need for infrastructure-aware approaches [3,4]. The present findings support this shift by showing that, under the adopted installed-capacity screening boundary for the assessed case-study building, a 140% increase in peak electrical demand and widespread coil derating are associated with material electrical and hydronic implications for electrification. These results suggest that electrification pathways in existing commercial buildings may be difficult to implement effectively unless electrical and hydronic constraints are explicitly considered.

Policy mechanisms that support electrification in existing commercial buildings may therefore need to include:

- a. Incentives for switchboard, transformer, and feeder upgrades;
- b. Support for hydronic system adaptation;
- c. Requirements for peak-load-based feasibility assessments;
- d. Recognition of envelope improvements as electrical capacity mitigation measures, consistent with the integrated perspectives proposed in [16,17].

These results can inform policy discussion by illustrating how electrification feasibility may be shaped by plant-level electrical uplift and hydronic compatibility in existing commercial buildings. However, the present study should be understood as a detailed

single-building case-study contribution rather than a direct basis for universal policy requirements across the wider office sector.

5.5. A Generalisable Framework for Broader Application

Although the numerical results presented in this study are specific to a single representative commercial office building, the underlying analytical methodology is applicable to a broader range of retrofit contexts. The principal contribution of the study lies not in the universal applicability of the reported values, but in providing a structured workflow for assessing electrical uplift, heat-pump performance, and hydronic compatibility in a consistent and transparent manner [3,4,8,11,14,17]. In other buildings, the specific outcomes will vary with building characteristics, climate, operating schedules, baseline plant configuration, heating-load basis, selected design-point COP, and hydronic operating regime. However, the workflow remains transferable because these variables can be substituted into the same peak-load-based screening framework to test retrofit feasibility under alternative conditions.

Notwithstanding its practical applicability, the present study is intentionally scoped as a building-scale, steady-state feasibility/screening assessment. It is based on a single commercial office building, a single climatic context, and a limited set of design-point assumptions, including the selected winter design COP and low-temperature hydronic operating regime. While this scope is appropriate for identifying governing infrastructure constraints, it does not capture transient plant performance, seasonal control interactions, detailed electrical network modelling, or full techno-economic optimisation. The workflow should therefore be interpreted as a transferable screening method rather than as a claim of universally generalisable numerical outcomes.

6. Conclusions

This study shows that the feasibility of air-source heat pump (ASHP) electrification in the assessed commercial office building is strongly influenced by peak electrical demand uplift and hydronic system compatibility, rather than by annual energy performance alone. By integrating thermal-to-electrical load translation, temperature-dependent heat-pump performance, and terminal-unit re-rating within a single analytical framework, the study provides a building-scale screening assessment that addresses key gaps identified in the literature.

When referenced to the adopted 1900 kW Stage 3 installed-capacity screening boundary, replacing gas-fired heating with ASHPs increases peak plant electrical demand by 557.7 kW, shifting the governing design condition from cooling to heating and reinforcing concerns raised in prior research regarding the peak-load implications of electrification. The sensitivity of peak electrical demand to COP further highlights the importance of evaluating heat-pump performance under design ambient conditions, consistent with field studies that report reduced efficiency in cold weather.

In parallel, the re-rating of AHU heating coils under 55/45 °C operation shows capacity shortfalls of 21–29%, together with required flow and UA uplift factors that would exceed the practical capability of many existing hydronic systems. These findings reinforce earlier work on low-temperature hydronic constraints and indicate that terminal-unit compatibility is a material determinant of retrofit feasibility.

Together, these results show that electrification of existing commercial buildings cannot be assessed solely through annual energy or emissions metrics. Instead, peak-load-based feasibility assessment is required, incorporating plant-level electrical uplift, hydronic performance, and real-world heat-pump behaviour. The decarbonisation significance of these findings should also be interpreted in relation to local electricity and gas emission factors,

as the emissions benefit of electrification depends on both the displacement of fossil-fuel heating and the carbon intensity of grid electricity. A full comparative emissions assessment was outside the scope of the present plant-level screening study and would depend on the applicable electricity and gas emission factors, control strategy, and operating profile for the assessed jurisdiction. The present analysis therefore focuses on a retrofit feasibility screening rather than on quantified lifecycle or operational emissions comparison.

The conclusions of the present study should be interpreted within the scope of a single-building, steady-state, design-point assessment undertaken for a Canberra office building under the stated baseline and retrofit assumptions. The study does not quantify actual switchboard ratings, transformer headroom, feeder limits, or measured whole-building demand data and should therefore be interpreted as a plant-level screening assessment rather than as an infrastructure certification exercise.

Accordingly, the reported numerical values are case-specific and are not intended to represent universal outcomes across the broader commercial building stock. Rather, the principal contribution of the study lies in demonstrating, through a transparent analytical workflow, how peak electrical uplift and terminal-unit compatibility can be evaluated together in a retrofit-screening context. This workflow provides a transferable screening method for evaluating similar retrofit conditions in other existing commercial buildings.

Future research should extend this framework across a broader range of building types, climatic conditions, and design-point assumptions, and incorporate time-series modelling to capture dynamic interactions among thermal demand, electrical peaks, plant controls, and occupant behaviour. Further work is also needed to examine detailed calibration procedures, transient defrost operation, techno-economic trade-offs, and the interaction of electrification with on-site renewables, thermal storage, and upstream grid capacity.

Author Contributions: D.K.: Data curation and assessment, formal analysis, Investigation, methodology, resources, software, validation, writing—original draft, review and editing. A.K. and S.W.: Visualisation, Supervision, review and editing. All authors have read and agreed to the published version of the manuscript.

Funding: This study received no external funding.

Data Availability Statement: The original contributions presented in the study are included in the article, and further enquiries can be made to the corresponding author. Data are available in Appendix A.

Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

The following abbreviations are used in this manuscript:

AHU	Air handling unit
ASHP	Air-source heat pump
COP	Coefficient of performance
GHG	Greenhouse gas
HVAC	Heating, ventilation, and air-conditioning
LMTD	Logarithmic mean temperature difference
NABERS	National Australian Built Environment Rating System
NCC	National Construction Code
NTU	Number of transfer units
N + 1	Redundant plant arrangement with one additional unit beyond the required duty

Nomenclature

Symbol	Definition	Units
A	Heat transfer surface area	m^2
c_p	Specific heat capacity of water	$\text{kJ}\cdot\text{kg}^{-1}\cdot\text{K}^{-1}$
C_{air}	Air-side heat capacity rate	$\text{W}\cdot\text{K}^{-1}$
C_{water}	Water-side heat capacity rate	$\text{W}\cdot\text{K}^{-1}$
C_{min}	Minimum heat capacity rate	$\text{W}\cdot\text{K}^{-1}$
C_{max}	Maximum heat capacity rate	$\text{W}\cdot\text{K}^{-1}$
C_r	Capacity ratio, C_{min}/C_{max}	–
$\dot{m}$	Mass flow rate	$\text{kg}\cdot\text{s}^{-1}$
$\dot{V}$	Volumetric flow rate	$\text{m}^3\cdot\text{s}^{-1}$
NTU	Number of transfer units	–
$P_{ASHP, peak}$	Peak plant electrical demand under ASHP operation	kW
$P_{base, max}$	Maximum baseline plant electrical demand	kW
P_{comp}	Compressor electrical demand	kW
P_{elec}	Electrical power input	kW
P_{pump}	Pump electrical demand	kW
Q	Heat transfer rate or thermal load	kW
Q_{55}	Coil heating capacity at 55 °C entering water condition	kW
Q_{70}	Coil heating capacity at legacy high-temperature condition	kW
$Q_{heat, peak}$	Peak heating load	kW
$Q_{cool, peak}$	Peak cooling load	kW
T_{amb}	Ambient outdoor temperature	°C
T_{sup}	Supply water temperature	°C
T_{ret}	Return water temperature	°C
UA	Overall heat transfer conductance	$\text{W}\cdot\text{K}^{-1}$
ΔP_{MSB}	Electrical uplift, $P_{ASHP, peak} - P_{base, max}$	kW
Δp	Hydraulic pressure differential	Pa or kPa
ΔT	Water temperature differential	K
ΔT_{lm}	Logarithmic mean temperature difference	K
η	Pump and motor efficiency	–
ε	Heat exchanger effectiveness	–
ρ	Density of water	$\text{kg}\cdot\text{m}^{-3}$

Appendix A

Appendix A.1. Purpose of This Appendix

This appendix documents the principal case-study building baseline inputs, system-boundary assumptions, operational schedules, plant configuration, AHU data, and staging basis used to support the peak-load electrification assessment presented in the main paper. Its purpose is to improve transparency and reproducibility by clarifying how the baseline thermal loads, baseline plant electrical demands, and AHU compatibility calculations were defined and interpreted within the screening framework adopted in Sections 3 and 4. The appendix should be read as supporting a fit-for-purpose engineering feasibility model for peak-load retrofit assessment rather than a full long-term utility-bill calibration or post-occupancy measurement-and-verification exercise.

Appendix A.2. Analytical Boundary

The analytical boundary adopted in this study is limited to the building-services plant and terminal-unit implications of heating electrification. The baseline case comprises the existing gas-fired heating plant, the existing water-cooled cooling plant, and the associated pumps and AHU heating-coil network. The retrofit case assesses the replacement

of combustion-based heating with ASHP-based heating under equivalent peak thermal demand, together with re-rating of the existing AHU heating coils under low-temperature hydronic operation. Accordingly, the principal comparison in the paper is between governing baseline plant electrical demand and electrified plant electrical demand under the most restrictive seasonal operating condition, rather than between total annual whole-building electricity consumption. This boundary is consistent with the main manuscript statement that the study is a plant- and terminal-unit-level electrification feasibility assessment.

Unless otherwise stated, the reported 1900 kW peak heating load and 1813.10 kW peak cooling load should be interpreted as plant-level screening loads used for retrofit feasibility comparison. The scheduled AHU duties reproduced later in this appendix support the terminal-unit compatibility assessment but do not by themselves define the full governing plant-level screening boundary.

Appendix A.3. Case-Study Building Description

The building is an existing commercial office building located in the Canberra CBD (postcode 2600). The office component has a reported net lettable area of 16,292 m², together with a 6508 m² multi-level basement car park. The building comprises basement car parking, ground-floor retail space, and office accommodation extending to Level 12. The building is a medium-to-large Canberra office with a glazed high-performance façade and mechanically intensive central HVAC systems, forming a suitable case-study basis for plant-level electrification screening.

The building is served by a centralised HVAC system comprising 13 air-handling units (AHUs) with hydronic heating and cooling coils. Space heating is provided by gas-fired boilers and cooling by water-cooled chillers, with primary and secondary hydronic circulation. This configuration is consistent with the main paper's description of the case-study building as a representative existing Australian office building used to assess the implications of ASHP-based retrofit.

Appendix A.4. Baseline Operational Assumptions

The baseline operational profiles were derived from NABERS-aligned office schedules. Occupancy, lighting, equipment, and HVAC operation were modelled using standard weekday office patterns, generally aligned to 8:00 AM to 6:00 PM Monday to Friday, with ACT public holidays included in the annual simulation basis.

For the conditioned office areas, the baseline model adopted a temperature control band of 22.5 ± 1.5 °C, while transient areas such as lobbies were modelled at 23.0 ± 3.0 °C. Minimum outside-air ventilation for office areas was modelled at 11.25 L/s per person, with an office occupancy density of 1 person per 10 m². Transient spaces were modelled at the same outside-air rate with an occupancy density of 1 person per 5 m². These assumptions are carried forward into the case-study baseline used for the electrification analysis.

Appendix A.5. Envelope, Infiltration, and Control Assumptions

The building envelope is described as a glazed high-performance curtain-wall system with insulated spandrel panels. Reported façade performance values include glazing U-values generally ranging from ≤ 2.1 to ≤ 2.8 W/m²·K and solar heat-gain coefficients in the range 0.25–0.41, depending on façade type. Infiltration was included for perimeter air-conditioning zones at 0.5 air changes per hour. These assumptions were adopted in the baseline model to establish a realistic but screening-level representation of heat transfer and perimeter-zone load behaviour.

AHU control assumptions included supply-air pressure reset, supply-air temperature reset, differential-enthalpy economiser operation, and demand-controlled ventilation using

CO₂-based outside-air damper modulation. The economiser logic was limited to favourable outdoor dry-bulb conditions, and office floors were modelled with CO₂-based minimum-outside-air control between lower and upper set points. These assumptions support the view that the baseline model reflects a reasonably sophisticated modern office control strategy, albeit one simplified for engineering feasibility modelling.

Appendix A.6. Baseline Model Status and Load Definition

As stated in the main manuscript, the baseline model used in the paper is a fit-for-purpose engineering feasibility model. Its role is to establish the governing plant-level heating and cooling loads and the baseline plant electrical reference conditions needed for comparative retrofit assessment. In the paper, the resulting governing loads are reported as 1900 kW heating and 1813.10 kW cooling. The paper further states that the governing baseline electrical reference is the summer cooling plant demand of 399 kW, while baseline winter heating remains largely electrically decoupled except for a small auxiliary load.

Appendix A.7. AHU Schedule Used in the Terminal-Unit Assessment

The AHU schedule used for the building terminal-unit compatibility assessment is reproduced in Table A1. This schedule provides the baseline airflow and heating/cooling duties used to infer the effective coil conductance and to re-rate the coils under low-temperature operation.

Table A1. AHU schedule used in the baseline and coil re-rating assessment.

AHU Reference	Description	Airflow (L/s)	Cooling Duty (kW)	Heating Duty (kW)
AHU-G.1	Main lobby	2544	40.6	46.4
AHU-G.2	Main lobby	908	17.4	15.9
AHU-G.6	Main lobby	345	7.2	4.2
AHU-Lift	Lift 3	1020	23.9	24.1
AHU-C1	Central zone 1	13,674	291.4	222.1
AHU-C2	Central zone 2	12,699	276.2	173.1
AHU-E	Eastern zone	8458	133.0	77.1
AHU-N1	Northern zone 1	4365	69.6	50.1
AHU-N2	Northern/eastern zone 2	4353	69.6	50.1
AHU-OA1	Supplementary outside air	2606	35.1	61.8
AHU-OA2	Supplementary outside air	2491	35.1	61.8
AHU-S	Southern zone	10,431	193.2	184.3
AHU-W	Western zone	9036	142.1	75.3

The scheduled AHU heating duties sum to approximately 1046.3 kW, while the scheduled AHU cooling duties sum to approximately 1334.4 kW. These totals are lower than the governing plant-level screening loads reported in the main paper. This is intentional: the AHU schedule supports the coil re-rating exercise, whereas the 1900 kW plant heating boundary reflects the broader staged plant-screening basis described in Appendix A.9 below.

Appendix A.8. Baseline Central Plant Assumptions

Appendix A.8.1. Cooling Plant

The baseline cooling system includes two water-cooled chillers, with nominal capacities of 866.5 kW and 946.6 kW. Chilled-water flow is reported as 41.3 L/s for each machine. Chilled-water pumps were modelled in primary and secondary arrangements, with primary pump duty reported at approximately 41.3 L/s, 230 kPa, 16.2 kW and secondary pump duty at approximately 17.58 L/s, 280 kPa, 8.1 kW, all at 70% efficiency. The

condenser-water system includes open-circuit and supplementary cooling towers with associated condenser and supplementary pumps. These data provided the baseline basis for the cooling-plant representation underlying the governing summer electrical reference used in the paper.

Appendix A.8.2. Heating Plant

The baseline heating system comprises two gas-fired condensing heating hot-water boilers, each with a reported nominal capacity of 950.2 kW. Heating hot-water reset was modelled against outside-air temperature, with the supply set point varying between 80 °C at low outside-air conditions and 40 °C under warmer outside-air conditions. Primary and secondary heated-water pumps were reported at approximately 10.23 L/s, 101 kPa, 2.1 kW and 8.7 L/s, 203 kPa, 3.3 kW, respectively, at 70% efficiency. These values support the baseline heating-side assumptions, but, consistent with the paper, winter heating remains primarily gas-driven and therefore largely decoupled from the building electrical peak except for auxiliaries.

Table A2. Principal baseline plant and ASHP retrofit-screening assumptions used to support the paper.

System	Parameter	Value	Unit	Use in Manuscript
Heating plant	Boiler nominal capacity	2 × 950.2	kW	Baseline gas-fired heating plant capacity
Heating plant	Heating-water reset low-outside-air setpoint	80	°C	Baseline heating-water operating condition
Heating plant	Heating-water reset high-outside-air setpoint	40	°C	Baseline heating-water reset condition
Heating pumps—baseline primary	Flow rate	10.23	L/s	Existing baseline heating-pump schedule
Heating pumps—baseline primary	System pressure differential	101	kPa	Existing baseline heating-pump schedule
Heating pumps—baseline primary	Motor rating	2.1	kW	Existing baseline heating auxiliary load
Heating pumps—baseline primary	Pump-and-motor efficiency	70	%	Existing baseline heating-pump schedule
Heating pumps—baseline secondary	Flow rate	8.7	L/s	Existing baseline heating-pump schedule
Heating pumps—baseline secondary	System pressure differential	203	kPa	Existing baseline heating-pump schedule
Heating pumps—baseline secondary	Motor rating	3.3	kW	Existing baseline heating auxiliary load
Heating pumps—baseline secondary	Pump-and-motor efficiency	70	%	Existing baseline heating-pump schedule
ASHP retrofit heating case	Heating load basis	1900	kW	Stage 3 installed-capacity screening boundary
ASHP retrofit heating case	Hydronic regime	55/45	°C	Low-temperature ASHP heating condition
ASHP retrofit heating case	Water temperature differential	10	K	Basis for calculated heating water flow
ASHP retrofit heating case	Calculated heating water flow	45.39	L/s	Flow used for ASHP retrofit pumping calculation
ASHP retrofit heating case	Equivalent retrofit heating-circuit pressure differential	88	kPa	Retrofit-screening pressure differential used in Equation (3)
ASHP retrofit heating case	Combined pump-and-motor efficiency	60	%	Retrofit-screening efficiency used in Equation (4)
ASHP retrofit heating case	Calculated pump electrical demand	6.66	kW	Winter ASHP heating pump demand used in the main results

Table A2. *Cont.*

System	Parameter	Value	Unit	Use in Manuscript
ASHP retrofit heating case	Design-point heating COP	2	–	Conservative winter ASHP screening assumption
ASHP retrofit heating case	Compressor electrical demand	950	kW	1900 kW/COP 2.0
ASHP retrofit heating case	Total winter ASHP plant electrical demand	956.66	kW	Compressor demand plus heating pump demand
Cooling plant baseline	Chiller nominal capacity	866.5; 946.6	kW	Existing baseline cooling plant capacity
Cooling plant baseline	Chilled-water flow per chiller	41.3	L/s	Existing baseline cooling-plant schedule
Cooling pumps baseline primary	Flow rate, pressure differential and motor rating	41.3 L/s, 230 kPa, 16.2 kW	–	Existing baseline chilled-water pump schedule
Cooling pumps baseline secondary	Flow rate, pressure differential and motor rating	17.58 L/s, 280 kPa, 8.1 kW	–	Existing baseline chilled-water pump schedule
Baseline electrical reference	Baseline winter auxiliary electrical load	5.54	kW	Baseline winter heating auxiliary electrical load
Baseline electrical reference	Governing baseline plant electrical demand	399	kW	Cooling-governed baseline electrical reference
Comparative ASHP cooling case	Cooling load basis	1813.10	kW	Comparative reversible-operation ASHP cooling case
Comparative ASHP cooling case	Design-point cooling COP	3	–	Assumed cooling-mode ASHP performance
Comparative ASHP cooling case	Compressor electrical demand	604.37	kW	1813.10 kW/COP 3.0
Comparative ASHP cooling case	Chilled-water regime	7/14	°C	Comparative ASHP cooling hydronic condition
Comparative ASHP cooling case	Water temperature differential	7	K	Basis for calculated cooling water flow
Comparative ASHP cooling case	Calculated cooling water flow	61.87	L/s	Flow used for comparative ASHP cooling pumping calculation
Comparative ASHP cooling case	Equivalent cooling-circuit pressure differential	192	kPa	Cooling-mode retrofit-screening pressure differential
Comparative ASHP cooling case	Combined pump-and-motor efficiency	60	%	Cooling-mode retrofit-screening efficiency
Comparative ASHP cooling case	Calculated pump electrical demand	19.80	kW	Comparative ASHP cooling pump demand
Comparative ASHP cooling case	Total summer ASHP plant electrical demand	624.17	kW	Compressor demand plus cooling pump demand
Ventilation	Minimum outside air	11.25	L/s per person	Baseline ventilation assumption
Infiltration	Perimeter infiltration	0.5	ACH	Baseline envelope/infiltration assumption

Note: The baseline pump schedule values describe the existing installed heating and cooling pump arrangements. The ASHP retrofit heating and comparative ASHP cooling rows describe the simplified screening assumptions used to calculate the pump electrical demands reported in the main text. The 203 kPa baseline secondary heating-pump pressure differential is therefore not the basis of the 6.66 kW ASHP retrofit heating pump demand.

Appendix A.9. Plant Staging Basis and Relationship to the 1900 kW Heating Load

A central point of clarification is the relationship between the scheduled AHU duties and the governing plant-level screening loads used in the paper. The baseline plant configuration uses a staged operating philosophy to define the governing capacity condition for subsequent retrofit screening. Three operating stages were identified: base/low load, intermediate load, and Stage 3 peak/governing condition, in which full available heating and

cooling plant capacity and associated pumps were enabled within the adopted operating boundary. The Stage 3 condition was not intended to represent normal diversified annual operation, but rather the most onerous credible plant condition for electrical, thermal, and hydraulic screening.

This staged screening basis explains why the 1900 kW heating load used in the paper is greater than the sum of the scheduled AHU heating duties. The scheduled AHU coil table represents the central AHU set used for terminal-unit compatibility assessment, whereas the 1900 kW plant-level heating boundary represents the conservative governing screening condition adopted for downstream retrofit analysis. In other words, the AHU schedule and the plant-level screening load serve different purposes: the former supports the coil re-rating calculations, while the latter defines the governing plant demand against which ASHP electrification is screened.

Appendix A.10. Relationship to the Main Paper Results

Using the boundary above, the paper adopts the following canonical plant-level values:

- Peak heating load: 1900 kW;
- Peak cooling load: 1813.10 kW;
- Baseline winter auxiliary electrical load: 5.54 kW;
- Governing baseline plant electrical demand: 399 kW;
- Base-case ASHP winter plant electrical demand: 956.66 kW;
- Electrical uplift: 557.7 kW;
- Base hydronic regime for terminal-unit re-rating: 55/45 °C.

The 1900 kW heating value represents the adopted Stage 3 installed-capacity screening boundary. The scheduled AHU heating-duty total of approximately 1046.3 kW is used to support terminal-unit compatibility assessment and is now also included in the main-text sensitivity analysis. These values should therefore be interpreted as plant-level design-point screening values under the adopted case-study baseline and retrofit assumptions. They are not intended to represent annual whole-building energy use, exact utility-bill outcomes, or universal values for the wider commercial office stock. This distinction is central to the interpretation of the Results, Discussion, and Conclusions in the main manuscript.

Appendix A.11. Limitations of Appendix A

This appendix documents the principal case-study baseline inputs and assumptions used in the screening assessment, excluding information considered commercially confidential. It does not provide:

- Built form or architectural information;
- Formal long-term utility calibration statistics;
- Measured whole-building switchboard headroom, transformer spare capacity, or feeder capacity;
- Detailed manufacturer capacity maps for the assumed ASHP;
- Transient defrost modelling;
- Full techno-economic optimisation.

Accordingly, the appendix should be understood as supporting a transparent screening framework rather than a full design submission or measured post-occupancy verification package.

References

1. Wells, L.; Rismanchi, B.; Aye, L. A review of Net Zero Energy Buildings with reflections on the Australian context. *Energy Build.* **2018**, *158*, 616–628. [\[CrossRef\]](#)
2. Lamb, W.F.; Wiedmann, T.; Pongratz, J.; Andrew, R.; Crippa, M.; Olivier, J.G.J.; Wiedenhofer, D.; Mattioli, G.; Al Kourdajie, A.; House, J.; et al. A review of trends and drivers of greenhouse gas emissions by sector from 1990 to 2018. *Environ. Res. Lett.* **2021**, *16*, 073005. Correction in *Environ. Res. Lett.* **2022**, *17*, 049502. <https://doi.org/10.1088/1748-9326/ac5b3c>. [\[CrossRef\]](#)
3. Ibrahim, M.; Harkouss, F.; Biwole, P.; Fardoun, F.; Ouldboukhite, S. Building retrofitting towards net zero energy: A review. *Energy Build.* **2024**, *322*, 114707. [\[CrossRef\]](#)
4. Chen, L.; Darko, A.; Adegoriola, M.I.; Chan, A.P.C.; Yang, Y.; Tetteh, M.O. Challenges to energy retrofitting of existing office buildings in high-rise high-density cities: The case of Hong Kong. *Energy Build.* **2024**, *312*, 114220. [\[CrossRef\]](#)
5. Żelazna, A.; Pawłowski, A. Review of the Role of Heat Pumps in Decarbonization of the Building Sector. *Energies* **2025**, *18*, 3255. [\[CrossRef\]](#)
6. Mukhtar, M.; Ameyaw, B.; Yimen, N.; Zhang, Q.; Bamisile, O.; Adun, H.; Dagbasi, M. Building Retrofit and Energy Conservation/Efficiency Review: A Techno-Environ-Economic Assessment of Heat Pump System Retrofit in Housing Stock. *Sustainability* **2021**, *13*, 983. [\[CrossRef\]](#)
7. Kumar, R.; Mukhopadhyaya, P.; Froese, T.; Dekin, A.; Prince, M. Emerging HVAC Technologies and Best Practices for Energy-Efficient, Low-Carbon Buildings: A Review. *Energies* **2026**, *19*, 1296. [\[CrossRef\]](#)
8. Carroll, P.; Chesser, M.; Lyons, P. Air Source Heat Pumps field studies: A systematic literature review. *Renew. Sustain. Energy Rev.* **2020**, *134*, 110275. [\[CrossRef\]](#)
9. Byrne, P. Research Summary and Literature Review on Modelling and Simulation of Heat Pumps for Simultaneous Heating and Cooling for Buildings. *Energies* **2022**, *15*, 3529. [\[CrossRef\]](#)
10. Deng, J.; Wei, Q.; Liang, M.; He, S.; Zhang, H. Does heat pumps perform energy efficiently as we expected: Field tests and evaluations on various kinds of heat pump systems for space heating. *Energy Build.* **2019**, *182*, 172–186. [\[CrossRef\]](#)
11. Lund, H.; Werner, S.; Wiltshire, R.; Svendsen, S.; Thorsen, J.E.; Hvelplund, F.; Mathisen, B.V., 4th. Generation District Heating (4GDH): Integrating smart thermal grids into future sustainable energy systems. *Energy* **2014**, *68*, 1–11. [\[CrossRef\]](#)
12. Østergaard, D.S.; Svendsen, S. Costs and benefits of preparing existing Danish buildings for low-temperature district heating. *Energy* **2019**, *176*, 718–727. [\[CrossRef\]](#)
13. Lämmle, M.; Bongs, C.; Wapler, J.; Günther, D.; Hess, S.; Kropp, M.; Herkel, S. Performance of air and ground source heat pumps retrofitted to radiator heating systems and measures to reduce space heating temperatures in existing buildings. *Energy* **2022**, *242*, 122952. [\[CrossRef\]](#)
14. Ma, Z.; Wang, S. Energy efficient control of variable speed pumps in complex building central air-conditioning systems. *Energy Build.* **2009**, *41*, 197–205. [\[CrossRef\]](#)
15. Johnson, R.K. *Measured Performance of a Low Temperature Air Source Heat Pump*; Tech. Rep. NREL/SR-5500-56393, DOE/GO-102013-3788; U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy: Washington, DC, USA, 2013. Available online: https://www1.eere.energy.gov/buildings/publications/pdfs/building_america/low_temp_air_source_heat_pump.pdf (accessed on 22 June 2026). [\[CrossRef\]](#)
16. Wan, S.; Ding, G.; Runeson, G.; Liu, Y. Sustainable Buildings' Energy-Efficient Retrofitting: A Study of Large Office Buildings in Beijing. *Sustainability* **2022**, *14*, 1021. [\[CrossRef\]](#)
17. Jafri, A.; Villeneuve, E.; Agelin-Chaab, M.; Hangan, H. Experimental investigation of building mock-ups and air source heat pumps in cold climates. *Energy Built Environ.* **2025**, *7*, 654–671. [\[CrossRef\]](#)
18. Xu, X.; Zhang, L.; Chen, J.; Lin, Q.; Chen, J. Device Modeling Method for the Entire Process of Energy-Saving Retrofit of a Refrigeration Plant. *Energies* **2025**, *18*, 4147. [\[CrossRef\]](#)

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.