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Improving the Energy Efficiency of the Modular Buildings Drying Room: A Case Study of Construction Site Cabins

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Abstract: Due to the nature of construction work projects that must be executed outside regardless of the weather, and because it rains most of the time in the UK, the workforce will need dry clothing to work in the best conditions for their health and productivity. This study aims to identify the energy currently used in a drying room at the Everton site in Liverpool, based on which improvements will be made to optimise the drying system and garment hanging arrangement to reduce the energy bill and carbon (CO_2) emissions to the environment. A thermal model using IESVE 2023 (Integrated Environmental Solutions Virtual Environment) software was developed to predict the energy consumption in the current intensive energy drying room to know the baseline energy use before implementing energy savings by constructing a test drying room composed of a heater to raise the temperature, an air circulation fan to circulate air in the room, and a dehumidifier to reduce humidity. Moisture content in the garments to dry was monitored hourly from the 25th of April to the 2nd of May for seven hours, and the results show that the best drying system in terms of energy consumption to adopt is the combination of a dehumidifier and an air mover, saving about 60%. However, adding a low-energy heater to that will still realise the same savings—58%—and the drying process will be faster in this case. Based on this fact, it can be concluded that the impact of low humidity, good air velocity, and high temperature have a great impact on reducing energy consumption, drying time, and carbon emissions.

Keywords: construction; drying energy efficiency; garments drying; protective personal equipment; thermal modelling

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1. Introduction

The UK has a temperate climate. It gets cool, wet winters and warm, wet summers [1], and construction workers are often outside working on projects throughout the year. Eventually, their protective equipment and clothing will inevitably come into contact with mud and water. Hence, to help staff keep their clothes dry and ready to wear for the next shift, most sites accommodate staff changing facilities by using temporary modular buildings or so-called drying rooms to provide employees with changing facilities [2]. These facilities are indispensable for construction sites, as they are used on a daily basis and become increasingly crucial as the workforce expands throughout the construction project. However, when it is rainy, these spaces become filled with wet kit, which makes the combination of drying racks and heating alone a slower drying option and not effective enough to have garments dry and ready to use for the next day shift. It is mostly the case when changing rooms are locked up overnight with little to no ventilation, causing evaporated moisture from wet garments to remain in the atmosphere, making the environment uncomfortable, which could lead to mould spread affecting employees' welfare, and to retard this phenomenon, an extractor needs to be installed simultaneously with the heater for long hours to dry garments, which consumes a huge amount of energy. It was predicted in June 2023 that the construction industry will increase by 12% in the UK in 2024 and 3% in 2025 [3]. Due to this increasing trend, innovative drying methods should be developed to reduce energy consumption and improve the drying performance of drying rooms in construction sites; otherwise, a large amount of energy will be wasted every year, exacerbating the global energy crisis.

Following the UK Government's 2019 amendment to the 2008 Climate Change Act, enshrining net zero in law, a construction company in the UK took on a board-level challenge and began the process of developing a new, long-term sustainability strategy that aims to create material change through the construction industry. Site drying room setups currently account for 10% of the company's carbon emissions; reducing this is vital for success. This project will bring a new approach to the market, using computer modelling and data analysis to help design an economically viable solution and push industry best practices for carbon reduction.

As per these facts, a comprehensive study to determine the optimum drying condition of protective personal equipment is important, and the results will be beneficial for construction and other businesses such as firefighters, water sports, etc.

The drying process, which refers to the removal of moisture remaining in fabric after squeezing or hydro-extraction, is one of the most energy-intensive processes [4]. The amount of moisture in a fabric depends on different properties such as thickness, structure, size, the shape of pores of the fabric, and also the chemical interaction between the water molecules and the surface of that fabric [5]. The drying capability is evaluated by the drying rate of the fabric, which is defined as the speed that the drying process takes, which is an important indicator to evaluate the drying performance of a wet garment [6].

There are three elements that favour the evaporation of water from wet clothes [7]:

- High temperature: to transform liquid molecules to vapour.
- Air movement: to carry water vapour away and prevent the air near clothes from becoming saturated with vapour.
- Low humidity: evaporation will continue steadily, and water molecules will not return to clothes from the air.

In general, the clothes drying process is divided into two parts. First, heat is to be provided to wet clothes through the air to generate evaporation of enough water molecules; then, the space above the clothes becomes saturated with water; the second important step is that an air stream is needed to completely remove the vapour from the air around them since the water vapour lingering near the clothes' surface would hinder water molecules from escaping from clothes, and some of the vapour molecules could also re-enter clothes, wetting them again. In addition, even if it is warm, the high level of humidity in the air will make it difficult for water to evaporate from clothes, and it is very unlikely they will dry. They may even pick up moisture and become wetter [7].

So far, multiple research projects have been undertaken on dryers in the agriculture domain, which showed that the temperature of drying air, airflow velocity, relative humidity, and type and maturity of agricultural crops influence the moisture removal process. A study by [8] investigated the impact of temperature and air velocity on evaporation rates. The results demonstrated that evaporation rates increase proportionally with air temperature and velocity due to an increased air absorption capacity for water vapour. However, evaporation rates tend to decrease when the temperature reaches its maximum and becomes constant, indicating saturation at constant velocity and temperature. Additionally, the study concluded that temperature's effect is less significant at high air velocities. Similarly, [9] examined a clothes dryer using waste heat from a split type of air conditioner. Two experiments were conducted: one with an auxiliary fan unit and one without. The results showed that the drying rate was higher with the fan unit (2.26 kg/h) compared to without (1.1 kg/h). Despite the fan unit consuming additional power, it significantly improved drying efficiency. In their study, ref. [10] presented an eco-friendly heat pump clothes dryer to address high-power consumption and environmental concerns in urban

Malaysia. Utilising waste heat from indoor air conditioner units, the prototype demonstrated faster drying times compared to outdoor methods, as it can dry up to 1.5 kg of clothes in 3 h, significantly reducing household costs. In another study, the authors in [11] investigated the distribution uniformity of the drying airflow by using a thermal resistor to measure material temperature and considering the temperature rising rate as an indicator of drying materials (fruits and vegetables), and good distribution of the airflow concluded that many factors affect the uniformity of the fruits and vegetables drying process, which are not only limited to the structural design parameters but are extended to the operating conditions parameters and the distribution of fruit and vegetables in the material tray.

Considerable studies have been made on clothes drying but not in the construction sector, such as [12] evaluating the drying properties of summer men's sportswear of different brands and thicknesses available in the Hong Kong market. The conclusion of this study stated that the fabric thickness has an effect on the drying rate; in other words, the higher the fabric thickness, the lower the drying rate.

The study [13] built a theoretical model to simulate the drying process inside a domestic tumble dryer and concluded that the energy consumption was primarily influenced by the ambient air temperature and relative humidity. Ref. [14] studied the effect of three different types of electric heating elements (the Positive Temperature Coefficient, resistance wire, and modified resistance wire) on the drying performance of the dryer; the results indicated that a modified resistance wire with aluminium splints in a tumbler clothes dryer might have great potential to reduce the residential energy consumption. However, most of these studies are conducted on tumble dryers, and while there is a need to investigate drying performance in construction sites, that is the purpose of the current case.

Interestingly, a recent study conducted by [15] introduced a new predictive maintenance system for VRF systems. The system uses machine learning to predict refrigerant leaks and reduce downtime and energy costs. Similar to how machine learning is used in predictive maintenance for VRF systems, it can also be applied to optimise drying processes in construction sites. By analysing historical data on energy consumption, drying times, and environmental factors, machine learning models can predict potential energy savings and identify opportunities for improvement in drying room operations. For example, a machine learning model could predict the optimal drying time based on factors such as garment type, moisture content, and ambient temperature, leading to reduced energy consumption and improved efficiency.

2. Research Gap, Study Objective, and Significance of This Study

Nevertheless, all the identified and reviewed articles explored agricultural products and investigated clothes drying using tumble dryers, which investigated the potential to make the drying process more efficient; however, it is outside of the construction field context within which sits the current research that investigates better ways to optimise energy consumption in drying rooms. Since the process of drying clothes consumes a significant amount of energy [16], no report on the energy consumption of drying construction garments exists to date in the UK. Hence the objective of the present study is to achieve the following:

- Show the inefficiency of using fan heaters to dry construction garments.
- Create a baseline computational model to assess and investigate the potential for energy savings and to ensure efficient functioning of the heating system.
- Reduce energy costs and carbon emissions in construction sites in the UK.

This work is oriented (but not limited) to construction site drying.

The novelty of this study lies in its focus on optimising the energy efficiency of drying rooms in the construction industry, specifically in the UK. This research contributes to the field by means of the following:

- Quantifying energy consumption: It provides a baseline measurement of energy usage in a traditional drying room, establishing a benchmark for comparison and improvement.

- Developing a thermal model: The use of IESVE software allows for accurate prediction of energy consumption, enabling informed decision-making regarding energy-saving measures.
- Testing alternative drying systems: This study compares various drying systems (dehumidifier, air mover, heater) to identify the most energy-efficient combination, offering practical solutions for industry professionals.
- Analysing the impact of environmental factors: This research demonstrates the significant influence of humidity, air velocity, and temperature on drying time and energy consumption, providing valuable insights for future design and optimisation.

Overall, this study advances the field of construction energy efficiency by offering a data-driven approach to optimising drying processes and reducing environmental impact. The findings can be applied to improve the sustainability and cost-effectiveness of construction operations.

3. Methodology

This research was conducted at two sites: The first one was the whole drying room of Everton stadium construction site, and second one encompassed only one drying unit in Wincham site. The point of using two sites is that in the original case study, the stadium was in the phase of construction, and the drying room onsite had open access to the workforce; then, no experiments took place in there, and only temperature and humidity sensors were installed to identify the usage profile of the fan heaters (3 kW) in the drying room to be able to model it using IESVE software to predict the energy use onsite which would represent the baseline against which energy reduction interventions will be compared. IESVE tool was used to generate the building model and to run the thermal simulation since it is easy to manipulate and gives accurate calculation results at no cost; also in the context of the current study, it enables the user to investigate and compare between the different suggested energy conservation measures in a virtual environment and to evaluate their viability before opting for real implementation. In addition, there were no historical data on the energy consumption platform onsite that state the energy used by the drying room separately from the whole site cabin due to the combined electrical distribution. In addition, it includes an extensive database and a wide selection of different structural building components with various energy consumption profiles [17]. CFD simulations were conducted to analyse air velocity, temperature, and moisture distribution in the room. This process helps identify optimal locations for different drying racks and system components. However, to be able to visualise real drying test results, CFD simulation on its own was not enough, as it is unable to determine the drying time of garments; hence, there was a need for a private drying room to test different drying scenarios other than only fan heaters that would reduce energy consumption; therefore, it has been resorted to the drying unit in Wincham, which was dedicated only for experimentation.

The dimensionless fraction of moisture in the fabric W_W is expressed by Equation (1):

$$W_w = \frac{m_w}{m_f} \tag{1}$$

where m_w is the mass of water (kg), and m_f is the mass of dry fabric (kg) [18].

3.1. Experimental Setup and Materials for Everton Site Drying Room

The Everton site drying room is located on the first floor; it contains 15 non-partitioned cabins, which are highlighted in green (Figure 1) and surrounded by other spaces such as a male and female sanitary area, cleaner's store, and male shower. The drying room, accommodating 700 lockers, currently doubles as a changing area and drying space. However, inefficient heating practices lead to unnecessary energy consumption. To remedy this, separating the drying room (Figure 1) into drying space and changing area is proposed. This would confine heat to the drying area, with controlled access for hanging garments. Implementing automation for precise drying times could optimise energy usage and minimise waste. The modelled area is highlighted in green (Figure 1). The drying room dimensions and construction materials reflecting the u-values have been provided in Tables 1 and 2.

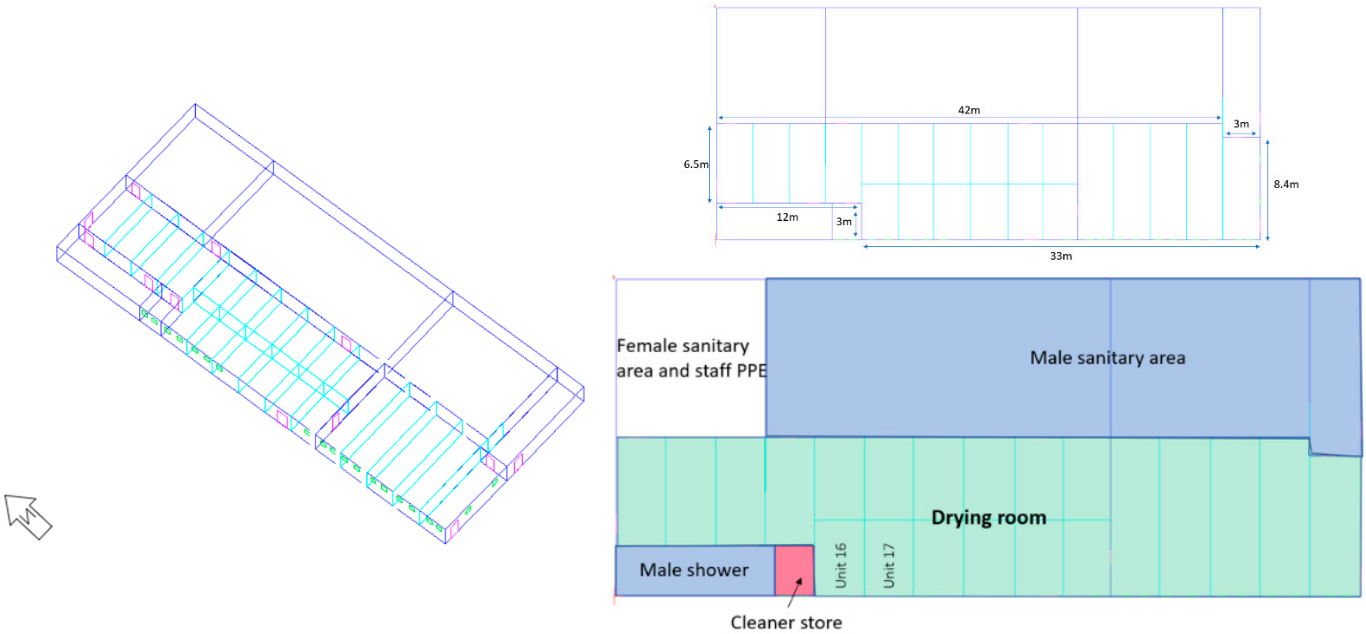


Figure 1. Axonometric and plan view of the drying room.

Table 1. Different dimensions of the drying room.

Element	Dimensions
Height	2.5 m
Windows area	0.366 m^2
External doors area	2.2 m^2
Internal doors area	1.8 m^2
Floor width	45 m
Floor length	9 m

The type of heaters used in the simulation are local room heater-fanned, with a power of 3 kW and a set point temperature of 30 °C, as this is the temperature setpoint selected in the thermostat.

There are two types of sensors installed in the drying room: Lascar EL-USB-1, Temperature Data Logger (STC) and LASCAR Temperature and Humidity USB Data Logger—EL-USB-2 (STH), as shown in the images (Figure 2a,b). These sensors measure and store relative humidity and temperature readings and offer user-settable logging rates, start-times, and alarms, allowing for humidity, temperature, and dewpoint data to be graphed and printed via a PC USB port and free-to-use easylog USB 7.6 software. STCs are connected to thermocouples and are placed just in front of the supply grill of each fan heater to measure temperature (see Figure 3). The primary purpose of these sensors was to monitor the operation profile of all the heaters from the temperature variation graph.

STH sensors are installed on and inside lockers in different locations in the room (Figure 4). These sensors measure temperature and humidity in the drying room; sensors 1, 3, 5, 7, 9, 12, 11, 13 are installed at a height of 1 m, and the remaining sensors 2, 4, 6, 8, 10 are at 1.98 m from ground level. Placing sensors at different heights and locations permits us to know the temperature and humidity distribution in the room.

Table 2. Construction materials of the drying room from Operations and Maintenance manual.

	Composition	Thickness (mm)	U-Value (W/m^2·K)
External wall	Steel Firestop10 Thermocore40 Steel	0.6 10 34 0.6	0.5
Internal partition	Thermocore	50	0.39
Ceiling	Thermocore 32	40	0.5
	Vinyl Rockwool insulation Cement particle board	3 60 8	
External door	Steel Mineral wool Steel	1.5 45 1.5	2.2
	Galvanised steel sheet Honeycomb Galvanised steel sheet	0.6 40 0.6	
Window	Outer pane Cavity Inner pane	6 15 6	1.3

Figure 2. (**a**) Temperature sensor (**b**) humidity sensor to track heater functioning time and room conditions.

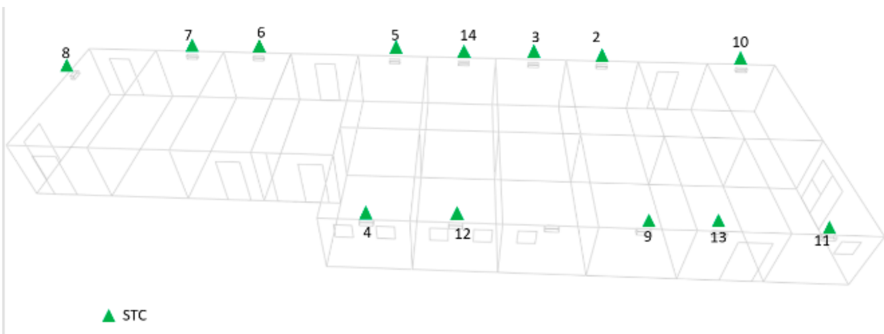


Figure 3. STC sensors distribution.

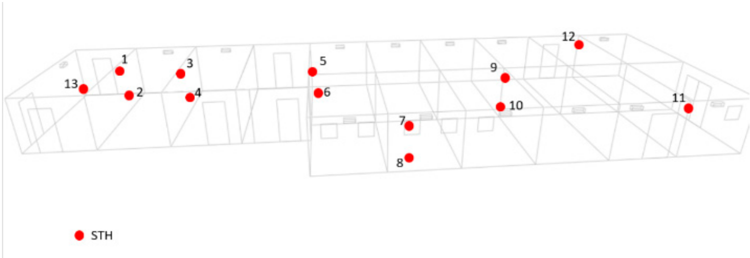
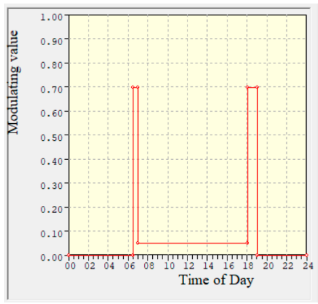
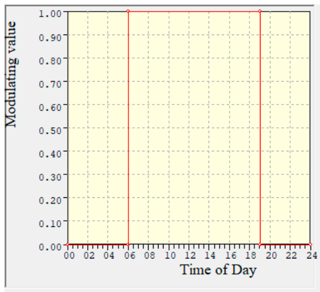


Figure 4. STH sensors distribution.

3.2. Thermal Model and Calibration (Everton Site)

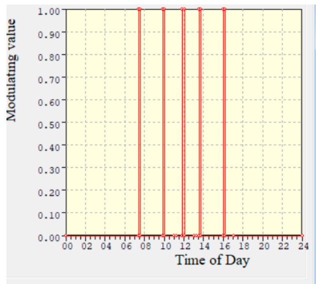
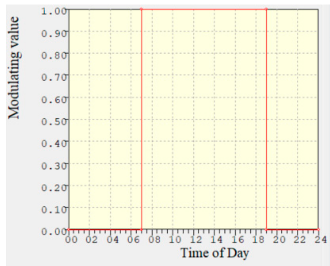
The model was constructed based on the dimensions of the drying room (Table 1), followed by the creation of a construction template utilising the materials listed in Table 2. Subsequently, the thermal template was developed using the temperature profile derived from sensor data, as illustrated in Figure 3. Additionally, all internal gains of the room (as listed in Table 3), air infiltration, microflow openings (as specified in Table 4), and adjacent conditions (as outlined below in this section) were incorporated into the model.

Table 3. Different internal gains.

	Sensible Gain (W)	Daily Profile
People (Occupancy)	90 pp (700 people)	
Lighting	36 W per bulb (42 bulbs)	

To accurately forecast the average heating load within the building and calibrate the model based on actual performance, an extensive analysis of data from temperature and humidity sensors was conducted. The challenge arose in delineating the specific profile followed by each heater, as these profiles exhibited variations from one heater to another. Additionally, the weekly profiles for a given heater displayed fluctuations throughout the month, complicating the calibration process. To streamline this calibration effort, a pragmatic approach was adopted, identifying the most frequently recurring profile in the drying room across multiple heaters. This predominant profile indicated that the heaters were consistently switched on from 4 to 7 am and from 4 to 11 pm on weekdays. December and January data were used to calibrate the model (refer to Figure 5), as this is the only dataset that was available then, with a designated "OFF" period during weekends. Noteworthy is the exception in June, during which the system was always inactive due to the absence of recorded rainfall in that particular month. In addition, lighting and extractor consumption were included in the simulation.

Table 4. Natural ventilation and air infiltration.

	Description	Profile
Air infiltration	Flow: 2.23 l/s·m^2 (3.2 ACH) (Operations and Maintenance manual)	On continuously, based on airtightness test results.
Door	Opening angle 90°	Opening time is assumed to be 10 min for 5 times a day. 
Window	Opening angle 20°	

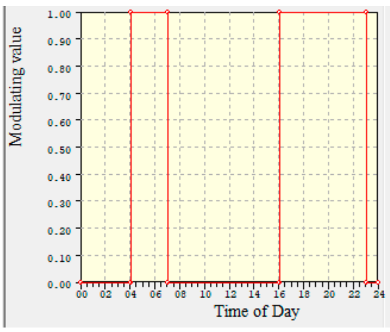


Figure 5. Heaters' operation profile.

The weather file used is Liverpool John Lennon United Kingdom, which contains historical weather data of the nearest site to Everton (17 km from Everton) already stored in the software library. Figure 6 shows John Lennon's monthly maximum, minimum, and average outdoor air dry bulb temperatures along with RH. It is evident that Liverpool experiences extreme temperature fluctuations that range from +27 °C in summer to −7 °C in winter during the year (according to IES weather data), and typically, heaters run at the end of the day shift from (4–11 p.m.) with another boost early in the morning before the shift from 4–7 a.m. (Figure 5). In addition, in Liverpool, rain is not restricted to winter; it could rain throughout all four seasons even in summer, which increases the energy bill. Consequently, the fan heaters used for drying purposes will run for a long time assumed to be 9 h to dry construction work garments.

The calibration process involved a meticulous examination that extended to a comparative analysis of the actual monthly energy consumption of the drying room, derived from the readings of the energy meter installed in two units adjacent to the cleaner store on the right (as depicted in Figure 1). This energy meter was strategically placed to monitor and record the comprehensive usage of energy. The available monthly data spans from January through August, providing a comprehensive temporal scope for the calibration endeavour. The calibration was not solely reliant on real-time data but also incorporated results from IES simulations, a critical aspect of this calibration process. The simulation results were generated under the consideration that the windows were open for half of the daily duration. This nuanced approach acknowledges the practical scenario that windows are not constantly open and aligns with the realistic conditions of not maximising heating needs at all times. The integration of these diverse data sources and simulation parameters enriched the calibration methodology, ensuring a comprehensive and accurate refinement of the model to enhance its predictive capabilities.

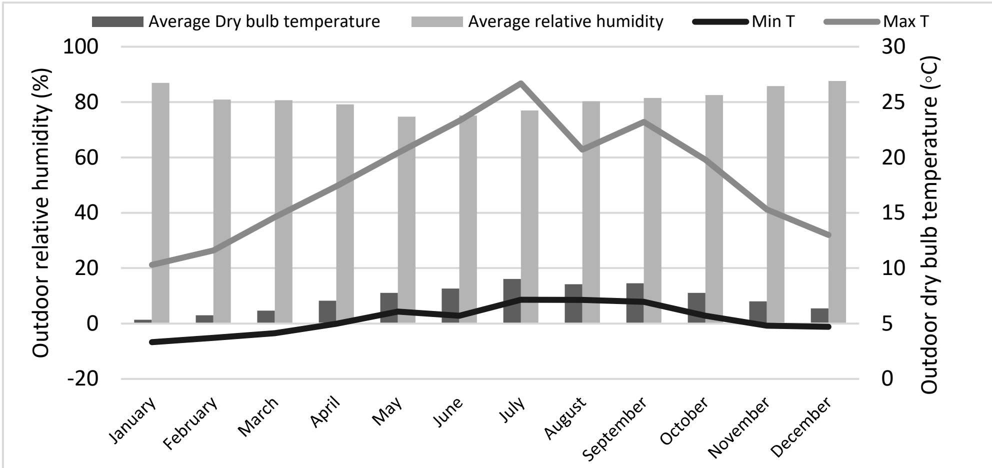


Figure 6. Liverpool John Lennon weather data.

To take into consideration the impact of heat exchange between the drying room and adjacent units and floors, it is important to set fixed or profile temperatures for the adjacencies, which are as follows:

The adjacent rooms to the main area have specific temperature settings. The floor and ceiling are maintained at a constant temperature of 21 °C, ensuring optimal human comfort. Additionally, rooms located near the drying room, including showers, the cleaner's store, and other units, are kept at a higher temperature of 25 °C. This is due to the presence of heat pumps in the cleaner's store.

3.3. Wincham Drying Room

Figure 7 depicts the Wincham depot drying room that is half of one unit ~3 × 5 m similar to Everton units; it is an enclosed area that was used to conduct experiments for the following 4 scenarios (Table 5).

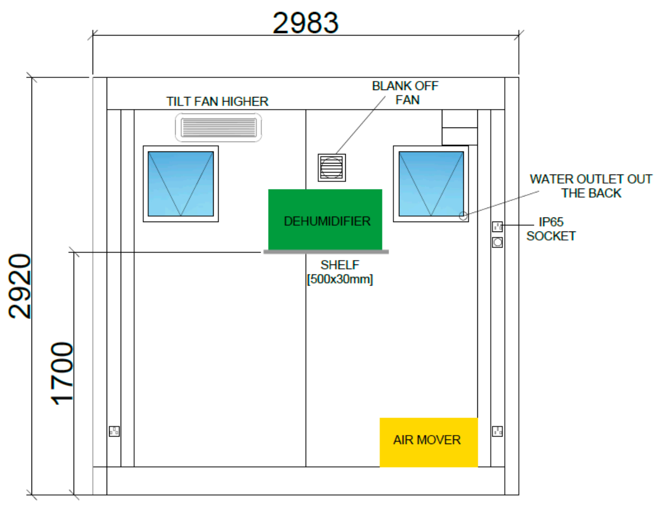


Figure 7. Wincham test drying room.

Table 5. Description of the four studied scenarios.

Scenarios Studied	
Scenario 1	Heaters ON, windows closed, and extractors ON.
Scenario 2	Heaters ON, air circulation fan ON dehumidifier OFF, windows closed, and extractors ON.
Scenario 3	Heaters ON, dehumidifier ON, air circulation fan ON windows closed, and extractors OFF.
Scenario 4	Heaters OFF, air circulation fan ON, dehumidifier ON windows closed, and extractors OFF.

Garments used in this experiment are ×10 softshell jackets, ×10 waterproof jackets, ×10 cargo trousers which are usually worn by the workforce onsite.

The equipment used in the experiment is as has been presented in Table 6.

Table 6. Equipment used in Wincham experiment.

Equipment	Description
Electric fan heater	Dimplex Air Curtain. Model: AC3N (3 kW) (Figure 8)
Dehumidifier	SENTINEL HD55 (Figure 9)
Air circulation fan	ZEUS 900 AIR MOVER (Figure 10)
Humidity and temperature sensor	ThermoProTP357 Bluetooth Hygrometer
Three temperature and humidity sensors	Lascar EL-USB-2 Temperature and Humidity Data Logger (measurement accuracy: ±0.5 °C, ±2.25% RH)
Crane scale	KERN HCB 200K500 with a precision of 0.005

Figure 8. Electric heater.

Figure 9. Dehumidifier.

Figure 10. Air circulation fan.

Three racks were used in this experiment; each hung 10 pieces of garments (Figure 11); this time, hangers were used to expose all sides to the air, which was suggested to improve the drying process. The extractor fan was ON in some scenarios to let humid air be sucked out because the dehumidifier was not running, and moisture would be stuck indoors, hindering the drying process.

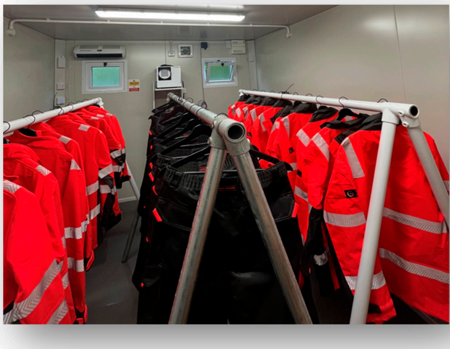


Figure 11. Drying experiment setup.

Equation (2) was used to calculate the moisture content in wet garments based on their weights to be able to determine the drying time. Regarding the final reading of the clothes' weight, it was taken after 7 h; regarding temperature setpoint, it was set at 30 °C, and humidity was undefined, as the dehumidifier was set to work continuously during the experiment.

$$M_w = \frac{W_w}{W_{w+}W_d} \times 100 \quad (2)$$

where Mw = moisture content (wet basis), %; Ww = moisture weight, kg; Wd = dry matter weight, kg.

Moisture weight = wet weight − dry weight

4. Results and Discussion

4.1. Calibration Results

A regression model has been used to determine the closeness of predicted energy consumption to reality, as shown in Figure 12; R^2 equals 0.65, which is comprised between 0.49–0.81, which can be described as good; hence, the simulation results can be used to predict the drying room energy use for the whole year; even the value of the coefficient of determination R^2 can be improved, as the observed deviation is caused by different reasons, including not using the exact real weather data of the site, as the format of the file that contained the weather data coming from the data logger was not compatible with the IESVE; also, the operation profile of the heaters is different from one heater to another; even the same heater does not follow the same profile each week; while in the model, to make things easier at the same time, close to reality, the dominant operation profile that was used was assumed to be the same for all heaters, and the same weekly profile was applied; therefore, all these input data have an impact on the ability of the model to predict real energy use; also, the behaviour of the occupants can have a huge impact on the data obtained.

Figures 13 and 14 represent a comparison between the monthly energy consumption using IES and real energy data from the energy meter for units equipped with energy meters that show the same pattern; even though there are some discrepancies, the baseline model data still describe a similar behavioural pattern of monthly energy consumption to reality.

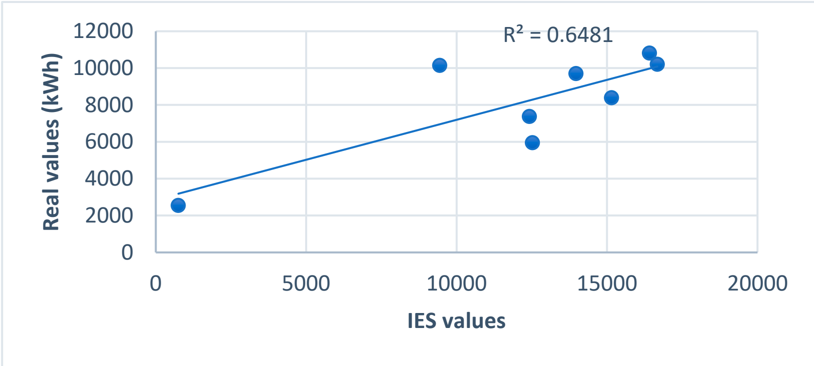


Figure 12. Linear correlation between IES and real monthly energy consumption (kWh).

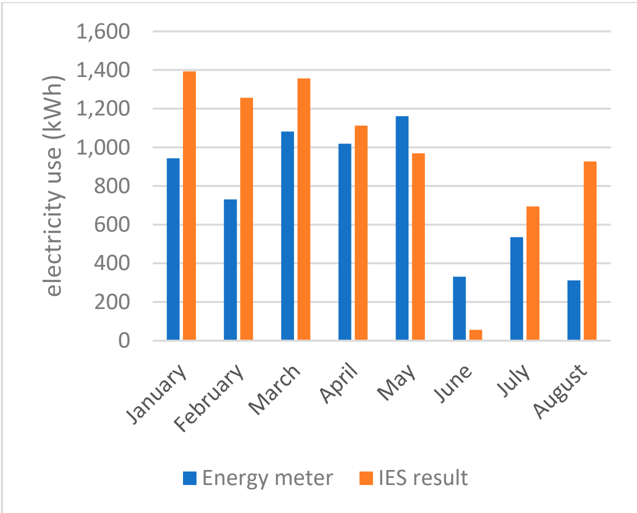


Figure 13. Comparison of monthly data for electricity use in unit 16 in 2023.

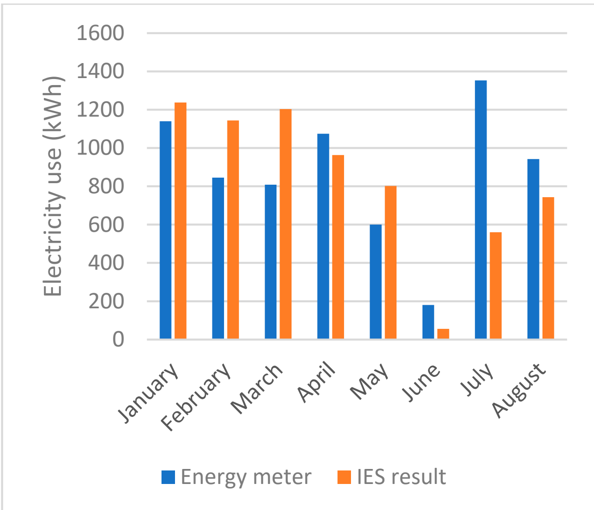


Figure 14. Comparison of monthly data for electricity use in unit 17 in 2023.

4.2. Energy Use in Everton Site Drying Room

According to the thermal modelling using IESVE software based on the profiles shown in Section 3.2, the drying room uses 151.2 MWh annually as a baseline case. Figure 15 shows the monthly energy consumption considering heaters are running for 9 h from Monday to Friday and were switched OFF on weekends and June. This energy consumption, which includes heater energy and lighting energy consumption, costs GBP 51,862.83 annually based on the single rate applied to Everton site 34.3064 PENCE_PER_KWH and emits 31.3 $TCO_{2e}q$ every year.

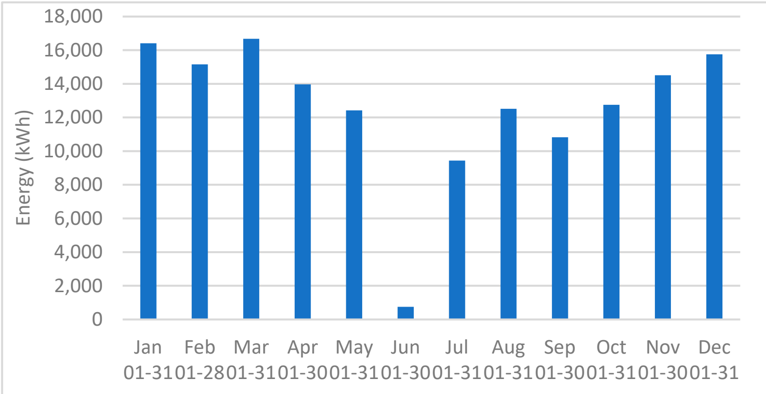


Figure 15. Everton drying room monthly energy consumption using IES VE 2023 software.

Figure 16 depicts the current arrangement of garments within the drying room where garments are stored in lockers and not evenly exposed to hot air due to the condensed hanging arrangement.

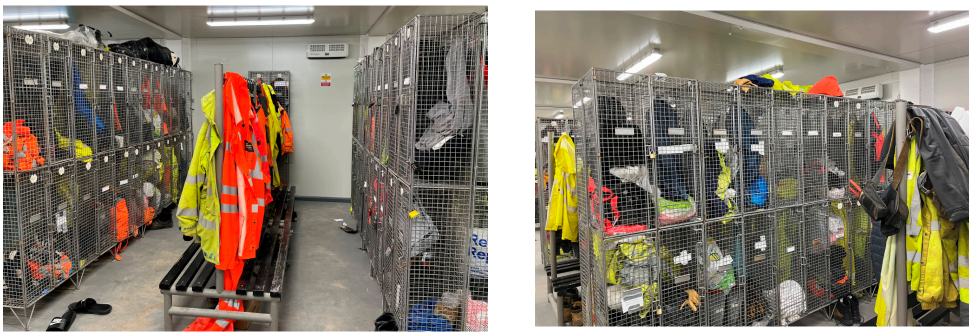


Figure 16. Drying room in Everton Site.

After having identified the energy use of heaters in the drying room, it was suggested to test different scenarios that could help reduce the energy consumption in the future. Table 7 shows different simulation scenarios that are proposed to be implemented and are divided into soft and hard schemes. Soft schemes denote energy-saving measures that do not necessitate the installation of any equipment in contrast to hard schemes.

Table 7. Soft and hard schemes to be implemented to save energy.

Soft Schemes	Hard Schemes
Raise awareness of the workforce Change (reduce) setpoint temperature	Add lobbies in front of external doors Add air circulation fans Install a dehumidifier Add timers to heaters Use a different hanging arrangement Separate the cabins Automation of indoor temperature using clothes and external climate conditions

In this paper, only four schemes were tested, which are the following: installing a dehumidifier, using an air circulation fan, using a different hanging arrangement, and using a separate cabin. As the project was in its early stages, the remaining three actions were scheduled for implementation during the summer, with testing slated for the winter season.

4.3. Drying Room Setup in Wincham

Before implementing this experiment, CFD simulation was carried out to spot the best location for each of the garments and the different equipment used in the drying process to save time and money. The simulation showed that aligning racks with each other would be the best arrangement to implement (Figures 17 and 18).

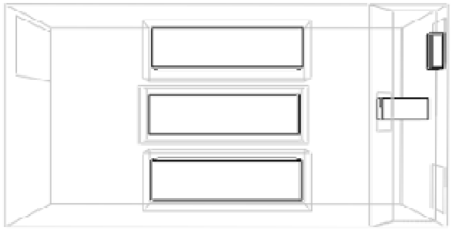


Figure 17. Garments rack arrangement in the test.

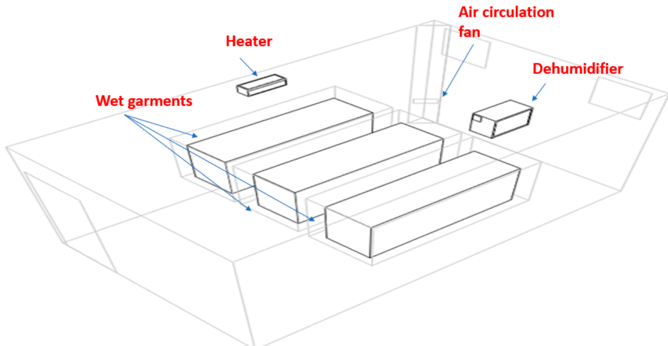
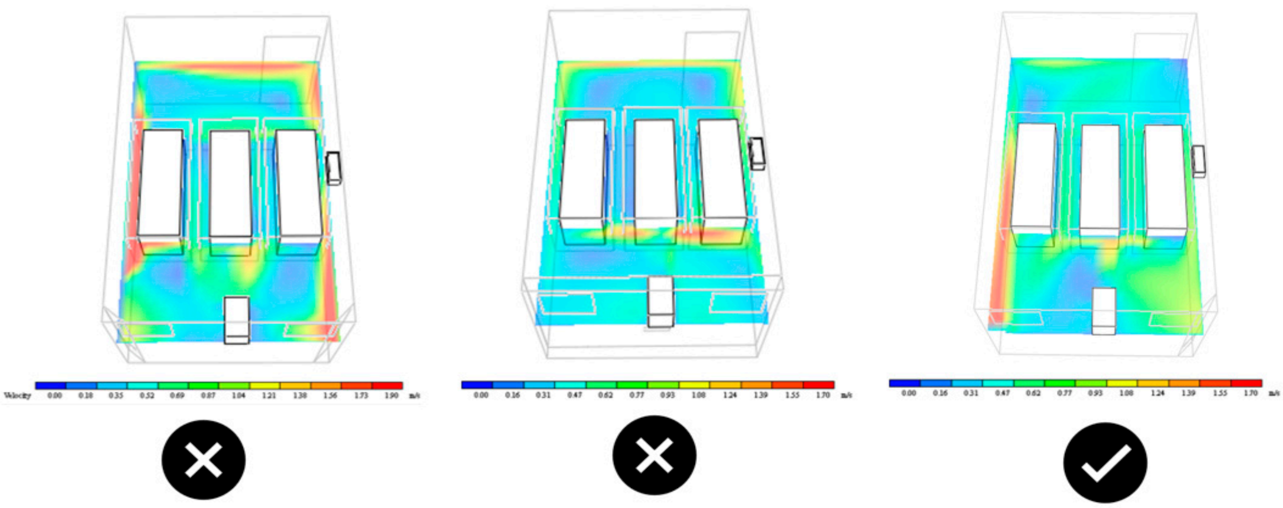


Figure 18. Three-dimensional experiment set up in IES VE software.

4.3.1. Equipment Location Validation Results

Figure 19 illustrates the air distribution in the drying unit with different fans' locations. Putting the air mover in the corner on the right 0.5 m from the ground is the best location, as homogenous air velocity distribution around and in between racks is depicted in Figure 19c, and the air velocity range is 0.7–1.2 m/s, compared to the other locations where fans are located in the left corner and under the dehumidifier, as shown in Figure 19a,b. The experiment arrangement is described in Figure 18.



(**a**) (**b**) (**c**)

Figure 19. CFD results: air velocity distribution (**a**) air fan on the left corner, (**b**) air fan below the dehumidifier, (**c**) air fan on the right corner.

4.3.2. Effect of Drying Temperature on Drying Time

Figure 20 shows the effect of different combinations of a heater, air mover, and dehumidifier on moisture content in wet garments in function of time. In all four tests, garment weight was measured every hour during the drying process and converted into moisture content using Equation (1). In Figure 20, temperature has an increasing trend in all cases, and the higher the temperature, the lower the moisture content becomes. However, it is worth noting that within a mere 2 h timeframe, the temperature surpassed 35 degrees in the last scenario featuring the operation of a heater, air mover, and dehumidifier. In contrast, in Figure 20a,c, even with the heater activated, the temperature took approximately 6 h to reach similar levels. This disparity underscores the pivotal role of air circulation in effectively distributing hot air throughout the room, thereby expediting the drying of garments. Furthermore, it is noteworthy that despite reaching 30 °C in the case of Figure 20a where only the heater was active, the moisture content remained notably high in all the tested garments. Contrastingly, with the introduction of an air mover in Figure 20c, the moisture content was lower compared to Figure 20a, underscoring the significant impact of enhanced air circulation in accelerating the evaporation process. The addition of a dehumidifier alongside the heater and air mover further amplified the drying process, yielding commendable results within just two hours. This multifaceted analysis underscores the crucial role of combining temperature, air circulation, and humidity control in optimising the efficiency of the drying system instead of relying only on heat by raising the temperature of the drying environment as is the case for the current drying room, which is the major aim of this research.

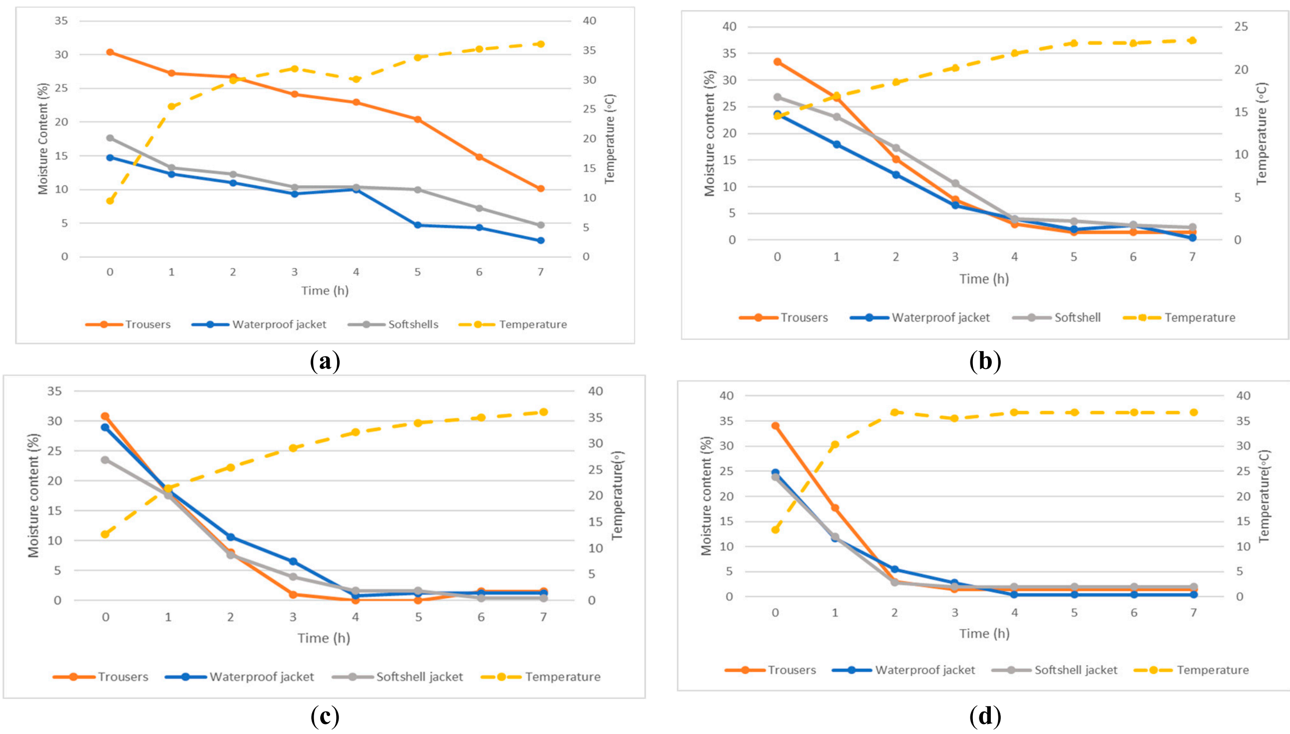
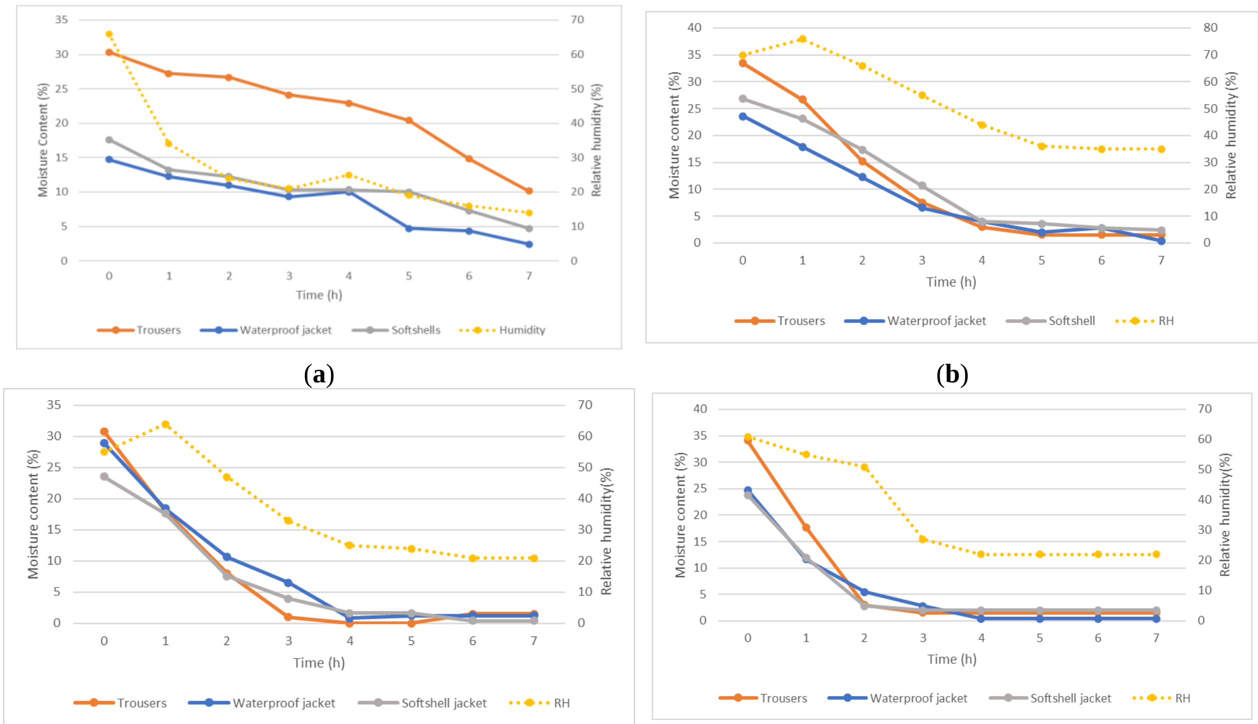


Figure 20. Moisture content in garments tested and temperature variation in four tests: (**a**) heater ON, (**b**) dehumidifier ON and air mover ON, (**c**) heater and air mover ON, (**d**) dehumidifier, air mover, and heater ON.

Therefore, at the same temperature and a higher air velocity induced by the circulation fan, the moisture content in wet garments is lower than in the case of the heater only, and the moisture content is reduced in a shorter time.

4.3.3. Effect of Relative Humidity on Drying Time

There is a direct correlation between relative humidity and moisture content in wet garments such that the relative humidity decreases at the same time, and the moisture content reduces, as shown in Figure 21. In fact, [19] showed in their study that relative humidity can be reduced in three possible ways: increasing operational drying temperature, removing moisture in the air, and combining these two, which was realised through these four tests. These results showed that combining a high temperature and removing moisture using a dehumidifier with a further enhancement of air circulation using an air mover gives the best results in terms of drying time, which is similar to [20]'s findings that revealed that adjusting air temperature, humidity, air velocity, and direction energy utilisation can be improved.



(a) (b) (c) (d)

Figure 21. Moisture content in garments tested and relative humidity variation in four tests: (**a**) heater ON, (**b**) dehumidifier ON and air mover ON, (**c**) heater and air mover ON, (**d**) dehumidifier, air mover, and heater ON.

These findings demonstrate the objectives of this study by analysing the impact of environmental factors (temperature, humidity, and air speed) on garment drying and concluding that adding a dehumidifier and air mover to the drying process helps reduce the drying time, which provides valuable insights for future design and optimisation.

4.3.4. Drying Time

Figure 22 illustrates the drying time of each of the trousers, waterproof jacket, and softshell jacket in the Wincham drying room experiment that took place in the morning from 7:45 a.m. to 15:15 p.m. The drying time was estimated based on the duration of garment drying from initial moisture content to final moisture content (0.4–2%). Data from Figure 22 has been translated into Table 8 for a clear view of the drying time. A general observation from Figure 22 is that the moisture reduction rate was higher in H (heater), DH (dehumidifier), and AM (air mover) cases, whereas in the baseline case, it was reducing slowly. Regarding DH and AM and H and AM, the moisture reduction rate was in the middle between the best and worst scenarios. This indicates that the combination of a heater, air mover, and dehumidifier accelerates the drying process. Data from Table 7 suggest that the longest drying time, exceeding 7 h for all types of garments, is in the baseline scenario when only the heater was running. Adding an air circulation fan reduced this time from 4 to 6 h depending on the type of garment; interestingly, the introduction of a dehumidifier to this setup has helped to reach the shortest time to dry all clothes to 3 to 4 h. In the meantime, it should be noted as well that combining a dehumidifier with an air mover has also been able to dry garments from 5 to 7 h. However, drying time is not a good indicator of the energy efficiency of the different drying setups used; hence, the forthcoming section will outline the criteria for determining the optimal drying system, with a focus on energy consumption.

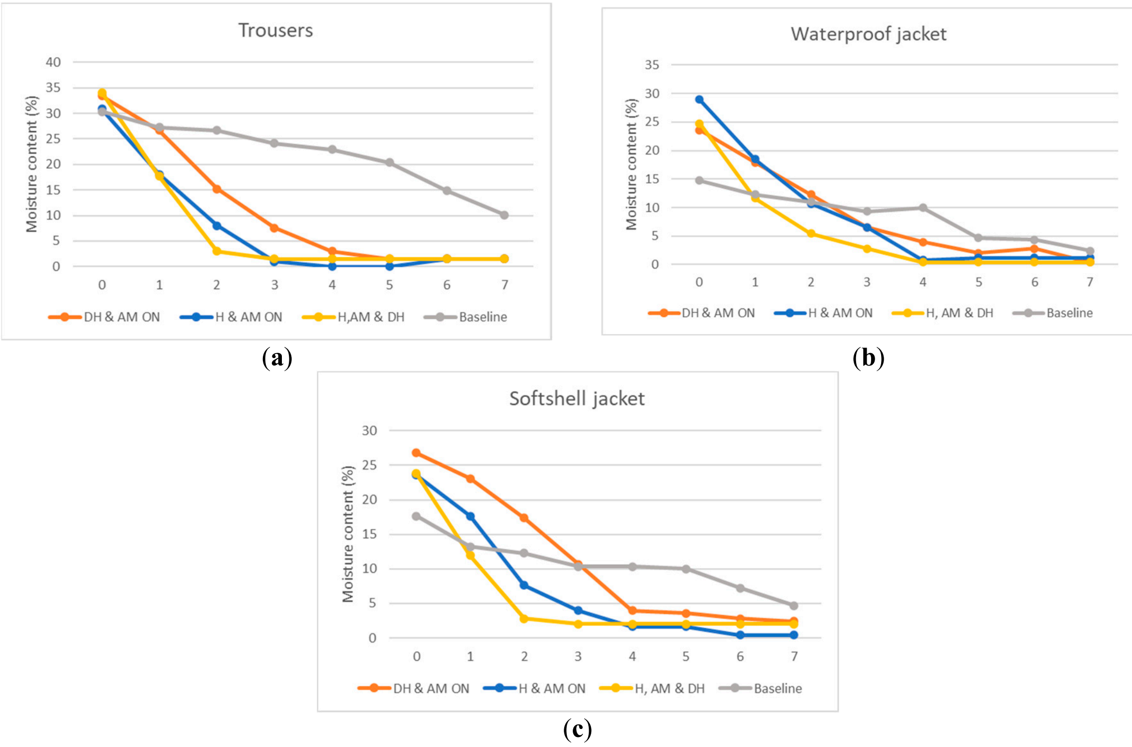


Figure 22. Drying time of garments tested for (**a**)Trousers, (**b**) waterproof jacket, (**c**) Softshell jacket.

Table 8. Drying time of different PPE used in this experiment.

Drying Time in Hours	H and AM	DH and AM	H, AM, and DH	Baseline
Trousers	4	5	3	>7
Waterproof jacket	5	7	4	>7
Softshell jacket	6	7	3	>7

4.4. Relative Humidity and Temperature Variations

Figure 23a–d describes the high air relative humidity at the start of the drying that decreased sharply with the increase of the temperature. Three sensors were used to measure relative humidity and temperature variation in the three hanging rails for the four tests with T1, T2, T3 and H1, H2, H3 referring to the temperature and humidity measured using the temperature and humidity sensors in the three locations (right end, middle, and left end of the hanging rails). These results are compatible with those of [21], who found that the relative humidity decreased as the temperature of the air increased. Another worth noting remark is that in all four tests, the slight difference in readings of temperature and humidity is due to the location of the sensor, and the proximity to the heater correlates with increased temperature and reduced relative humidity, as evidenced by the findings illustrated in Figure 23b where the heater was turned OFF, showing the same value of temperature no matter where the sensor is located. However, this does not affect which type of garment will be dried first. The drying time is dependent on the type of garment fabric whether it is a softshell jacket, a waterproof jacket, or cargo trousers.

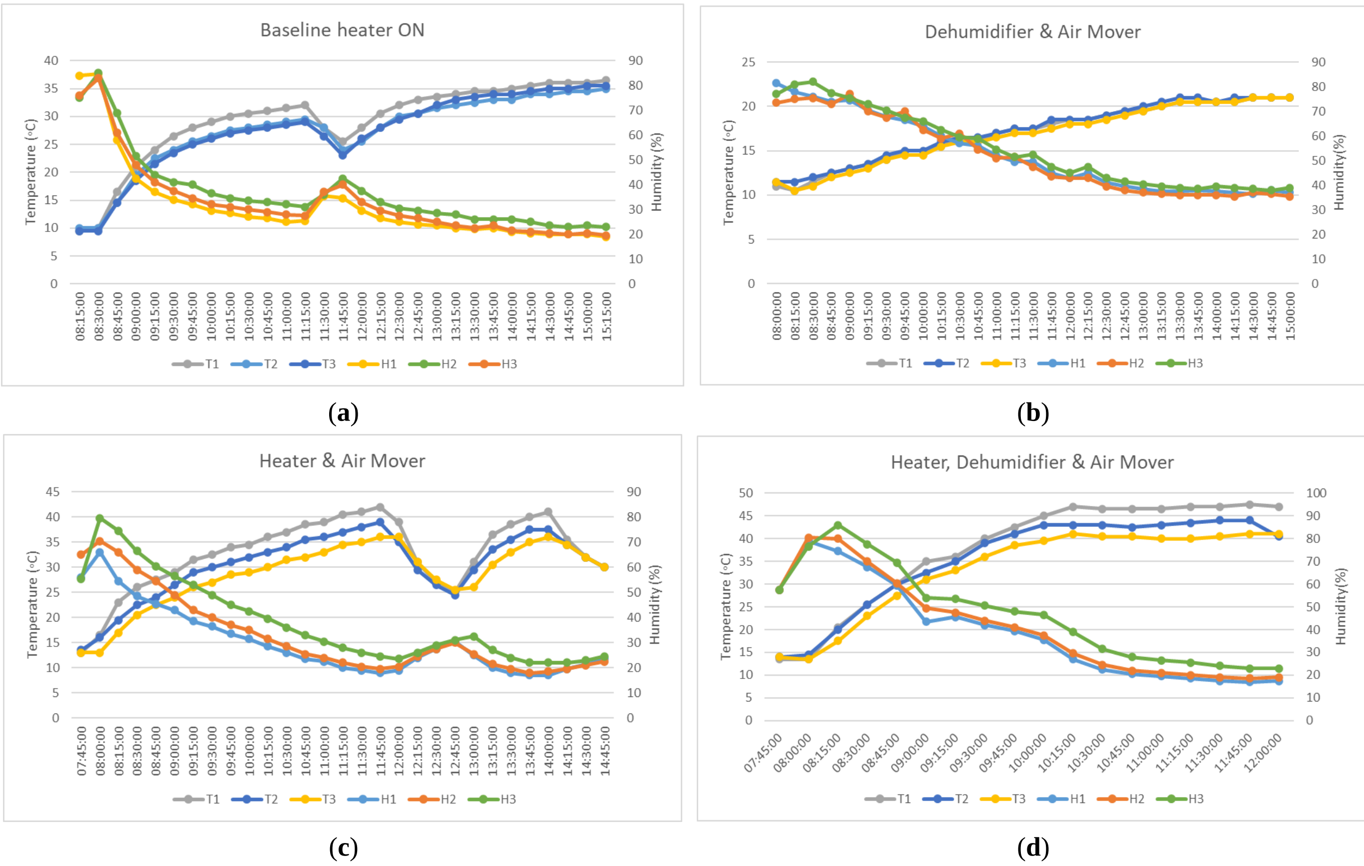


Figure 23. Relative humidity variation with DC temperature in (**a**) heater ON, (**b**) dehumidifier ON and air mover ON, (**c**) heater and air mover ON, (**d**) dehumidifier, air mover, and heater ON.

4.5. Energy Consumption and Savings

Based on the power of equipment (Table 9) and the time taken to dry, the energy consumption of each of the four systems was calculated and is depicted in Figure 24 where the highest value of 21.175 kWh is due to the baseline case, as the 3 kW heater was running for 7 h, followed by heater and air mover scenario that consumes about 20.8 kWh, which is not very different from the baseline scenario, as the drying time in this case was still high. However, when adding a dehumidifier, the consumption dropped to 15.3 kWh, as the dehumidifier is low-power equipment, and the drying time was the shortest among all the four scenarios. Finally, the lowest energy use came from the dehumidifier + air mover, which are low-energy equipment even though the drying time was longer than in the previous scenario. Also, it is worth noting that in cases where the dehumidifier was OFF, the extractor fan was running to release the excess of moisture outdoors.

Table 9. Power of equipment used in the experiment.

	Power kW
Heater	3
Air mover	0.437
Extractor fan	0.025
Dehumidifier	0.775

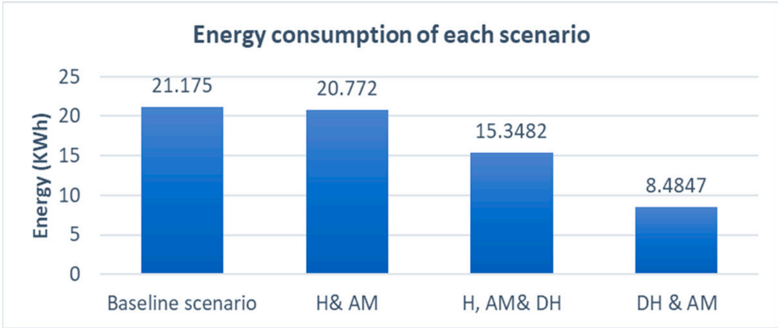


Figure 24. Comparison of energy consumption in the 4 scenarios.

Dehumidifier and fan power were worked out through the Amps used from the operations manual, as no energy meter was installed to take real energy data.

Figure 25 shows the energy savings realised from each of the three scenarios compared to the baseline scenario. The DH and AM scenario reached 60%, the highest level of savings, followed by H, AM, and DH with 27%, and lastly, 2% of H and AM, which is not viable at all. The H, AM, and DH scenario could show further savings if a low energy heater was used instead of the 3 kW fan heater. The computations indicated that incorporating a 1 kW infrared heater as a component of the upcoming hard schemes scheduled for implementation in the summer could yield a 58% savings. This aspect warrants experimentation to assess and compare the drying outcomes of the 1 kW heater against the existing 3 kW convective fan heater.

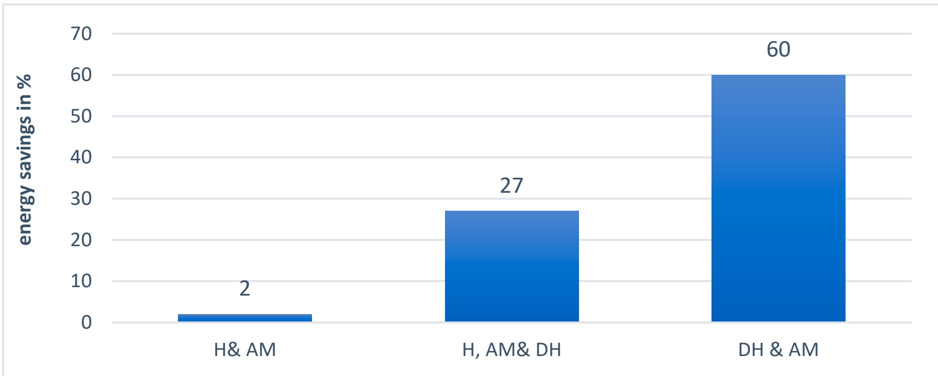


Figure 25. Energy savings realised compared to the baseline case.

After spotting that the quickest way to dry garments is using H, DH, AM, further testing should be carried out to investigate the impact of varying temperatures on the drying time.

4.6. New Suggested Hanging Arrangement

In the test conducted in Wincham, three rails were used, but the spacing between them was narrow; hence, there was a need to develop real hanging rails that would be implemented in the future drying room; with the help of CFD modelling, hanging rail locations were identified for optimal drying. Figure 26 depicts the two units where the upcoming test will take place; the selection of this area is based on the fact that a smart energy meter is installed in these cabins, which would allow us to know the energy consumed during the test; also, two horizontally adjacent units were chosen instead of a vertical one to limit doors opening by people passing through the corridor to have more representative data. The red highlighted area will encompass seven hanging rails with a total capacity of hanging 60 garments.

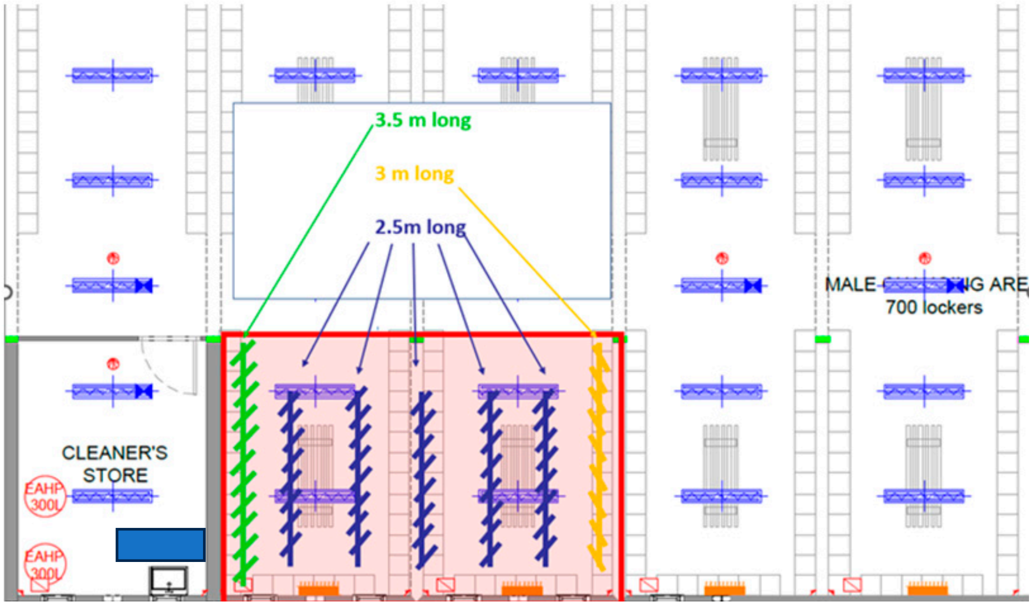


Figure 26. Drying area showing hanging rails to be implemented.

5. Conclusions

The UK climate is temperate maritime, which often results in frequent rainfall even outside of the winter season. Construction workers are in contact the whole day with water and therefore need dry garments for their next day shift. Fan heaters currently used in Laing O'Rourke's drying rooms, especially the Everton site, which is the case study of this paper, are energy-intensive and take a long time to dry PPE. This study investigated the drying process of garments in a controlled environment, utilising the Wincham drying room prototype. This research involved four experimental scenarios, each combining different configurations of a heater, air circulation fan, dehumidifier. It was found that adding a dehumidifier and a circulation fan to a low-energy heater will save all together 58% of energy, reduce the drying time, and maintain better drying conditions (high temperature, good air circulation, and low humidity). Furthermore, a new garment arrangement has been suggested to replace the current hooks with hanging rails that will provide more space between garments to dry. This new arrangement is expected to enhance the overall drying process; this will be shown in the upcoming study by comparing the current Everton drying room energy use (baseline) with the new suggested setup to identify savings based on different energy efficiency scenarios.

6. Limitations and Future Research

The sample size in this study was limited to 30, which means it did not generate significant cost savings. This is because the cabin can accommodate more garments than were used in this experiment. Additionally, the current method of determining garment dryness by weighing is labour-intensive and could be replaced with a more efficient technology. Future research should address these limitations to improve this study's findings by exploring the potential of incorporating advanced technologies, such as water sensors and infrared heating to improve efficiency and further refine the garment arrangement design to optimise airflow and drying performance.

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Nomenclature

IESVE	Integrated Environmental Solutions Virtual Environment
PPE	Personal protective equipment
CFD	Computational Fluid Dynamic
DH	Dehumidifier
AM	Air mover
H	Heater
RH	Relative humidity (%)
T	Temperature (°C)

References

1. BBC. Atmosphere and Climate. 2022. Available online: https://www.bbc.co.uk/bitesize/guides/zpykxsg/revision/3#:~:text=The%20UK%20has%20a%20temperate,conditions%20are%20also%20very%20changeable (accessed on 15 June 2023).
2. Bailey, M. Why Every Construction Site Should Invest in a Drying Room. 19 April 2022. Available online: https://www.danthermgroup.com/en-gb/calorex/why-every-construction-site-should-invest-in-a-drying-room (accessed on 15 June 2023).
3. Jackson, A. UK Construction in 2024 Predicted to Improve by 12%. 2023. Available online: https://constructiondigital.com/articles/uk-construction-in-2024-predicted-to-improve-by-12 (accessed on 2 February 2023).
4. El Fil, B.; Garimella, S. The State of the Art in Energy Saving Techniques for Garment/Textile Drying. *Dry. Technol.* **2022**, *40*, 2235–2250. [CrossRef]
5. Fangueiro, R.; Filgueiras, A.; Soutinho, F.; Xie, M. Wicking Behavior and Drying Capability of Functional Knitted Fabrics. *Text. Res. J.* **2010**, *80*, 1522–1530. [CrossRef]
6. Belgasmia, M. (Ed.) *Optimization of Design for Better Structural Capacity: Advances in Civil and Industrial Engineering*; IGI Global: Hershey, PA, USA, 2019. [CrossRef]
7. Woodford, C. Clothes Dryers. 2023. Available online: https://www.explainthatstuff.com/how-clothes-tumble-dryers-work.html (accessed on 2nd February 2023).
8. Putra, R.N.; Ajiwiguna, T.A. Influence of Air Temperature and Velocity for Drying Process. *Procedia Eng.* **2017**, *170*, 516–519. [CrossRef]
9. Suntivarakorn, P.; Theerakulpisut, S.; Satmarong, S.; Benjapiyaporn, C. An Experimental Study on Clothes Drying Using Waste Heat from Split Type Air Conditioner. 2009. Available online: https://citeseerx.ist.psu.edu/document?repid=rep1&type=pdf&doi=ba4936ac58cc581ce226161b1796fe270baef613 (accessed on 30 June 2023).
10. Lim, W.L.; Bahar, R. Experimental Study of a Heat Pump Clothes Dryer Using Air-Conditioner's Waste Heat. *IOP Conf. Ser. Earth Environ. Sci.* **2022**, *1074*, 012019. [CrossRef]
11. Zhang, R.; Long, J. Study on Drying Uniformity of Static Small-sized Drying Box for Fruits and Vegetables. *Proceedia Eng.* **2017**, *205*, 2615–2622. [CrossRef]
12. Fan, Y.-N.; Wang, W.; Kan, C.-W.; Roengthanapiboon, N. Drying Rate Evaluation of Men's Quick-Dry Sportswear. 2022. Available online: https://www.researchgate.net/publication/363401907_Drying_Rate_Evaluation_of_Men's_Quick-Dry_Sportswear (accessed on 30 June 2023).
13. Deans, J. The Modelling of a Domestic Tumbler Dryer. *Appl. Therm. Eng.* **2001**, *21*, 977–990. [CrossRef]
14. Zhao, J.; Jian, Q.; Zhang, N.; Luo, L.; Huang, B.; Cao, S. The Improvement on Drying Performance and Energy Efficiency of a Tumbler Clothes Dryer with a Novel Electric Heating Element. *Appl. Therm. Eng.* **2018**, *128*, 531–538. [CrossRef]
15. Es-sakali, N.; Zoubir, Z.; Idrissi Kaitouni, S.; Mghazli, M.O.; Cherkaoui, M.; Pfafferott, J. Advanced predictive maintenance and fault diagnosis strategy for enhanced HVAC efficiency in buildings. *Appl. Therm. Eng.* **2024**, *254*, 123910. [CrossRef]
16. Hassan, M.M.; Leighs, S.J. Quick Dry Ability of Various Quick Drying Polyester and Wool Fabrics Assessed by a Novel Method. *Dry. Technol.* **2017**, *35*, 585–592. [CrossRef]
17. Zhour, F.; Abdellatif, M.; Osman, Y.; Lee, D. Comparison between the life cycle carbon footprint of refurbished and new buildings: A case study of Community centre. *J. Build. Des. Environ.* **2023**, *2*. [CrossRef]
18. Heinisch, T.; Bajzík, V.; Hes, L. New Methodology and Instrument for Determination of the Isothermal Drying Rate of Cotton and Polypropylene Fabrics at Constant Air Velocity. *J. Eng. Fibers Fabr.* **2019**, *14*, 155892501987348. [CrossRef]

19. Djaeni, M.; Van Asselt, C.J.; Bartels, P.V.; Sanders, J.P.M.; van Straten, G.; van Boxtel, A.J. Low Temperature Drying with Air Dehumidified by Zeolite for Food Products: Energy Efficiency Aspect Analysis. *Int. J. Food Eng.* **2011**, *7*, 4. [CrossRef]
20. Huang, S.; Ding, T.T.; Yan, C.; Wang, Z.S. Optimal Design of Heating and Ventilation for Drying Room Based on Transient CFD Simulation. *Appl. Mech. Mater.* **2013**, *364*, 524–528. [CrossRef]
21. Shammi, S.; Hossen, M.A.; Al Mamun, M.R.; Soeb, M.J.A. Temporal and Spatial Representation of Temperature and Moisture in Drying Chamber and Its Impact on Vertical Vacuum Dehumidifying Rice Seed Dryer Performance. *J. Agric. Food Res.* **2022**, *10*, 100424. [CrossRef]