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A techno-economic evaluation of low-grade excess heat recovery and liquid desiccant-based temperature and humidity control in automotive paint shops

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A B S T R A C T

The paint shop is the most energy-intensive process in an automotive manufacturing plant, with air management systems that supply air to paint booths consuming the most energy. These systems are crucial for temperature and humidity control, in which they ensure the quality of the final product by preventing paint defects and thus avoid the additional cost of reworking. This is especially true for water-based paints, in which evaporation and film formation processes are influenced by the temperature and humidity of the surrounding air. This study aims to investigate the incorporation of liquid desiccant technology into a conventional air management system for paint shops operating in different climates, which presents the novelty of the study. The technology is promising because it can regulate humidity, act as a dehumidifier or humidifier depending on the demand and stores energy in a thermo-chemical form. In addition, waste heat sources available in the paint shop can be used for the regeneration of the liquid desiccant solution. The techno-economic evaluation of this novel process indicates that the proposed system can control the temperature and humidity of the supply air within the range required for optimal painting and achieve significant energy savings in both cold and hot/humid climates, with a reduction of 44.4% and 33.6% of the energy cost compared to the conventional operation and a payback period of 6.15 and 5.74 years respectively, using calcium chloride as the desiccant solution. The sensitivity analysis investigates the effect of the energy and carbon price on the performance of the system. It is concluded that the integration of liquid desiccant technology into conventional air management systems for paint booths has a huge potential to increase the energy-efficiency of automotive painting.

1. Introduction

Automotive manufacturing is a complex process that involves numerous facilities, processes, and energy sources. The various processes in the automotive manufacturing plant necessitate a high consumption of primary (fuel and electricity) and secondary (steam, compressed air, chilled and hot water) energy. Throughout the whole manufacturing process, whilst the body shop, powertrain, chassis and final assembly processes, which include metal treating, casting, forming, forging, joining, pressing, *etc.*, are all energy-intensive, it has been reported that the paint shop consumes the most energy. Values ranging between one-third and one-half of the total energy consumed to produce a vehicle. A full review of the automotive manufacturing and painting process is presented in [1].

Paint provides aesthetic (optical quality and attractiveness) and physical properties (corrosion resistance, mechanical protection and protection against weather conditions) to the vehicle. Paint deposition and curing processes require a variety of operation steps and components and they consume a significant amount of electricity, fuel, compressed air, hot and chilled water, with painting and working booths accounting for the majority of the paint shop's electricity and natural gas consumption [2]. The high air volume flow rates required by paint booths, working decks and ovens necessitate the use of electricity to operate the fans, whereas natural gas is primarily used to heat the air for both paint booth and oven operation. In recent decades, water-based paints have become the primary choice for automotive painting due to improved environmental performance (resulting in reduced emissions of volatile organic compounds (VOCs)) and overall paint quality (colour and brilliance offered by better rheology control) [3]. However

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Nomenclature

a_e	effective area to volume ratio (m^2/m^3)
a_p	surface area to volume ratio (m^2/m^3)
C	constant
CAPEX	capital expenditure (£)
E	energy consumption (kWh)
h	enthalpy (kJ/kg)
H	height of the packing material (m)
i	discount rate (%)
IRR	internal return rate (%)
L	length of the packing material (m)
LCOSE	levelised cost of saved energy (£/kWh)
m	mass flow rate (kg/s)
n	lifespan of the technology (y)
N	number of dehumidifiers and regenerators
NPV	net present value (£)
NPV/CAPEX	ratio between net present value and CAPEX (-)
OPEX	operating expenses (£/y)
P	pollutant emissions (kg)
R	ratio solution-air flow rate (-)
RH	relative humidity (%)
T	temperature (°C)
t	air-desiccant contact time (s)
U	superficial velocity (m/s)
V	volumetric flow rate (m^3/h)
VOC	volatile organic compounds
W	width of the packing material (m)
x	liquid desiccant solution mass fraction (kg$_{desiccant}$/kg$_{solution}$)

Greeks

ε	effectiveness (-)
μ	dynamic viscosity (Pa·s)
φ	environmental emission coefficient (kg$_{poll}$/kWh)
ρ	density (kg/m^3)
σ	surface tension (N/m)
ω	moisture content (kg$_{H2O}$/kg dry air)

Subscripts

a	air
CaCl$_2$	calcium chloride
cold	cold water
conv	conventional
da	dry air
DB	dry bulb
elect	electricity
eq,sol	equilibrium solution
hot	hot water
in	inlet
LiCl	lithium chloride
K	Kelvin
NG	natural gas
out	outlet
poll	pollutant
repl	replacement
salt	desiccant salt
SHE	solution heat exchanger
sol	solution
w	water
WB	wet bulb

Abbreviations

ARU	air regeneration unit
ASU	air supply unit
PM	particulate matter
RTO	regenerative thermal oxidiser
SC	specific cost
VOC	volatile organic compound

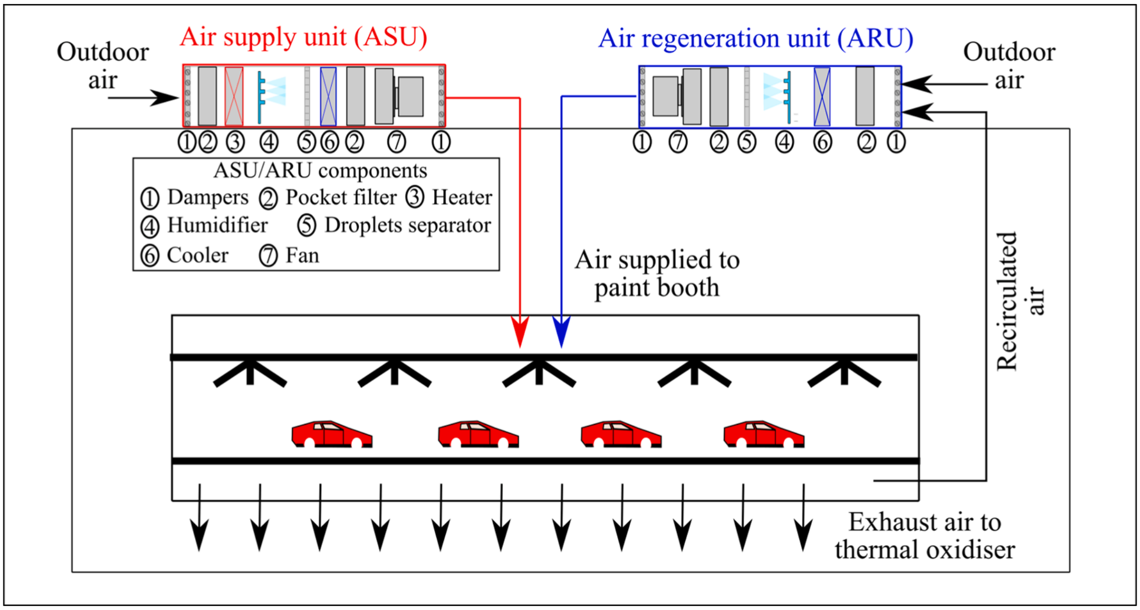


Fig. 1. A typical example of the paint booth and the relevant air management system.

compared to solvent-based paints, the effect of temperature and humidity on paint evaporation and film formation is more sensitive for water-based paints, meaning they have a higher energy consumption when supplying air within the required temperature and humidity range. The process of paint evaporation and film formation is driven by factors such as the temperature of the painted surface, the vapour pressure of the solvent, the airflow over the painted surface and the temperature and humidity of the air surrounding the vehicle in the paint spraying booth [4]. Undesired humidity in the paint booth will cause paint defects such as checking, blistering, popping, *etc.* [5]. If too much water remains trapped in the paint film, it will spot the painted surface resulting in popping, blistering, collapse of the inner layers, *etc.* Whereas an overly dry environment, may cause the paint layer to harden too quickly, resulting in cracks and lesions. Vehicle reworking can be required to remove paint defects, which is a time-consuming and costly process. The importance of temperature and humidity control in paint booths is one of the justifications for the large amount of energy that automotive manufacturers currently consume.

Paint booths are isolated enclosures for paint spraying operation to minimise exposure to VOCs and particulate matter (PM) present in the paint [6]. Depending on the configuration of the air supply unit (ASU) which delivers air to the paint booth, technological solutions employing only external air or recovering exhaust air from the paint booth can be found in the automotive paint shop. Fig. 1 shows how the conventional air management system for air supplied to paint booths consists of two main units: (i) an ASU with 100% outdoor air; and (ii) an air regeneration unit (ARU) with mixed recirculated air and outdoor air.

Supplying air by ASUs within consistent temperature and humidity ranges is a top priority for the painting process quality. The outdoor air is aspirated by fans, filtered in pocket filters, air-conditioned and supplied into the spray-painting booth [7]. Depending on the outdoor air conditions, ASUs must be able to fulfil different requirements during the year, such as filtration, heating/cooling, and (de)humidification. In cold climates, the air supplied to the paint booth is heated and humidified until the required values of temperature and humidity for optimal painting are achieved. The air is heated to 23 °C and then humidified by using boiled water in a steam humidifier. Alternatively, the air is heated until the isenthalpic line is reached (at a minimum temperature of about 40 °C in winter) and then humidified/cooled by spraying water droplets in an adiabatic humidifier. On the contrary in hotter climates, air requires dehumidification (by condensation) and is reheated. The process of outdoor air supply for painting is energy-intensive due to the high volume of air required in the paint shop (high electricity consumption for fans) and the need for heating, cooling and de/humidification. ARUs have been developed as an energy-efficient strategy to reduce energy consumption for paint booth air-conditioning, by recovering exhaust air from the paint booth and partially mixing it with outdoor air. ARUs are less sensitive to outdoor air conditions [5]. The quantity of recirculated air is a function of the system used to collect over-sprayed paint [8,9], which can typically recirculate 75–85% of the air back to the paint booth [2]. The exhaust air from the paint booth must be usually cooled down and dehumidified to remove sensible and latent heat gains in the paint booth before being reused for spraying application.

Thermal energy recovery, management and utilisation is a central strategy to leverage the excess heat from the paint shop and to realise a more efficient manufacturing process. Common sources of waste heat for the automotive manufacturing process include high-, medium- and low-temperature industrial systems for heating (furnaces, kilns, ovens, dryers and boilers) and their exhaust gases, compressed air, ventilation and refrigeration. As reported by Roelant *et al.* [10], positive energetic, economic and environmental benefits can be obtained by the realisation of an on-site heat recovery network that can reduce the cost of the heating, cooling, and paint drying process.

In such a scenario, liquid desiccant technology could be appealing due to its temperature and humidity control characteristics [11], capability to store thermal energy in thermo-chemical form [12], being regenerated by low-grade heat sources at 45–70 °C [13] and being flexible, *i.e.* dehumidifiers and humidifier (regenerators) can be located in different locations [13]. Liquid desiccant technology finds applications in different sectors, such as the manufacturing, processing and packaging of food, beverages, paper, textiles, *etc.*, residential buildings, hospitals and operating rooms, museums, libraries, *etc.* [14]. The main working fluids used as desiccant solutions are LiCl, LiBr, $CaCl_2$, HCO_2K, and $MgCl_2$ aqueous solutions [15]. Each of these fluids presents positive and negative aspects regarding the liquid desiccant process. LiCl and LiBr present the highest dehumidification ability, but their cost is high and the salts used are corrosive to metals. The performance and limited corrosion of alternative desiccant solutions, such as HCO_2K, makes it interesting for application as a stand-alone working fluid or in combination with other desiccant solutions [16]. $CaCl_2$ present lower dehumidification performance but its lower cost makes it competitive for use in large volume systems, such as paint booth ventilation systems. The potential impact of the liquid desiccant technology for automotive painting is further illustrated in Fig. 2.

The literature review showed that the knowledge of liquid desiccant technology has not been extensively transferred to the automotive painting sector and there are limited studies that attempted to evaluate the potential application of the technology for the automotive painting process prior to this research. Guan *et al.* [17] investigated the use of a segmented liquid desiccant system driven by a heat pump for a bus paint shop in Henan, China. The study identified that energy savings of about 40% of the total could be achieved by the liquid desiccant technology in comparison to the conventional operation due to the reduction of the cooling load of the outdoor air and the avoidance of air reheating after dehumidification by condensation. The use of the liquid desiccant technology for automotive painting in climates that require heating and humidification of the outdoor air was not assessed before. This study aims to investigate for the first time from a technical and economic point of view the potential of the liquid desiccant technology for automotive painting in both cold and hot/humid climates and how the outdoor air conditions affect the configuration of the liquid desiccant system integrated into the conventional air management system for paint shops, the choice of the desiccant solution, *etc.* Concerns in this matter had led to this research funded by the Engineering and Physical Sciences Research Council (EPSRC), which main aim was to study the efficient use of the available heat and the reduction of the energy consumption at a paint shop located in the UK, which represents the baseline case for this study. Therefore, this study investigates from a technological and economic point of view the utilisation of the liquid desiccant technology in an automotive paint shop where humidity control is a key working parameter.

This article is organised as follows. **Section 2** describes the methodology used for the techno-economic appraisal of the use of liquid desiccant technology in paint booth operation. **Section 3** describes and quantifies the waste heat sources that are potentially available for heat recovery at the baseline paint shop, while **Section 4** illustrates the effect of the outdoor air on the painting operation, identifying a psychrometric-based strategy for the operation of the liquid desiccant air handling unit. **Sections 5** shows the results of the techno-economic analysis for cold and hot/humid climates and is complemented by a final discussion, which describes the effect of energy and carbon prices on the feasibility of the process and suggests future improvements required by the liquid desiccant technology to further increase its competitiveness and limitations of the study.

2. Methodology

The aim of this research is to develop a methodology for identifying feasible and cost-effective designs for heat recovery processes with liquid desiccant technology in different applications. A framework for the heat recovery process from a technological and economic point of view was developed and used for the analysis of two case studies, as

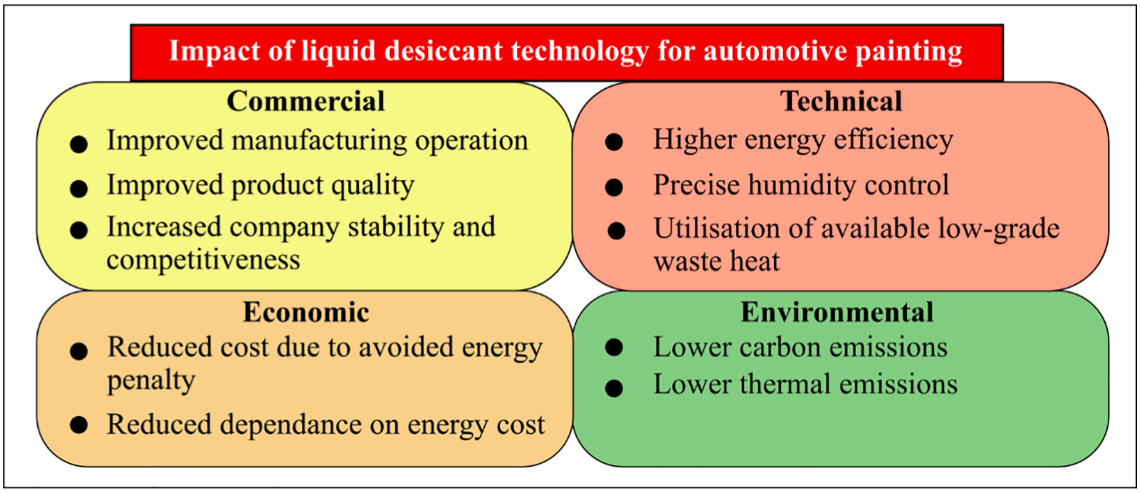


Fig. 2. Potential impact of the liquid desiccant technology for automotive painting.

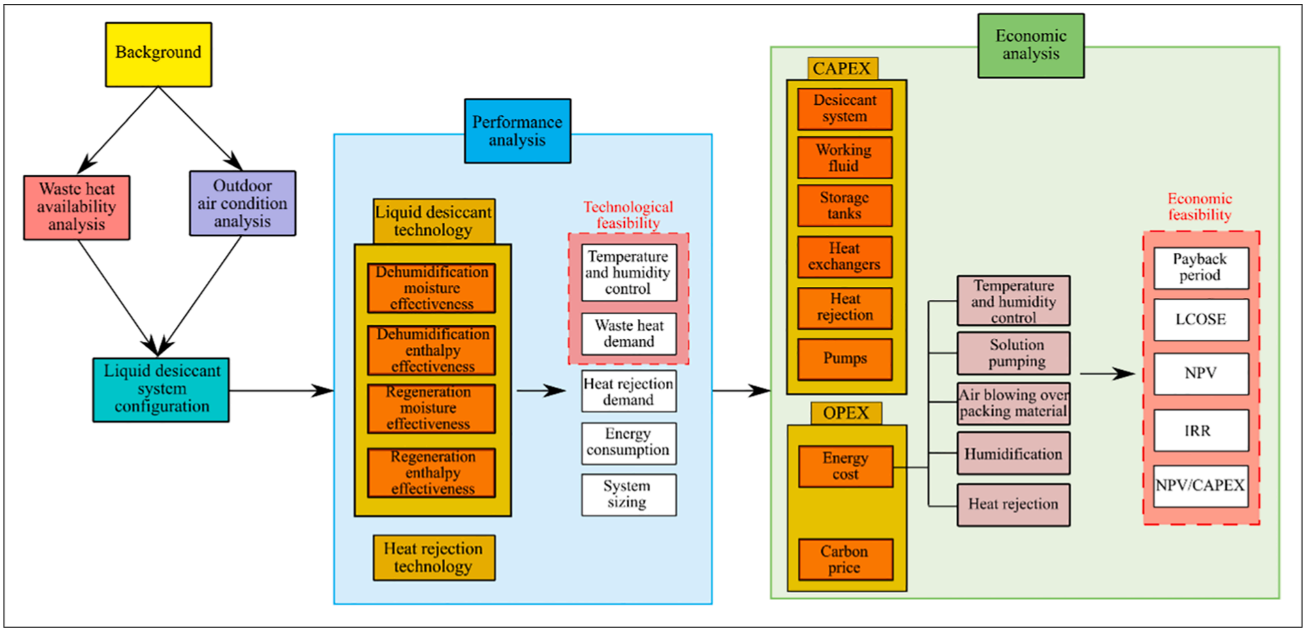


Fig. 3. Methodology developed for the techno-economic appraisal of the use of the liquid desiccant technology for automotive painting.

shown in Fig. 3. The assessment categories used for the feasibility study are (i) quantification and potential use of low-grade waste heat sources, (ii) analysis of outdoor air conditions, (iii) performance analysis, (iv) appraisal of economic benefits (including the cost benefit associated with the air pollution emissions) of the heat recovery process.

For heat recovery processes with "open-air" systems, such as liquid desiccant technology, it is fundamental to consider the availability and requirements of waste heat of the technology (first step of the feasibility analysis) together with outdoor air conditions (second step of the analysis) to identify the best performing configuration of the liquid desiccant system. Energy and mass balance equations solved by using the moisture and enthalpy effectiveness of the dehumidification and regeneration processes were used to estimate the performance of the liquid desiccant technology and assess the technological feasibility of the heat recovery process in terms of temperature/moisture control and waste heat demand. The outlet parameters of the performance analysis were then used to estimate the main capital costs and operating expenses identified as relevant for the liquid desiccant process and to assess the economic feasibility of using the liquid desiccant technology for automotive painting for different application cases.

2.1. *Waste heat availability analysis*

The identification and quantification of low-grade heat sources is fundamental for technical and economic appraisal. The choice of the best configuration for the liquid desiccant system is dependent on the required energy demand and application but most importantly on the availability of waste heat. To assess that, the quantity, quality and continuity of the available low-grade waste heat sources were evaluated for the baseline paint shop. The analysis was performed based on the collection of primary or secondary data (*i.e.* data published in literature).

2.2. *Outdoor air analysis*

Being an "open-air" technology, the performance of liquid desiccant systems is affected by the state of outdoor ambient air. This in turn, influences the selection of the best performing working fluid. The analysis of the outdoor air condition in the various case studies aids in providing a preliminary estimate of the potential economic savings and designing a case-specific configuration of the liquid desiccant system for the application requirement. The main collected parameters for the outdoor air analysis were the dry-bulb temperature, T_{DB}, relative humidity, *RH*, moisture content, ω, and wet-bulb temperature, T_{WB}. The outdoor air data were collected from [18] every three hours and represented on a psychrometric chart along with the temperature and humidity demand for optimal painting to evaluate the case studies' year-round demand. The influence of the outdoor air condition on the operation of the ASUs for optimal painting operation was identified and a psychrometric-based strategy for operating the liquid desiccant air handling unit was proposed.

2.3. Performance analysis

Coupled heat and mass transfer between the solution and the air occurs in the dehumidifier. The desiccant solution with suitable temperature and concentration has low equilibrium vapour pressure, allowing moisture to be removed from the air while diluting the solution and releasing heat of absorption. The governing equations in the dehumidifier are given as follows [19]:

- Energy balance:

$$m_{sol,out}\cdot h_{sol,out} - m_{sol,in}\cdot h_{sol,in} + m_a\cdot\left(h_{a,in} - h_{a,out}\right) = 0 \tag{1}$$

- Desiccant solution mass balance:

$$m_{sol,in}\cdot x_{sol,in} = m_{sol,out}\cdot x_{sol,out} \tag{2}$$

- Moisture mass balance:

$$m_{sol,out} - m_{sol,in} - m_a\cdot\left(\omega_{a,in} - \omega_{a,out}\right) = 0 \tag{3}$$

where $m_{sol,in}$ and $m_{sol,out}$ represent the mass flow rate of the desiccant solution (kg/s) at the inlet and outlet of the dehumidifier, respectively, $x_{sol,in}$ and $x_{sol,out}$ represent the mass of salt in the desiccant solution (kg_{salt}/kg_{sol}) at the inlet and outlet of the dehumidifier, respectively, $h_{sol,in}$ and $h_{sol,out}$ represent the enthalpy of the desiccant solution (kJ/kg) at the inlet and outlet of the dehumidifier, respectively, m_a represents the mass flow rate of dry air (kg/s), $\omega_{a,in}$ and $\omega_{a,out}$ represent the moisture content of the air ($kg_{H2O}/kg_{dry\ air}$) at the inlet and outlet of the dehumidifier, respectively, and $h_{a,in}$ and $h_{a,out}$ represent the enthalpy of the air (kJ/kg) at the inlet and outlet of the dehumidifier, respectively. The regenerator, on the other hand, undergoes the inverse process. The hot and diluted desiccant solution (characterised by high equilibrium vapour pressure) desorbs moisture to the air, concentrating the solution.

Three heat exchangers are considered for the desiccant system: one solution-to-solution heat exchanger, one for solution heating and one for solution cooling. The solution-to-solution heat exchanger is used to improve energy efficiency by precooling the warm concentrated solution leaving the regenerator and preheating the diluted solution leaving the dehumidifier. There is no direct contact between the two desiccant solutions, and the process involves only sensible heat transfer. The temperature efficiency of the solution-to-solution heat exchanger can be defined as follows [20]:

$$\varepsilon_{SHE} = \frac{T_{hot,in} - T_{hot,out}}{T_{hot,in} - T_{cold,in}} \tag{4}$$

where $T_{hot,in}$, $T_{hot,out}$ and $T_{cold,in}$ represent the temperature of the hot desiccant solution (concentrated) at the inlet and outlet of the solution heat exchanger and that of the cold desiccant solution (diluted) at the inlet of the solution heat exchanger, respectively. For the solution-to-solution heat exchanger, an efficiency of 0.5 was considered in this study [20]. The desiccant solution must be heated and cooled by the solution heater and cooler to achieve the conditions required for the regeneration and dehumidification processes, respectively. The efficiency of the solution heater and cooler was assumed as 0.75 [20].

To carry out a simple performance prediction and preliminarily design dehumidifiers and regenerators, empirical correlations of two parameters, moisture effectiveness and enthalpy effectiveness, have been proposed. These parameters are incorporated into Eqs. (1–3) for performance prediction of the liquid desiccant technology. The moisture effectiveness, ε_ω, is defined as a dimensionless ratio of the actual moisture content reduction/increase of the air to the maximum potential reduction/increase when the air and the inlet liquid desiccant solution reach an equilibrium state. The moisture effectiveness for the dehumidification and regeneration process are expressed in Eqs. (5) and (6), respectively [21]:

$$\varepsilon_{\omega,deh} = \frac{\omega_{a,in} - \omega_{a,out}}{\omega_{a,in} - \omega_{eq,sol}} \tag{5}$$

$$\varepsilon_{\omega,reg} = \frac{\omega_{a,out} - \omega_{a,in}}{\omega_{eq,sol} - \omega_{a,in}} \tag{6}$$

where $\omega_{a,in}$ and $\omega_{a,out}$ represent the moisture content of the air at the inlet and outlet of the dehumidifier/regenerator, respectively, while $\omega_{eq,sol}$ is the equilibrium moisture content of the desiccant solution, which is defined as the moisture content of the air in equilibrium with the inlet solution. Similarly, the enthalpy effectiveness of the dehumidification and regeneration process are evaluated in Eqs. (7) and (8), respectively [21]:

$$\varepsilon_{h,deh} = \frac{h_{a,in} - h_{a,out}}{h_{a,in} - h_{eq,sol}} \tag{7}$$

$$\varepsilon_{h,reg} = \frac{h_{a,out} - h_{a,in}}{h_{eq,sol} - h_{a,in}} \tag{8}$$

where $h_{a,in}$ and $h_{a,out}$ represent the enthalpy of the air at the inlet and outlet of the dehumidifier/regenerator, respectively, while $h_{eq,sol}$ is the enthalpy of the air in equilibrium with the solution.

Based on the analysis of secondary experimental data [22–26] and correlations available in the literature [27–33], four correlations for the moisture and enthalpy effectiveness of the dehumidification and regeneration process were derived, as expressed in Eq. (9):

$$\varepsilon_{\omega,h} = C_1\cdot\left(\frac{m_{sol}}{m_a}\right)^{C_2}\cdot\left(\frac{T_{K,sol}}{T_{K,a}}\right)^{C_3}\cdot\left(\frac{h_{eq,sol}}{h_a}\right)^{C_4}\cdot\left(\frac{\omega_{eq,sol}}{\omega_a}\right)^{C_5}\cdot t^{C_6}\cdot\left(\frac{a_e}{a_p}\right)^{C_7} \tag{9}$$

where $C_1,\ldots, C_7$ are the fitting constants obtained through nonlinear regression analysis using power law from the collected experimental data, m_{sol} and m_a are the mass flow rate (kg/s) of the desiccant solution and the air, $T_{K,sol}$ and $T_{K,a}$ are the inlet temperature of the desiccant solution and the air (in Kelvin), h_a and $h_{eq,sol}$ are the enthalpy of the inlet air and the air in equilibrium with the desiccant solution (kJ/kg), ω_a and $\omega_{eq,sol}$ are the moisture content of the inlet air and the air in equilibrium with the desiccant solution (kg_{H2O}/kg_{air}), t is the contact time between air and solution (s), a_e and a_p are the effective and the surface area to volume ratio of the packing material (m^2/m^3). The calculation of t and a_e is described in [34] and [35,36], respectively. The values of $C_1,\ldots, C_7$ for the moisture and enthalpy effectiveness correlations of the dehumidification and regeneration process are reported in Table 1.

Once the moisture effectiveness of the dehumidification or regeneration process is calculated based on Eq. (9), the moisture content of the outlet air can be calculated using Eqs. (5) or (6) for given moisture content of the inlet air and desiccant solution. Similarly, using Eq. (7) or (8) for specified inlet air and desiccant solution conditions, the enthalpy effectiveness can be estimated using Eq. (9) and used to calculate the enthalpy of the outlet air (and its temperature once the moisture content is known) in the dehumidifier or regenerator. Once the mass flow rate, temperature, and moisture content of the outlet air are known, Eqs. (1–3) can be used to calculate the mass flow rate, temperature, and concentration of the outlet solution. Eq. (4) is then used to calculate the

Table 1
Fitting constants in the developed empirical correlations.

		C_1	C_2	C_3	C_4	C_5	C_6	C_7
Dehumidification	ε_ω	0.6665	0.0589	9.8644	−1.6592	0.6278	0.1716	0.1620
	ε_h	0.5397	0.108	13.1312	−2.1748	0.9327	0.1617	−0.0222
Regeneration	ε_ω	1.5236	0.3267	5.727	−1.198	−0.0775	0.2493	0.4979
	ε_h	0.8892	0.2979	−0.002	0.6514	−1.103	0.1516	0.0718

waste heat and heat rejection demands for the solution-to-solution heat exchanger and the solution heater and cooler.

2.4. Economic analysis (taking account of equipment, energy and emissions)

The detailed list of the equations used to estimate the *CAPEX* and *OPEX* of the main equipment considered in the economic analysis is reported in Table 2. A description of the parameters listed for each equation is presented in the next paragraphs.

The total capital expenditure, *CAPEX*, factored into the economic assessment analysis was the sum of various components, including liquid desiccant technology, desiccant solution, storage tanks, additional pumps, and cooling towers. For calculating the capital cost of liquid desiccant systems, a cost function based on the air volume flow rate was regressed in [37] and used to calculate the capital cost of the liquid desiccant system as reported in Eq. (10), where $CAPEX_{LD}$ is the capital cost (£) of the liquid desiccant system, V_a is the air volume flow rate (m^3/h) and $C_{£,€}$ is the conversion pound-to-euro (assumed as 1.11 in the analysis). Two assumptions were considered in the liquid desiccant CAPEX estimation: (i) the setup costs are included in the CAPEX of the desiccant system, (ii) the cost is inclusive of auxiliary components (pumps, fans, solution heater/cooler and solution heat exchanger). For the salt used in the desiccant solution, the capital cost, $CAPEX_{salt}$, was estimated through Eq. (11), where $CAPEX_{salt}$ is the capital cost for the desiccant solution (£), x_{sol} and m_{sol} are the mass fraction (kg_{salt}/kg_{sol}) and the mass flow rate (kg/s) of the desiccant solution, respectively, C_{salt} is the cost per kg of desiccant salt, as reported in [15] (the cost of one kg of LiCl is £6.48, while that of one kg of $CaCl_2$ is £0.224), $t_{storage}$ is the minimum time required for continuous operation of the system, assumed as 30 min, and $N_{Deh/Reg}$ is the number of air-solution contactors (dehumidifiers or regenerators) used in each case study. The sizing of the storage tank was based on the volume of solution calculated by Eq. (11) and the number of storage tanks required by the process. Once the volume of desiccant solution that is required in the system had been determined, the cost of the storage tank was obtained based on the manufacturer's price. For the cost of additional pumps, a cost function was regressed by Zalewski *et al.* [38], as shown in Eq. (12), where $CAPEX_{Pump}$ is the capital cost of the pump (£), $a = 16.9049$, $b = 556.444$, m_{sol} is the pump flow rate (kg/s), and $C_{£,\$}$ is the pound-to-dollar conversion (assumed as 1.30 in the analysis). The pump flow rates required by the process were determined based on the performance analysis. For heat rejection with wet cooling towers, a specific cost function was regressed by Lucas *et al.* [40] and used to calculate the capital cost in Eq. (14), where $CAPEX_{CT}$ is the capital cost (£/kW) of the wet cooling tower, Q is the heat rejection capacity of the cooling tower (kW).

Table 2
List of main equipment considered in the economic analysis and equations used to estimate their *CAPEX* and *OPEX*.

Equipment	Equation	Equation number	Ref.
Liquid desiccant system	$CAPEX_{LD} = \left[\left(-7.9319 \cdot V_a^{0.0877} + 24.6067\right) / C_{£,€}\right] \cdot V_a$	(10)	[37]
Desiccant salt	$CAPEX_{salt} = x_{sol} \cdot m_{sol} \cdot C_{salt} \cdot 60 \cdot t_{storage} \cdot N_{Deh/Reg}$	(11)	[15] *
Pumps	$CAPEX_{Pump} = \left(a + b \cdot m_{sol}^{0.5}\right) / C_{£,\$}$	(12)	[38]
	$OPEX_{Pump} = E_{Pump} \cdot OperatingHours \cdot C_{El}$	(13)	[39] *
Cooling towers	$CAPEX_{CT} = \left[\left(2,348.2 \cdot Q^{-1.0398} + 26.15\right) / C_{£,€}\right] \cdot Q$	(14)	[40]
	$OPEX_{CT} = 0.0043 \cdot Q^{1.2336} \cdot OperatingHours \cdot C_{El}$	(15)	[40]
Air blowing over wetted packing material	$\Delta P_{spec} = -35.7 + 58.4 \cdot U_a + 41.5 \cdot U_a^2$	(16)	[41]
	$OPEX_{AirBlowing} = \frac{\Delta P_{spec} \cdot L \cdot V_a \cdot OperatingHours \cdot C_{El}}{3600 \cdot 1000}$	(17)	[41] *
Humidifier	$OPEX_{Hum} = C_{Hum} \cdot Q_{Hum} \cdot C_{El}$	(18)	[42]

* Estimated with values available from relevant Ref.

For operating expenses, *OPEX*, the cost is the one required to operate the components of the system: heating and cooling equipment, solution pumps [39], air blowing over the wetted packing material [41], humidifiers [42] and cooling towers [40]. Energy cost (natural gas and electricity price) has a primary effect on the *OPEX* and the cost-effectiveness of the process. The electricity and natural gas tariffs assumed in the economic analysis were £110/MWh and £23/MWh, respectively [43]. For solution pumping, the number of pumps and their energy consumption were determined based on the results of the performance analysis. The annual operation cost of a solution pump, $OPEX_{Pump}$ (£/y), was calculated as reported in Eq. (13), where E_{Pump} is the pump power requirement (kW), *OperatingHours* is the number of hours per year that the pump is in operation (h/y) and C_{El} is the electricity price (£/kWh). For the operating cost required to blow the air over the packing material, the air velocity and size of the packing play a primary role in the determination of the pressure drop, which can result in a high cost if the size of the packing is large. In the study, the additional pressure drop due to the liquid desiccant system, ΔP_{spec}, was calculated for cross-flow dehumidifiers/regenerators as reported by Liu *et al.* [41] and reported in Eq. (16), where ΔP_{spec} is the additional pressure drop due to the liquid desiccant system per unit of thickness of the packing (Pa/m) and U_a is the air superficial velocity (m/s). The annual operating cost to blow the air over the packing material, $OPEX_{AirBlowing}$ (£/y), was then calculated as reported in Eq. (17), where L is the length of packing material (m), V_a is the air volume flow rate (m^3/h), *OperatingHours* is the number of hours per year that the dehumidifier/regenerator is in operation (h/y) and C_{El} is the electricity price (£/kWh). Various types of humidifiers (isothermal or adiabatic) are used in air supply units deployed for automotive painting operation, each with its own characteristics in terms of performance and cost [5]. In this study, high-pressure humidifiers were considered. As reported by Lazzarin and Nalini [42], the electricity consumption for their operation, C_{Hum}, is 0.0055 kWh/$kg_{H2O,evap}$. The annual cost to operate the humidifier, $OPEX_{Hum}$ (£/y), was calculated as reported in Eq. (18), where Q_{Hum} is the annual humidity requirement ($kg_{H2O,evap}$/y) estimated from performance analysis and C_{El} is the electricity price (£/kWh). For heat rejection with wet cooling towers, an operating cost function for the electrical power required by a centrifugal system and dependent on the heat rejection was regressed by Lucas *et al.* [40] and included in Eq. (15), where $OPEX_{CT}$ is the annual operating cost of a centrifugal cooling tower (£/y), Q its cooling capacity (kW) estimated from performance analysis, *OperatingHours* is the number of hours per year that the cooling tower is in operation (h/y) and C_{El} is the electricity price (£/kWh). When the wet-bulb temperature of the outdoor air limits the heat rejection ability of the wet cooling tower, an alternative strategy for solution cooling, such as the use of an electrical chiller, was considered.

The analysis is concluded by the evaluation of the environmental benefits resulting from the use of liquid desiccant technology instead of the conventional one and the cost associated with air pollution emissions. The air pollutants considered in the analysis were carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O). The annual air emission of pollutants was calculated as shown in Eq.(19) [44]:

$$P_{poll} = \sum_i \left(\varphi_{i,elect} \cdot E_{elect} + \varphi_{i,NG} \cdot E_{NG}\right) \tag{19}$$

where P_{poll} is the total emission of pollutants (kg), $\varphi_{i,elect}$ and $\varphi_{i,NG}$ are the coefficients of emission for different pollutants in the UK in 2019 attributable to the annual consumption of electricity, E_{elect}, and natural gas, E_{NG}, calculated in kWh/y from performance analysis, respectively. The values of the coefficients of emission of the considered pollutants were obtained from [45] and reported in Table 3.

The emissions affect the economic feasibility of the process due to the carbon emission price, in line with the Government's decarbonisation policies, as presented in [46]. The value of the carbon price, C_{CO2e}, was considered as £16/ton_{CO2e} [47]. The emissions in terms of CO_{2e} of CH_4 and N_2O were calculated by multiplying the emission of the pollutant by its value of *global warming potential* (GWP), where GWP_{CH4} was considered as 25 $\text{kg}_{CO2e}/\text{kg}_{CH4}$ and GWP_{N2O} as 298 $\text{kg}_{CO2e}/\text{kg}_{N2O}$ [48]. The annual cost for the carbon price, $OPEX_{Carbon}$ (£/y), was calculated based on the carbon price and the emissions produced from the technology, $P_{CO2}e$ (ton_{CO2}e/y), as reported in Eq. (20):

$$OPEX_{Carbon} = \frac{P_{CO_2e} \cdot C_{CO_2e}}{1016.47} \tag{20}$$

The cost-effectiveness of the liquid desiccant process was assessed using four different economic indicators: the *payback period,* the *levelised cost of saved energy (LCOSE),* the *net present value (NPV)* and *the internal rate of return* (*IRR*). The *payback period* represents a simple comparison between capital and operational costs of the conventional and replacement technology and identifies the time required for the economic return on the initial investment, as reported in Eq. (21) [44]:

$$Paybackperiod = \frac{CAPEX_{repl} - CAPEX_{conv}}{OPEX_{conv} - OPEX_{repl}} \tag{21}$$

where $CAPEX_{repl}$ (£) and $CAPEX_{conv}$ (£), and $OPEX_{repl}$ (£/y) and $OPEX_{conv}$ (£/y) represent the capital and operational cost of the replacement and conventional technology, respectively. $CAPEX_{conv}$ was assumed equal to zero because a retrofitting project was considered. Payback period analysis is used by companies for preliminary screening of heat recovery projects due to its simplicity and practicality [49]. For heat recovery processes, the limit of payback period analysis is to not include the long-term benefits of the heat recovery technology, which lifespan could be longer than the payback period. A value of 3 years is recommended in the literature for industrial projects [50]. To evaluate the feasibility of the heat recovery process over the lifespan of the technology and the *time value of the money* (TVM), three additional metrics were used. These alternative metrics are based on the method of discounted evaluation, where the value of the money changes with time, depending on the life of the project, the discount rate, *etc.* [51]. The *LCOSE* indicates the cost for saving each kilowatt-hour of electric or thermal energy by replacing the conventional system over the lifespan of the technology, defined in Eq. (22) [52]:

$$LCOSE = \frac{Investment}{Energysaved} = \frac{CAPEX_{repl} - CAPEX_{conv} + \sum_{k=1}^{n}\left[\frac{OPEX_{repl}}{(1+i)^k}\right]}{\sum_{k=1}^{n}\left[\frac{E_{conv} - E_{repl}}{(1+i)^k}\right]} \tag{22}$$

where the parameter expresses the economic viability (£/kWh) of the technology replacement over the lifespan of the machine*,* *n*, assumed as 20 years [53], and *i* is the discount rate, assumed as 5% in the analysis [50]. For the evaluation of the *LCOSE*, a comparison with the retail price energy paid by the consumer was performed. If the retail energy cost was higher than the *LCOSE*, then the heat recovery process would save energy compared to conventional technology. The *NPV* is one of the most commonly used tools for analysis of the profitability of heat recovery processes and is defined as *the sum of the annual discounted cash flows over a period of n years* [54], as reported in Eq. (23):

$$NPV = \sum_{k=1}^{n} \frac{\left(OPEX_{conv,k} - OPEX_{repl,k} - CAPEX_{repl} + CAPEX_{conv}\right)}{(1+i)^k} \tag{23}$$

Heat recovery processes with *NPV* higher than zero present economic return over the lifetime of the technology. The *NPV* value can be used for the comparison of heat recovery processes. When comparing different heat recovery projects, the one with a higher *NPV* has a higher economic return and should be selected. The discount rate, *i*, which determination is equivocal and depends on the economic risk that the company is willing to take for an investment [50], influences the economic feasibility analysis performed with *LCOSE* and *NPV*. As an alternative, the *IRR*, defined as the discount rate at which the *NPV* is equal to zero, was used. Compared to *LCOSE* and *NPV*, the advantage of using the IRR is its independence on the discount rate which makes the metrics representative of the quality of the heat recovery process, enabling better comparison between different projects [54]. Higher *IRR* means higher efficiency of the heat recovery process from an economic point of view. It is reported that every investment with an *IRR* of over 15% should be accepted [51]. The economic analysis was concluded by the evaluation of the ratio between the *NPV* and the *CAPEX* to highlight the margin between the economic return and the initial investment of the heat recovery process. Assumptions used in the economic analysis are summarised in Table 4.

3. Waste heat availability analysis

Low-temperature waste heat from VOCs treatment systems (e.g. regenerative thermal oxidiser), compressed air systems, chilled water systems, intermediate ovens, *etc.* is available abundantly but has not been efficiently exploited in the paint shop [1]. The idea of exploiting these heat sources to regenerate a liquid desiccant solution, which would be potentially able to (i) provide heating, cooling, and de/humidification, as required by the painting process and (ii) efficiently

Table 3

Coefficients of emission from different energy sources in UK in 2019, adapted from [45].

Energy source	Electricity			Natural gas		
Pollutant	CO_2e	CH_4	N_2O	CO_2e	CH_4	N_2O
Emission (kg_{poll}/kWh)	0.2556	0.00065	0.00137	0.20428	0.00027	0.00011

Table 4

Summary of assumptions used in the economic analysis.

Parameter	Value
Salt price, C_{salt}	£0.224/kg ($CaCl_2$), £6.48/kg (LiCl)
Electricity price, C_{El}	£110/MWh
Natural gas price, C_{NG}	£23/MWh
Conversion pound-to-euro, $C_{£,€}$	1.11
Conversion dollar-to-pound, $C_{£,\$}$	1.3
Electricity consumption humidifier, C_{Hum}	0.0055 kWh/kg_{H2O}
Carbon price, C_{CO2e}	£16/ton_{CO2e}
GWP_{CH4}	25 $\text{kg}_{CO2e}/\text{kg}_{CH4}$
GWP_{N2O}	298 $\text{kg}_{CO2e}/\text{kg}_{N2O}$
Lifespan of the technology, *n*	20 years
Discount rate, *i*	5%

control temperature and humidity in paint booths, reducing paint defect, vehicle reworking and additional costs, was explored. The characteristics (quantity, quality, temporal availability and location) of three potential sources of waste heat available at the paint shop but currently unexploited were evaluated. In the calculations, it was assumed that the paint shop operates 22.5 h per day, 265 days per year (equivalent to 5,962.5 h/y).

- Regenerative thermal oxidiser (RTO): after being exhausted by the painting operation, the process air is sent to the RTO, where it is burnt at about 800 °C to remove the VOC present. The ceramic material of the RTO chamber is effective in storing thermal energy for internal heat recovery and the air exhausted by the RTO chamber (usually with a concentration of VOCs lower than 0.01%) is sent to the stack at a temperature of 174 ± 20 °C. The process air flow rate varies according to vehicle production, with a maximum flow rate of 14,000 m^3/h and nominal and minimum operating conditions of 75% and one-third of the maximum flow rate, respectively. The system operates in nominal condition most of the time. The acid dew point of VOCs in the exhaust stream limits the amount of heat that can be recovered from the RTO [55]. As such, the temperature of the exhaust air must not be lowered than 110 °C. During normal operation, the available waste heat ranges between 62.18 and 156.14 kW. As such, an average of 650.87 MWh/y of heat could be recovered from the RTO stack. Table 5 summarises the characteristics of waste heat that could be recovered from the RTO.
- Compressed air units: in the ultra-low temperature range, the heat released by the cooling circuit of the compressed air system could be recovered. The cooling water for water-cooled compressors is currently used in automotive manufacturing plants for space heating, hot water production, *etc.* [1] In the baseline case study, four water-cooled units producing about 9,000 m^3/h of compressed air were employed in the paint shop, with a minimum duty requirement of 5,520 m^3/h. Table 6 summarises the specifications of the compressed air systems used in the paint shop.

As illustrated in Table 6, the overall compressed air system requires 975.8 kW of power. Considering a conversion efficiency of 10% [56], approximately 878.22 kW of heat is dissipated from the compressed air units when all the compressors are in operation. A minimal duty of 92 m^3/min of compressed air is required when the paint shop is in operation, resulting in the continuous availability of approximately 550 kW of heat. In the baseline paint shop, this heat is removed through a water-cooled system, which produces hot water at 47 °C.

- Condenser of the chilled water system: in a temperature range comparable to that of compressed air systems, the heat released by the condenser of chilled water systems could be recovered. In the paint shop, an air-cooled chiller system with a cooling capacity of 1 MW is currently used. Air-cooled chillers require approximately 3.4–5.7 m^3/min of coolant per kW [57]. Considering the cooling capacity of the chiller system and a ΔT of 5 °C for the hot water production, the waste heat available from the chilled water system ranges between 356.77 kW and 594.61 kW in a temperature range between 40.9 °C and 43.1 °C, resulting in an average of 2,836.3 MWh/y of heat annually available from the paint shop.

Table 5
RTO waste heat quantification.

Variable	Quantity
Process gas volume flow rate (m^3/h)	Maximum: 14,000 Average: 10,500 Minimum: 4,6667
T (°C)	174 ± 20
T_{min} (°C)	110
Waste heat available (kW)	Nominal: 62.18–156.14 Maximum: 208.22 Minimum: 27.64

Table 6
Characteristics of compressed air systems used at the paint shop.

Number of compressors	Compressed air (m^3/min)	Unitary power (kW)	Total power (kW)	Pressure (bar)
2	49	327.9	655.8	7.5
1	27	160	160	7.5
1	20.5	160	160	7.5
Total	145.5	/	975.8	/

Table 7 compares the identified waste heat sources available in the plant and their potential for heat recovery. When the paint shop is in operation, a minimum of 934.41 kW of waste heat is available from the RTO, the compressors and the chilled water system. The low quality of the heat available from the air-cooled chilled water systems and the need for additional heat exchangers for hot water production make its use for liquid desiccant regeneration less appealing. The heat available from the RTO could be appealing for liquid desiccant regeneration, in particular considering the fluctuating nature of RTO operation and the ability of the desiccant solutions to store thermal energy in the form of concentrated solution. This would allow bridging the intermittent operation of the RTO between the minimum and maximum operating conditions, regenerating and storing solution when more heat is available and ensuring a continuous temperature and humidity control process. However, the higher temperature of the waste heat available at the RTO stack suggests a different approach for its recovery, as for example by using absorption chillers capable of reducing the electricity consumption of the chilled water system at the paint shop. As such, the heat recovery from the chilled water system and the RTO was discarded in the study. On the contrary, the high quantity of hot water produced by the compressors' cooling at a low temperature (47 °C) is appealing for liquid desiccant regeneration and is considered further in the analysis.

Table 7
Summary of quantity and quality of waste heat sources at the baseline paint shop.

Source	Waste heat (kW)	Temperature (°C)	Fluid	Potential for application with liquid desiccant technology
RTO	27.64–208.22	174 ± 20	Air	Moderate: the waste heat has high quality but is intermittent. Absorption cooling is a potential alternative to the liquid desiccant technology
Compressors	550–872.22	47	Water	High: large quantity of waste heat is available at the temperature required for liquid desiccant regeneration
Chilled water system	356.77–594.61	40.9–43.1	Air	Low: the temperature of the heat source might not be sufficient for desiccant regeneration

4. Outdoor air condition analysis

4.1. Psychrometrics of painting process

According to the annual handling requirements of the outdoor air with regard to the optimal painting demand with water-based paint (23 ± 1 °C, 70 ± 2% RH), the psychrometric chart can be divided into 6 different zones, as shown in Fig. 4.

The psychrometric chart is divided into two main sections by two horizontal lines that pass through the minimum and maximum acceptable moisture content values. Humidification is required below the minimum moisture content line (when ω is equal to or lower than 11.2 g_{H2O}/kg_{da}, *i.e.* Zones I and II), while dehumidification is required above the maximum moisture content line (when ω is equal to or higher than 13.5 g_{H2O}/kg_{da}, *i.e.* Zones V and VI). The isenthalpic line, which passes through 23 °C and 70% RH ($h = 54.46$ kJ/kg_{da}) further divides the psychrometric chart, identifying points for evaporative cooling. This zone division can be used to assess the capability of liquid desiccant technology as a replacement for traditional air handling units in automotive painting processes, and it is further described:

- In Zone I, heating and humidification are required. The moisture content is lower than the value required for painting. The traditional method for using adiabatic humidifiers involves heating the air until it reaches the isenthalpic line and then spraying water into it to reach the recommended painting window on the psychrometric chart.
- In Zone II, cooling and humidification are required. The moisture content is lower than the value required for painting, but the temperature is significantly higher. Sensible heat is removed by cooling the air until the isenthalpic line is reached and then spraying water into it to reach the recommended painting window on the psychrometric chart.
- In Zone III, only heating is required. The moisture content is the same as that required by the painting process, but the temperature is lower. Air heating is the most efficient and economical strategy for the process.
- In Zone IV, only sensible cooling is required. The moisture content in the air is within the range required by the painting process but its temperature is higher. Conventional cooling is the most efficient and economical strategy for the process.
- In Zone V, moisture removal is required. While the temperature of the air is lower than the value required for painting, its moisture content is higher. The conventional process involves cooling and water condensation until the requirement in terms of moisture content is reached and then reheating. The process is not particularly efficient.
- In Zone VI, cooling and dehumidification are required. This condition, typical of hot and humid climates such as South-East Asia, requires high consumption of electricity and fossil fuel for moisture removal by condensation and reheating with conventional technology. Liquid desiccant technology for automotive painting application could be also particularly favourable in Zone VI.

Based on the previous considerations, liquid desiccant technology can be integrated into automotive painting air handling units to achieve energy-efficient dehumidification and/or humidification, as shown in Fig. 5. Because the system is open-cycle, the regenerator and dehumidifier can be separated and strategically placed near the locations where dehumidification/cooling and humidification/heating processes are required. Each air handling unit, as shown in Fig. 5, is made up of an air-solution contactor (regenerator or dehumidifier), humidifier, droplet separator, cooler, heater, pocket filters and fans. To form the entire liquid desiccant system, besides dehumidifier and regenerator, two storage tanks (for diluted and concentrated solutions, respectively), a solution heat exchanger, one solution heater for waste heat recovery, and one solution cooler (cooling tower or chilled water system) are needed. The storage tanks are used to store the desiccant solution at various concentrations and to vary the solution flow rate based on the ASU and ARU operation requirements. The new liquid desiccant air handling unit must meet the air requirement and be able to operate all year.

4.2. Region selection

Principal automotive manufacturers are multinational companies with manufacturing plants located all over the world. The realisation of innovative painting strategies able to efficiently work in different climates would be advantageous to study and develop the technology. As such, the psychrometric chart developed in Fig. 4 was used for the identification of alternative manufacturing sites where the technology could be favourable. A literature review of the world's major automotive manufacturing plants was conducted and classified by region to assess the potential of liquid desiccant technology for automotive painting in different climates [58]. The framework developed for this analysis is as follows:

- choice of alternative sites of automotive manufacturing plants.

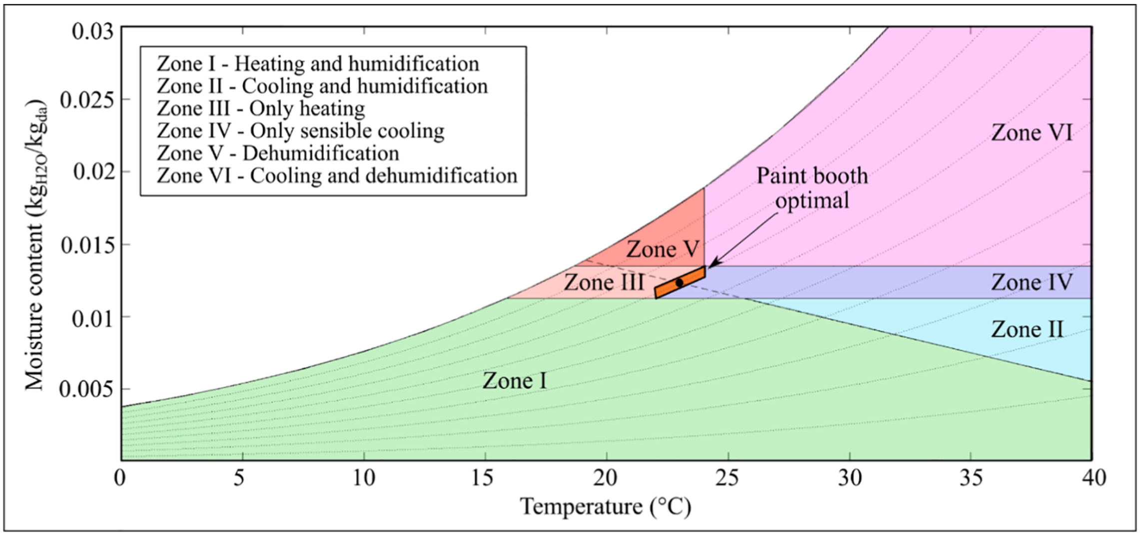


Fig. 4. Sub-division of the psychrometric chart based on the automotive painting process requirement with water-based paint.

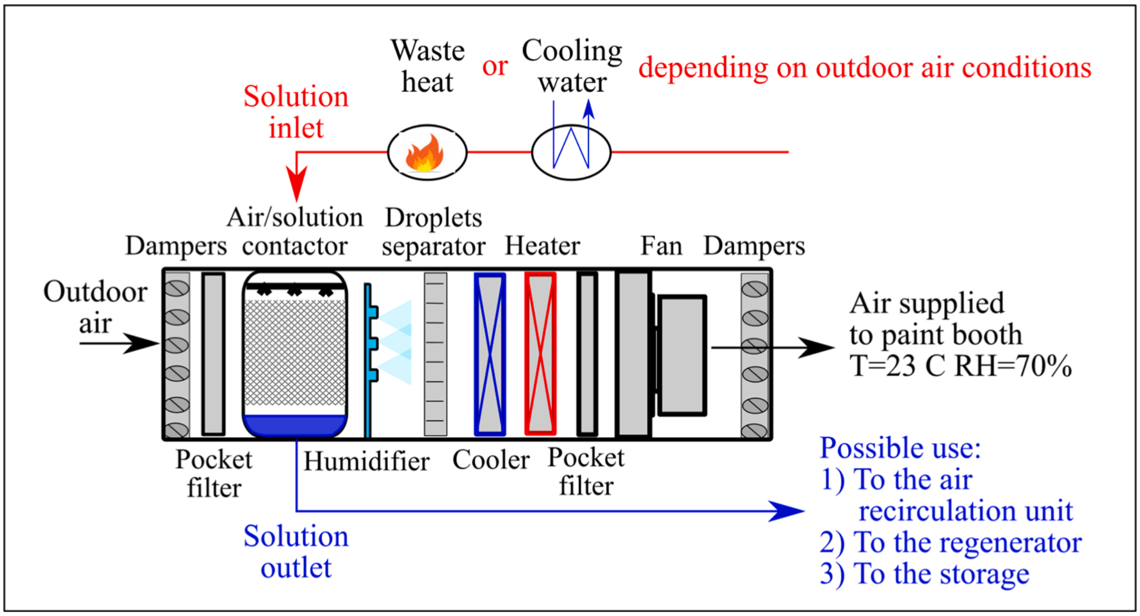


Fig. 5. Integration of liquid desiccant technology in air handling units for automotive paint shop application.

- analysis of temperature and moisture control requirement for ASU and ARU on the psychrometric chart for alternative manufacturing plants.
- calculation of the difference between the annual temperature, moisture content and enthalpy difference of both outdoor and recirculated air and the water-based optimal painting condition for the identified manufacturing plants and comparison with the reference case.
- identification of alternative sites for liquid desiccant automotive painting and techno-economic performance analysis.

Appendix A contains a complete list of the automotive manufacturing plants that were considered in the region selection analysis for the operation of liquid desiccant air handling units, showing the process on psychrometric charts and the differences in temperature and relative humidity between the outdoor air conditions and optimal painting demand.

In operating the novel configuration of the liquid desiccant air handling unit for automotive painting application, it is required that the difference in moisture content between the outdoor air and the optimal painting requirement is significant. It is worth noting that:

- for cold climates, conventional systems consume large amounts of energy to heat and humidify outdoor air for the painting operation requirement. The novel liquid desiccant air handling unit could produce significant benefits in terms of natural gas consumption reduction. The feasibility of the technology in cold climates represents the baseline case of the study. Cheap desiccant solutions with higher desorption ability (such as $CaCl_2$) can find application in this climate.
- for climates where the air to supply to paint booths requires energy consuming heating/humidification in winter and energy-consuming cooling/dehumidification in summer, the ability of the technology to use the same desiccant solution to supply air with temperature and humidity within the range required for optimal painting may not be insured. Highly performing cooling/dehumidification processes might not be accomplished by $CaCl_2$ (particularly at low concentration) as well as heating and humidification with LiCl solution. The use of two different desiccant solution cycles (one for humidification and one for dehumidification) could find application in this climate. Further studies should be conducted to evaluate the potential of such a configuration.
- for hot and humid climates with outdoor air in Zones V and VI of the psychrometric chart in Fig. 4, the conventional technology for painting operation consumes large amounts of energy to cool, dehumidify and reheat both the outdoor and the recirculated air all year round. These climates might benefit from the use of liquid desiccant air handling units for painting.

The application of the liquid desiccant technology for automotive painting was investigated in cold (such as the UK) and hot/humid (such as Singapore) climates to highlight differences in the operating condition and compare technological ability and economic performance. For the UK, the weather data collected for the year 2017 showed that heating and humidifying the outdoor air is required mostly throughout the year whilst cooling and dehumidification are necessary for only a few days in summer to reach the desired condition for optimal painting. On the contrary, the outdoor air condition analysis in Singapore showed little variation in temperature and humidity throughout the year and constant demand for dehumidification to reach the desired condition for optimal painting.

5. Results and discussion

5.1. Performance analysis

Based on the psychrometric chart for water-based painting operation described in **Section 4.1**, the multifunction ability of the liquid desiccant air handling unit (ASU/ARU) operation and the framework used for the simulation of the annual performance of the technology is shown in Fig. 6. According to the outdoor air condition (temperature and humidity), the main components of the air handling unit (liquid desiccant system, humidifier, heater and chiller) are operated to supply the demand for optimal painting in paint booths.

5.1.1. Cold climates

The outdoor air analysis at the UK paint shop (which is located in Zone I of the psychrometric chart of Fig. 4 for the majority of the year) revealed that, due to the low temperature and moisture content of the outdoor air, the ASU necessitates heating and humidification throughout the year. On the contrary, the ARU process is less affected by

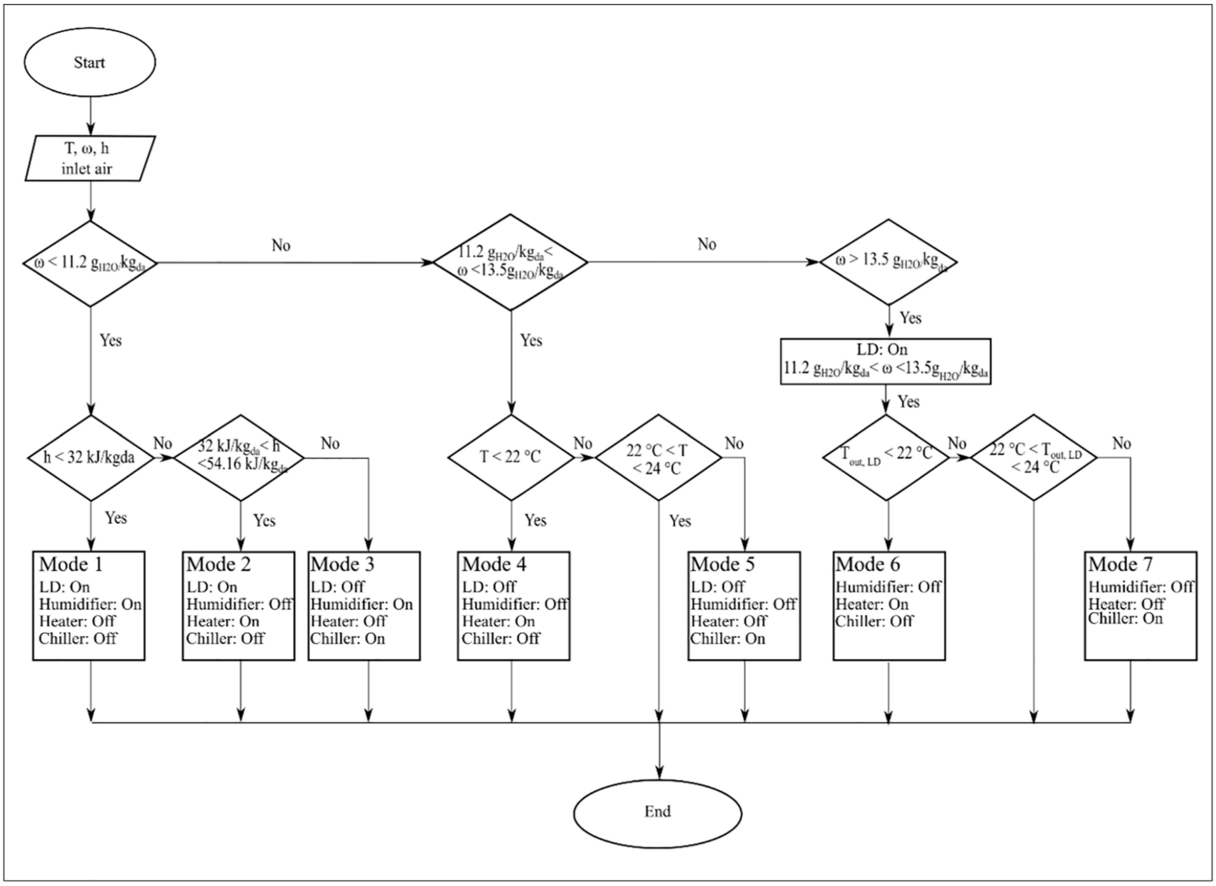


Fig. 6. Flow chart of liquid desiccant ASU/ARU operation for painting process.

the outdoor air condition. After running the simulation for the use of the liquid desiccant technology in both the ASU and the ARU, the use of the desiccant technology for ARU operation in cold climates was discarded since the air handling process in the conventional ARU is energy-efficient and the heating energy savings would be surpassed by the energy costs for pumping the desiccant solution (which would require a desiccant solution flow rate of 483 L/min) and blowing the air through the wetted packing material, hindering the economic feasibility of the process.

The cycle of the desiccant solution used in the 100% outdoor air ASU for paint booth operation in cold climates is illustrated in Fig. 7. The technology can operate according to the outdoor air condition in 3 operating modes:

1. Humidification operating mode: in the ASU, the solution, which is heated by the compressors' waste heat, is used to heat and humidify

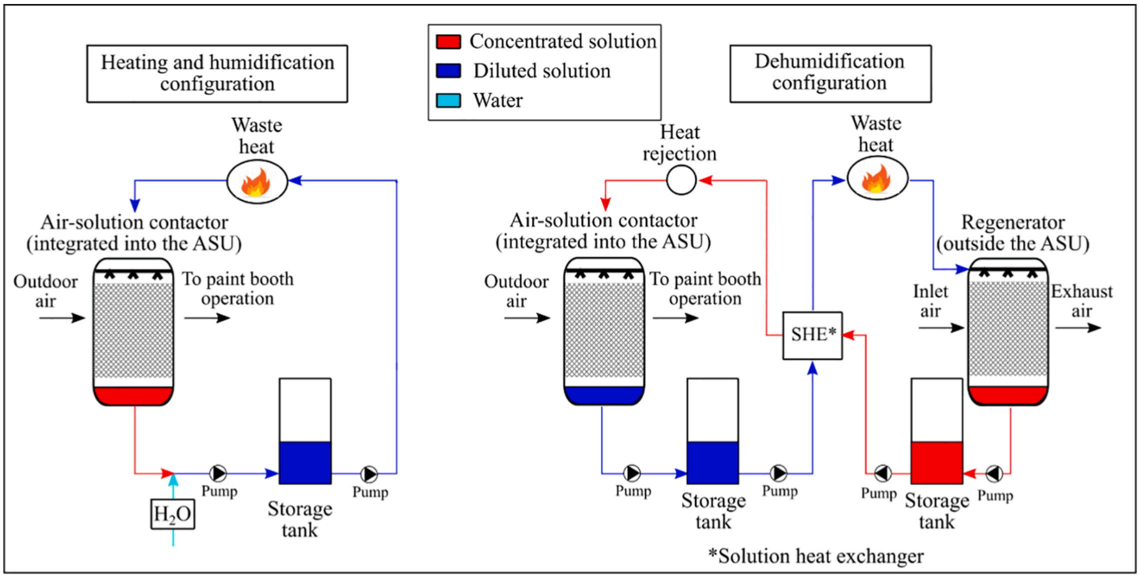


Fig. 7. Desiccant cycle for automotive painting operation in humidification (left) and dehumidification (right) configuration.

the outdoor air (becoming cooler). Following the process, additional humidification or heating may be required to supply air within the range for optimal painting. To stabilise the concentration of the solution, water is added. In humidification mode, the regenerator is not used.

2. Dehumidification operating mode: the solution is used in the ASU to remove the moisture from the air. The regenerator is located next to the ASU on the rooftop of the paint shop. Heat rejection (cooling tower or chilled water) is required to cool the solution before the ASU. Due to the low dehumidification demand in July in the UK, the dehumidification process can operate with a lower m_{sol}/m_a ratio compared to the humidification mode.
3. The solution is stored when the outdoor air condition is in Zone III. The outdoor air is directly heated in the ASU and supplied to the paint booth.

With this configuration, the desiccant solution would be able to treat the air all year-round. The simulation of performance over the course of the year was carried out to assess the variation of performance as the outdoor air condition changed. The liquid desiccant air handling unit for automotive painting in cold climates can deploy desiccant solutions with higher desorption ability, such as a low-concentrated cheap desiccant solution as a 25% wt. $CaCl_2$ (characterised by higher humidification ability and lower regeneration temperature compared to LiCl), which is considered in the analysis and enables the use of ultra-low grade heat sources, such as the heat available from the compressed air units (872.22 kW of heat available in the form of hot water at 47 °C).

For the design and techno-economic analysis of the novel liquid desiccant air handling unit for automotive painting application, the predictive model described in **Section 2.3** was used. Table 8 summarises the simulation parameters for packing geometry and configuration, flow rates, and desiccant selection. The air flow rate of the system (50,000 m^3/h) was estimated based on the available waste heat from compressed air units.

The results of the simulation for different operating modes are described. Fig. 8 depicts the psychrometric chart and performance of the novel liquid desiccant ASU calculated using data from January 2017 collected every three hours [18].

As shown in Fig. 8, the low temperature and moisture content of the outdoor air (red points) is significantly increased until optimal painting isenthalpic line is reached (blue points) then followed by additional humidification (cyan points). The temperature required by the desiccant solution to perform the process in the ASU ranges between 26.2 and 44.4 °C, according to the outdoor air condition. In winter, the capability of the system to supply the air demand for optimal painting can significantly reduce the energy consumption for heating and humidification compared to the conventional technology. The simulation showed that for points in Zone I of the psychrometric chart where enthalpy is greater than 32 kJ/kg_{da} (observed in mild months, such as October, see Appendix B) it is impossible to obtain the above-described process. In this case, the temperature of the air after the liquid desiccant process is lower than the temperature required for painting and it is required to increase the temperature of the air by an additional heating process.

Fig. 9 shows the supply air produced by the liquid desiccant ASU for summer operation simulated for July 2017. As shown in the figure, there is a couple of days having higher moisture content than the target value, which requires the ability of the ASU to dehumidify the air. When dehumidification is required, the solution is cooled up to about 20 °C (to reduce its equilibrium vapour pressure) before entering the ASU and removing the moisture from the outdoor air. After the liquid desiccant dehumidification, additional heating is required to reach the temperature required for painting (see Appendix B for a representation of the process on a psychrometric chart). Examples of this behaviour of the system are shown in days 6, 18, and 26. For the majority of the time, humidification is required (colder days or night-time) and the system operates similarly to the process shown in Fig. 8. The full results of the performance for the year 2017 are shown in Table 9, where the average temperature and moisture content of the air produced from the ASU for paint booth operation are illustrated together with the range of variation between its minimum and maximum values.

As shown in Table 9, the novel liquid desiccant ASU technology is able to supply the air for optimal painting all year round. A more constant supply of air is observed in the coldest months, while the variation between operating modes in the hottest months results in a fluctuation of the temperature and humidity.

The waste heat requirement for the process is illustrated in Fig. 10. As illustrated in the figure, the waste heat requirement for the 50,000 m^3/h liquid desiccant ASU is lower than the maximum waste heat available from compressors (872.22 kW) all year. While during the period April–October the requirement is lower than the minimum duty of compressors (550 kW), additional heating (natural gas or additional waste heat sources in the plant) might be required depending on the compressed air production during the coldest days of the period November–March. In the simulated case, the energy consumption of the conventional technology for heating, cooling and humidification amounts to 2,774,673.14 kWh/y compared to the liquid desiccant system (400,094.06 kWh/y), reducing the annual energy consumption by 85.58%.

5.1.2. *Hot and humid climates*

The analysis of the novel liquid desiccant technology for automotive painting operation is continued by the analysis of the performance of the technology in hot and humid climates such as Singapore, where both the outdoor and recirculated air require dehumidification and cooling all year round, resulting in the cycle of the desiccant proposed and illustrated in Fig. 11.

The cycle illustrated in Fig. 11 is composed of two dehumidifiers (one for ASU and one for ARU operation, respectively), one regenerator, two storage tanks, one solution heat exchanger, two cooling towers and one solution heater for regeneration. In the ASU, the concentrated solution can reduce the high humidity of outdoor air, decreasing its concentration. After the dehumidification process performed by the liquid desiccant solution, the air requires additional humidification and cooling provided by the high-pressure humidifier (stand-alone or in combination with an electrical chiller) to reach the temperature and humidity requirements for optimal painting. After being cooled in the cooling tower 2, the diluted solution is sent to the ARU where its dehumidification ability is enough to remove the moisture from the recirculated air, decreasing more its concentration. Additional air humidification and cooling are required also in the ARU after the liquid desiccant dehumidification process. After the ARU, the solution is heated by the waste heat and then sent to the regenerator where it desorbs the moisture, increasing its concentration before being cooled (in the cooling tower 1) and sent back to the ASU.

The dimensions and packing characteristics of desiccant packed bed in ASU/ARU are chosen like those shown in Table 8. The performance of the novel liquid desiccant system in Singapore was simulated considering two different desiccant solutions (LiCl and $CaCl_2$) with similar $\omega_{eq,}$

Table 8
Simulation parameters used for the analysis in cold climates.

Parameter	V_a (m^3/h)	Salt	L (m)	H (m)	W (m)	a_p (m^2/m^3)	e (-)	θ (°)	*ASU**	*ARU***
Value	50,000	$CaCl_2$	2.5	1.8	1.8	396	0.9	45	2	0.6

* Ratio m_{sol}/m_a in the ASU; ** Ratio m_{sol}/m_a in the ARU.

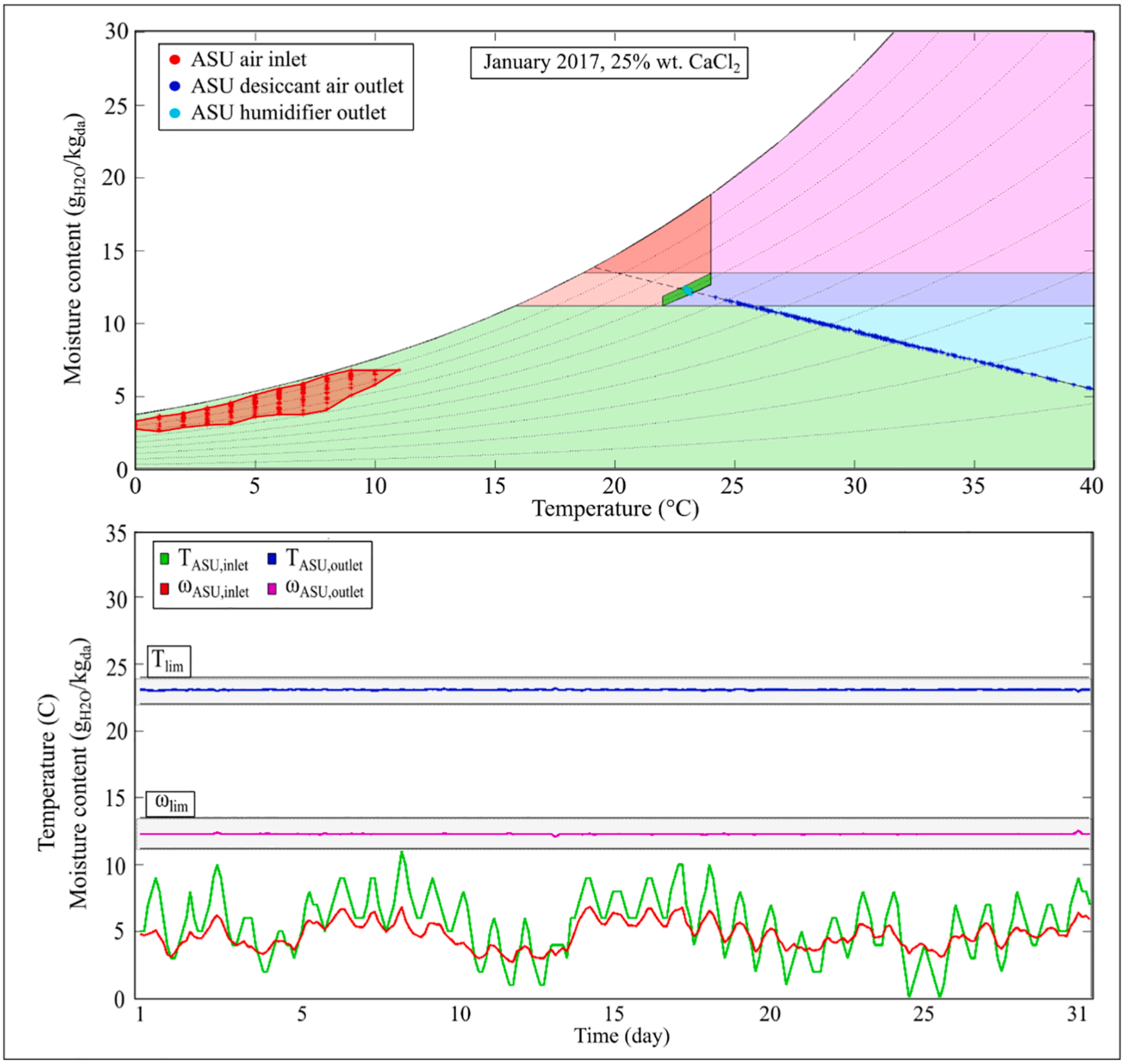


Fig. 8. Psychrometric chart and performance of liquid desiccant ASU process simulated for January 2017.

sol and able to perform a similar dehumidification process ($x_{LiCl} = 30\%$ wt., $x_{CaCl2} = 40\%$ wt.). The temperature of the solution required for the process (23.93 °C and 26.15 °C in the ASU and ARU, respectively) cannot be reached with wet cooling towers due to the high wet-bulb temperature in Singapore. Electrical cooling could be used to further reduce the temperature of the solution but the effect on the energy consumption and associated cost would reduce the benefits achievable by the liquid desiccant dehumidification. Therefore, the wet-bulb temperature (high humidity) in Singapore limits the minimum temperature achievable by the desiccant solution and affects, in turn, the dehumidification process.

An example of the performance of the novel liquid desiccant ASU and ARU simulated for January 2018 in Singapore with $CaCl_2$ as desiccant solution is shown in Figs. 12 and 13. In the psychrometric charts, the blue points represent the state of the air in the ASU and ARU after the liquid desiccant dehumidification process and the black points represent the air supply to the paint booth.

The following conclusions are drawn from the performance analysis in **Section 5.1.2**:

- unlike the case for cold climates in **Section 5.1.1**, the energy consumption required to control the temperature and humidity of the recirculated air for optimal painting is high and the use of the liquid desiccant technology for ARU operation makes sense from an energetic and economic point of view.
- for the ASU process, the effect of the wet-bulb temperature on the minimum air temperature achievable after dehumidification is more important due to the higher dehumidification demand. Although able to remove the moisture, the temperature of the air in the ASU after liquid desiccant dehumidification can be as warm as 30.96 °C (with LiCl) and 30.16 °C (with $CaCl_2$). Additional cooling and humidification must be performed by evaporative cooling or a combination of electrical and evaporative cooling to supply the air within the range required for optimal painting. The effect of the environmental wet-bulb temperature on the temperature of the solution (by cooling tower) is more prominent during the day exactly when the higher temperature and humidity of the outdoor air produces higher dehumidification and cooling demand.
- for the ARU process, the effect of the environmental wet-bulb temperature on the performance of the liquid desiccant dehumidification process is less significant. The temperature required by the solution (about 26 °C) is usually higher than the wet-bulb throughout most of the year.
- the performance of the two desiccant solutions is similar in terms of temperature and humidity control.

Fig. 14 shows the waste heat and heat rejection demand using a 30%

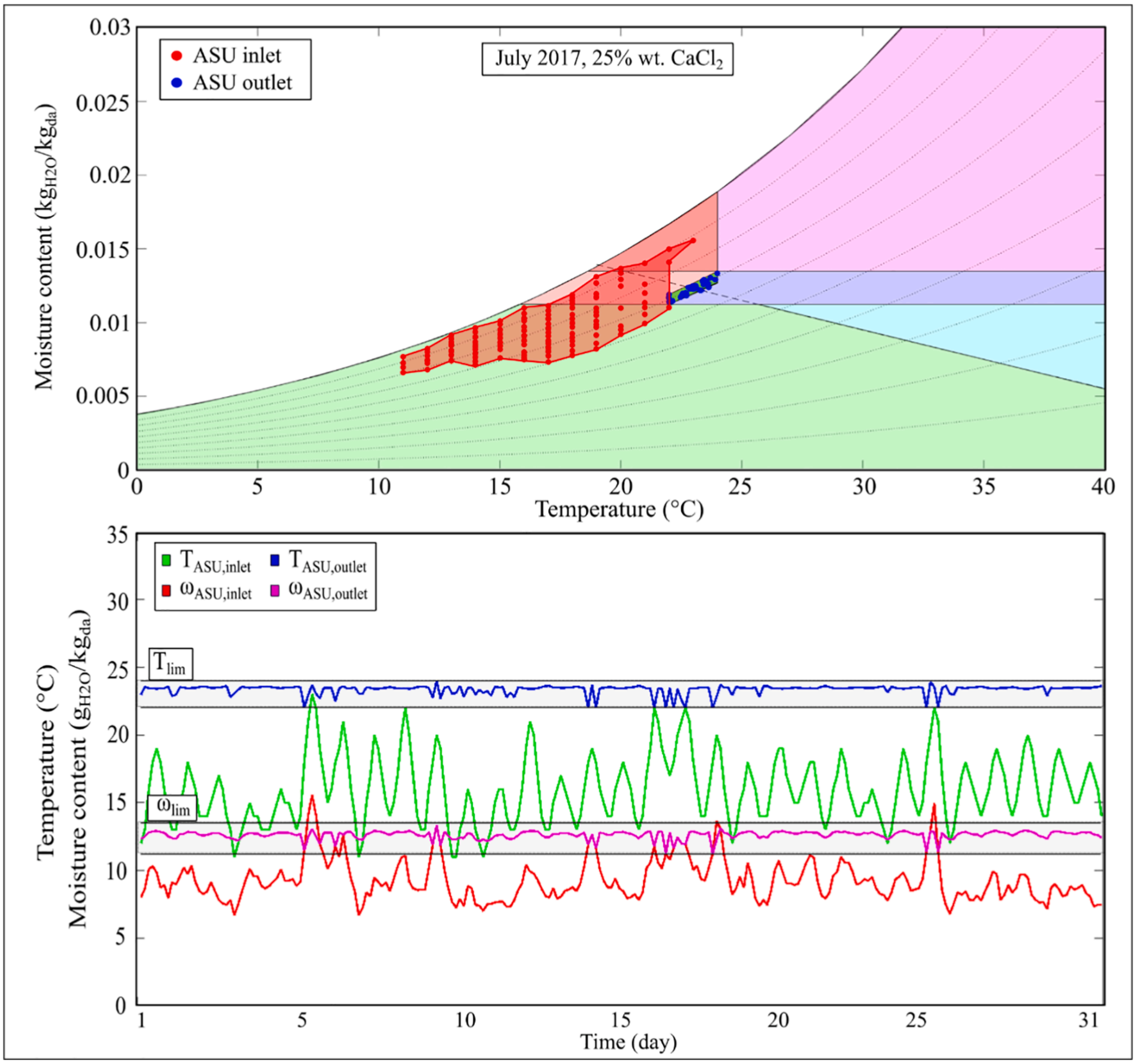


Fig. 9. Psychrometric chart and performance of liquid desiccant ASU process simulated for July 2017.

Table 9
Temperature and humidity ratio of supplied air by liquid desiccant ASU.

Month	T (°C)	ω (g_{H2O}/kg_{da})
January	23.07 (22.94–23.18)	12.28 (12.2–12.4)
February	23.06 (22.93–23.21)	12.28 (12.18–12.34)
March	23.07 (22.98–23.26)	12.27 (12.21–12.49)
April	23.07 (23.02–23.58)	12.27 (12.24–12.72)
May	23.19 (22–23.63)	12.41 (11.41–12.9)
June	23.34 (22–24)	12.54 (11.39–13.4)
July	23.37 (22–24)	12.61 (11.22–13.35)
August	23.37 (22–23.65)	12.64 (11.22–12.95)
September	23.33 (22–23.63)	12.45 (11.36–12.89)
October	23.24 (22.72–23.65)	12.4 (12.03–12.9)
November	23.06 (22.77–23.6)	12.27 (12.12–12.47)
December	23.06 (22.95–23.18)	12.27 (12.19–12.33)

wt. LiCl and a 40% wt. $CaCl_2$ solution for the ASU and ARU dehumidification process for the month of January 2018.

As shown in Fig. 14, a similar performance in terms of waste heat and heat rejection demand is observed for the two desiccant solutions. An average waste heat of 482.04 and 450.98 kW is required for the process with LiCl and $CaCl_2$ solution, respectively. The temperature required for regeneration of the desiccant solution, which can be as high as 47 °C for LiCl and $CaCl_2$ solutions, is higher than that required in cold climates, limiting the use of heat from compressed air units. In the UK baseline paint shop, the temperature of the cooling water (at 47 °C) would not allow its recovery for liquid desiccant regeneration. However, the compressor could be designed to provide low-grade heat at a higher temperature that matches the temperature required for the regeneration of the desiccant solution (in this case about 60 °C) [59]. Alternatively, heat sources with higher temperatures, such as RTO, solar energy, *etc.*, could be investigated to enable the regeneration of the desiccant solution in the paint shop.

5.2. Economic analysis

5.2.1. Cold climates

According to Eq. (10), the capital cost of a 50,000 m^3/h liquid desiccant system in the cold climate case study is £185,575. The cost includes two air/solution contactors (dehumidifier/regenerator), three heat exchangers (solution heater, solution cooler, and solution-to-solution heat exchanger), two main solution pumps and air blowers. Based on Eq. (11) and on the process described in **Section 5.1**, the cost of the $CaCl_2$ salt for the desiccant solution is £7,065.5. The sizing of the solution tank is based on the analysis of the volume of solution required by the process. Based on manufacturer pricing, the cost of two 54,000 L galvanised steel storage tanks is £4,024 [60]. The cost of the additional pumps for the storage tanks is £5,090.6. The cost of the cooling tower is based on the maximum cooling required during summer (150 kW) and amounts to £5,266.9. No cost for heat recovery of hot water was added

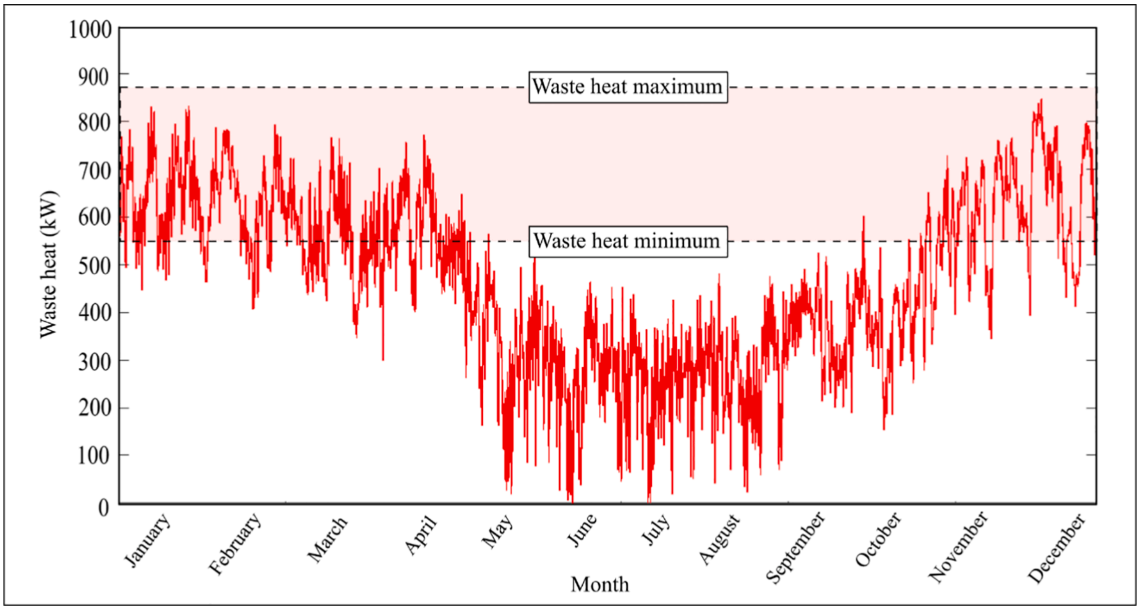


Fig. 10. Performance of compressed air system waste heat recovery for liquid desiccant ASU.

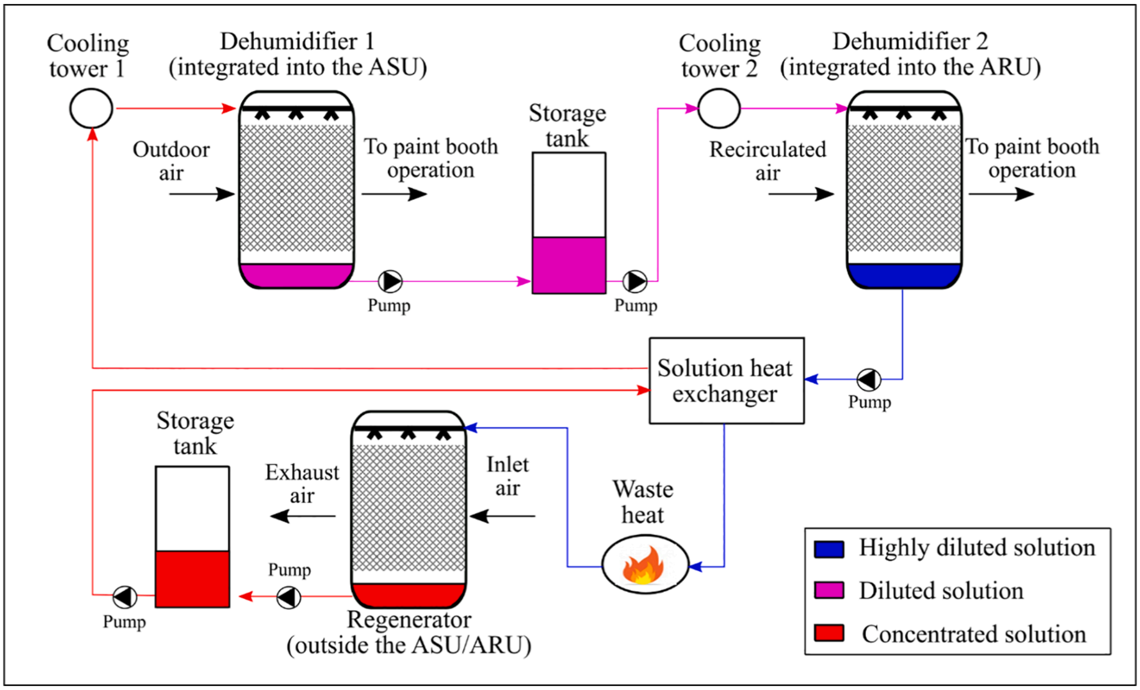


Fig. 11. Schematics of the desiccant cycle for automotive painting application in hot and humid climates.

to the economic analysis since hot water from compressed air units is available at the plant. The total *CAPEX* for the liquid desiccant ASU in the cold climate scenario is £207,022. The pie chart of Fig. 15 summarises the different parameters considered in the economic analysis and their weight in relation to the total cost.

The *OPEX* of the desiccant system is based on the electricity consumption for solution pumping, air blowing, humidification, and heat rejection and on natural gas consumption for the additional heating required by the process and the related carbon price. For the air blowing cost, the technological analysis performed in **Section 5.1.1** shows that the high velocity of the air (4.29 m/s) and the length of the packing (2.5 m) significantly affect the energy consumption to blow the air over the surface of the wetted packing material. Depending on the operating condition of the novel liquid desiccant technology for painting operation, the air is blown through one or two packed columns. The total *OPEX* to blow the air amounts to £22,361.65/y. For the solution pumping cost, four 10 kW pumps with a max flow rate of 2,300 L/min were considered: two pumps would be running in heating/humidification mode while four in dehumidification mode. When the outdoor air is in Zone III of Fig. 4, only direct heating is required for optimal painting, *i.e.* no solution pumps are running. The *OPEX* for solution pumping amounts to £12,883.7/y. The cost of additional air heating with liquid desiccant ASU is £1,531.9/y. The cost of heat rejection is low: when in heating/humidification mode, no heat rejection would be required; when in dehumidification mode, the temperature of the wet-bulb temperature slightly limits the minimum temperature achievable by the

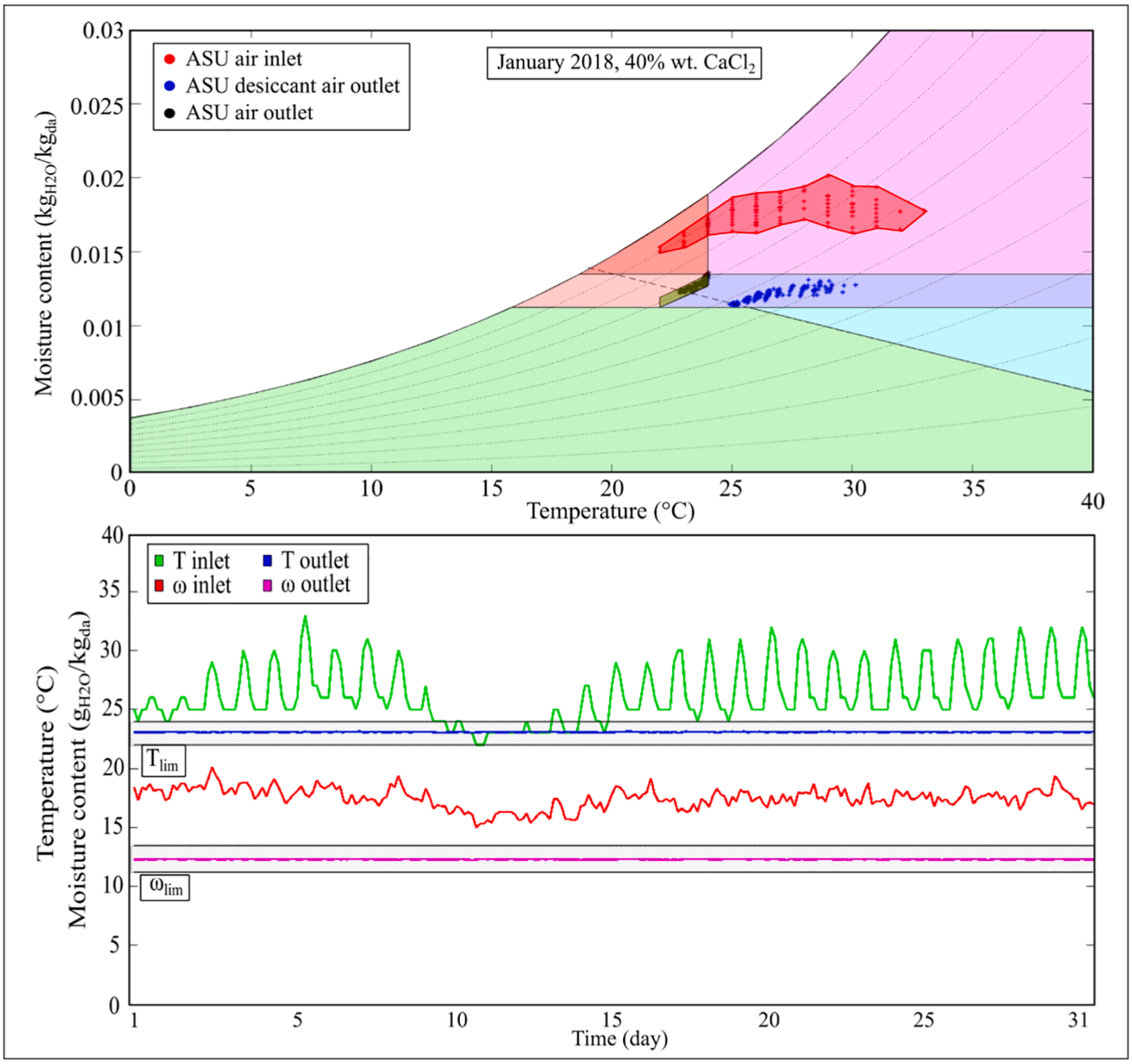


Fig. 12. Psychrometric chart and performance of liquid desiccant ASU process with 40% wt. $CaCl_2$ solution in Singapore simulated for January 2018.

desiccant solution with a wet cooling tower. Considering the limited dehumidification demand at the paint shop, a combination of heat removal performed by the cooling tower and electrical chiller would not particularly affect the economics of the process, resulting in a cost of £139.06/y. For the energy consumption calculated in **Section 5.1.1**, emissions and carbon price were determined, as shown in Table 10.

Fig. 16 compares the monthly energy costs of the conventional and novel liquid desiccant technology for the painting application in cold climates.

The economic savings per year with liquid desiccant ASU amount to £34,222. During winter operation, a high economic benefit is observed from the implementation of the novel technology which can cut about 60% of the costs compared to the conventional technology because the latter has high natural gas consumption. While months such as May (-35.7%), September (-25.3%) and October (-36.9%) still present quite favourable economic performance, the benefits are more limited in summer. In July, the additional cost for heating (£385.3), in addition to the high cost for solution pumping and air blowing, results in worse economic performance (+9.2%). The economic benefits of the heat recovery process are further increased by the carbon price due to environmental policies, which account for 14.19% of the total *OPEX* with conventional technology (£10,741.1/y) while for 9.1% in the liquid desiccant case (£3,827.4/y). Fig. 17 shows the total *OPEX* for the conventional and liquid desiccant process in cold climates and the breakdown of single *OPEX*. A reduction of 44.44% of the annual costs was observed.

The high potential of the use of liquid desiccant technology for painting is currently limited by the high air flow rate (which results in a high solution flow rate, $V_{sol} = 1{,}700$ L/min) and the large volume of the packing ($V = 8.1$ m^3), resulting in high costs for solution pumping and air blowing through the wetted packing material, which are almost constant during the year. The annual *OPEX* for pumping and blowing amounts to 30.64% and 53.19% of the total *OPEX* of the liquid desiccant ASU, respectively. Table 11 shows the results of the economic feasibility analysis for cold climates.

The payback period is 6.15 years. This value is considered quite high by the automotive manufacturer that is interested in investments in heat recovery processes with a payback period of around 2 years. However, the high energy savings for heating result in an interesting value of *LCOSE* (£24.55/MWh), slightly higher than the retail price of natural gas considered in the analysis (£23/MWh). This is because the liquid desiccant air handling unit in cold climates converts part of the fuel energy savings in electricity use, which increases energy costs. The *NPV* and the *IRR* were also evaluated, showing the good economic performance of the liquid desiccant air handling unit (*NPV*=£212,101, *IRR* = 15.3%).

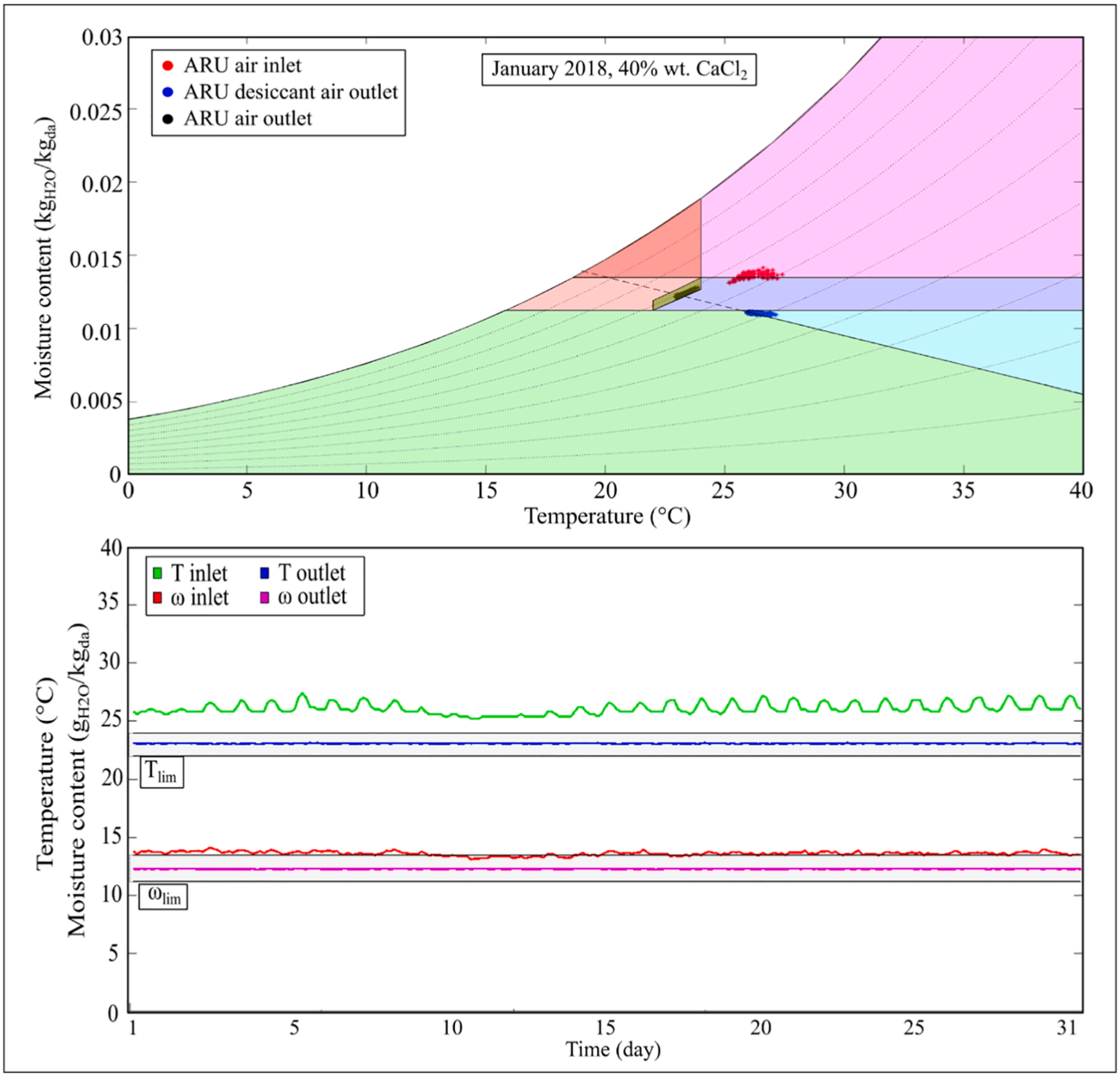


Fig. 13. Psychrometric chart and performance of liquid desiccant ARU process with 40% wt. $CaCl_2$ solution in Singapore simulated for January 2018.

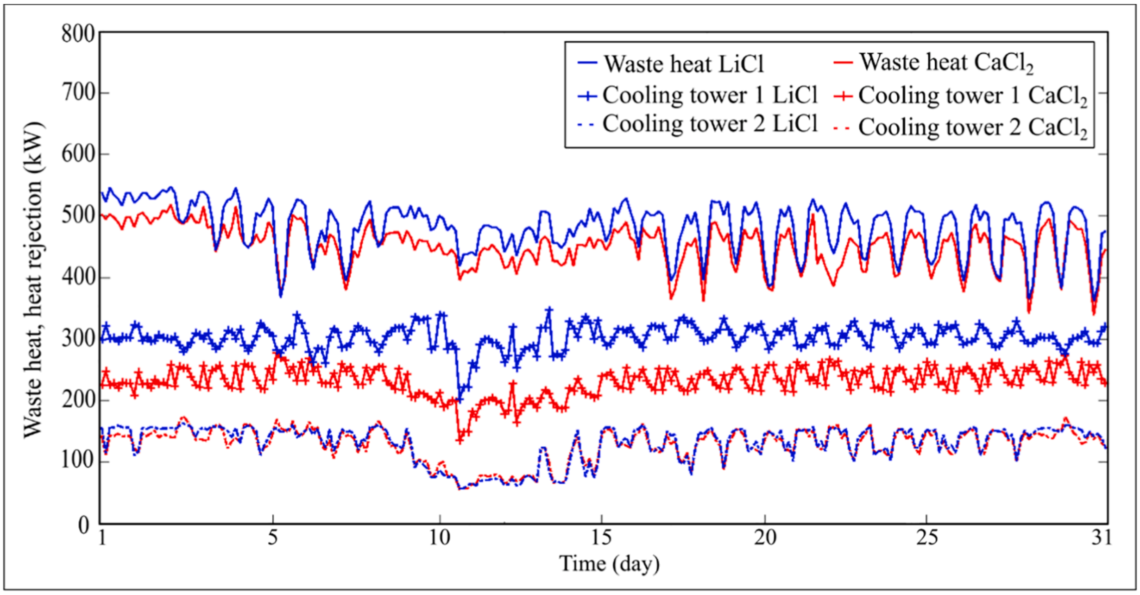
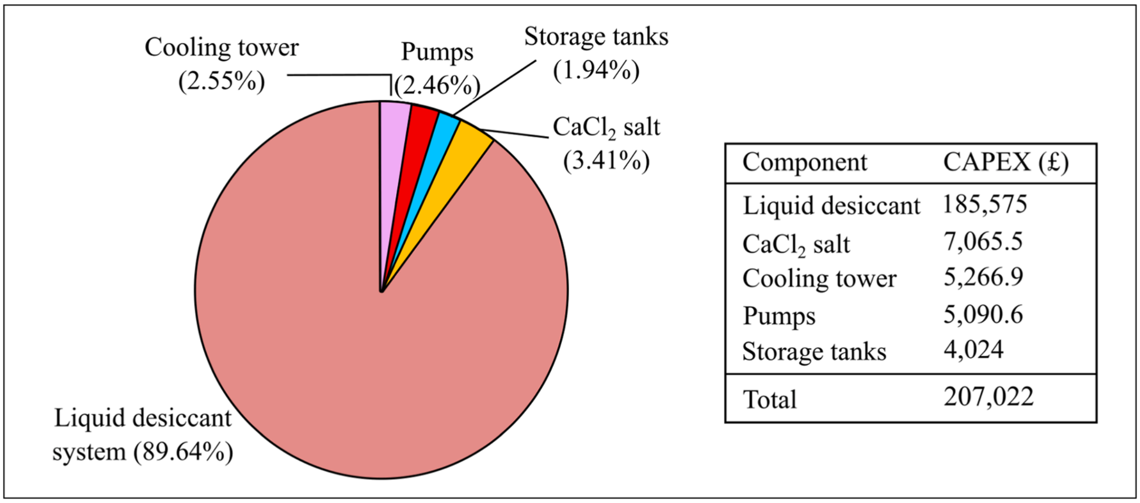


Fig. 14. Waste heat and heat rejection demand of liquid desiccant air handling unit simulated for Singapore in January 2018 with LiCl and $CaCl_2$ solution.



Component	CAPEX (£)
Liquid desiccant	185,575
$CaCl_2$ salt	7,065.5
Cooling tower	5,266.9
Pumps	5,090.6
Storage tanks	4,024
Total	207,022

Fig. 15. Breakdown of the *CAPEX* of the liquid desiccant technology in cold climates.

Table 10
Emissions and carbon price per year for conventional and liquid desiccant process in cold climates.

Parameter	Conventional	Liquid desiccant	Difference (%)
CO_2 emission, $P_{CO2,e}$ (kg/y)	567,468.56	98,554.2	−82.63
CH_4 emission, P_{CH4} (kg/y)	754.04	234.75	−68.59
N_2O emission, P_{N2O} (kg/y)	321.38	462.21	43.95
Carbon price, $OPEX_{Carbon}$ (£/y)	10,074.1	3,827.4	−62

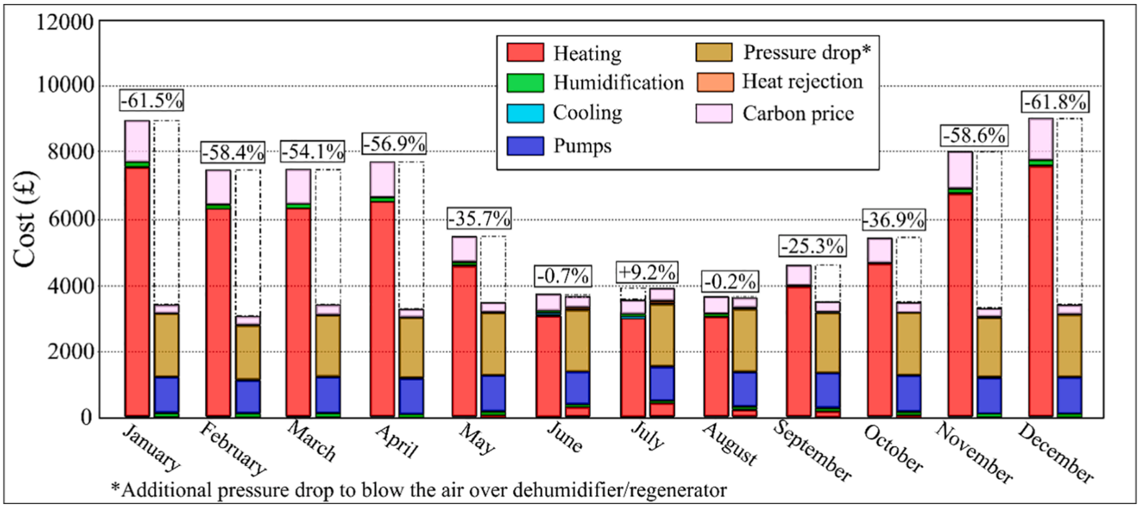
5.2.2. *Hot and humid climates*

Based on Eq. (10), the capital cost of the liquid desiccant system in the hot and humid climate case study is £278,363. It includes two dehumidifiers, one regenerator, three main pumps, two solution coolers, one solution heater and one solution-to-solution heat exchanger. Based on Eq. (11) and the performance analysis, the cost of the LiCl and $CaCl_2$ salt for the desiccant solution was estimated. Based on the volume of solution used for the process, two storage tanks (36,000 L) are considered in the analysis for a total cost of £3,092 [60]. The cost of the two additional pumps for the storage tanks considered in the schematics of Fig. 11 is £3,112.6. Two cooling towers are used in the process, which capital cost is based on the maximum cooling required by the performance analysis in **Section 5.1.2**. Fig. 18 recapitulates the *CAPEX* of the liquid desiccant air handling units for the process performed with LiCl and $CaCl_2$ as the desiccant solution.

As clear in Fig. 18, the impact of the cost of the LiCl salt on the economic performance is significant despite the lower concentration of the solution. The use of LiCl as the liquid desiccant in large size systems is not recommended. The *OPEX* of the desiccant system is based on the electricity consumption for solution pumping, air blowing, humidification, and heat rejection with cooling towers and additional sensible air cooling required by the process and the related carbon price. For the energy consumption calculated in **Section 5.1.2**, emissions and carbon price were determined, as shown in Table 12.

Fig. 19 shows the breakdown of *OPEX* for the conventional and liquid desiccant process (considering $CaCl_2$ as the desiccant solution, while similar values of *OPEX* are obtained with LiCl as the desiccant solution) for painting application in Singapore.

As shown in Fig. 19, £53,294.2/y could be saved by employing liquid desiccant technology, reducing the annual costs by 33.57%. Analogous to the analysis in cold climates, the large packing volume and air flow rate result in high *OPEX* to blow the air over the packing material. Compared to the heating and humidification process performed in cold climates, the lower solution-to-air flow rate ratio required by the liquid desiccant dehumidification for optimal painting in the considered case study results in lower energy consumption for solution pumping. The



*Additional pressure drop to blow the air over dehumidifier/regenerator

Fig. 16. Comparison of monthly energy costs between conventional (right) and novel liquid desiccant (right) ASU for cold climates.

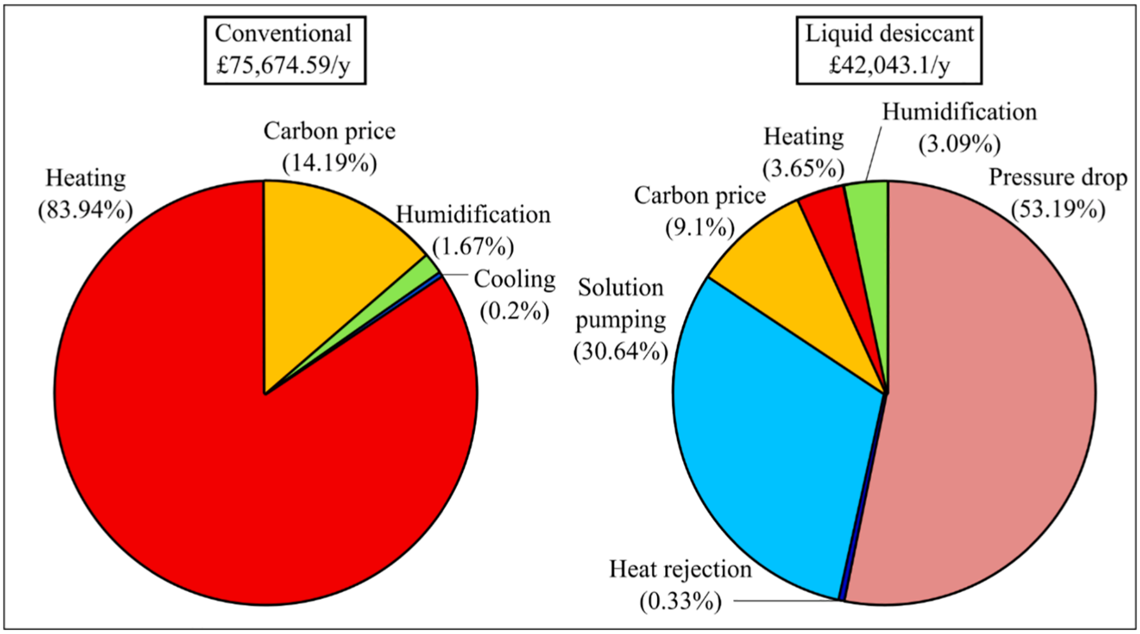


Fig. 17. Breakdown of *OPEX* of the conventional and liquid desiccant process for cold climates.

Table 11
Summary of the results for the economic feasibility analysis in cold climates.

Parameter	Payback (y)	*LCOSE* (£/MWh)	*NPV* (£)	*IRR* (%)	*NPV/CAPEX* (-)
Value	6.15	24.7	212,101	15.3	1.02

results of the economic feasibility analysis are illustrated in Table 13 for both LiCl and $CaCl_2$ solutions.

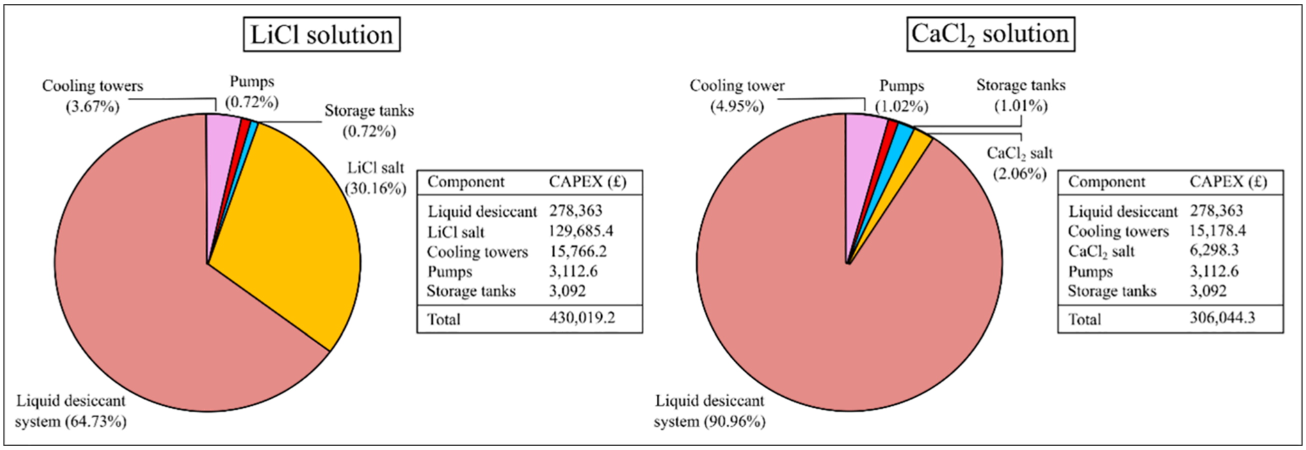
The payback period of the process with LiCl as the desiccant solution is high (9.02 years). Table 13 highlights further the importance of the salt cost for the economic feasibility of the process. By using $CaCl_2$ as salt, it is possible to reduce the payback period by more than 3 years, significantly increasing the economic performance of the process. When large volumes of liquid desiccant solution are required, as in this case, cheaper desiccant solutions are always the proper choice. By using $CaCl_2$ as the desiccant solution, the process shows all favourable economic indicators: the *LCOSE* is £97.61/MWh (lower than the retail price for electricity considered in the analysis), the *NPV* is the highest among the analysed scenarios (£358,119) and the *IRR* (16.61%) is higher than the value for recommended investment. Fig. 20 compares the monthly energy costs of the conventional and novel liquid desiccant technology for the painting application in hot and humid climates, showing that the potential for the use of liquid desiccant technology for automotive painting in hot and humid climates is high, with monthly savings ranging between 18% and 39%.

5.2.3. Summary

Table 14 and Fig. 21 highlight the economic analysis results gained from the simulated scenarios in this study for the use of the liquid desiccant technology for automotive painting. The results show high

Table 12
Emissions and carbon price per year for conventional and liquid desiccant process in hot and humid climates.

Parameter	Conventional	Liquid desiccant	Difference (%)
CO_2 emission, $P_{CO2,e}$ (kg/y)	504,927	233,141	−53.83
CH_4 emission, P_{CH4} (kg/y)	24,959.7	14,953.1	−40.09
N_2O emission, P_{N2O} (kg/y)	470,442	375,206.8	−20.24
Carbon price, $OPEX_{Carbon}$ (£/y)	15,752.5	9,815.3	−37.69



Component	CAPEX (£)
Liquid desiccant	278,363
LiCl salt	129,685.4
Cooling towers	15,766.2
Pumps	3,112.6
Storage tanks	3,092
Total	430,019.2

Component	CAPEX (£)
Liquid desiccant	278,363
Cooling towers	15,178.4
$CaCl_2$ salt	6,298.3
Pumps	3,112.6
Storage tanks	3,092
Total	306,044.3

Fig. 18. Breakdown of the *CAPEX* of the heat recovery processes with LiCl and $CaCl_2$ solution in Singapore.

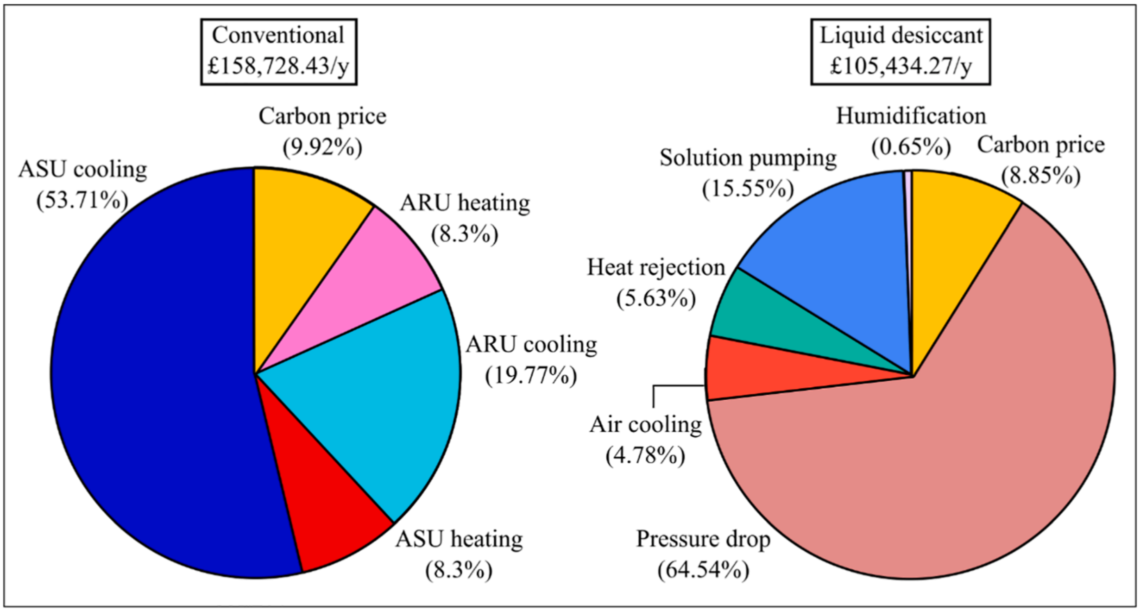


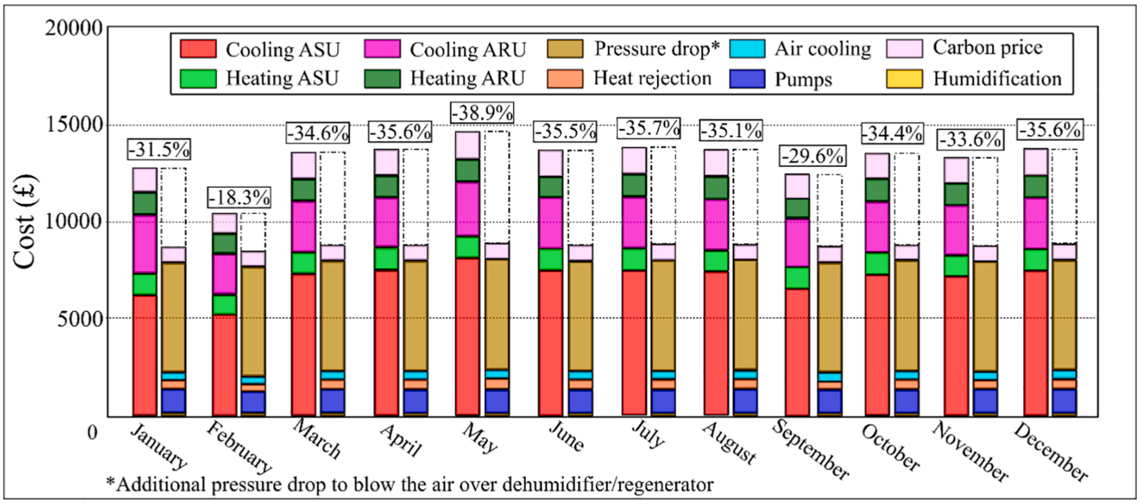
Fig. 19. Breakdown of the *OPEX* of the conventional and liquid desiccant process for painting application in Singapore with $CaCl_2$ solution.

Table 13
Results of the economic analysis with LiCl and $CaCl_2$ solutions for painting process in Singapore.

Salt	Payback (y)	*LCOSE* (£/MWh)	*NPV* (£)	*IRR* (%)	*NPV/CAPEX* (-)
LiCl	9.02	113.25	164,331	9.17	0.38
$CaCl_2$	5.74	97.61	358,119	16.61	1.17

potential in both cold and hot/humid climates with economic benefits over the lifetime of the technology for all the considered scenarios. The higher cost-effectiveness of $CaCl_2$ indicated greater potential as a working fluid in larger volume systems such as those considered for painting operation. In addition to economic benefits, the lower regeneration temperature required by the $CaCl_2$ solution would allow a higher capacity for low-grade waste heat recovery (such as the heat available from compressed air units). Alternatively, mixtures of desiccant solutions could be used to ensure good performance at a relatively low cost [61].

Badami and Portoraro [62] estimated a payback period ranging between 6.5 and 8 years for the use of a liquid desiccant system which recovered heat (available from the cooling water and the flue gases of a reciprocating internal combustion cogenerator) and employed LiCl as the desiccant solution to supply air to a building that was used for education activities in Torino, Italy. In [62], the benefits over the lifetime of the technology (which was assumed as 15 years) resulting from the use of liquid desiccant systems were also investigated, identifying a *NPV* and an *IRR* ranging between €200 k and €220 k and between 9.7% and 11.5%, respectively. Similarly, a payback period of 6 years was estimated by Abdel-Salam and Simonson [63] for a membrane liquid desiccant system used for air-conditioning in Miami, Florida, while Su *et al.* [64] proposed a payback period of 7.51 years for a liquid desiccant system combined with photovoltaic-thermal (PV-T) for the regeneration of the LiCl desiccant solution. Lower values for the payback period were obtained by She *et al.* [65] which investigated the use of the liquid desiccant technology using LiCl as the desiccant solution in combination with a vapour compression refrigeration system to sub-cool refrigerant in China. It calculated the payback period in Beijing, Shanghai, and Nanjing as 2.4, 3 and 3.2 years, and reported the ratio of the *NPV* to the *CAPEX* as 1.84, 1.5 and 1.41 for these cities, respectively. For the *LCOSE*,



*Additional pressure drop to blow the air over dehumidifier/regenerator

Fig. 20. Comparison of monthly energy costs between conventional (right) and novel liquid desiccant (right) ASU and ARU for hot and humid climates.

Table 14
Results of the economic analysis.

	Case study		
	Cold climate	Hot/humid climate	Hot/humid climate
Desiccant solution	$CaCl_2$	$CaCl_2$	LiCl
$CAPEX_{LD}$ (£)	207,022	306,044.3	430,019.2
$OPEX_{LD}$ (£/y)	42,043.1	105,434.3	111,036.3
$OPEX_{Conv}$ (£/y)	75,674.6	158,728.4	158,728.4
Payback period (y)	6.15	5.74	9.02
LCOSE (£/MWh)	24.7	97.61	113.25
NPV (£)	212,101	358,119	164,331
IRR (%)	15.3	16.61	9.17
NPV/CAPEX (-)	1.02	1.17	0.38

limited studies are available in the literature for the economic feasibility assessment of heat recovery processes and, in particular, liquid desiccant technology. Giampieri *et al.* [37] investigated the use of the liquid desiccant technology employing $CaCl_2$ for temperature and humidity control in the thyristor valve hall of a high-voltage direct current (HVDC) interconnector connecting Scotland and Northern Ireland, which estimated £305/MWh as the *LCOSE* required for retrofitting, which could be lowered to £200/MWh and £155/MWh in new projects if the technology was integrated with vapour compression refrigeration and direct evaporative cooling system, respectively. A price of £100/MWh was considered for electricity in [37]. Therefore, the results of the economic analysis in this study are in line with the results available from the literature, although these will be, in general, dependent on the size,

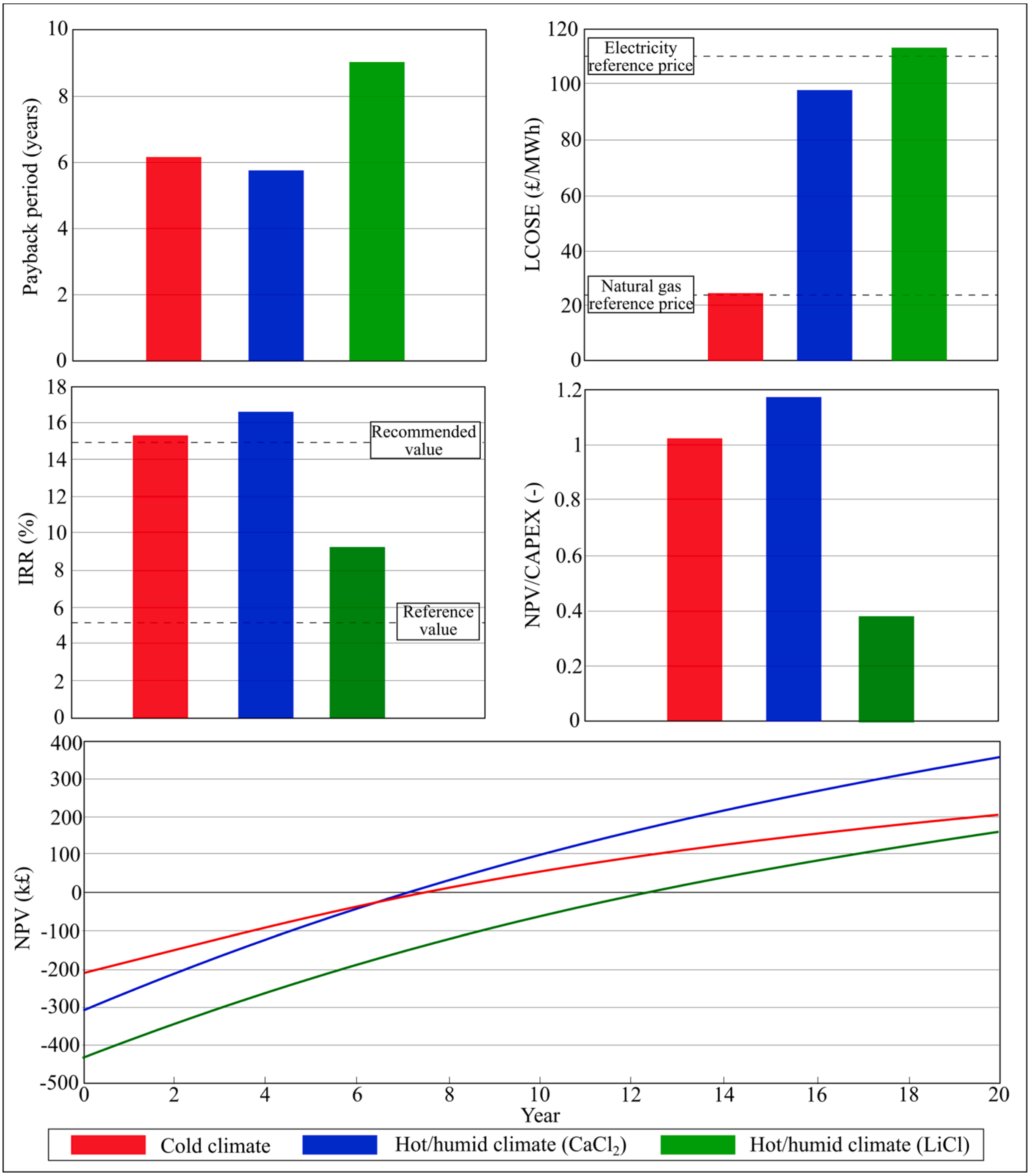


Fig. 21. Summary of the economic analysis for the use of liquid desiccant technology in automotive painting in cold and hot/humid climates.

configuration and application of the liquid desiccant system, choice of the desiccant solution, outdoor air conditions, energy cost, *etc.*

5.3. Discussion and future research

As mentioned in Section 2.4, energy cost (natural gas, C_{NG}, and electricity price, C_{El}) has a primary effect on the *OPEX* and the cost-effectiveness of the process. To evaluate to what extent these two variables and carbon price, C_{CO2e}, would impact the economic feasibility of the process, a sensitivity analysis was conducted using a range of prices (as presented in Table 15) and various economic indicators (*i.e. IRR*, payback period, *NPV*, *NPV/CAPEX* and *LCOSE*). Fig. 22 shows the results of the sensitivity analysis when the *IRR* was applied. Results of the sensitivity analysis which applied other economic indicators are shown in Appendix C.

As shown in Fig. 22, energy cost will affect the economic feasibility of the two case studies differently:

- For the cold climate case study, the use of the liquid desiccant technology instead of the conventional system would result in a significant reduction of the energy consumption for heating. The increase of C_{NG} has a great effect in improving the cost-effectiveness of the process. It was observed that an increase of C_{NG} from £23/MWh to £100/MWh would increase the *IRR* from about six times to more than 30 times for the considered scenarios of C_{El} and C_{CO2e}. When C_{El} is equal to £100/MWh, C_{NG} must be higher than £25/MWh for the liquid desiccant technology to be cost-effective with positive *IRR*s. On the contrary, the use of liquid desiccant technology in cold climates would increase electricity consumed for solution pumping, air blowing over the wetted packing material and solution cooling. As such, the sensitivity analysis shows that an increase in C_{El} would result in a decrease of *IRR* (ranging between 11.97% and 142.2% depending on C_{NG}).
- For the hot/humid climate case study, the use of the liquid desiccant technology instead of the conventional one would reduce the consumption of both natural gas (as reheating after dehumidification would be avoided) and electricity. The increase in C_{NG} from £23/MWh to £100/MWh would be responsible for an increase of *IRR*, which ranges between 129.67% and 178.17% for different electricity prices. The effect of the increase in C_{El} on the cost-effectiveness of the liquid desiccant technology would be less significant, with an increase of *IRR* that ranges between 11.91% and 35.54% for different electricity prices.

The increase in C_{CO2e} has a beneficial effect on the cost-effectiveness of the liquid desiccant technology, as the proposed system would be able to reduce the energy consumption for automotive painting compared to the conventional operation. When C_{CO2e} ranged between £16/ton and £100/ton, the *IRR* varied 17.1–120% and 21.32–69.99% for the cold and hot/humid climates case studies respectively.

To further increase the cost-effectiveness of the liquid desiccant technology, the main challenges are related to the high capital cost of the technology at the current market state and the need to minimise the electricity consumption of auxiliary components, such as pumping the large volumes of solution required, blowing the air over a large volume of packing material and cooling the desiccant solution. Technological solutions able to reduce the solution pumping cost (*i.e.* low-flow systems) and air blowing cost (*i.e.* more efficient air-solution surface contact) could further reduce the operating cost of the liquid desiccant technology and increase its cost-competitiveness with the conventional ASU. The development of internally-cooled and heated dehumidifiers and regenerators is fundamental for the performance and economics of liquid desiccant systems, which when operating with very low flow rates of solution would enable: (i) having lower volumes of the solution, resulting in lower operating (solution pumping and heat rejection) and solution cost, particularly important if expensive LiCl is used, (ii) the more efficient use of the available waste heat due to the lower energy consumption of low-flow regenerators, (iii) performance improvement of the dehumidification and regeneration process because the larger difference in concentration between diluted and concentrated solutions achieved in low-flow systems increases the driving force of the moisture absorption/desorption process, (iv) increase in the thermochemical energy storage ability (v) the use of smaller systems (which are better for retrofitting) compared to conventional packed beds and (vii) reduction/elimination of the carryover of desiccant droplets in the supply air [66,67].

Table 15
Price ranges of natural gas, electricity and carbon assessed in the sensitivity analysis.

Parameter	Range
Natural gas price, C_{NG} (£/MWh)	23–100
Electricity price, C_{El} (£/MWh)	110–200
Carbon price, $C_{CO2,e}$ (£/ton)	16–100

In addition, heat and mass transfer are still limited by ineffective wetting of the dehumidifiers and regenerators due to the high surface tension of commonly used desiccants [15]. Identification of alternative working fluids to use as liquid desiccant replacements, such as ionic liquids, could overcome the main drawbacks of common desiccant solutions (high surface tension, crystallisation and corrosion) while increasing the performance of low-flow dehumidifiers/regenerators [68,69]. One of the most interesting aspects of ionic liquids is the flexibility of their properties that can be tuned to the application by adjusting the cation and/or the anion. This would potentially allow identifying an ideal desiccant, characterised by the requirement of health and safety legislation, non-corrosive, non-volatile, low equilibrium vapour pressure, low density and viscosity, high specific heat capacity, high thermal conductivity, high diffusion coefficient of water vapour in the desiccant and low surface tension [15]. The use of ionic liquids that are less or not responsible for crystallisation and corrosion has the potential to significantly reduce both capital (use of cheaper metals) and maintenance costs of the liquid desiccant technology.

The cost-effectiveness of the process could be further increased by the economy of scale. Due to the high paint booth air requirements (more than 1,000,000 m^3/h of air is supplied to different painting operations in the baseline paint shop), the implementation on the paint shop of a thermo-chemical district network [13] that utilises liquid desiccant solutions to recover the waste heat available from all the heat sources, such as the condenser of the chilled water system, the RTO, *etc.* and use it to control the temperature and humidity for paint booth operation, flash-off drying, *etc.* [1] has the potential to drastically improve the economics of the process. The study showed that the research on liquid desiccant systems should particularly focus on reducing the auxiliary energy consumption due to the high cost of solution pumping and air blowing over the wetted packing material. Another advantage of using liquid desiccant technology for heating and humidification is that it can solve the problem of the degradation of the water used for humidification, which can go bad or putrefying bacteria can grow inside the tank [70].

The current research lacked data provided from the manufacturer for the temporal variation of the waste heat sources available in the baseline paint shop, which was under construction when the research was conducted. Although this study provided significant insights on how the recovery and use of the heat sources could be beneficial for automotive painting operation, further research should account for real-time variation data of waste heat sources to evaluate how the variation of the quantity and quality of waste heat affects the performance of the liquid desiccant technology in terms of temperature and humidity control characteristics and regeneration performance. In addition, the research could be complemented by the collection of primary data on the performance of liquid desiccant dehumidification and regeneration

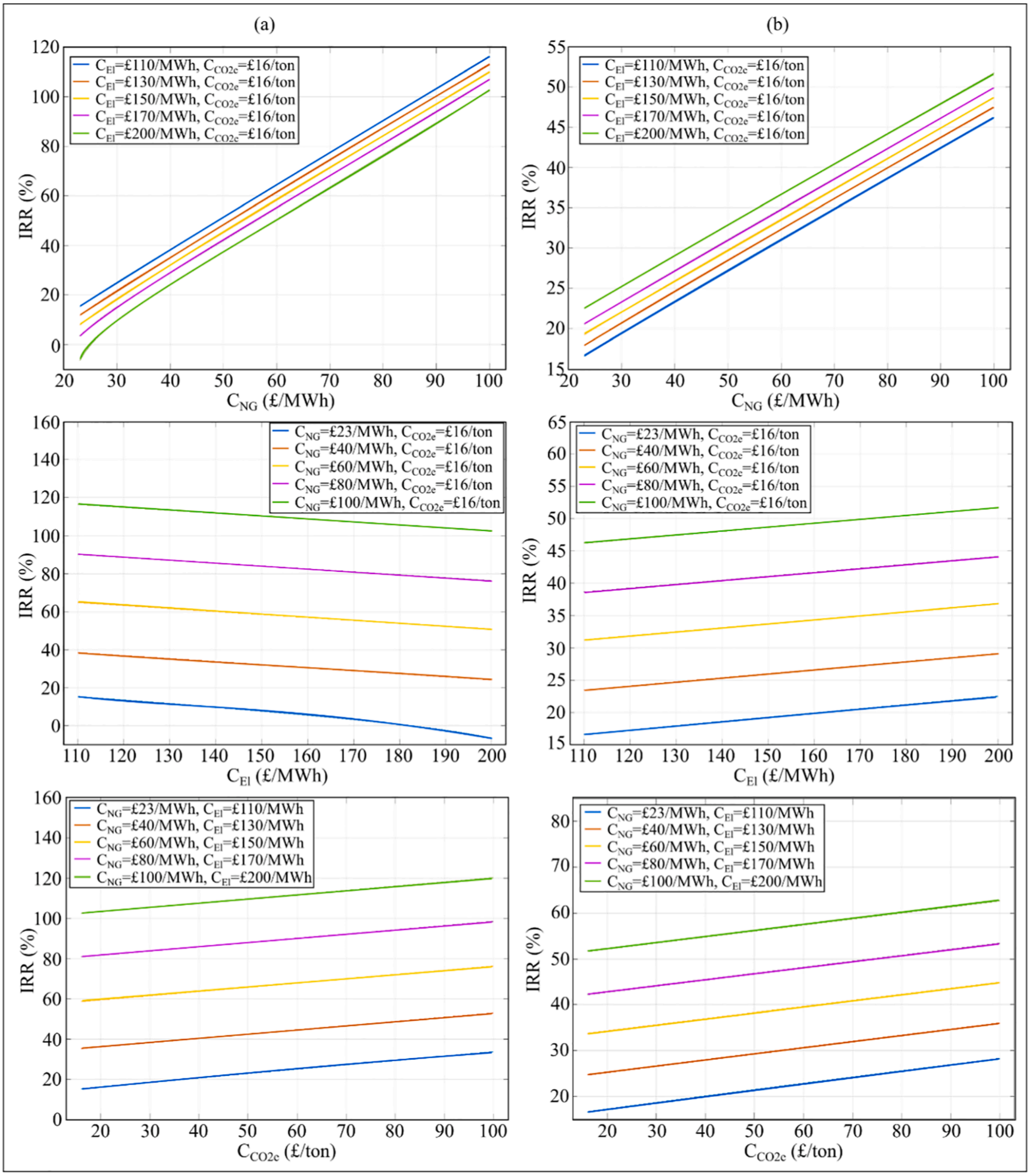


Fig. 22. Results of the sensitivity analysis based on the *IRR* if the proposed system used $CaCl_2$ as the desiccant solution and operated in (a) cold climates and (b) hot and humid climates.

processes for large systems, such as those used for painting operation.

6. Conclusions

The study investigates the replacement of an air management system conventionally applied by paint booths with a novel liquid desiccant air handling unit, which can utilise low-grade waste heat sources on site and provide precise humidity control. In supplying air within the range required for optimal painting (T = 23 °C, RH = 70%), the proposed system could significantly reduce natural gas consumption for heating in cold climates as well as reduce electricity consumption for cooling and dehumidification and natural gas consumption for reheating in hot/humid climates. A reduction of 44.4% and 33.6% in the energy cost is observed, associated with payback periods between 5.74 and 9.02 years. The cost of the desiccant salt shows a large share of the capital cost of the system if expensive LiCl is used as the salt, indicating that cheap desiccant solutions are required as the working fluid for applications in large volume systems such as those considered for painting operation. The sensitivity analysis shows that the economic feasibility of the proposed system in cold and hot/humid climates varies differently with the energy cost. Future research should focus on reducing the capital cost of the technology and the electricity consumption for auxiliary processes, such as pumping the desiccant solution, blowing the air over the wetted packing material, and cooling the desiccant solution.

CRediT authorship contribution statement

Alessandro Giampieri: Conceptualization, Methodology, Software, Investigation, Writing – original draft. **Zhiwei Ma:** Conceptualization, Methodology, Writing – review & editing, Supervision. **Janie Ling-Chin:** Methodology, Visualization, Writing – review & editing, Supervision. **Andrew J. Smallbone:** Supervision, Project administration, Funding acquisition. **Anthony Paul Roskilly:** Supervision, Project administration, Funding acquisition.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.enconman.2022.115654.

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