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BEYOND project: from field data to evaluation of soft faults in heat pumps as an enabiling technology for smart maintenance

A.W. Mauro[a,*], L. Viscito[a] , F. Pelella[a], R. Cilento[a], E. Navarro-Peris[b], B. Llopis Mengual[b]

[a]Department of Industrial Engineering, Università degli Studi di Napoli–Federico II, P.le Tecchio 80, 80125 Naples, Italy
[b]Instituto Universitario de Investigación de Ingeniería Energética (IUIIE), Universitat Politècnica de València (UPV), Camino de Vera s/n, 46022 Valencia, Spain

Abstract

Soft faults in heat pumps, such as refrigerant leaks or fouling of heat exchangers, are detrimental to energy performance as they can leave the system capable of balancing the thermal load, but with worsened energy efficiency. This leads to an efficiency reduction of even 10%-15% before the malfunction becomes apparent to the user. It would therefore be useful to have methods for estimating the extent of soft faults, especially in the case of several concurrent faults. The BEYOND project (www.beyondproject.eu), funded by the European Innovation Council, aims to identify innovative methods that, starting from direct and cost-effective measurements on a vapor compression system, attempt to assess the extent of refrigerant leaks and heat exchanger fouling. This paper describes the main ideas behind the project to determine innovation and possible technological advantages, especially to provide maintenance companies or cooling providers with the necessary information to perform smart maintenance, reducing environmental impact and, at the same time, any unnecessary customer service calls.

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1. Introduction

1.1. Context: Heat Pumps and Decarbonization

The building sector is responsible for approximately 30% of global final energy consumption and 26% of global CO2 emissions [1]. Achieving the ambitious decarbonization goals set globally and in Europe, such as the Net Zero Emission (NZE) scenarios by 2050 [2] and the Energy Performance of Building (EPBD) directives [3], depends on a rapid and effective electrification of thermal energy consumption. In this scenario, vapor compression heat pumps (HPs) represent the most promising and commercially available mature technology to replace traditional fossil fuel systems, both for space heating and domestic hot water production.

The adoption of this technology is growing strongly; in Europe, annually sold units increased by approximately 1.5 million between 2014 and 2024 [4]. However, the real-world (in-situ) efficiency of these systems rarely matches the nominal performance declared by the manufacturer. A HP's seasonal performance is, in fact, highly sensitive to operating conditions and, above all, to its state of health.

* Corresponding author. Tel.: +39 0817682198
E-mail address: wmauro@unina.it

1.2. The Problem of Faults

A heat pump's efficiency can degrade significantly over time due to the onset of operational faults. It is essential to distinguish between two main categories of faults [5]:

- Hard Faults: Sudden and catastrophic failures, such as compressor breakdown, electronics failure that cause an immediate service interruption and are therefore easily identifiable.
- Soft Faults: Progressive and subtle anomalies, such as micro-leaks of refrigerant, dust accumulation on the heat exchanger that do not stop the system but gradually reduce its performance.

Precisely because the machine continues to operate, apparently meeting the user's needs, "soft faults" are particularly insidious. They can go undetected for months or years, leading to considerable extra energy consumption. Typical examples of operational soft faults include refrigerant leakages from gaskets or faulty joints, "fouling" of finned-tube heat exchangers due to dust accumulation, and refrigerant bypass in the compressor or 4-way valves due to ageing . Other faults can arise from incorrect installation or maintenance, such as refrigerant overcharge or the presence of non-condensable gases dissolved in the refrigerant [6].

1.3. The impact of Concurrent Faults

The impact of these faults is far from negligible. Field studies have found issues related to refrigerant charge in 69% of inspected air conditioning units [7]. Recent research highlights that soft faults can increase daily energy consumption by up to 26% [8].

The problem is further aggravated by the fact that faults rarely occur in isolation. Real-world operation is dominated by multiple and concurrent faults [9]. Numerical simulations analyzing this overlap have shown that while a single fault of refrigerant leakage or heat exchanger fouling can cause seasonal performance degradation of between 12% and 40%, the simultaneous presence of multiple faults can lead to degradation exceeding 50% [10] [11] .

1.4. From FDD to FDDE

The severity of this impact makes the need for continuous monitoring systems clear. To optimize maintenance and ensure energy efficiency, it is not enough to know if a fault is present; it is crucial to understand which fault and how severe it is. This introduces a hierarchy in diagnostic methodologies [12] [13]:

- Fault Detection (FD): Identifies the presence of an anomaly.
- Fault Detection and Diagnosis (FDD): Identifies the specific type of fault.
- Fault Detection, Diagnosis and Evaluation (FDDE): Identifies the type and quantifies its severity.

The "Evaluation" capability is the crucial missing step in most current systems and is fundamental to enabling predictive maintenance services. Knowing the severity of a fault (e.g., "15% refrigerant loss" or "30% fouling on the coil") allows for a thermo-economic-environmental analysis and helps decide if a maintenance intervention is convenient and urgent.

This paper outlines the approach of the BEYOND project, which aims to fill this technological "gap". Section 2 analyses the state of the art and the limitations of existing FDD methods. Section 3 introduces the innovative concept of BEYOND. Section 4 presents in detail the technical-scientific results obtained in the first year of activity. Finally, Section 5 outlines the future steps and conclusions

2. State of the Art and "Research Gap"

2.1. Existing FDD Methodologies

FDD methodologies for vapor compression systems have been classified into three main categories: quantitative model-based (physics-based), qualitative (rule-based), and data-driven approaches, according to Zhao et al. [14].

Quantitative (physics-based) models use the fundamental equations of thermodynamics and heat transfer to simulate system behaviour. Although potentially very accurate, their use is often limited by high development complexity, computational burden, and the need for extensive experimental calibration to adapt semi-empirical correlations to specific components.

Qualitative (rule-based) models are the most common approach in industrial applications and patented solutions. They rely on a set of heuristic rules (e.g., "IF superheat is low AND subcooling is low, THEN charge is low"). While simple to implement, their reliability is limited: the thresholds are system-specific and struggle to handle the complexity of modern machines, for instance using inverter compressors, and variable operating conditions.

In recent years, data-driven methods, powered by Machine Learning (ML), have become the primary focus of research. These can be subdivided into:

- Unsupervised Learning: These methods, analyze unlabeled data to identify deviations from "normal" behaviour. They are useful for Fault Detection (FD) but cannot diagnose or quantify the fault (no FDD/FDDE) as they do not know the nature of the anomaly they are observing. Examples of such methodologies are clustering techniques.
- Supervised Learning. These algorithms are preferred for complex FDD tasks but have a fundamental prerequisite: they require large amounts of labelled experimental data for the training phase. Example of such methodologies are Artificial Neural Networks (ANN), Support Vector Machines (SVM), k-Nearest Neighbors (kNN).

2.2. The “Gap” in the State of the Art

The prerequisite of supervised ML methods constitutes the main practical obstacle. Obtaining a complete training dataset is prohibitively expensive and time-consuming: it would mean experimentally testing every single combination of operating conditions, including external and internal temperatures and relative humidities, for every single combination of simultaneous faults (e.g., 10% leak + 20% fouling; 10% leak + 30% fouling; etc.).

A thorough review of existing patents [13] confirms this "gap" . Industrial innovation is still focused on rule-based methods for the diagnosis of a single fault. Most solutions focus only on refrigerant leakage and fail if fouling is also present. Even the most advanced patents handle multiple faults only sequentially and in isolation.

No commercial product or patent currently provides a quantitative Evaluation of severity, especially in the presence of multiple, concurrent faults.

2.3. The Problem of “Indeterminacy Zones”

The technical reason why all current approaches fail with simultaneous faults lies in the so-called "indeterminacy zones".

An "indeterminacy zone" occurs when multiple, distinct combinations of faults and/or operating conditions produce overlapping thermodynamic effects, resulting in nearly identical measurements, including pressures, temperatures, on low-cost sensors. For example, a slight performance drop could be caused by a small refrigerant leak, or by slight fouling, or by a combination of both.

Furthermore, modern components like variable-speed compressors and the presence of liquid receivers can actively "mask" the symptoms of a fault. A liquid receiver, for instance, can compensate for a refrigerant leak, up to a certain level, without the thermodynamic cycle undergoing measurable changes, making the fault "invisible". The very accuracy of the sensors used plays a crucial role: imprecise readings can make two different fault states indistinguishable.

To overcome this state of the art, a method is needed that is:

1. Cost-effective: It cannot rely on massive experimental campaigns for training.
2. Comprehensive: It must perform FDDE including severity evaluation.
3. Intelligent: It must be able to resolve the "indeterminacy zones" of simultaneous faults.

3. The BEYOND Projects: The Proposed Solution

To meet this challenge, the BEYOND project (GA 101162436), funded by the European Innovation Council (EIC) Pathfinder program, was launched in September 2024.

The primary objective of BEYOND is to develop and validate an innovative, cost-effective, and knowledge-based method for Fault Detection, Diagnosis and Evaluation (FDDE) capable of identifying and quantifying up to three concurrent soft faults, with a specific focus on refrigerant charge leakage and heat exchanger fouling.

3.1. The Hybrid (Model-Experimental) Approach

To overcome the training data "bottleneck" that plagues pure ML methods, BEYOND adopts a hybrid approach. This approach combines the precision of experimental data with the extrapolative power of physical models, following a precise logical flow:

1. Model Development (WP2): Development of high-fidelity physics-based numerical models for all key system components, including compressor, heat exchangers, and expansion valve.
2. Experimental Campaign (WP3): Execution of a limited but high-quality experimental campaign on accurately instrumented laboratory test rigs. This campaign serves to map the prototype's behaviour under known conditions, both fault-free and faulty.
3. Calibration and Validation (WP2-WP3): The limited experimental data is used to calibrate and validate the physics-based models, ensuring that the "digital twin" of the system faithfully reproduces reality.
4. Synthetic Database Generation (WP2): Once validated, the digital twin is used to generate a massive synthetic database, containing millions of operating points. This virtual database can cover every possible combination of operating condition, fault type, and simultaneous severity level—a feat impossible to achieve experimentally.

3.2. The Innovation: Resolving Indeterminacy

The final FDDE algorithm, developed in WP4, will use this comprehensive synthetic database to diagnose and evaluate faults. The fundamental innovation of BEYOND lies in this method's ability to resolve the "indeterminacy zones".

The project's hypothesis is that, by actively operating on the machine's degrees of freedom (such as compressor or fan speed), the algorithm can "force" the system to move from an ambiguous operating point to a state where the combination of faults becomes uniquely identifiable. This approach transforms diagnosis from passive monitoring into an active "interrogation" process of the machine.

This method, if validated, will allow for the extension of advanced diagnostic capabilities, which are currently restricted to large-scale plants, to low-cost residential systems, enabling predictive maintenance services that reduce operating costs and environmental impact for manufacturers, service companies (ESCos), and end-users.

4. First Year Progress (M1-M12): Preliminary Results

The project has been active since September 2024. The first 12 months of activity focused on building the project's technical-scientific foundations, with main activities in Work Packages WP2 (Modelling), WP3 (Experimentation), WP6 (Exploitation), and WP8 (Portfolio Management).

4.1. Physical Foundations (WP3): Case Study 1 and Experimental Platform

Following a market and literature analysis of over 70 commercial configurations from 8 major manufacturers , Case Study 1 was selected: a reversible air-to-water heat pump for residential applications, using R290 (Propane) as the refrigerant. This choice is strategic, given the growing market trend towards natural, low-GWP refrigerants in response to regulations (e.g., F-Gas [15]).

At the laboratories of Universitat Politecnica de Valencia (UPV, experimental partner), a commercial unit (Vaillant aroTHERM plus) was acquired. The unit is reversible and equipped with a rotary compressor, an electronic expansion valve (EEV) able to control the evaporator outlet superheating, a plate and a fin-and tube heat exchanger. A liquid receiver operates as a refrigerant charge buffer, and the piping of the experimental apparatus is properly realized to guarantee that the receiver is always placed between the outlet of the condenser and the inlet of the expansion valve, in both heating and cooling operating modes. A picture of the experimental apparatus is provided in Figure 1 (left), with the schematic of the machine operating in cooling mode shown in Figure 1 (right).

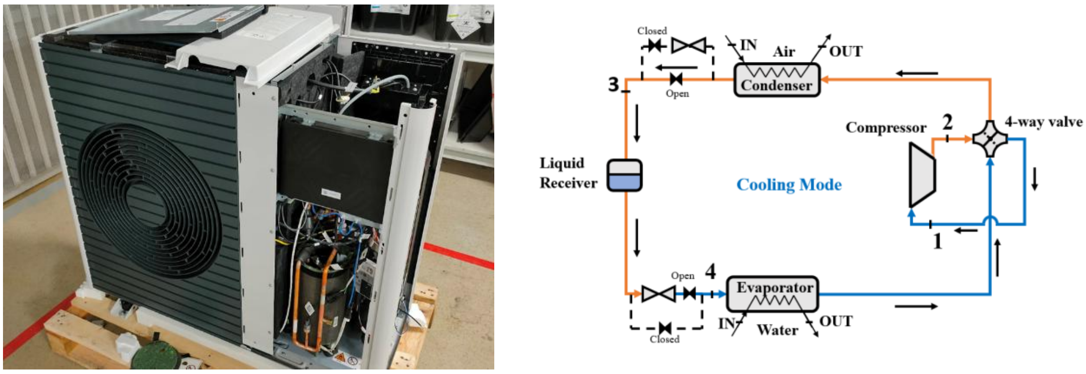

Figure 1. Picture of the experimental air-to-water heat pump (left) and schematic of the system operating in cooling mode (right), for the Case Study 1 analyzed within the BEYOND project

The test rig was instrumented with several high-precision sensors. For water and air temperatures, 4-wire RTDs PT100 were used with a measurement uncertainty of 0.50°C. Type T thermocouples were used for measuring the refrigerant temperature, with an uncertainty of 0.06°C, whereas Rosemount pressure transducers for the compressor and valve suction and discharge pressures have a measurement error of 0.75%. Finally, a Coriolis mass flow meter was used for measuring the water mass flow rate with an uncertainty of 0.15%, whereas a Gossen Metrawatt power analyzers was used to measure the compressor power consumption, with an uncertainty of 0.50%. The air flow rate, critical for fouling analysis, is measured using a custom wind tunnel compliant with the ASHRAE 41.2 standard and equipped with multiple nozzles, placed at the finned-tube coil outlet .

After iterative testing, the nominal refrigerant charge for the modified prototype was set at 1100g. An extensive experimental campaign in fault-free conditions (approximately 100 tests) was then conducted, mapping the entire operating domain. Experienced boundary conditions included compressor speed between 30 and 90 s^{-1}, cooling capacities between 1.8 kW and 8 kW, inlet water temperature between 35 and 60 °C in heating mode, between 10 and 25°C in cooling mode, and inlet air temperature between -10 and 20°C in heating mode, and 20 and 40°C in cooling mode.

Energy balances, comparing the heat transfer rate on the air side (obtained by directly measuring the air inlet and outlet temperatures and volumetric flow rate) and the refrigerant side (calculated by means of an energy balance on the plate heat exchanger, measuring the water inlet/outlet temperatures and mass flow rate), showed excellent closure, with a Mean Absolute Percentage Error (MAPE) of 3.47% in cooling and 6.99% in heating. This validates the reliability and accuracy of the entire experimental setup.

4.2. Digital Foundations (WP2): Model Development

Concurrently, at the University of Naples Federico II (UNINA, modelling partner), the thermal research group developed detailed numerical models of the prototype's key components: rotary compressor, plate heat exchanger (both refrigerant and water sides), finned-tube heat exchanger (both refrigerant and air sides), and EEV .

To maximize flexibility and identify the optimal approach, three different modelling methodologies were implemented for each component:

1. Physics-based Approach: Based on phenomenological equations, mass and energy balances, efficiency maps, both volumetric and global, for the compressor and expansion valve [10] [11], and known correlations for heat transfer and pressure drop including Dittus-Boelter [16], Gungor-Winterton [17], Martin [18], Wang et al. [19].
2. Regression-based Approach: Use of polynomial and multivariate regressions. including 1st or 2nd-order equations, calibrated on the data.

3. Machine Learning (ML) Approach: Use of feedforward Artificial Neural Networks (ANN) (e.g., 2 hidden layers, 3 neurons) trained on the data.

More details regarding the modelling approaches implemented for each single component of the heat pump analyzed are provided in Table 1.

Table 1. Summary of models developed, and modelling approaches employed, in the framework of the BEYOND project

Component	Physics-based	Regression Based	Machine Learning Based
Compressor	Phenomenological equations for volumetric and global efficiencies, and heat losses	Polynomial expressions for mass flow rate, electrical power and heat losses	ANN for the evaluation of mass flow rate, electrical power and discharge temperature
Expansion Valve	Phenomenological equation for valve mass flow rate	Not Developed	ANN for the evaluation of valve mass flow rate
Heat Exchangers	Characterization of geometry and heat transfer with well-known correlations, to evaluate thermal load and requested refrigerant charge	Not Developed	ANNs for the evaluation of thermal loads and refrigerant charge as a function of the boundary conditions

Preliminary fault models were also developed, modelling fouling as a reduction in flow area and/or heat transfer coefficient and leakage by analyzing the liquid receiver level and the potential onset of vapor quality at the EEV inlet .

4.3. The Hybrid Link (WP2/WP3): Preliminary Calibration and Results

The data from the ~100 fault-free tests were used for the preliminary calibration of the three sets of models. The data was split into training/validation sets (tests at 30 and 90 s^{-1} for the compressor, 30%, 60% and 90% opening percentages for the expansion valve) and a testing set (tests at 60 s^{-1} for the compressor, all the other opening percentages for the expansion valve) to verify the models' generalization capability. As first attempt, the training database is composed of approximately the 60% of the total points, with the 40% belonging to the testing database. Further database division will be considered in future works in order to assess the generalization capabilities of each modelling approach.

The results of this preliminary calibration are the key finding of the first year:

- The Regression-based and ML-based models showed excellent performance (low MAPEs) on the training data, but significantly worse performance (high errors) on the testing data, demonstrating poor extrapolation capability. For example, the regression model for compressor power recorded a MAPE of 0.6% on training but 5.6% on testing, as shown in results reported in Figure 2 (left). Similarly, for the expansion valve, the ANN model for the valve mass flow rate went from 1.8% to 12.4%, as shown in Figure 2 (right).

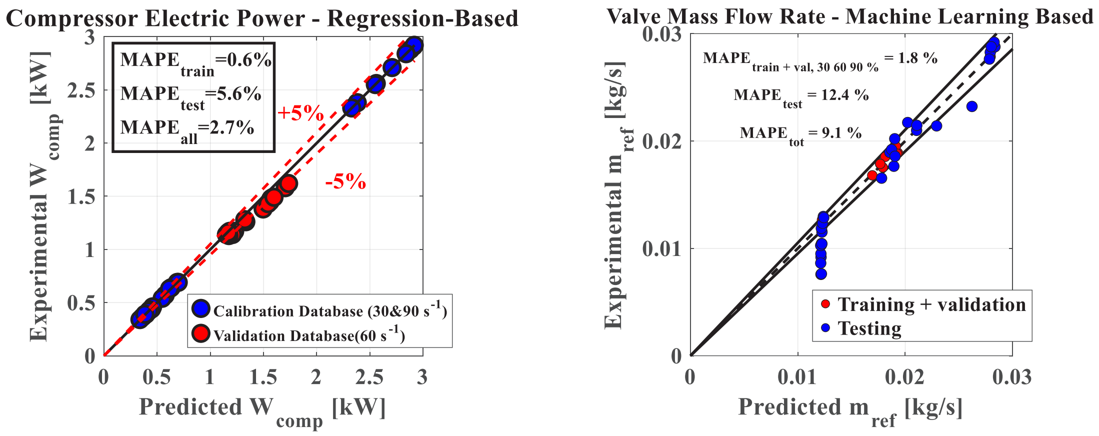

Figure 2. Preliminary model calibration results for the compressor electric power with the regression-based model (left) and the expansion valve mass flow rate with the machine learning based approach (right)

- The Physics-based models, in contrast, despite being more complex, demonstrated superior robustness, maintaining high accuracy even on the testing data. In detail, for the compressor power a MAPE of 1.7% for the training subset, and 2.9% for the testing are achieved, as shown in Figure 3 (left). Conversely, for the valve mass flow rate a MAPE 2.0% for the training, and 3.7% for the testing are obtained, as shown in Figure 3 (right).

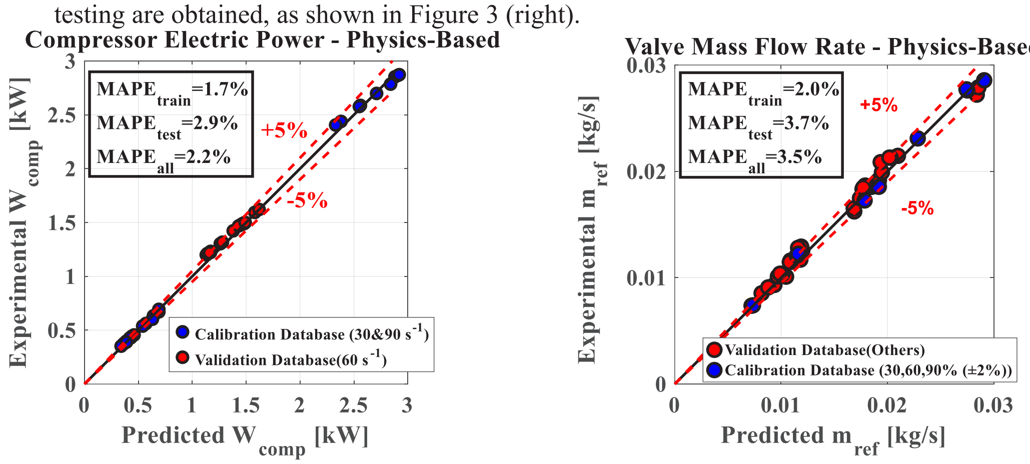

Figure 3. Preliminary model calibration results for the physics-based approaches, for the compressor electric power (left) and for the expansion valve mass flow rate (right)

This conclusion is fundamental to the project: it confirms that a purely data-driven approach based on limited experimental data is not reliable. The hybrid approach based on calibrated physics-based models is the only robust strategy for generating a reliable synthetic database.

5. Conclusions and Next Steps

The first 12 months of the BEYOND project (M1-M12) have successfully established the scientific, experimental, and methodological foundations required to enable a new generation of Fault Detection, Diagnosis and Evaluation (FDDE) tools for residential heat pumps. The activities carried out so far have demonstrated the feasibility and robustness of the proposed hybrid strategy and provided valuable insights for the subsequent phases of the project. Preliminary results from the first project year highlight the following achievements

- Development and commissioning of a high-fidelity experimental platform for the first case study (R290 air-to-water heat pump), fully instrumented and validated through an extensive fault-free test campaign. The high-quality dataset obtained (≈100 tests) confirmed excellent energy balance closure and measurement accuracy.

- Implementation and calibration of multiple modelling approaches, including physics-based, regression-based, and ML-based component models. Comparative analysis demonstrated that physics-based models, once calibrated, ensure superior extrapolation capability and robustness compared to purely data-driven formulations.
- Preliminary modelling of soft-fault mechanisms, including refrigerant leakage via liquid receiver dynamics and heat exchanger fouling through reduced heat transfer capability, providing the basis for subsequent faulty calibration.

These results confirm the central hypothesis of the project: a hybrid model–experimental approach is essential to build a reliable synthetic database and to overcome the limitations imposed by scarce experimental fault data.

The next steps for the second year of the project will focus on translating these foundations into full FDDE capabilities:

- Execution of the faulty experimental campaign, introducing controlled single and concurrent soft faults (leakage and fouling) on Prototype 1. For leakage, different refrigerant charge in the system piping will be investigated. For fouling, several obstructions (cardboard or plastic strips) will be placed at the fin-and-tube heat exchanger coil face front.
- Final calibration and validation of the physics-based models under faulty conditions, ensuring reliable reproduction of machine behaviour across the full fault spectrum.
- Generation of the large-scale synthetic database, enabling systematic exploration of all combinations of operating conditions and simultaneous fault severities.
- Development and preliminary testing of the FDDE retrieval algorithm, leveraging the synthetic database to identify and quantify soft faults, including the resolution of indeterminacy zones through active interrogation strategies.
- Launch of Case Study 2, extending the methodology to an air-to-air residential heat pump and consolidating the generalizability of the proposed approach.
- IP Protection: Preparation of the patent application text, in line with the exploitation roadmap

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References

[1] IEA (International Energy Agency), Buildings, Energy System, Paris (2023) https://www.iea.org/energy-system/buildings. Accessed on 15/10/2025.
[2] European Commission: Directorate-General for Climate Action, Going climate-neutral by 2050 – A strategic long-term vision for a prosperous, modern, competitive and climate-neutral EU economy, Publications Office, 2019, https://data.europa.eu/doi/10.2834/0.
[3] 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).
[4] EHPA (European Heat Pump Association), Market Report 2022, https://www.ehpa.org/market-data/market-report-2022/.
[5] Breuker MS, Braun JE, 1998. Common Fault and Their Impacts for Rooftop Air Conditioners, HVAC&R Research, 4, p.303-318.
[6] Bellanco I, Belío F, Vallés M, Gerber R, Salom J, 2022. Common fault effects on a natural refrigerant, variable-speed heat pump, International Journal of Refrigeration 133(2022), 259-266.
[7] Downey T, Proctor J, 2002. What can 13,000 air conditioners tell us? The Proceedings of the 2002 ACEEE Summer Study on Energy Efficiency in Buildings 1, p. 53-67.
[8] Llopis-Mengual B, Yuill DP, Navarro-Peris E, 2025. Time series analysis of field data for soft faults detection and degradation assessment in residential air conditioning systems. Applied Thermal Engineering, 269 126104.

[9] Hu Y, Yuill DP, 2021. Effects of multiple simultaneous faults on characteristic fault detection features of a heat pump in cooling mode, Energy & Buildings 251, 111355.
[10] Pelella F, Viscito L, Mauro AW, 2022. Combined effects of refrigerant leakages and fouling on air-source heat pump performances in cooling mode, Applied Thermal Engineering 204, 117965.
[11] Pelella F, Viscito L, Mauro AW, 2022. Soft faults in residential heat pumps: Possibility of evaluation via on-field measurements and related degradation of performance, Energy Conversion and Management 260, 115646
[12] Melgaard SP, Andersen KH, Marszal-Pomianowska A, Jensen RL, Heiselberg PK, 2022. Fault detection and diagnosis encyclopedia for building systems: a systematic review. Energies, 15(12) 4366.
[13] Pelella F, Passarelli AF, Llopis-Mengual B, Viscito L, Navarro-Peris E, Mauro AW, 2025. State-of-the-Art Methodologies for Self-Fault Detection, Diagnosis and Evaluation (FDDE) in Residential Heat Pumps. Energies, 18(13) 3286.
[14] Zhao Y, Li T, Zhang X, Zhang C, 2019. Artificial intelligence-based fault detection and diagnosis methods for building energy systems: Advantages, challenges and the future, Renewable and Sustainable Energy Reviews 109, p.85-101.
[15] The European Parliament and the Council of the European Union, 2024. Regulation (EU) 2024/573 of the European Parliament and of the Council of 7 February 2024 on fluorinated greenhouse gases, amending Directive (EU) 2019/1937 and repealing Regulation (EU), No 517/2014.
[16] Dittus FW, Boelter LMK, 1930, Heat transfer in automobile radiators of the tubular type, Univ. Calif. Publ. Eng. 2, 443–461.
[17] Gungor K, Winterton R, 1986, A general correlation for flow boiling in tubes and annuli, Int. J. Heat Mass Transf. 29, 351–358.
[18] Martin H, 1996, A theoretical approach to predict the performance of chevron-type plate heat exchangers.Chemical Engineering and Processing: Process Intensification 35, Vol. 4, 301-310.
[19] Wang CC, Chi YY, 2000, Heat transfer and friction characteristics of plain fin-and-tube heat exchangers: Part II. Correlation, International Journal of Heat and Mass Transfer 43, 2693-2700.
[20] Llopis-Mengual B, Pelella F, Viscito L, Mauro AW, Navarro-Peris E, 2025. Soft Fault Diagnosis and Evaluation Strategies: An Approach BEYOND the State of the Art to Reduce Emissions Associated with Heating and Cooling in the Residential Sector, in Heat Pumping Technologies Magazine Vol.43. No.2/2025. DOI: 10.23697/h63c-vx93
[21] Mauro AW, Pelella F, Viscito L, 2025. Rilevamento, diagnosi e valutazione dei guasti per pompe di calore residenziali e servizi correlati, AiCARR Journal. Special Issue CLIMA 2025, Year 16 - May-June 2025.