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HP systems in buildings: integrating detailed heat pump models with simplified building thermal network characterization for efficient and flexible evaluations

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Abstract

Accurate thermal load calculation is essential for assessing building energy performance and designing HVAC systems. While detailed dynamic simulation tools — such as EnergyPlus or TRNSYS — offer high accuracy, they demand significant effort in model development and require a large amount of input data. This complexity motivates the development of simpler but reliable modeling approaches. In this work, a simplified thermal model based on the thermal network approach is adopted to estimate the thermal demand in buildings, validated against a detailed TRNSYS simulation with a deviation of 4.8% in heating demand prediction. The main contribution of this study lies in the comparative analysis of three heat pump modeling strategies when coupled with the building model: (i) a basic representation assuming constant COP, (ii) a simplified polynomial model relating COP to source and sink temperatures, and (iii) a detailed model developed using specialized simulation software, which maps capacity and energy consumption across the entire operating range of the unit. This comparison highlights the impact of heat pump model complexity on integrated system performance evaluation. The proposed approach combines a simplified and input-efficient building model with multiple levels of heat pump representation, offering a fast, flexible, and accurate calculation platform. It enables rapid analysis of coupled building-HVAC behavior, facilitating the evaluation of advanced control strategies and assessing heat pump flexibility under diverse operating conditions with reduced input requirements.

Keywords: Thermal Building model ; Demand response ; Aerothermal Source Heat pump ; HP detailed model

1. Introduction

Driven by concerns about global warming and ambitious international energy policies [1-2], the decarbonization of the building sector is a critical priority. Heating, Ventilation, and Air Conditioning (HVAC) systems account for a significant portion of global energy consumption, with approximately 50% of all energy used in the EU dedicated to heating and cooling, primarily derived from fossil fuels (over 70%) [3]. In this context, heat pumps (HPs) are recognized as highly efficient units and classified as a renewable energy source [4], establishing them as the most viable alternative for replacing conventional gas boilers and promoting urban decarbonization. This transition is central to the European Union's broader goals, as outlined in the European Green Deal [5], a long-term strategy aiming for net-zero greenhouse gas emissions by 2050, which is legally mandated by the European Climate Law [6].

The urgency of this shift has been significantly heightened by the REPowerEU plan [7], which seeks to reduce the EU's energy dependence, particularly on natural gas. Consequently, policy measures are accelerating HP adoption: Directive (EU) 2024/1275 [8] prohibits incentives for installing standalone fossil-fueled boilers — responsible for nearly 39% of residential heating consumption — starting in 2025, positioning HPs as the key technology to achieve zero-emission buildings by 2050. The importance of this technology is supported by recent studies [9], confirming its central role in building stock decarbonization and integration with renewable systems, demonstrating the potential for substantial climate impact reduction (ranging from −48% to up to −91% when renewable electricity is used). Although heat pumps are a mature technology, widely regarded as the most viable alternative for decarbonizing domestic heating [10], maximizing the benefits derived from their massive integration requires further development, particularly concerning accurate characterization of their performance when integrated into buildings and implementing effective control strategies.

Specifically, maximizing the benefits of massive HP implementation requires an accurate prediction of a building's dynamic thermal demand, alongside detailed and reliable models for the heat pump systems. Methodologies for modeling building demand are well-developed and extensively studied; however, their subsequent coupling with heating and cooling systems often relies on simplified representations of heat pump performance. Given that modern units frequently incorporate variable speed components (such as compressors, fans, and circulation pumps), these simple models fail to capture the complex multivariable dependencies governing actual operational efficiency, requiring a higher level of modeling detail for precise characterization and integrated performance optimization.

Related to building models, several methodologies exist for modeling its thermal demand, differing significantly in complexity and required level of detail. At one end of the spectrum are detailed models, often developed using dynamic simulation tools like EnergyPlus [11] or TRNSYS [12], which accurately represent the intricate interactions among the envelope, HVAC systems, and climatic conditions by using the heat balance method approach. This detailed approach, however, demands a large volume of input data, including precise geometry, thermal properties of building materials, occupancy patterns, and internal heat gains quantification. Consequently, it is generally better suited for studies conducted at the scale of an individual building. However, when the objective shifts to estimating thermal demand at an urban or district scale, aggregated models are preferred, simplifying the representation of the building stock. This field primarily distinguishes between two approaches: bottom-up and top-down [13] methodologies. The bottom-up method extrapolates the characteristics of individual buildings to the urban ensemble, whereas the top-down method relies on establishing statistical relationships between energy consumption and socioeconomic or climatic variables, without needing to describe each structure individually. Within the bottom-up framework, physical models are particularly relevant, simulating thermal behavior based on physical principles; a common technique here is the thermal network approach, which simplifies dynamic heat flow representation and transient response by modeling the building and using thermal nodes, resistances and lumped capacitances representation for its elements.

The thermal network approach has been standardized in several building energy evaluation regulations. Main standards include EN ISO 13790 [14], which uses a simplified 5R1C model (five resistances and one capacitance) to represent thermal exchanges, and the more recent EN ISO 52016 [15], which introduces a more detailed scheme with multiple nodes and capacitances for each opaque element, thereby improving the representation of building's thermal inertia. Additionally, the German guideline VDI 6007 [16] proposes the 7R2C model, offering an even more granular representation of thermal behavior for dynamic calculations.

These methods, using the thermal network approach, significantly reduce computational complexity compared to full dynamic simulations like EnergyPlus, while maintaining adequate accuracy. A comparative study by Ballarini et al. [17] demonstrated reduced deviations when using consistent conditions compared to EnergyPlus software. Specifically, based on a case study of a two-storey single-family house located in Northern Italy, the authors reported that the EN ISO 52016 thermal network model underestimated annual heating demand by 4.7% and overestimated cooling demand by 0.3%, while EN ISO 13790 overestimated heating by 2.0% and cooling by 4.1%.

These results validate R-C network models as an effective compromise between simplicity and reliability. This approach has contributed the development of open-source tools — such as TEASER and EUReCA packages [18-19] — that implement R-C network models aligned with standards like EN ISO 13790 and VDI 6007, providing practical solutions for scaling building energy demand analysis to urban contexts.

Despite advances in predicting building's thermal demand across several methodologies, the subsequent coupling with heating and cooling systems, such as heat pump units, is usually implemented using simplified methods. In practice, basic models are employed, assuming a constant Coefficient of Performance (COP) or relying on polynomial expressions — typically second or third order polynomials — that depend only on source and sink temperatures (e.g., as used in EnergyPlus or TRNSYS) [20-22]. While attractive due to their simplicity and low computational cost, these models fail to capture the complexity of modern units that incorporate variable speed components — such as variable speed compressors, fans, and circulation pumps — which introduce a complex multivariable dependence. In such systems, performance is conditioned by at least five or six boundary variables, including temperatures, flow rates, and actuator speeds. This complexity requires detailed mapping of the operational conditions using highly detailed models, crucial for accurately characterizing their behavior and supporting integrated optimization strategies for both the heat pump and the building's thermal demand. Recent research [23] evaluated optimized polynomial formulations for air and ground source heat pumps, confirming their suitability for simulation and control in real-world scenarios.

The abovementioned challenges, combined with the pivotal role of heat pumps in future decarbonization strategies, underscore the requirement for modeling approaches that balance simplicity and accuracy. Such approaches are essential for reliably characterizing current HP technologies and enabling an effective integration with building energy models. In this context, this work analyzes the coupling between a building energy model and a detailed representation of a heat pump. For the building, a simplified approach based on the thermal network methodology is adopted, which allows demand estimation with low computational cost. Regarding the heat pump, three modeling levels are compared: (i) a basic representation considering a constant COP, (ii) a simple polynomial model relating the COP to source and sink temperatures [24], and (iii) a detailed model developed using the IMST-ART software [25-26], which is implemented by describing the unit's main internal components and used to map its heating capacity and energy consumption across the full operating range.

2. Methods

This section explains the approach adopted to analyze the prediction of heat pump energy consumption when coupled with the thermal demand of a building. The first part (Section 2.1) describes the building model, which is based on the thermal network approach and validated against a detailed TRNSYS simulation to ensure accuracy with reduced computational effort. The second part (Section 2.2) focuses on the heat pump modeling strategies, including two simplified representations — a constant COP and a polynomial model dependent on source and sink temperatures — and a detailed model generated with IMST-ART, which provides accurate performance maps for all operating conditions.

2.1. Building model

The building model simulated in this work follows Case 620 from ANSI/ASHRAE Standard 140 [27], which defines test procedures for evaluating the accuracy of building performance simulation software. The main characteristics of the building are summarized in Table 1.

Table 1. Summary of main characteristics of the selected building

Properties	Walls	Roof	Floor
Area [m^2]	63.8	48	48
Heat Capacity [kJ/K]	924	872	936
Resistance air-to-air [m^{2}K/W]	2.391	3.626	25.716
Solar absorptance (interior and exterior)	0.6	0.6	0.6
Infrared emittance (interior and exterior)	0.9	0.9	0.9
Exterior convective surface coefficient [W/(m^{2}K)]	11.9	14.4	0.8
Interior convective surface coefficient [W/(m^{2}K)]	2.2	1.8	2.2

The building is situated in Denver, USA, using a TMY3 dataset of a typical meteorological year as weather data. In order to study the behavior of the model the simulation was done for the second day of January using a time step of 1 hour. The zone temperature was set to 23ºC.

In order to simulate the building model, the thermal network approach (R-C model) was implemented, which consist of a set of differential equations that describe the dynamic thermal behavior of the building envelope. A thermal circuit composed of two resistances and one capacitance was selected for each opaque element of the building envelope in order to obtain simple representation for these components.

Figure 1 illustrates the thermal network approach as implemented in the model.

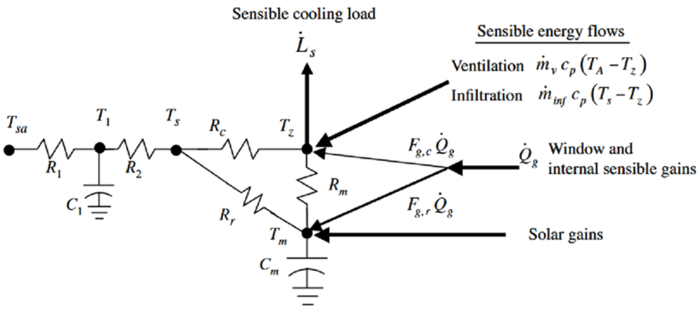

Figure 1. Thermal circuit selected for the thermal network approach model

The two resistances (R_1 and R_2) and the capacitance (C_1) reproduce the thermal behavior of the opaque building envelope. In particular, one set of resistances and capacitance for each opaque building element was implemented, connected then to the internal mass capacitance, one for each oriented wall (North, South, East and West) and one for the roof. East and West walls include two windows of 6m^2 (Clear Double-Pane Glazing).

The capacitance C_m represent the internal mass of the building. In the simulation was taken equal to the heat capacity of the floor. Internal heat gains of 200 W (entirely sensible, continuous over 24 hours) were considered, with a distribution of 60% radiative and 40% convective.

The building model was implemented using Engineering Equation Solver (EES) [28], a software widely employed for solving algebraic and differential equations. EES was selected primarily for its capability to efficiently handle differential equation systems. Additionally, the latest update of EES enables a simple and efficient communication with the programming language Python [29], which facilitates integration with external workflows.

In particular, the integration with Python enables the calculation of two key aspects:

- Easy handling of meteorological data files.
- Simple interaction with the working maps generated by using the IMST-ART model for the detailed heat pump modeling approach.

A comparison was performed between the results obtained with the simplified building model and those generated by a more detailed and complex simulation using TRNSYS (Figure 2). The results presented in Figure 2 are based on input data from Case 620 of ANSI/ASHRAE Standard 140 [27]. Table 1 provides a summary of the key input parameters used in the simulations. In particular, the building model heating demand over the entire simulated day was highly comparable between the two software solutions. The TRNSYS simulation estimated a daily heating demand of 36.3 kWh, while the R-C network model predicted 34.5 kWh, resulting in a relative error of 4.8%. This level of deviation confirms the suitability of the simplified approach for accurate thermal load estimation with significantly reduced computational effort.

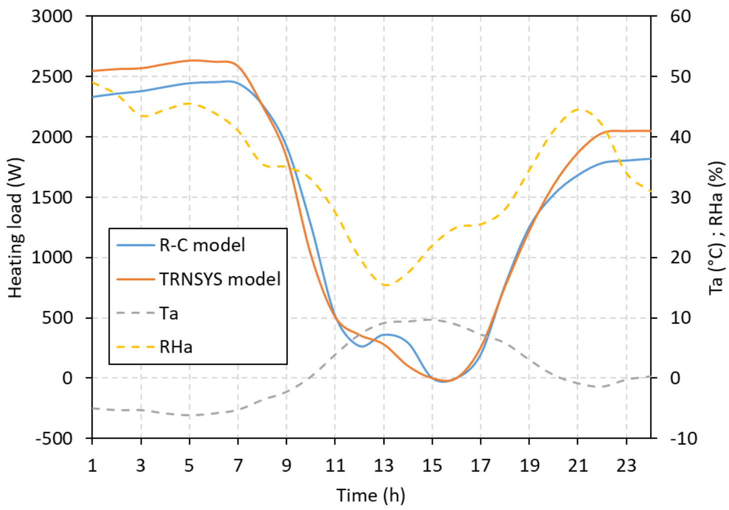

Figure 2. Comparison between the heating load from TRNSYS and R-C model

2.2. HP model

Three different approaches were considered to characterize the heat pump performance when coupled with the building model. The first two are simplified representations widely used in building energy simulations:

- Constant COP model, which assumes a fixed Coefficient of Performance regardless of operating conditions, Equation (1).
- Polynomial model [24], where COP is expressed as a function of source and sink temperatures through a second-order polynomial, Equation (2).

$$COP = \frac{Q_c}{W_c} \tag{1}$$

$$COP = k_0 + k_1(T_{co} - T_a) + k_2(T_{co} - T_a)^2 \tag{2}$$

These approaches offer low computational cost and ease of implementation but fail to capture the complex behavior of modern variable-speed heat pumps under the entire operating range.

The third approach employs a detailed model based on IMST-ART, a specialized software developed for the analysis and optimization of vapor compression systems. IMST-ART enables high-fidelity simulation of heat pump components — compressor, heat exchangers, expansion devices, and piping — by solving a system of nonlinear equations derived from energy and mass balances. Heat exchangers are discretized using a finite-volume scheme, accounting for heat transfer and pressure drop phenomena, while fluid properties are evaluated through integrated thermodynamic libraries. In practice, the model is implemented by providing IMST-ART with the geometric and performance data of the main components, such as the compressor and heat exchangers, extracted from manufacturer specifications. This level of detail allows accurate prediction of unit performance across a wide range of operating conditions.

In this work, IMST-ART was used to precompute performance maps describing the heat pump behavior under different boundary conditions. For an air-source heat pump, six variables govern its performance: compressor frequency, fan speed of the coil heat exchanger (CHEX), outdoor air dry-bulb temperature, outdoor air humidity, water supply temperature, and water flow rate in the hydraulic loop of the BPHE. To simplify the analysis, three of these variables — water supply temperature (35 °C), water flow rate, and fan speed — were kept constant, while the remaining three (compressor frequency, outdoor air temperature, and humidity) were varied. A full factorial design was applied to these independent variables, generating the operating maps summarized in Table 2.

Table 2. HP operating conditions (full factorial design)

Variable	Range	Number of levels
T_a (°C)	[-8, 12]	11
RH_a (%)	[10, 60]	11
f_c (rpm)	[1800, 4200]	5
Total number of operating points = 11 x 11 x 5 = 605 simulated points		

The heat pump considered in this study is a variable-speed unit operating with refrigerant R32 based on a previous developed model, validated experimentally in [23]. Its nominal capacity was adapted using IMST-ART's unit scaling capabilities to match the required heating demand at the nominal compressor frequency. This ensures consistency with the building load while preserving the detailed operation and physical trends of the original validated model.

Once the performance maps were generated, they were integrated into the simulation workflow. For the constant COP approach, the average COP from the map was adopted (4.8). For the polynomial model, coefficients were fitted to the map data generated with IMST-ART. In both cases, the Coefficient of Performance was evaluated considering only compressor power, COP, and also including auxiliary consumption (fan and circulation pump), COP_{aux}. For the detailed approach, the operating point was determined by linear interpolation within the IMST-ART generated maps, enabling accurate estimation of capacity and power consumption under dynamic conditions.

The combined use of EES and Python provides a significant advantage in the detailed heat pump modeling process. The working map generated with IMST-ART describes the unit performance under variable operating conditions, considering outdoor air temperature, air humidity, and compressor speed as boundary variables.

As mentioned above, in the modeled case, water supply temperature and flow rate, as well as the fan speed of the coil heat exchanger, are kept constant, while the indoor zone is maintained at 23 °C to ensure thermal comfort. Under these conditions, the building model determines the required sensible heating capacity, which the heat pump must deliver by adjusting the compressor speed. Instead of manually iterating this parameter, the integration of EES with Python enables an automated calculation of the necessary compressor frequency based on the heating capacity demand as input information for the HP detailed model.

Finally, the three modeling approaches were applied to determine the hourly electricity consumption of the heat pump throughout the analyzed day. For simplicity, no capacity degradation due to frost formation was considered under negative outdoor air temperatures. Additionally, when operating at the minimum compressor speed, no part-load penalty was applied in any of the three approaches, as the objective is to isolate and compare the differences between modeling strategies. The detailed IMST-ART-based model served as the reference for error evaluation. Relative error was calculated for the comparison of total daily energy consumption, while RMSE and CV_{RMSE} was used to assess average deviations in hourly values.

3. Results and discussion

The comparison of the three heat pump modeling approaches — constant COP, polynomial model, and detailed IMST-ART model — highlights discrepancies in predicted energy consumption when integrated with the building model. The analysis starts with the hourly results in Table 3, which illustrate the dynamic behavior of each approach throughout the simulated day. It includes the compressor and total energy consumption.

Table 3. Hourly Energy consumption and thermal demand for the simulated day

Time	T_a	RH_a	Q_c	f_c	Load percentage	IMST-ART		COP cte.		COP poly.	
						W_c	W_{tot}	W_c	W_{tot}	W_c	W_{tot}
h	°C	%	W	rpm	-	W	W	W	W	W	W
1	-5.0	49	2332	2949	1.00	582	688	486	583	593	705
2	-5.3	47	2359	3001	1.00	591	698	491	590	604	719
3	-5.3	44	2379	3025	1.00	596	703	496	595	609	725
4	-5.9	45	2415	3111	1.00	613	720	503	604	626	745
5	-6.2	46	2446	3172	1.00	625	732	510	612	639	760
6	-5.9	44	2454	3159	1.00	623	730	511	614	636	757
7	-5.3	41	2444	3101	1.00	612	718	509	611	625	744
8	-3.6	36	2267	2780	1.00	551	657	472	567	558	663
9	-2.3	35	1920	2311	1.00	462	568	400	480	457	542
10	0.3	33	1269	1800	0.81	301	386	264	317	283	336
11	3.9	28	517.1	1800	0.30	111	142	108	129	105	124
12	7.3	20	265.6	1800	0.14	52	66	55	66	49	58
13	9.2	16	359.2	1800	0.18	66	85	75	90	63	74
14	9.4	18	292.7	1800	0.15	54	69	61	73	51	60
15	9.7	22	0	1800	0.00	0	0	0	0	0	0
16	8.9	25	0	1800	0.00	0	0	0	0	0	0
17	7.3	26	196.3	1800	0.10	38	49	41	49	36	43
18	5.9	28	771	1800	0.42	156	200	161	193	148	175
19	3.1	35	1252	1800	0.74	275	352	261	313	259	307
20	0.6	41	1520	1800	0.96	357	458	317	380	337	399
21	-0.9	45	1682	1972	1.00	402	507	350	421	386	458
22	-1.4	42	1783	2111	1.00	427	532	371	446	415	493
23	-0.3	34	1804	2075	1.00	420	525	376	451	408	484
24	0.3	31	1819	2063	1.00	418	523	379	455	405	481

During the first nine hours, corresponding to the highest thermal demand, the detailed IMST-ART model predicts compressor power ranging from 582 W to 625 W, with total unit consumption (including auxiliaries) peaking at 732 W in hour 5. In contrast, the constant COP approach underestimates consumption significantly during these peak periods, with total power values around 612 W at hour 5, representing a deviation of more than 16% compared to the reference. This discrepancy is expected, as the assumption of constant efficiency neglects the influence of outdoor air temperature and humidity, which directly affect evaporating temperature and, consequently, compressor mass flow rate and power input. The polynomial model, calibrated using IMST-ART performance maps, provides a closer approximation, predicting 760 W of total consumption at hour 5, slightly higher than the reference but within a reasonable margin. This behavior confirms that the polynomial approach captures the main trends under the constrained conditions of the study, where water supply temperature and auxiliary speeds remain constant.

As the day progresses and thermal demand decreases, absolute differences between models become less evident at partial load conditions. For example, at hour 10 (81% load), the detailed model predicts 386 W total consumption, while the constant COP approach estimates 317 W, and the polynomial model 336 W. At very low loads (hours 12–14), all models converge toward similar values, with deviations below 10 W, indicating that simplified approaches perform adequately when the compressor operates near its minimum speed. However, during intermediate loads (hours 18–20), the constant COP model continues to underestimate consumption, while the polynomial model maintains a closer alignment with the detailed reference, with these deviations increasing as we approach the last hours of the day and the building's thermal demand rises.

The evaluation of model accuracy over the entire analysis period was also performed using normalized error metrics, specifically RMSE and CV_{RMSE} (Table 4). These metrics confirm the abovementioned differences between the energy consumption prediction using the constant COP approach and the polynomial-based model compared to the detailed model in IMST-ART. For the constant COP model, CV_{RMSE} values reached 18.6% for compressor power and 18.2% for total consumption, with corresponding RMSE values of 64.6 W and 76.7 W. In contrast, the polynomial model achieved much lower errors, with CV_{RMSE} of 3.3% and 7.1%, and RMSE of 11.4 W and 29.9 W, respectively. These results highlight the superior accuracy of the polynomial approach, particularly in capturing variations under full and partial load conditions. However, it is important to note that these results are obtained within the limited mapping range of the analyzed unit. Systems where fan speed or circulation pump frequency modulation is significant may not exhibit similar performance, especially considering that the applied polynomial model is relatively simple and relies on a low number of independent variables. Furthermore, in the analyzed case, the compressor operated within a constrained range, varying only from minimum to medium speeds (1800–3000rpm). At higher compressor speeds, prediction errors for the polynomial approach could become more pronounced compared to the IMST-ART model, making the use of a detailed heat pump model a more reliable option in such conditions.

Table 4. Summary of normalized error metrics for energy prediction accuracy

	COP cte.		COP poly.	
	W_c	W_{tot}	W_c	W_{tot}
CV_{RMSE} (%)	18.6	18.2	3.3	7.1
RMSE (W)	64.6	76.7	11.4	29.9

The aggregated results in Table 5 reinforce the analyzed trends. For the entire simulated day, the detailed IMST-ART model predicts 10.11 kWh of total energy consumption, compared to 8.64 kWh for the constant COP approach (-14.6% error) and 9.85 kWh for the polynomial model (-2.6% error). When only compressor consumption is considered, the polynomial model achieves an almost negligible deviation (-0.48%), while the constant COP approach underestimates by more than 13%.

Table 5. Total daily energy consumption according to the three model approaches

IMST-ART		COP cte.		COP poly.	
W_c	W_{total}	W_c	W_{total}	W_c	W_{total}
kWh	kWh	kWh	kWh	kWh	kWh
8.332	10.108	7.197	8.637	8.293	9.849
Relative Error (%). IMST-ART model as reference model					
0.000	0.000	-13.623	-14.557	-0.478	-2.560

These findings highlight the limitations of assuming constant performance in dynamic simulations and demonstrate the robustness of the polynomial approach under constrained operating conditions. Nevertheless, the increased error observed when auxiliaries are included suggests that simplified models struggle to capture the relative impact of these components, particularly at low compressor speeds where their contribution becomes proportionally significant.

The interpretation of the reported figures below provides further insight into the analyzed trends. Figure 3 illustrates the COP variation as a function of the temperature difference between the supply water temperature in the condenser and the outdoor air temperature in the evaporator ($T_{co} - T_a$) for five compressor speeds. While several speeds converge toward similar trends, the lowest speed (1800 rpm) exhibits a marked COP reduction, a behavior commonly associated with variable-speed compressors due to insufficient lubrication at low frequencies. In some units, COP also decreases at very high speeds because of increased dissipative losses, although this effect is not prominent in the present case. Under the constrained conditions of the study — constant water supply temperature and fixed auxiliary speeds — the polynomial fit reproduces the observed trends accurately, validating its applicability for this scenario. However, Figure 4, which incorporates auxiliary consumption into COP calculation, reveals greater dispersion among the data series. At low compressor speeds, COP declines more sharply and fails to converge to a common trend, as auxiliary loads become proportionally more significant. This observation explains the increased error of the polynomial model when total consumption is considered and underscores the need for detailed approaches in comprehensive analyses.

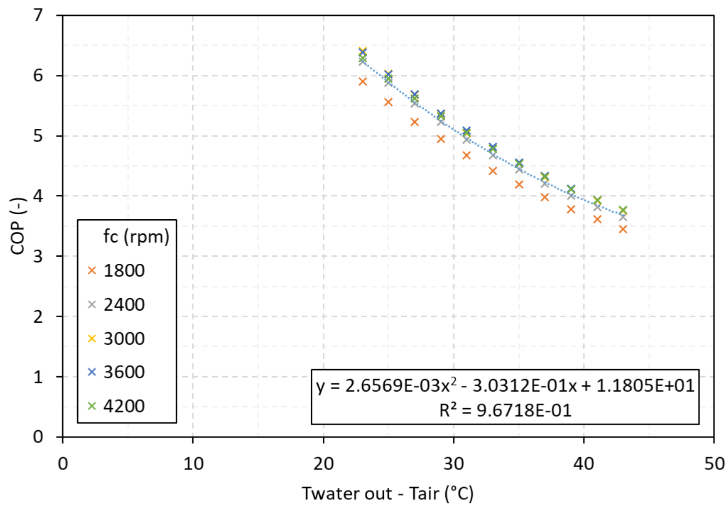

Figure 3. COP polynomial model. Polynomial equation adjusted with IMST-ART generated map

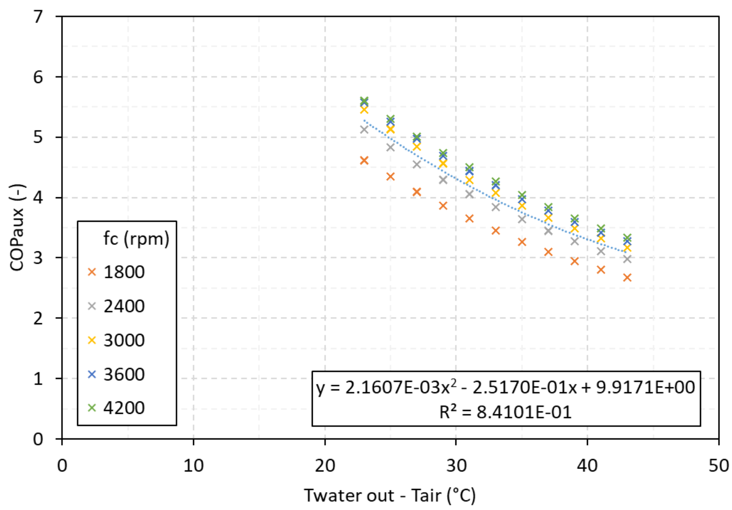

Figure 4. COP polynomial model including auxiliaries' consumption. Polynomial equation adjusted with IMST-ART generated map

Finally, Figure 5 and Figure 6 present the hourly evolution of compressor-only and total energy consumption, respectively, for the three modeling approaches. In Figure 5, the constant COP model consistently predicts lower consumption than the detailed reference during peak demand hours, reflecting the oversimplification inherent in assuming constant efficiency. The polynomial model closely follows the detailed approach, confirming its suitability for short-time period simulations. In Figure 6, however, the polynomial model exhibits a stronger deviation from the detailed reference, consistent with the dispersion observed previously in Figure 4. The corresponding errors in compressor energy consumption and total energy consumption for the heat pump models were previously presented in Tables 4 and 5. Although these discrepancies are moderate for a single-day simulation, they could accumulate significantly over annual periods, compromising prediction reliability. This suggests that polynomial models are appropriate only within a restricted operating range and short-time simulation periods. For systems with more complex control strategies or variable auxiliary operation, higher-order polynomials with interaction terms would be required, introducing risks of overfitting and extrapolation errors if the performance map is not thoroughly characterized.

Summarizing the abovementioned findings, the results confirm that the constant COP approach, while computationally efficient, is unsuitable for dynamic simulations where outdoor conditions vary significantly. The polynomial model offers a reasonable compromise between simplicity and accuracy under constrained conditions, but its reliability decreases when auxiliary consumption is included or when operating conditions deviate from the calibration range. Consequently, the detailed IMST-ART-based model remains the most robust option for scenarios demanding high accuracy, improving long-time simulation periods or when evaluating system performance under a wide range of operating conditions.

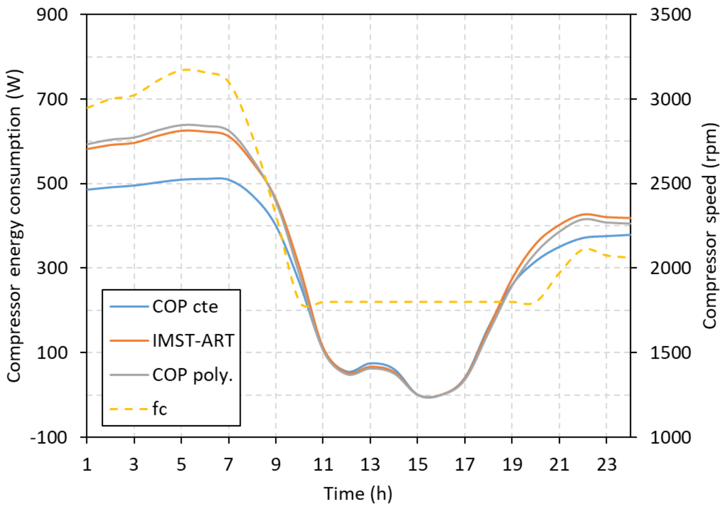

Figure 5. Compressor energy consumption according to the three modeling approaches for the simulated day

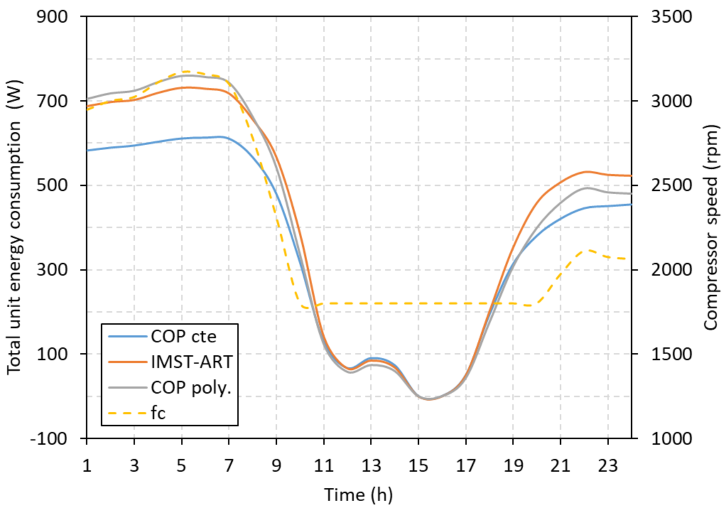

Figure 6. Unit energy consumption according to the three modeling approaches for the simulated day

4. Conclusions

This study analyzed the impact of heat pump model complexity on the prediction of energy consumption when coupled with a simplified building thermal model based on the thermal network approach. Three modeling strategies were compared: (i) a constant COP representation, (ii) a polynomial model fitted to detailed performance maps, and (iii) a high-fidelity model developed using specialized simulation software (IMST-ART). The building model was validated against TRNSYS with a deviation of 4.8% error in daily heating demand prediction, confirming its suitability for thermal load estimation with reduced computational effort.

From the three HP modeling strategies analyzed, the results demonstrate that the constant COP approach, although computationally efficient, introduces significant errors under dynamic conditions. For the simulated day, this method underestimated daily total energy consumption by approximately 15%, with an RMSE of 76.7 W and a CV_{RMSE} of 18.2 % in hourly predictions. These deviations were most pronounced during peak demand periods, reflecting the inability of this approach to account accurate HP performance prediction for variations in outdoor temperature and humidity.

The polynomial model provided a higher accuracy. When only compressor consumption was considered, the error for the daily total energy consumption was negligible (-0.48%), and the RMSE dropped to 11.4 W with a CV_{RMSE} of 3.3 %, confirming its effectiveness under constrained operating map conditions. However, when auxiliary consumption was included, this error increased to 2.6% (RMSE 29.9 W; CV_{RMSE} of 7.1 %), and dispersion in COP values became evident at low compressor speeds when representing as a function of source and sink temperatures. This limitation suggests that polynomial models are reliable only within a restricted operating range and may require higher-order formulations or additional independent variables for systems with more complex control strategies (variable speed fan or circulation pumps).

The detailed IMST-ART-based model remains the most robust solution for scenarios requiring high accuracy, particularly in long-time simulation periods or when evaluating system performance under a wide range of operating conditions. Its ability to capture multivariable dependencies ensures precise characterization of heat pump behavior across the entire operating map.

Although the analysis was conducted under a single climatic dataset (Denver, TMY3) and a specific building configuration (Case 620 from ANSI/ASHRAE Standard 140), the reported results are expected to yield similar trends under other weather conditions and building typologies. Simplified models generally perform well when the heat pump operates within a limited region of its performance map, but their accuracy decreases as the operating range expands or auxiliary consumption becomes significant. These aspects should be considered when extending the approach to broader scenarios.

In conclusion, the study demonstrates that heat pump model complexity plays a critical role in energy prediction accuracy. Simplified models enable fast simulations but introduce higher errors under dynamic conditions, whereas detailed models ensure robust performance over extended periods and operating conditions. Future work should address more complex scenarios involving units with additional control variables, such as fan speed or circulation pump modulation, and extend the evaluation to annual simulation periods to quantify cumulative deviations. Furthermore, experimental validation under controlled demand profiles and outdoor conditions would provide valuable insights into the dynamic behavior of heat pumps. Given the inherent thermal inertia of buildings and the relatively slow response of these systems, it is reasonable to expect that full-day operation would approximate a sequence of steady-state conditions. Nevertheless, experimental validation under controlled demand profiles and outdoor conditions is an important and valuable step to confirm this assumption and to provide deeper insights into the dynamic behavior of heat pumps.

Nomenclature

BPHE	Brazed Plate Heat Exchanger	f_c	Compressor speed (rpm)
CHEX	Coil Heat Exchanger	Q_c	Heating capacity (W or kWh)
COP	Coefficient of Performance	RH_a	Outdoor relative humidity (%)

COP_{aux}	Coefficient of Performance including auxiliary consumption (-)	T_a	Outdoor air dry-bulb temperature (°C)
CV_{RMSE}	Coefficient of Variation of the RMSE. RMSE/mean(y) (%)	T_{co}	Water supply temperature (°C)
HP	Heat Pump	W_c	Compressor energy consumption (W or kWh)
HVAC	Heating, Ventilation, and Air Conditioning	W_{total}	Total HP energy consumption (W or kWh)
RMSE	Root Mean Square Error (W)		

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References

[1] European Commission, “COM(2011) 885: Energy Roadmap 2050.” 2011. Accessed: Nov. 13, 2025. [Online]. Available: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex:52011DC0885

[2] European Council, “EUCO 169/14 (Europe’s 2030 energy strategy).” 2014. [Online]. Available: https://data.consilium.europa.eu/doc/document/ST-169-2014-INIT/en/pdf

[3] European Commission, “COM(2016) 51: An EU Strategy on Heating and Cooling.” 2016. Accessed: Nov. 13, 2025. [Online]. Available: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex:52016DC0051

[4] European Parliament, *Directive (EU) 2018/2001 of the European Parliament and of the Council of 11 December 2018 on the promotion of the use of energy from renewable sources (recast) (Text with EEA relevance)*. 2024. Accessed: Nov. 13, 2025. [Online]. Available: http://data.europa.eu/eli/dir/2018/2001/2024-07-16

[5] European Commission, *European green deal: delivering on our targets.* Publications Office, 2021. doi: 10.2775/595210.

[6] European Parliament, *Regulation (EU) 2021/1119 of the European Parliament and of the Council of 30 June 2021 establishing the framework for achieving climate neutrality and amending Regulations (EC) No 401/2009 and (EU) 2018/1999 (‘European Climate Law’)*. 2021. Accessed: Nov. 13, 2025. [Online]. Available: http://data.europa.eu/eli/reg/2021/1119/oj

[7] European Commission, “COM(2022) 230: REPowerEU Plan.” 2022. Accessed: Nov. 13, 2025. [Online]. Available: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex:52022DC0230

[8] European Parliament, *Directive (EU) 2024/1275 of the European Parliament and of the Council of 24 April 2024 on the energy performance of buildings (recast) (Text with EEA relevance)*. 2024. Accessed: Nov. 13, 2025. [Online]. Available: http://data.europa.eu/eli/dir/2024/1275/oj

[9] C. Vering *et al.*, “The environmental performance of nationwide heat pump deployment in residential buildings in Germany,” *Cell Rep. Sustain.*, p. 100461, Aug. 2025, doi: 10.1016/j.crsus.2025.100461.

[10] International Energy Agency, “The Future of Heat Pumps,” 2022. Accessed: Feb. 07, 2024. [Online]. Available: https://www.iea.org/reports/the-future-of-heat-pumps

[11] J. Woods *et al.*, *EnergyPlus™ v.23.2.0 2023 [SWR-17-23]*. (2023). National Renewable Energy Laboratory (NREL), Golden, CO (United States). doi: 10.11578/DC.20240605.1.

[12] S. A. Klein *et al.*, *TRNSYS 18: A Transient System Simulation Program*. (2017). Solar Energy Laboratory, University of Wisconsin-Madison. [Online]. Available: http://sel.me.wisc.edu/trnsys

[13] L. G. Swan and V. I. Ugursal, “Modeling of end-use energy consumption in the residential sector: A review of modeling techniques,” *Renew. Sustain. Energy Rev.*, vol. 13, no. 8, pp. 1819–1835, Oct. 2009, doi: 10.1016/j.rser.2008.09.033.

[14] UNE, "UNE-EN ISO 13790: Eficiencia térmica de los edificios. Cálculo del consumo de energía para calefacción de espacios," Asociación Española de Normalización, 13790, Nov. 2011.

[15] UNE, "UNE-EN ISO 52016-1: Eficiencia energética de los edificios. Cálculo de las necesidades energéticas de calefacción y refrigeración, temperaturas interiores y carga calorífica y de enfriamiento. Parte 1: Procedimientos de cálculo," Asociación Española de Normalización, 52016–1, 2017.

[16] German Association of Engineers, "VDI 6007-1: Calculation of Transient Thermal Response of Rooms and Buildings - Modelling of Rooms," German Association of Engineers, VDI 6007-1, 2015. [Online]. Available: https://www.vdi.de/mitgliedschaft/vdi-richtlinien/unsere-richtlinien-highlights/vdi-600

[17] I. Ballarini, A. Costantino, E. Fabrizio, and V. Corrado, "The Dynamic Model of EN ISO 52016-1 for the Energy Assessment of Buildings Compared to Simplified and Detailed Simulation Methods," presented at the Building Simulation 2019, Rome, Italy, 2019, pp. 3847–3854. doi: 10.26868/25222708.2019.210431.

[18] P. Remmen, M. Lauster, M. Mans, M. Fuchs, T. Osterhage, and D. Müller, "TEASER: an open tool for urban energy modelling of building stocks," *J. Build. Perform. Simul.*, vol. 11, no. 1, pp. 84–98, Jan. 2018, doi: 10.1080/19401493.2017.1283539.

[19] E. Prataviera, P. Romano, L. Carnieletto, F. Pirotti, J. Vivian, and A. Zarrella, "EUReCA: An open-source urban building energy modelling tool for the efficient evaluation of cities energy demand," *Renew. Energy*, vol. 173, pp. 544–560, Aug. 2021, doi: 10.1016/j.renene.2021.03.144.

[20] J. J. Allen and J. F. Hamilton, "Steady-state reciprocating water chiller models," in *ASHRAE Transactions. Volume 89(2)-2786*, Anual Meeting - Washington DC, 1983, pp. 398–407. [Online]. Available: https://www.ashrae.org/File%20Library/Technical%20Resources/ASHRAE%20Transactions%20and%20Conferences%20Programs/1983-Washington-DC-TOC.pdf

[21] T. Afjei and R. Dott, "Heat pump modelling for annual performance, design and new technologies," in *Proceedings of Building Simulation 2011: 12th Conference of International Building Performance Simulation Association*, Jan. 2011, pp. 2431–2438.

[22] C. Verhelst, F. Logist, J. Van Impe, and L. Helsen, "Study of the optimal control problem formulation for modulating air-to-water heat pumps connected to a residential floor heating system," *Energy Build.*, vol. 45, pp. 43–53, Feb. 2012, doi: 10.1016/j.enbuild.2011.10.015.

[23] J. Marchante Avellaneda, "Study of Response Surface Models for the characterization of the performance in Refrigeration Equipments and Heat Pumps," PhD thesis, Universitat Politècnica de València, 2023. doi: 10.4995/Thesis/10251/192653.

[24] J. Vivian, E. Prataviera, F. Cunsolo, and M. Pau, "Demand Side Management of a pool of air source heat pumps for space heating and domestic hot water production in a residential district," *Energy Convers. Manag.*, vol. 225, p. 113457, Dec. 2020, doi: 10.1016/j.enconman.2020.113457.

[25] J. Miguel. Corberán, José. Gonzálvez, P. Montes, and Rafael. Blasco, "'ART' a computer code to assist the design of refrigeration and A/C equipment," in *International refrigeration and air conditioning conference. Paper 570*, West Lafayette, Indiana: Purdue University, Jan. 2002. [Online]. Available: https://docs.lib.purdue.edu/iracc/570

[26] Thermal Area IUIIE, "IMST-ART: A simulation tool to assist the selection, design and optimization of refrigeration equipments and components," IMST-GROUP, Instituto de Ingeniería Energética (Universitat Politècnica de València), Camino de Vera S/N, 46022, Valencia (Spain), manual, 2024. [Online]. Available: http://www.imst-art.com/

[27] ASHRAE, "ANSI/ASHRAE Standard 140: Method of Test for Evaluating Building Performance Simulation Software," American Society of Heating, Refrigerating and Air-Conditioning Engineers, 140, 2023.

[28] S. A. Klein, *Engineering Equation Solver (EES)*. (2025). F-Chart Software. [Online]. Available: https://fchartsoftware.com/ees/

[29] Python Core Team, *Python Language*. (2023).