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A LOW-COST DATA ACQUISITION SYSTEM FOR THE OPTIMIZATION OF MAINTENANCE STRATEGIES AND FAULT DIAGNOSTICS IN HEAT PUMPS

Pedro Barandier[a*], Joao Dinis[a], Antonio, J. Marques Cardoso[a]

[a]CISE - Electromechatronic Systems Research Centre, University of Beira Interior, Calçada Fonte do Lameiro, P – 6201-001 Covilhã, Portugal

Abstract

Building sector comprises around 30% of the final energy consumption (FEC) worldwide whose forecasts indicate an increase of more than 50% by 2050. Therefore, it reveals an extensive potential for improvements, especially in the domain of Heating, Ventilation, and Air-Conditioning (HVAC), which accounts for about 50% of the FEC in buildings. In the HVAC framework, because of its great capability in providing heating, cooling, and domestic hot water efficiently, the heat pumps (HPs) market has been under a continuous expansion. Nevertheless, HPs clean operation might be jeopardised by the occurrence of faults. Accordingly, efficient methods for the fault detection and diagnostics (FDD) in HPs must be executed effectively. Although there are several FDD methods nowadays, including data-driven models, regardless of the method employed, equipment information is required either to conduct a punctual non-invasive FDD or to establish an on-condition based maintenance strategy. Since mostly FDD methods rely on the analysis of electromechanical parameters, such data acquisition might be costly.
This paper addresses the conceptualization and prototyping of a low-cost data acquisition system for HPs based on a printed circuit board (PCB) with a microcontroller and ten temperature sensors to measure some the most important circuit parameters. The developed system might be used by either technicians in the field or embedded in the equipment itself for constant monitoring through Internet of Things (IoT) applications. Therefore, through the utilization of the measured parameters, it is possible to inspect the system and detect faults within it before they propagate or increase their severity. The collected data might be recorded and accessed physically, through a micro-Secure Digital (micro-SD) card, or remotely, through Bluetooth or Wi-Fi connection. The former improves the data to be analysed later for FDD, and the latter provides the possibility to implement an on-condition based maintenance strategy through an IoT approach.

Keywords: Heat Pumps; Fault Detection; Fault Diagnostics; Data Acquisition; Printed Circuit Board.

1. Introduction

As FEC unveiled an unprecedent increase in the last decades, green-house-gases (GHG) emissions also revealed a remarkable escalation due to the dependence on fossil fuels. Nevertheless, as energy demand keeps increasing, the decarbonization of society has been acknowledged as a common objective worldwide. As a result, society's electrification has been undergoing a progressive fomentation that encompasses different aspects. Firstly, renewable energy generation comprehends a fundamental feature, not only for reducing GHG emissions, but also for achieving oil and gas independence. Secondly, electricity utilization, when generated by non-polluting sources, as main energy vector, discloses a great potential in several sectors, such as mobility, commercial and residential buildings, industry and many more. This potential is exploited by the emerging technologies market which, when considering five key components: i) solar, ii) wind, iii) batteries, iv) electrolysers, and v) HPs, presented an average increase nearly 20% over the previous year as its average costs have fallen almost 80% in the last decade [1].

* Corresponding author. *E-mail address:* pedro.barandier@ubi.pt

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Considering the HPs technology only, as the manufacturing process has already reached a certain maturity, such market is a spreading sector with a progressive increase on its sales and with a forecast increase over 200% in the next years [1], [2]. Moreover, even though HPs manufacturing process have attained maturity, the technology itself has not. At the moment, HPs systems are still in development and continuous improvements can be made, especially in the matter of their performance and capacity. Following this reasoning, the International Energy Agency predicts that, by 2050, the climatised area may increase about 30% whereas the energy consumption may decrease in about 70%. In addition to their utilization for thermal comfort and domestic hot water, as technology evolves, HPs will eventually replace boilers and other systems, spreading out to industry applications and processes ranging from alumina electrolysis and electrowinning, for aluminium and copper production, respectively [2], [3].

Even though HPs reveal a more sustainable alternative with a performance remarkably greater in comparison to traditional systems, as any others electromechanical devices, they are prone to faults, which may compromise their operation by deteriorating their performance and capacity while increasing their energy consumption until their total failure, if such faults are not handled appropriately. Thus, the reliability of such systems must be improved so that the acceptance of such technology keeps being fostered and its implementation diffused. For this intent, FDD methods in HPs must be continuously developed and effectively implemented [4].

In addition to the systems reliability guarantee, a proper FDD method also aligns with the strategy to achieve a sustainable development as it induces a considerable impact in three domains: i) economic, ii) social, and iii) environmental. Firstly, as aforementioned, faulty equipment leads to a remarkably greater power consumption, that can be translated into greater operational costs. Secondly, depending on the fault severity, as the systems' capacities deteriorate with the occurrence of faults, the thermal comfort might be compromised and, depending on the facility analysed, the conducted activities as well. Lastly, regardless of more sustainable refrigerants have been conceived, their leakage, which is the most prevalent fault in HPs, might still have some environmental impact. Moreover, as the power consumption might increase with the presence of faults, depending on the carbon intensity of the electricity, the CO_2 indirect emissions might increase as well [4]–[6].

Due to the progressive unfolding of HPs technology that has boosted its market expansion, new monitoring and FDD methods have also evolved in the HVAC applications, encouraged in particular by advancements in the domain of computer science, such as Industry 4.0 concepts, IoT, and Artificial Intelligence [7]–[16]. These advances hold a great potential as they enable, when properly employed, the implementation of on condition-based and proactive maintenance strategies. As a result, the need for direct interventions in the system, one of the main factors contributing to faults' occurrence, is considerably reduced [4].

Accordingly, the systems' reliability is increased. Nevertheless, to exploit the full potential of the synergy of these advancements and maintenance strategies, a FDD process must be thoroughly coordinated. For this intent, a reliable monitoring system is imperative, especially for systems comprising HPs, which present a high complexity as they include several electromechatronic components, such as electrical motors, heat exchangers, valves and many others. For large systems, usually utilized in commercial buildings, the monitoring structure is even more important, particularly for the ones operating in critical environments [6].

The monitoring systems currently employed in HPs and vapour compression machines for FDD may include various arrangements with different types of sensors and controllers and be based on distinct communication protocols. Regardless of the great complexity of such systems and the extensive number of variables that can be assessed in the FDD process, the temperatures of the circuit comprise some of the most important and accessible parameters. As a result, some of the most reliable FDD methods of vapour compression systems depend exclusively on direct temperature monitoring along the circuit. Among the assessed temperature parameters, there are seven key measurements that respect superheat, subcooling, compressor outlet temperature, evaporating and condensing temperatures, and temperature differences in both evaporator and condenser [17].

Furthermore, these temperature measurements can also be utilized for the development and deployment of virtual sensors to estimate other parameters, such as circuit pressures, system's refrigerant charge, and even refrigerant mass flow rate [18]–[20]. Therefore, temperature monitoring throughout the vapour compression cycle constitutes a leading aspect of the FDD process, particularly given that it is not invasive as alternative measurements, like the aforementioned circuit pressures, refrigerant charge, and mass flow rate, whose instrumentation, besides costly, might also engender additional faults in the system.

Usually, the sensors engaged to measure temperature data for this type of application, either in the field or in the laboratory, concern the traditional thermocouples (TC) and resistance thermometer detectors, commonly known as RTD. Thermistors are also employed, nevertheless, they are often employed for control and monitoring close to ambient temperatures and not for data acquisition of the HPs circuit, as they might degrade under such very high temperatures, what reduces their suitability for this type of application [15], [16], [21]–[23].

Even though such sensors hold a considerable precision on their measurements, they still require peripherals to operate, such as analog-to-digital converters (ADC) and gain amplifiers to provide signal conditioning and, particularly in the case of thermocouples, components to provide compensations, what might result in increased costs. Furthermore, as these transducers operations rely on analog signals, they are consequently susceptible to noise and interference during the measurements [24], [25].

Regarding controllers, a key component for the monitoring system, various possibilities can be utilized in this context, from commonly settled microcontrollers, like Arduino, Raspberry Pi, and ESP32, to even more robust and traditional data loggers. From all these architectures, ESP32 discloses a remarkable prevalence in IoT applications due to its robust wireless connectivity, efficient processing, and cost-effectiveness [7], [10], [26]–[28]. For this reason, ESP32 has already been utilized in HVAC appliances, albeit for other purposes apart from the FDD of vapour compression systems, such as fault detection of HVAC indoor thermal comfort systems, boiling detection for heating, optimizing HVAC power consumption, and monitoring of commercial freezer systems [7], [29]–[31].

Considering the great potential of ESP32 for IoT applications along the constraints of the traditional types of temperature sensors, a low-cost system can be designed to provide monitoring of HPs operations. Thereby, it can establish a solid foundation for the implementation of smart maintenance strategies and automated HPs FDD relying on Industry 4.0 and IoT concepts. For this purpose, a set-up of an ESP32 with ten DS18B20 sensors was deployed.

Although such combination has already been reported in the literature, there are no records of being used for the proposed objective and arranged set-up. The reports on the utilization of ESP32 along DS18B20 sensors are relatively recent, with less than 15 years. In [25], a pragmatic description of the potential of such combination was carried out and its cost-effectiveness in comparison to the traditional sensors aforementioned was acknowledged. In [32], the authors developed a prototype with ESP32, DS18B20 sensors, and circulating pumps to control the temperature of a diesel generator. In [33], a method for calibrating DS18B20 connected to an Arduino microcontroller and improving its precision and accuracy was conceived based on a linear equation resulting from a regression. In [34], the authors developed a prototype comprising DS18B20 and an Arduino for health monitoring in real time. The developed model comprised an IoT application based on zigbee network for communication of the net components.

As aforementioned, in [29], a system comprising ESP32 was utilized to efficiently monitor the temperatures of the freezers for the storage of foods and beverages and control the quality of the operation. In addition to given microcontrollers, the system also integrated DS18B20 sensors for temperature measuring and a buzzer that was sounded. Moreover, all the data was recorded in a cloud system for further analysis, if necessary.

For the boiling detection system previously acknowledged and depicted in [30], the authors proposed a system architecture that integrated an ESP32 along DS18B20 sensors to provide real time temperature data, which was stored in a Firebased database. Furthermore, as this type of sensor requires a voltage pull-up to reliably transmit data to the microcontroller (MC), a 4.7 kΩ resistor was employed.

Finally, the present work addresses the conceptualization, design, and prototype of a low-cost data acquisition system with the intent of providing a feasible and reliable solution for the deployment of efficient FDD methods in HPs and, consequently, the implementation of smart maintenance strategies in HVAC systems. For this purpose, the system was idealized to work in two different perspectives, either embedded in the HVAC system for constant monitoring, following Industry 4.0 and IoT concepts, or in the field by technicians.

For the first perspective, regardless of IoT protocols might comprise several layers, in the present study, only the first layers, responsible for data acquisition and monitoring are analysed. For the second perspective, to ensure total autonomy, the system is projected to be portable, powered by batteries and the data, when no connections are available, can be stored in a micro-SD card to be analysed later on. Lastly, this work is structured in four sections: i) the present Introduction; ii) Methodology; iii) Results and Discussion; and iv) Conclusions.

2. Methodology

2.1. Parameters Selection for Fault Diagnosis

The deployment of any maintenance strategy must be consistent and aligned with the faults management structure, so it can be truly effective. Therefore, to implement on condition-based and proactive maintenance strategies, any faults or malfunctions must be detected and diagnosed to be handled as soon as possible. Within the scope of vapour compression, it is deeply depicted in the literature the great potential of using temperature measurements for the FDD of such equipment [17], [35]–[37].

In addition to the HPs FDD based on the circuit temperatures, such parameters might also operate as virtual sensors, providing the basis for the estimation of other parameters, such as pressure, mass flow rate, and refrigerant charge. Moreover, the utilization of virtual sensors based on temperature measurements reveal to be particularly advantageous for the FDD process as they are non-invasive and therefore, do not require any intervention in the system to be installed, which could otherwise lead to faults [15], [19], [38], [39]. In this manner, considering the circuit temperatures commonly assessed in a HP FDD process, as depicted in Figure 1, the proposed system comprises 10 sensors to collect data regarding such parameter in the circuit.

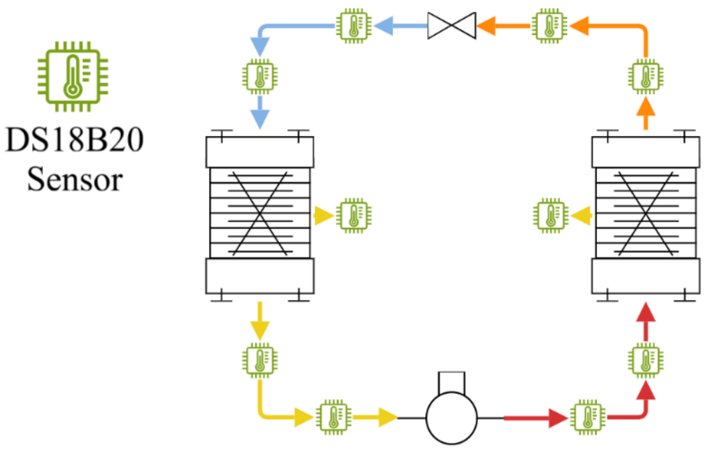

Figure 1. Temperature Sensors Positioning on the HP Circuit.

2.2. DS18B20 Features

As previously stated, the sensors proposed to integrate the system are DS18B20 devices, a temperature sensor with measurement range between -55°C and 125°C and a built-in analogic-to-digital converter from 9-bit to 12-bit, corresponding to a resolution from 0.5°C to 0.0625°C. Their operation is based on a one-wire communication protocol that requires no external components to operate, which makes the data acquisition process relatively straightforward. Due to their precision and simplicity, these sensors have been largely employed in several applications that include HVAC environmental controls and monitoring of equipment, machinery, processes, and systems.

In addition to the data pin, responsible for the data transmission, the DS18B20 also features two additional pins, regarding the ground and supply voltage. Because of its architecture, this sensor might either be powered by an external source through the supply voltage pin or operate in parasitic mode, which requires only two connections, data and ground. Nevertheless, if the system is powered by a battery, for example, its autonomy will subsequently deteriorate when operating in parasitic mode.

One aspect that must be regarded when working with DS18B20 sensors is their cable length. Unlike what usually occurs with the traditional analogic sensors, the cable length does not affect the measurement itself, but the integrity of one-wire signal as longer cables might increase the bus capacitance. Therefore, DS18B20 sensors with a cable length up to 10 metres do not pose any limitations and provide reliable measurements. Meanwhile, cables longer than 10 metres might require a lower pull-up through a resistor to maintain signal integrity and provide proper measurement reading, especially when the sensors are operating in parasitic mode.

As observed in [40], in an unlikely scenario where this solution was to be employed in uncommonly high electrically noisy environment, and the cabling distance was to prove to be too lengthy and vulnerable to noise, special cables with braided shielding could be adopted for improved noise immunity. Lastly, as DS18B20 are digital sensors, changes in battery voltages do not affect the accuracy of precision of reading either.

Accordingly, for package HPs, the data acquisition system either for IoT embedded applications or field punctual measurements might be placed close to the primary circuit, where main components are centralized, and provide reliable measurements that do not demand any further signal processing. For split systems, a signal processing might be required only if the outdoor and indoor units are not close enough to each other, otherwise, reliable measurements can still be accomplished.

2.3. Prototype Design

The prototype design comprised a basic assembly of the complete set-up, including one ESP32, ten DS18B20 sensors and a micro-SD card, as presented in Figure 2. Since each DS18B20 has a unique 64-bit serial code, multiple sensors can be connected in the same bus. Nevertheless, depending on the application and the number of sensors, a pull-up resistor might be required to function properly. In the developed system, for example, it was experimentally confirmed that, using the pull-up provided by ESP32 itself, only two sensors can be connected per bus. Beyond this number, the signal provided by the sensors is not enough to be computed and all the measurements are compromised. In the following, the MC was programmed to collect data, display it and store it as a csv file in a micro-SD card. The developed code is available in [41]. With all the components connected, the proposed system was experimentally validated as it will be discussed in the next section.

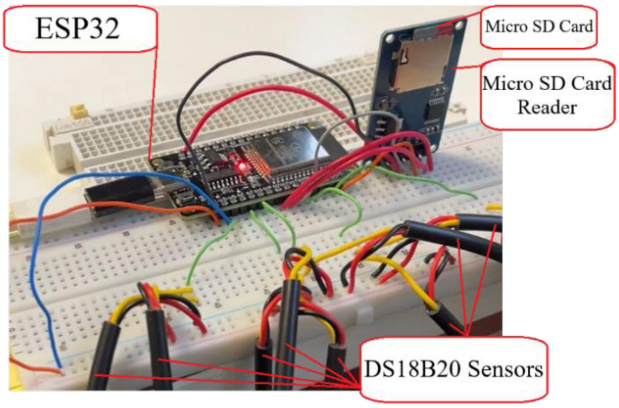

Figure 2. Prototype Assembly.

Subsequently, based on the electrical circuits of the conceived prototype, a PCB comprising all the components of the proposed system was designed and manufactured, as shown in Figures 3 and 4, to optimize its layout and functionality. To ensure its field deployment and facilitate its utilization, besides the micro-SD, the PCB design also included a pin reserved to transmit the measured data to an OLED screen so that it can be displayed and a battery power supply to ensure its portability and enable punctual monitoring when there are no further power sources. Finally, based on the current of each one of the components, as presented in Table 1, the total current demand was estimated and two slots for the mentioned batteries were included in the PCB architecture.

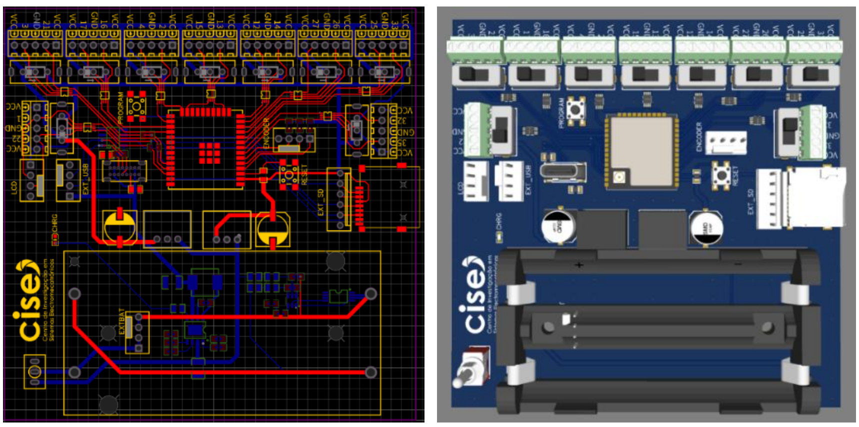

Figure 3. PCB Design.

With the purpose of guaranteeing the system's reliability and proper operation, the designed PCB battery slots support lithium iron phosphate (LFP) and lithium-ion batteries architectures. Regardless of these latter ones are more common, they are also more susceptible to overheating. Thus, LFP batteries solution might reveal to be advantageous when the proposed system is installed in outdoor heat exchangers of HPs operating in cooling mode during extremely hot days. Additionally, to prevent battery discharge when the equipment is not in operation, a power switch was also integrated in the PCB along a LED lamp to indicate the system's on/off status.

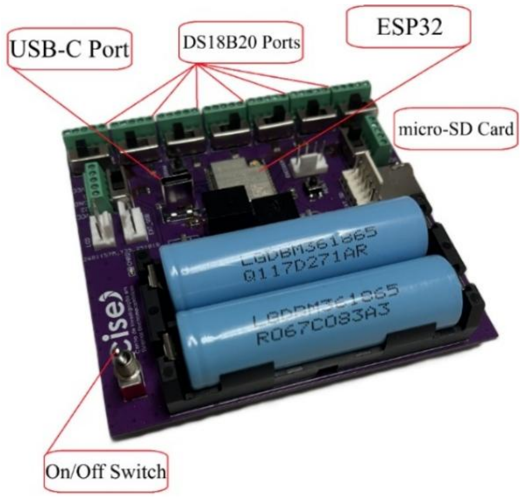

Figure 4. Manufactured PCB.

Table 1. System's Requirements.

Component	Function	Peak Current [mA]	Amount	Total Peak Current [mA]
ESP32	Microcontroller	240	1	240
DS18B20	Temperature Sensor	1.5	10	150
Micro SD Card Reader	Stores Measured Data	240	1	240
OLED Screen	Display Measured Data	30	1	30
	Total Peak Current [mA]			**690**

Finally, considering the total peak current in the system, the peak current required by the converters is 1 A, either for 3.3 V or for 5 V voltage. Meanwhile, the peak current for the batteries charging is 1.34 A. With the PCB design and the manufacturing concluded, the whole system was assembled and DS18B20 sensors with a cable length of 1 metre each were connected to the ESP32 through the PCB.

2.4. Battery Lifetime

Acknowledging this portable operation mode, the total battery lifetime is largely dependent on temperature sensors acquisition frequency required and the chosen battery capacity. According to the manufacturer's, the current consumption of the ESP32 is stated in the datasheet as: 180 mA for active mode with radio frequency communication enabled, 25 mA for modem-sleep mode in normal speed and single-core, and 0.8 mA for light-sleep mode. As for the temperature sensors, according to the manufacturers datasheet, each sensor consumes approximately 1mA during active mode and during sleep mode less than 1 µA.

The OLED screen used can be turned off during acquisition to reduce power consumption. In OLED-based screens, power consumption is highly dependent on the ON-time and the displayed content. For this case, a maximum of 50 mA for a worst-case scenario an average of 25 mA for a more realistic scenario can be considered. The SD card module power consumption is negligible and the circuit responsible for voltage conversion has an efficiency of approximately 96%.

The battery capacity is the most defining factor when it comes to device usable time. The proposed solution employs two 18650-format cells, connected in series. Therefore, by considering two 3000 mAh batteries with a nominal voltage of 3.6 V each, a total capacity of 21.6 Wh can be achieved.

Based on the features of the proposed solution, the battery lifetime was estimated considering three operating modes. The first one comprises the most demanding scenario, where the power consumption is at its maximum, with the MC wireless communication modules activated and a constant data acquisition. The second one is an off-line scenario, where the MC Wi-Fi and Bluetooth modules are disconnected and data is solely saved on the external memory card. The third operating mode is an optimised scenario, where the MC is kept in a low power consumption mode (light-sleep mode), but is activated every 1 minute, acquires data, saves it and is then deactivated again. The entire process takes about 10 seconds, and the screen is kept off. Finally, a converter efficiency of 96% was considered for all scenarios.

2.5. Techno-economic Analysis

In order to assess the feasibility of the proposed system, a techno-economic analysis was conducted. For this purpose, the components of the proposed system were compared in technical and economic terms, as presented in Table 2 and Table 3, which concern the most commonly used sensors for this type of application, and in Table 4, which regard the most commonly employed microcontrollers. Moreover, the techno-economic analysis didn't comprise the PCB costs since they are practically independent of the system employed. Still, the manufacturing costs of the PCB designed are approximately €30 per unity.

Table 2. Sensors Technical Features.

Sensor	Temperature Range	Accuracy	Peripherals Required
DS18B20	-55°C to 125°C	±0.5°C	-
RTD PT-100	-200°C to 850°C	±0.1°C to ±0.5°C	Precision Resistor, Amplifier, and ADC
Thermocouple Type K	-270°C to 1200°C	±1.5°C or ±0.4%	Cold-junction compensation circuit, Amplifier, and ADC
Thermocouple Type J	-210°C to 1270°C	±2.2°C or ±0.75%	Cold-junction compensation circuit, Amplifier, and ADC

Table 3. Sensors Economical Comparison.

Sensor	Average Cost [€]	Average Peripheral Costs [€]	Total Costs [€]	Difference
DS18B20	7.37	-	7.37	-
RTD PT-100	19.48	10.24	29.73	304%
Thermocouple Type K	15.48	12.35	27.83	278%
Thermocouple Type J	15.37	6.77	22.14	201%

Table 4. Microcontrollers Techno-economic Comparison.

Microcontroller	Functions and Applications	Average Cost [€]	Difference
ESP32	Due to built-in wi-fi and Bluetooth, it is commonly used in IoT Systems, wireless sensor networks, smart home automation, and low-power embedded applications.	11.75	-
Arduino	Due its extensive number of libraries, it is ideal for education, prototyping, robotics, automation, and data-acquisition.	20.80	77%
Raspberry Pi	Capable of running a full operating system. Used for data processing, edge computing, machine vision, IoT gateways, and automation controls.	52.05	343%

3. Results and Discussion

3.1. Experimental Test

The experimental validation firstly comprised a test relatively simple with the purpose of confirming the potential and accuracy of the proposed system. After connecting ten DS18B20 one metre length each to ESP32 and programming it to provide the required pull-up for the referred sensors, collect data, display it, and store it in a csv file, the ten sensors were firstly placed in a water radiator providing hot water at a 55°C temperature during heating season to collect data for one hour.

Subsequently, they were placed inside a recipient with ice at 0°C to test the measurements at low temperatures as well. For both scenarios, besides the DS18B20 sensors, the temperatures of the sensors were also measured by a TC type K and an infrared thermometer, which indicated temperatures quite close to the DS18B20 measurements with deviations no greater than ±0.5°C.

In the following, for a final test, the sensors were placed along type K TC in the external circuit of an air-to-air HP of 6 kW of thermal power in heating mode, as presented in Figure 5. Such test lasted approximately one hour and regarded an outdoor temperature of 8℃ and an indoor temperature of 25℃. The greatest deviations observed among the measurements were approximately ±1.5℃, which occurred because the sensors were not properly isolated, especially the TC, which were not encapsulated, and the equipment cover which was provisionally removed for the test. In this manner, it can be considered that the results converge with the information available in the manufacturer's datasheet. In regard to such results and the fact that there is no noise in the measurements, sensor calibration is not necessary for the considered purpose. However, it might be pertinent to critical applications that require lower measurement deviations, such as ±0.1℃, and might it also be recognized for an accuracy improvement in a future project.

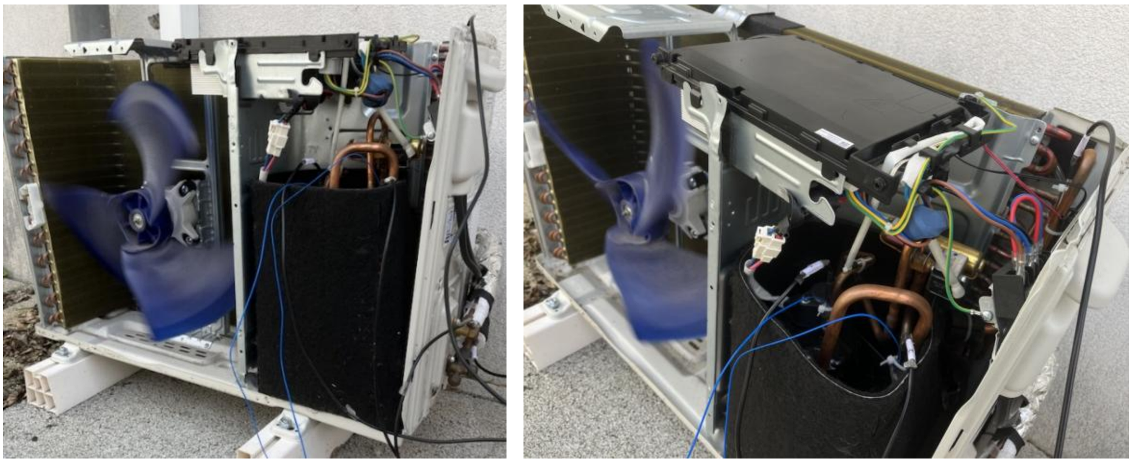

Figure 5. Final Test Experimental Setup.

3.2. Battery Lifetime Estimation

Acknowledging that battery is a critical factor for the system's portability in the field, its lifetime was estimated considering the three different operating modes previously featured. Therefore, the lifetime for each one of the regarded operating modes is depicted in Table 5 and Table 6.

As detailed in Table 5, in a more critical scenario, where the system operates fully and uninterruptedly, the estimated lifetime of the battery is approximately 1 day. However, such operating mode does not reflect reality, as the data acquisition process can be optimized and it was only considered to determine the minimum battery lifetime that can be accomplished with the developed setup.

Table 5. Battery Lifetime in Most Power Consuming and Off-line Scenarios.

Most Power Consuming Scenario		**Off-line Scenario**	
ESP32 Current	180 mA	ESP32 Current	25 mA
10 Sensors Current	10 mA	10 Sensors Current	10 mA
Micro SD Card Reader	Negligible	Micro SD Card Reader	Negligible
OLED Screen Current	50 mA	OLED Screen Current	25 mA
Total Current	240 mA	Total Current	60 mA
Total Power Consumption	$\frac{(240\ mA\ \times 3.3\ V)}{96\%} \cong 0.825\ W$	Total Power Consumption	$\frac{(60\ mA\ \times 3.3\ V)}{96\%} \cong 0.206\ W$
Battery Lifetime	$21.6\ Wh/0.825\ W = 26.2\ hours\ \rightarrow 1\ day$	Battery Lifetime	$21.6\ Wh/0.206\ W = 104.7\ hours\ \rightarrow 4.4\ days$

Also depicted in Table 5, an off-line scenario provides a lifetime of approximately 4.4 days, over 340% longer than the previously analysed scenario. Meanwhile, as depicted in Table 6, an optimised scenario, considering light-sleep mode function in ESP32, provides a battery lifetime of approximately 24 days, 445% and 445% longer than the most power consuming scenario and the off-line scenario, respectively.

Table 6. Battery Lifetime in Optimised Scenario.

System Active		System in Light-Sleep Mode	
ESP32 Current	25 mA	ESP32 Current	0.8 mA
10 Sensors Current	10 mA	10 Sensors Current	Negligible
Micro SD Card Reader	Negligible	Micro SD Card Reader	Negligible
OLED Screen Current	25 mA	OLED Screen Current	Negligible
Total Current	60 mA	Total Current	0.8 mA
Total Power Consumption	$\frac{(60\ mA\ \times 3.3\ V)}{96\%} \cong 0.206\ W$	Total Power Consumption	$\frac{(0.8\ mA\ \times 3.3\ V)}{96\%} \cong 0.003\ W$
Combined energy consumption in one hour		$0.167h\ \times 0.206 + 0.833h\ \times 0.003\ Wh\ =$ 0.037 Wh	
Battery Lifetime		$21.6\ Wh/0.037\ W\ = 584\ hours\ \rightarrow 24\ days$	

3.3. Techno-economic Analysis Discussion

Because of its wide temperature range, as presented in Table 2, DS18B20 sensors can meet the operating temperatures of most HPs, however, as the maximum temperature measure is 125°C, their utilization might not be suitable for systems operating above this limit, such as transcritical systems using R-744 as refrigerant. Despite this constraint that does not interfere on most common systems, the DS18B20 sensors present a major advantage in comparison to other sensors as they do not demand any extra peripherals to function since the MC provides an internal pull-up.

Besides the simplicity in DS18B20 architecture and deployment, their utilization also benefits from a remarkable accuracy, which is quite similar to RTDs', commonly known for their accurate measurements, and, in some cases, greater than the analysed thermocouples'. Moreover, DS18B20 costs also reveal to be quite advantageous when compared to other sensors, with a difference, on average, of at least 200% assuming these sensors as reference. Despite the large number of options of microcontrollers available in the market, three of the most largely applied devices were deemed. For the proposed application, systems with ESP32 reveal to be promising due to the embedded wi-fi and Bluetooth and more economically attractive than Arduino and Raspberry Pi as their acquisition costs are considerably lower.

In addition to its lower costs, given that faulty HPs result in a significant increase in power consumption, leading to a raise of energy costs, an on-condition based maintenance strategy might provide the early detection of such faults and ensure the energy efficiency of facilities. As depicted by [37], a degradation of over 30% in coefficient of performance, depending on the faults, raising from faulty operation might be noticed. Thus, in terms of power consumption, the average energy price in Europe of €0.287 per kWh would increase to €0.373 per kWh. Considering such difference, the increase in the energy costs of a faulty system with electrical power of 1 kW after 900 hours of operation, approximately 40 days, would be comparable to the costs of the proposed system. For larger systems with higher power ratings, or in countries with higher energy prices, the relative cost of the proposed system in comparison to the increase in the energy expenditure would be even lower.

Conclusively, systems relying on the combination of ESP32 with DS18B20 reveals a promising solution for the data acquisition and monitoring of HPs systems, either to be punctually adopted by technicians in the field to diagnose faults or applied for smart monitoring in buildings through an IoT approach. For both scenarios, the proposed system encompasses an extremely cost-effective strategy in comparison to other commonly employed solutions, as presented in Figure 6, which depicts 12 different combinations based on the discussed sensors and microcontrollers.

4. Conclusions

Following the expressive growth of the HPs market and technology evolution in the last years, actions to ensure and improve their reliability are required. For this intent, plans and research to efficiently establish effective maintenance strategies and develop FDD methods must be arranged since the occurrence of faults, when not properly handled, might lead to major issues in different domains. To prevent such issues, the arising of any faults or malfunctions requires an active FDD and management.

Considering that most FDD methods rely on different measurements along the vapour compression circuit, particularly temperature measurements, this paper proposes a low-cost data acquisition system for this parameter in such equipment. The referred system consists of ten DS18B20 temperature sensors, a sensor that relies on a one wire communication protocol, connected to an ESP32 MC. The data acquired by the system may be either displayed in a screen or stored in a micro-SD card to be assessed later on, what provides an extensive dataset for data analysis and, consequently, the basis for the development of data-driven FDD methods. Furthermore, a smart maintenance strategy, previously referred, might also be enabled, what also presents a great potential to increase the systems reliability while reducing their downtime and necessity of corrective actions and their respective costs.

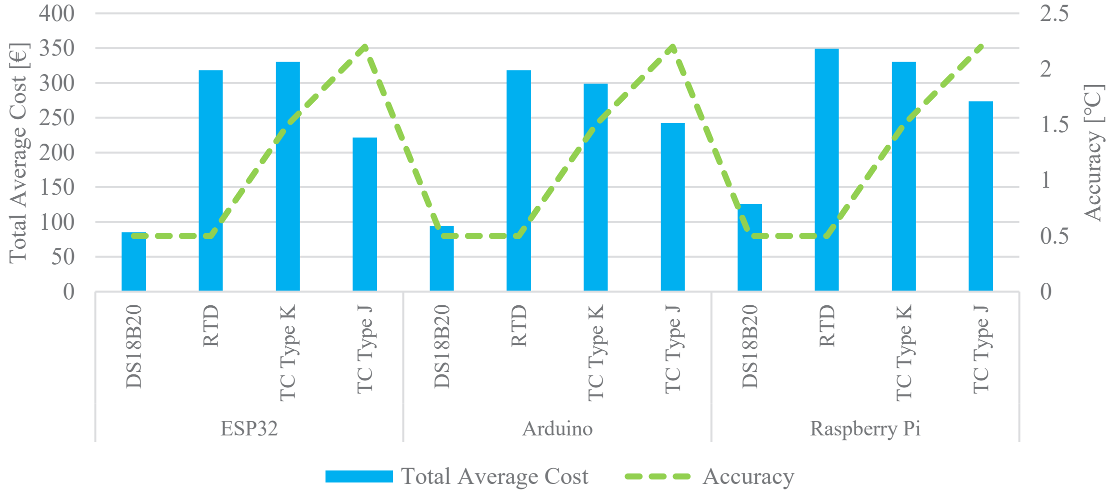

Figure 6. Average Costs for Different Systems with 10 Sensors.

Because of the architecture of ESP32, the proposed solution can be employed by technicians in the field to collect equipment data or embedded in the system itself to monitor its parameters. In this manner, any deviation from normal operation can be assessed and the faults detected in a still incipient stage. Regardless of the application, to ensure the solution's portability, a PCB was designed to centralise the sensors and the microcontroller into a small device that can be either directly supplied by the grid or by batteries as well.

Aiming to verify the proposed solution's functionality, the conceived system was experimentally validated by reliably collecting temperature data from the circuit of an air-to-air HP with deviations no greater than ±1.5°C. Moreover, to ensure its portability in the field, the battery lifetime was estimated. Acknowledging that it depends on the battery capacity and the operating mode, an optimised strategy through light-sleep function available in ESP32 was considered. As a result, a lifetime of more than three weeks can be achieved.

To assess the conceived solution with the systems currently employed in the literature for similar purposes, a techno-economic analysis was conducted. Such analysis comprised three different microcontrollers and four different temperature sensors largely used in both academia and industry. In technical terms, RTD sensors perform very similarly to DS18B20, however, in economic terms, they present remarkably greater costs. Considering all the analysed systems, the combination of ESP32 and DS18B20 sensors reveal to be the most profitable from a technical and economical perspective.

Even though the focus application of the addressed system are HPs, it might be employed in other systems for temperature data-acquisition as well. Still, in the event of HPs data-acquisition, it is mandatory to analyse the system since the temperature range of DS18B20 sensors spans from -55°C to 125°C, what is not appropriate for transcritical cycles as such systems operate above this temperature range.

The next step of the proposed system is to transmit the collected data for other systems via wi-fi, Bluetooth and other network architectures, which encompass an IoT approach and will be presented in a future work. Additionally, even though calibration is not necessary for the present application, it might be considered for the improvement of measurement accuracy, which will be discussed in the future along an experimental comparison of DS18B20 with other sensors, including TC and RTD.

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