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An integrated smart thermo-chemical energy network

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ABSTRACT

Managing the intermittency of renewable sources together with transient (hourly to daily to seasonal) energy demands is one of the principal challenges of delivering a net-zero energy system. Smart multifunctional thermo-chemical energy networks represent an alternative energy network and storage system, a solution based on the distribution of energy via thermo-chemical material rather than thermal energy, gas, fuels or electricity– an option that has scope for integrated short- and long-term energy storage. This is the first research work to realise such a system and demonstrate how it might operate using smart control strategies and how thermo-chemical fluids (TCFs) can be used as a medium for timely energy storage and distribution. The experimental study also describes the effect of steady and variable heat sources on TCF regeneration performance and estimates the potential of thermo-chemical energy networks, which would be particularly beneficial in buildings with high energy consumption for humidity control. This research proves the practicality of the design idea for such a network, which would be governed by centralised control, regenerated by steady or transient heat loads and capable of supplying a variety of demands in an experimental setting. The energy and economic potential of the network were also assessed, identifying temperature and humidity control application scenarios with energy savings of more than 60% compared to conventional operation and payback periods of 6.6–9.7 years.

1. Introduction

Delivering upon mandated net-zero emission requires bringing forward novel solutions across the transport, energy, agricultural and industrial sectors alongside the reduction of energy consumption. For example, across society there is a significant opportunity to support decarbonisation by finding more value from the excess heat that is generally lost to or given up to the surroundings from industrial processes to domestic appliances [1]. At the same time, district networks represent a better means of utilising energy resources by increasing energy efficiency by valorising the heat produced through the co-generation of electricity or industrial products/commodities. The technology is based on the utilisation of pipelines to connect heat sources, such as combined heat power (CHP), industrial waste heat, heat from waste-to-energy, renewable energies (geothermal and solar thermal heat, etc.), to provide heating to industrial, commercial and residential buildings [2]. The advantages of these systems are that they are able to improve energy consumption, carbon dioxide emissions and air quality. Nevertheless, this technology carries several drawbacks, such as the temperature required by the network (conventional 3rd generation district heating systems supply hot water at temperatures as low as 80 °C [3]), which precludes the utilisation of low-grade heat and influences the return temperature of the water in the network, increasing the distribution losses and requiring expensive insulated pipelines [4]. Due to high distribution costs and heat losses, heat demand must be concentrated locally to ensure the economic viability of the network [2], resulting in the inadequacy of less densely populated zones to be served by district heating technology. Thermal energy storage (TES) may also be required to balance the energy demand and supply in time and location in district networks and allow seasonal storage [5]. This technological solution often employs hot water sensible energy storage systems with large and insulated tanks, which require large availability of space and high capital cost [6].

Due to the worldwide increase in cooling demand [7], district cooling networks are also becoming more attractive for industrial, commercial and residential buildings, particularly in hot and humid climates [8]. Less common than district heating, the district cooling technology supplies chilled water through pipelines by exploiting cold sources, such as seawater in winter, mechanical and absorption chillers, cold storage, etc. [9]. Analogously to district heating, the technology presents some disadvantages, such as the high capital (in particular if absorption cooling is used) and operating cost, the temperature required by the process (which must be higher than 80 °C for a single-effect

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Nomenclature

Abbreviations

$CaCl_2$	calcium chloride
CAPEX	capital expenses
CHP	combined heat and power
COP	coefficient of performance
HCO_2K	potassium formate
HR	heat rejection
LiBr	lithium bromide
LiCl	lithium chloride
MAF	mass air flow sensor
$MgCl_2$	magnesium chloride
M-TES	mobile thermal energy storage
OPEX	operating expenses
PCM	phase-change material
PV-T	photovoltaic-thermal
R	ratio solution-to-air flow rate
TES	thermal energy storage
TCF	thermo-chemical fluid
ZEC	zero energy community

Symbols

m	mass flow (kg/s)
H	enthalpy (kJ/kg)
RH	relative humidity (%)
T	temperature (°C)
V	volumetric flow rate (L/min)
ω	moisture content (g_{H2O}/kg_{da})

Subscripts

air	air
Deh1	dehumidifier 1
Deh2	dehumidifier 2
in	inlet
Reg 1	regenerator 1
Reg 2	regenerator 2
TCF	thermo-chemical fluid
out	outlet

lithium bromide (LiBr)/water absorption cooling system) [10], the effect of the choice of the cold source on the environmental benefits of the technology, etc. [11,12].

As reviewed by Lund et al. [2] and Vandermulen et al. [13], future district energy networks must be able to overcome the challenges that limit their efficiency by (a) supplying low-temperature district heating, domestic hot water and district cooling, (b) reducing its heat losses, (c) exploiting low-grade heat sources and renewable energy, (d) being integrated into smart energy systems and (e) being flexible. As a result, networks operating at lower temperature ranges, such as 4th (supplying hot water at the lowest admissible temperature for domestic hot water production and direct space heating, i.e. 50–55 °C) and 5th (supplying water at neutral temperature, i.e. 15–25 °C) generation district networks have been explored [2,3,6,14,15]. In particular, the innovative concept of 5th generation energy networks (also called cold district networks) [14], based on the supply of low temperature water connected by decentralised reversible heat pumps, is gaining growing interest due to their capacity to realise a prosumer approach, where all the energy nodes of the district energy network can act either as a consumer, i.e. requesting heat from the network, or as a producer, i.e. rejecting heat to the network [15].

In recent years, alternative technologies for the storage and transport of thermal energy over short-to long-distances were also studied. Li et al. [16] investigated the use of a phase-change material (PCM), erythritol ($C_4H_{10}O_4$), for waste heat recovery, transport and end-use. The technological and economic viability of the process, which was defined by the author as mobile thermal energy storage (M-TES), was identified as suitable for applications in remote less densely populated areas, for example rural areas, where conventional district heating networks are economically inefficient. Guo et al. [17,18] investigated the use of M-TES to connect by truck a coking plant and heat a group of small- and middle-size residential buildings at a distance of 13 km. The research evaluated the effect of different transportation schemes on the economics of the process, identifying the best operating condition for the transport of thermal energy. Liu et al. [19] and Yang et al. [20] investigated the utilisation of an innovative double-effect absorption cooling system using low-temperature geothermal energy sources to provide cooling in an office at a distance of 16 km by using tractor-trailer transportation, widening the scope of using geothermal energy for cooling application in buildings. Krönauer et al. [21] investigated the use of a zeolite sorption storage system to recover the excess heat from a waste incineration plant and transport it up to a distance of 8 km by a semi-trail to perform an industrial drying process.

An identified opportunity for the storage and transport of thermal energy and the realisation of district networks with increased efficiency is the replacement of water, used as the thermal fluid in conventional district heating networks, with a class of thermo-chemical fluids (TCFs) [8], namely desiccant solutions of hygroscopic salts, such as LiCl, LiBr, $CaCl_2$, $MgCl_2$, HCO_2K, etc. [22]. These fluids are characterised by (a) temperature and humidity control ability, (b) low-grade heat recovery (temperature required by the process about or lower than 60 °C), (c) relatively low cost, (d) environmental benefits, (e) storage of thermal energy in thermo-chemical form, (f) increased indoor air quality and (g) sanitising properties [22,23]. District energy networks employing TCFs as working fluids could represent an alternative to 5th generation district networks. Compared to water-based competitors, TCF-based technology could broaden the scope of district networks realising multifunctional systems able to provide heating, cooling, humidity control and drying. In addition, TCFs could be used in existing thermal district networks with no or reduced additional installation costs, being able to efficiently use low-grade excess heat and responsible for lower emissions. A summary of the main characteristics of 5th generation and thermo-chemical district networks is illustrated in Table 1.

The first uses of TCFs as energy storage medium can be found in the work of Kessling et al. [24,25]. In the last few years, different strategies for thermo-chemical energy storage with TCFs were developed. Buchholz et al. [26] developed a solar heating and cooling system that uses $MgCl_2$ as the seasonal thermo-chemical storage medium. The proposed technology can work in different operating modes according to the season and it showed high energy storage density (267 kWh/m^3), reduced losses and costs. Quinnell et al. [27,28] developed a single tank that is able due to buoyancy forces to simultaneously store water, diluted and concentrated TCF solution for sensible heat and thermo-chemical energy storage. Whilst the capability to store thermal energy with desiccant solutions and the transport of thermo-chemical energy over short to long distances has been separately investigated, the combination of the two technologies in thermo-chemical district networks results in a quite innovative approach with a lack of experimental data. Burch et al. [29] analytically investigated the realisation of a zero energy community (ZEC) coupled with a large solar central plant, exploiting liquid desiccant technology to produce heating, cooling and water heating for residential and commercial buildings. Unlike conventional district heating/cooling, the technology showed a reduction in the distribution costs of the thermal network due to the reduced piping

Table 1
Comparison of the main characteristics of 5th generation and thermo-chemical energy district network.

District network type	Low-temperature energy network (5th generation)	Thermo-chemical energy network
Working fluid	Water	Desiccant solutions, such as LiCl, $CaCl_2$, $MgCl_2$, etc.
Temperature range (°C)	10–40	15–60
Application	Space heating and cooling, domestic hot water	Space heating and cooling, humidity control, drying
Working principle	Temperature boost of low-temperature water by using reversible water-to-water heat pumps to reach temperature required for domestic hot water or space heating and simultaneously provide cooling	Temperature (heating or cooling) and humidity (de/humidification) control characteristics depending on the temperature and concentration of the solution
Advantages	• Flexibility to simultaneously provide heating and cooling from a single supply line, resulting in increased efficiency and reduced capital costs • Advantageous when the cooling demand is higher than 40% of the total load • The low temperature of the network reduces the distribution losses and allows the use of less insulated pipelines • The energy supplied from the supply side is self-balanced with the energy used by the demand side • The nature of reversible heat pumps mutes the role of the users of the network into prosumers	• Capability to recover ultralow-grade heat sources (about or lower than 60 °C) • Capability to transport thermal energy over long distances (up to 50 km) with limited losses, i.e. uninsulated pipelines can be used • Time shifting of the energy supply over mid-term storage period (up to weeks) • The flexibility of the network allows integrating additional services, splitting the cost over a larger number of customers, resulting in being more cost-effective in less densely populated areas • Sanitising properties of desiccant solutions, no problems associated with legionella
Disadvantages	• Not suitable for direct heating application, resulting in higher capital cost for heat pumps • Low temperature variation between water supply and return results in higher flow rates, i.e. higher pumping cost and larger pipelines • Potential problem of legionella for water between 20 and 40 °C	• Technology maturity and reliability • Lack of availability of equipment at large scale • Need for corrosion resistant materials if halide salt solutions of LiCl and $CaCl_2$ are used as TCFs

size. Geyer et al. [8] introduced the principle of using TCFs in thermo-chemical networks and described the technology that would be required, estimating that a significant reduction in energy consumption can be achieved with the technology for applications such as industrial drying (−85%). In another study by Geyer et al. [30], the technological and economic feasibility of multifunctional thermo-chemical district networks was investigated. It was reported that humidity-related applications, such as humidity control, humidity removal and industrial drying, are the most promising, although space heating and space cooling would also be feasible with thermo-chemical district networks. Delwati et al. [31] developed a dynamic simulation model to conduct a technological, economic and environmental analysis of a large scale thermo-chemical network, located in Hasselt, Belgium. The simulation showed the attractiveness of the technology compared to water-based district heating from a technical and economic point of view for the long-distance transport of heat. The literature review identified the high potential of thermo-chemical networks as being an alternative technological solution for the valorisation of heat but lacked experimental data and, in particular, the implementation of control strategies for this type of network, although experimental control strategies for conventional liquid desiccant systems are found in the literature [32–34].

As such, the present work experimentally investigates a first-of-a-kind smart thermo-chemical energy network and its control. The nature of the research was to put forward a strategy for operating such a network across multiple energy nodes (storage, supply and demand) by managing demand and supply side response with a centralised network control system. The demonstrator was set out to connect up to two sources and two demands across a network with two storage tanks and investigate the effect of alternative energy sources and demands, steady and transient state operation and different atmospheric and seasonal conditions on the network control. The paper is structured as follows. Section 2 describes the concept of thermo-chemical district networks, identifying potential applications and illustrating the centralised network control strategy. Section 3 describes the experimental rig developed for the study of thermo-chemical district networks, while Section 4 illustrates the experimental results obtained with steady and transient load and provides an insight into the potential economic benefits of such a technology.

2. Concept and control strategy

Fig. 1 shows the schematics of a potential thermo-chemical district network, highlighting the different markets that could benefit from the use of TCFs on both the supply (heat recovery) and demand (temperature and humidity control) side, from residential and commercial buildings to the industrial sector.

The inclusion of additional services, such as humidity control, into the benefits of the technology is one of the main advantages of thermo-chemical energy networks, being humidity control a primary factor for indoor air quality and health effects in buildings [35] and optimal quality of manufacturing processes [36], in particular of hygroscopic products, such as food, paper, textiles, paint, etc. [37]. Table 2 summarises the potential benefits of thermo-chemical networks in various types of residential and commercial buildings and industry.

It is important to note that industrial sectors, such as the food and drink, textiles, paper and printing industry, would present the opportunity to both supply low-grade excess heat and demand for energy-efficient temperature and humidity control, making interesting the prosumer approach for thermo-chemical networks. A further illustration of the main categories and potential applications for the use of the network on the demand side (residential and commercial buildings and industry) is presented in Fig. 2.

The concept of the operation of the thermo-chemical network is shown in Fig. 3. On the supply side, the heat required for regeneration is supplied by low-grade heat sources (from industrial processes, CHP, PV-T systems, etc.) to the TCF, driving the moisture desorption process from the TCF to the air and concentrating the solution. After being regenerated, the TCF is pumped to the demand side, where it is used for temperature and humidity control (such as for the air-conditioning of an indoor pool and a gym in the baseline case shown in Fig. 3), diluting the TCF that can be pumped back to the supply side.

The heat and mass transfer between air and TCF in dehumidifiers and regenerators is affected by various operating parameters, such as the flow rates and temperature of air and TCF, air humidity, TCF concentration, etc. [38], which can be controlled to operate the thermo-chemical district network, such as:

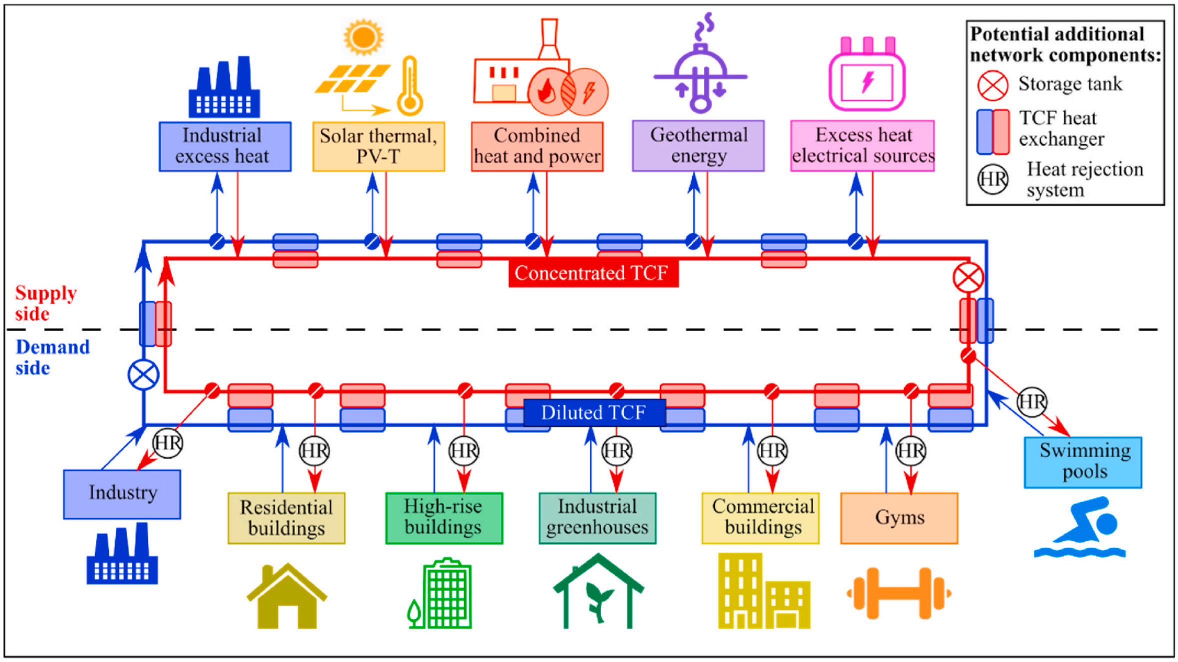

Fig. 1. Schematics of a potential thermo-chemical district network.

1) The parameter R, defined as the ratio between the mass flow rate of the TCF, m_{TCF}, and the air mass flow rate, m_{air}, plays a primary role in the performance of the moisture absorption/desorption process and the variation in concentration of the TCF. When R increases, the effectiveness of the moisture absorption/desorption process increases while the TCF concentration variation decreases. It is possible to operate the system such that the concentration of the TCF at the outlet of each regenerator is constant.
2) On the supply side, the temperature of the heat source affects the regeneration of the TCF. Compared to conventional district networks, thermo-chemical district networks would be able to recover excess heat from a larger temperature range and type of heat sources and both steady and transient heat sources. For the operation of the technology with fluctuating heat sources from renewable energy, such as PV-T systems, or intermittent industrial processes, the ratio R can be varied according to the variation of the temperature profile of the heat source, obtaining a constant value for the concentration of the TCF that is circulated in the thermo-chemical district network.
3) On the demand side, the ratio R and the operation of the cooling towers or chilled water system supplying cooling water can be varied according to the temperature and humidity control demand.
4) The storage tanks are used to balance the energy supply and demand and are located upstream of the supply and demand side.

3. Experimental set-up

Based on the previous considerations, the realisation of smart control of the thermo-chemical district network would allow managing demand and supply side response by a centralised network control system. An experimental test apparatus was built to investigate this operating principle and prove the concept of a thermo-chemical multi-nodal network that recovers heat from multiple heat sources and uses it for applications with different temperature and humidity control demands. The system was configured such that the network could be controlled, operated and monitored by National Instruments LabVIEW software to evaluate the impact of recovering different thermal energy sources (steady or variable with various temperature profiles) and supply various demand profiles. Fig. 4 illustrates the schematic of the experimental apparatus together with photographs from different angles.

The components used in the experimental apparatus are further described:

- Input process air: the air for the experiment was drawn directly from the main laboratory. The intake air had an average temperature of 21 °C and relative humidity (RH) of 45%. To emulate different atmospheric conditions, the inlet air was conditioned to achieve a specific temperature and humidity by using (a) an industrial dehumidifier (Model: Ebac PD120 230V 50 Hz 1Ph with a power of 1.5 kW) to pre-condition the air, (b) a 3-kW process air heater to elevate the temperature, followed by (c) a water injector to increase humidity. If an increased value of humidity was required, additional steam (from a boiling 10-Litre hot water tank) was supplied to the intake air system via a duct. The target humidity and temperature were set by the master control system which controlled the heater and injection rate to meet the targets. The air flow was handled by means of 4 throttles (Model: Body Inlet Manifold Flap for AUDI Seat VW Mk5 1.9 2.0 TDI 038128063 G F) and their control was regulated using LabVIEW.
- Design of dehumidifiers and regenerators and configuration: the air drawn blown from the bottom of the dehumidifier/regenerator contacts counter-flow the TCF, which is pumped at the top of the packed columns and sprayed over them by misting nozzles (Type: Hypro 301AF D.1.6–100). Each column (dehumidifier and regenerators) shown in Fig. 4, is a cylinder filled with a wood wool packing material 520 mm in height and 550 mm in diameter. The wood wool was supplied by the manufacturer Wood Wool UK [39].
- Pumps: the TCF was circulated between dehumidifiers, regenerators and storage tanks using four electric pumps with a maximum flow rate of 8 L/min (Model: 12V High Pressure Self-Priming Diaphragm Water 160 psi), represented as Pump 1, …, Pump 4 in Fig. 4. For the two main rings connecting the storage tanks, two larger pumps with a maximum flow rate of 11.36 L/min were used (Model: 12V 3GPM Water Adjustable Pressure 4 Diaphragm Pump 30 PSI for Caravan RV Boat), represented as Pumps 5 and 6 in Fig. 4. The opening of the pumps and the resulting TCF flow rate were controlled by LabVIEW. After dehumidification/regeneration, the TCF goes down to the tanks due to gravity.

Table 2
Potential benefits of thermo-chemical district networks, based on [36,37].

Sector		Benefit
Buildings	Residential buildings	•Energy efficiency due to decoupling of sensible and latent cooling •Improved indoor air quality
	High-occupancy buildings	•Desiccant solutions able to remove latent heat and volatile organic compounds (VOCs) from the air
	Hospitals, operating rooms and healthcare facilities	•Sanitising characteristics of the desiccant solutions reduce the risk of airborne viruses' transmission and increase indoor air quality
	Storage/conservation of goods	•The storage of wooden and paper objects (hygroscopic materials) in paintings, books, documents, etc. Is affected by humidity •Humidity control limits the growth of moulds and fungi (which proliferates in ambient with RH>60%)
	Condensation prevention	•Moisture surrounding cold surface creates quality and structural problems
Industry	Food and drink	•Humidity control prevents the proliferation of bacteria on meat, dairy, fruit, vegetables, etc. And ensures food safety •Humidity affects the consistency of the packaging used in the food and drink industry
	Textile	•Natural and synthetic fibres are hygroscopic and absorb or desorb water depending on the humidity of the surrounding air
	Electronic	•Clean, sterile and humidity-controlled air is required to avoid condensation and provide high-quality manufacturing
	Metal	•Moisture responsible for the corrosion of ferrous metals at the gross and microscopic level
	Paper and printing	•Humidity affects paper (hygroscopic material) quality during its production, storage and transport process •Humidity affects paper runnability (which causes printing defects during the printing process) and ink receptivity
	Chemical	•Moisture affects the rate of the chemical reaction and the chemical stability of the products
	Pharmaceutical	•Moisture regain in tablets, pills, capsules, etc. Affects the dimensions and quality of the product and machinery operation
	Industrial drying	•Air drying improves the quality of the product without sacrificing processing speed

- Heat sources and chiller: the heating systems are composed of two 18 kW industrial immersion heaters, two 30 kW submersible stainless-steel heat exchangers, piping and insulation. The heating performance of the systems can be controlled by LabVIEW and scheduled to follow transient profiles emulating the operation of a PV-T or CHP system. The heating systems are the yellow tanks shown in Fig. 4. Cooling water available from the laboratory was used to reduce the temperature of the TCF before dehumidification on the demand side.
- Storage tanks and thermo-chemical fluid: the TCF was stored using two 200 L storage tanks with dimensions of 950 mm in height and 550 mm in diameter. LiCl aqueous solution was used as TCF fluid. The LiCl salt (4272 Lithium Chloride Anhydrous Standard Crystals) was provided by the manufacturer Leverton Lithium [40]. Experiments were conducted with 32% wt. LiCl solution. The density of the TCF was determined by offline measurement with a pycnometer. Once the density and temperature of the TCF fluid were measured, its mass fraction was estimated by using the thermodynamic functions formulated by Conde [41] for LiCl aqueous solutions. The full list of thermodynamic functions of the TCF and the moist air used in the study are reported in the Appendix.
- The measured variables are shown in Fig. 4, while their measurement devices are summarised in Table 3. The temperature and humidity of the air were measured by 5 temperature and humidity transducers, one for the air inlet duct (shown as H1 in Fig. 4) and for each air outlet (H2, …, H5). The air mass flow rate was measured using 4 mass flow sensors (Model: Mass Air Flow Sensor Meter for Audi A3 1.8 2.0 Skoda VW 0280218002 06A906461A), one for each dehumidifier/regenerator. The TCF flow rate of the adjustable pumps (Pumps 1–4) was calibrated by varying the voltage supply and measured, while its temperature was measured by K-type thermocouples (Model: RS PRO Type K Thermocouple).
- Control system: the operating variables were measured by the sensors and acquired by LabVIEW software. An intelligent control strategy was developed for the operation of the controllable variables (flow rates of air and TCF, opening of the throttle valves, temperature and humidity of the inlet air and temperature of the electrical heaters). The ability in controlling the system was used to estimate future demand (over 24 h) and manage balancing supply and demand, emulating different operational cases of operation of the thermo-chemical district network, as discussed in Section 4.1.

4. Results

4.1. Operational cases

The system was set-up to explore the operation of a thermo-chemical network in several scenarios, as summarised in Table 4 and further described in the next sections.

1) Alternative energy sources (supply side) – A combined heat and power system used to power a district heating system (DHS) does not always fully utilise its heat, especially at the return line of the system. This return temperature was emulated as an energy source. A PV-T system was also explored as a potential energy source for the system. In addition, the potential for electrical system demand response by utilising a heater element was investigated.
2) Alternative energy demands (demand side) – The potential of supporting different demands was explored, as shown by the demands listed in Table 5.
3) Steady state and transient state operation – The system was operated at representative supply and demand conditions at steady state and over the daily transient supply offered by the PV-T system.
4) Different atmospheric and seasonal conditions – The challenges of operating the network in alternative geographical locations and seasonal conditions have been explored. Northern, Central and Southern Europe were represented by carrying out tests based on air temperature and humidity measurements from Newcastle-upon-Tyne, Amsterdam and Rome, respectively. These geographical locations were selected on the basis that they showed the breadth of atmospheric conditions across Northern, Central and Southern Europe.

The experimental analysis was conducted through two main experiments: (a) analysis of the performance of the experimental rig for baseline operation in different atmospheric conditions and (b) analysis of the performance of the experimental rig for different transient loads of heat.

4.2. Use cases

Different groups of experiments were conducted to evaluate the ability of the thermo-chemical network test rig to emulate the baseline

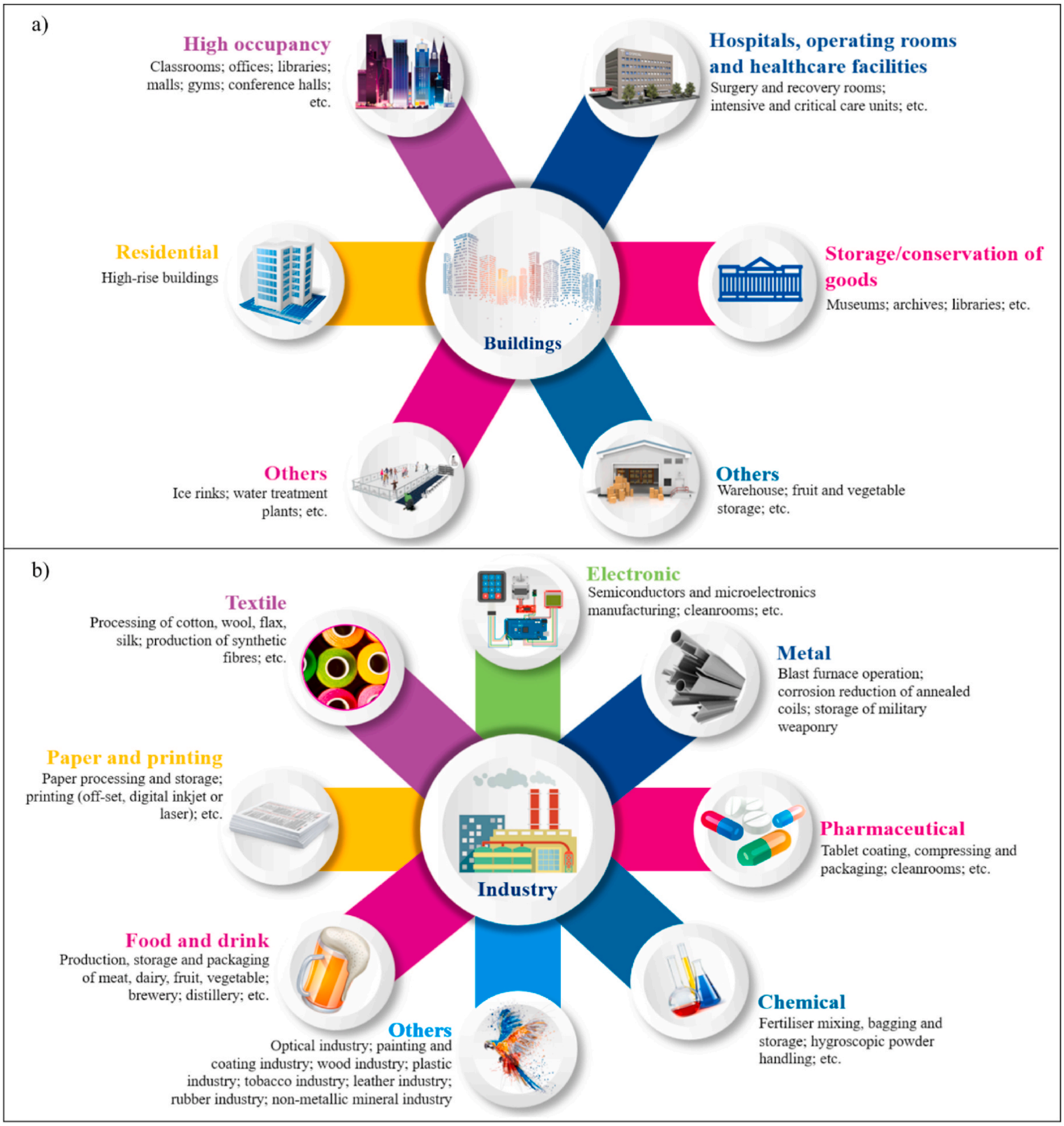

Fig. 2. Main categories and potential applications of thermo-chemical district networks on the demand side.

case study. The average performance of the experimental results for a thermo-chemical district network supplying air to an indoor pool and a gym and regenerated by two heat sources, one fixed at 70 °C and the other variable at approximately 70 °C during summer in Newcastle (223 experimental test cases) is shown in Fig. 5 on the moisture-enthalpy diagram, where the value for average outdoor air condition is T_{air} = 22.6 °C and RH_{air} = 76.97% and the sensible cooling after the dehumidification process was simulated.

As shown in Fig. 5, the air must be cooled after the dehumidification process performed by TCF. For applications where moisture control or removal is required, the latent heat removal characteristics of TCFs reduce the sensible cooling required, resulting in the opportunity of reducing the size of the integrated cooling systems and using energy-efficient high-temperature chilled water systems [46]. The full experimental results for the moisture content of the air produced by the dehumidification and regeneration processes are shown in Fig. 6.

Fig. 6 shows the ability of the TCF used in the experimental test rig to be regenerated by the two different heat sources and to supply the air in the humidity range required by indoor pools and gyms. This is because is possible to adjust the flow rate of the solution coming from the main ring with the LabVIEW control system to match the supply air within the temperature and humidity range required by the demand. The dehumidification performance of both dehumidifiers is approximately constant with the variation in moisture content during the experiments, while a larger fluctuation was observed for the moisture content of the air after the regeneration process. For the supply side, the temperature of the electric heaters and the TCF at the inlet and outlet of the regenerators is also shown in Fig. 7.

Similar to the previous case, Fig. 8 shows the experimental results of the thermo-chemical district network supplying air to an indoor pool

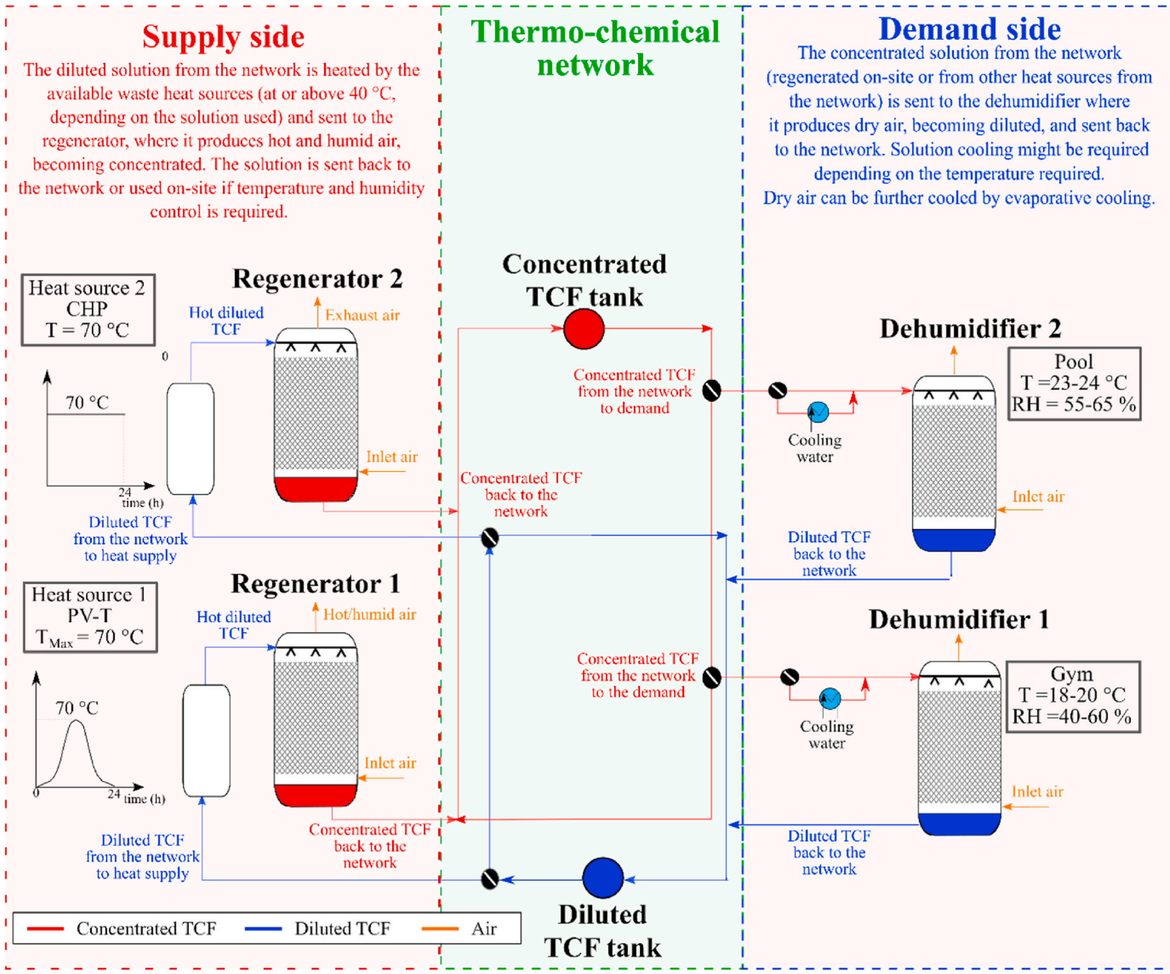

Fig. 3. Concept of operation of thermo-chemical district networks.

and a gym and driven by two heat sources, one fixed at 70 °C and the other variable at approximately 70 °C during summer conditions in Amsterdam (63 experimental test cases), where the value for average outdoor air condition is T_{air} = 25.07 °C and RH_{air} = 66.07% and the sensible cooling after the dehumidification process was simulated.

For hot climates, the performance of the thermo-chemical network experimental rig was emulated for Rome. Fig. 9 shows the experimental results of the thermo-chemical district network supplying air to an indoor pool and a gym and driven by two heat sources, one fixed at 70 °C and the other variable at approximately 70 °C during summer conditions in Rome (1133 experimental test cases), where the value for average outdoor air condition is T_{air} = 33.5 °C and RH_{air} = 60.66% and the sensible cooling after the dehumidification process was simulated.

As shown in Fig. 9, the higher temperature and humidity of outdoor air in summer in Rome requires a higher performance of the dehumidification process in the thermo-chemical district network. This can be achieved by increasing the flow rate or concentration of the TCF or decreasing its temperature using more efficient heat rejection systems (cooling towers or chilled water units). Table 6 summarises the experimental results and performance of the dehumidification and regeneration processes of the thermo-chemical network experimental rig, where the subscript air, in represents the inlet air, while the subscripts Deh1, out, Deh2,out, Reg 1, out and Reg 2, out represent the air at the outlet of dehumidifiers and regenerators, as illustrated in Fig. 4. In the table, the reduction of the enthalpy produced by the dehumidifiers 1 and 2, ΔH_{Deh1} and ΔH_{Deh2}, is also shown.

4.3. Transient load

The next step of the research was the evaluation of the ability of the thermo-chemical district network to recover variable heat sources. The first step was the analysis of a heat source with a load on/off, similar to CHP systems. The heating was controlled by LabVIEW with the maximum temperature set at 80 °C. Fig. 10 shows the regeneration performance of the thermo-chemical network test rig with typical summer outdoor air conditions (T = 22.46 °C, RH = 87.07%).

As shown in Fig. 10, the moisture content of the air at the outlet of the regenerator increases with the temperature of the heat source. Under the above-mentioned experimental conditions, the temperature of the heat supplied by the CHP must reach a temperature higher than 70 °C (and a temperature of the TCF higher than 60 °C) to enable the desorption process of water molecules from the TCF to the air and the regeneration of the TCF. It is important to note that the experiments were conducted using LiCl aqueous solution as the TCF. Lower regeneration temperatures could be achieved by using solutions with higher moisture desorption potential, such as $CaCl_2$ and $MgCl_2$ [22].

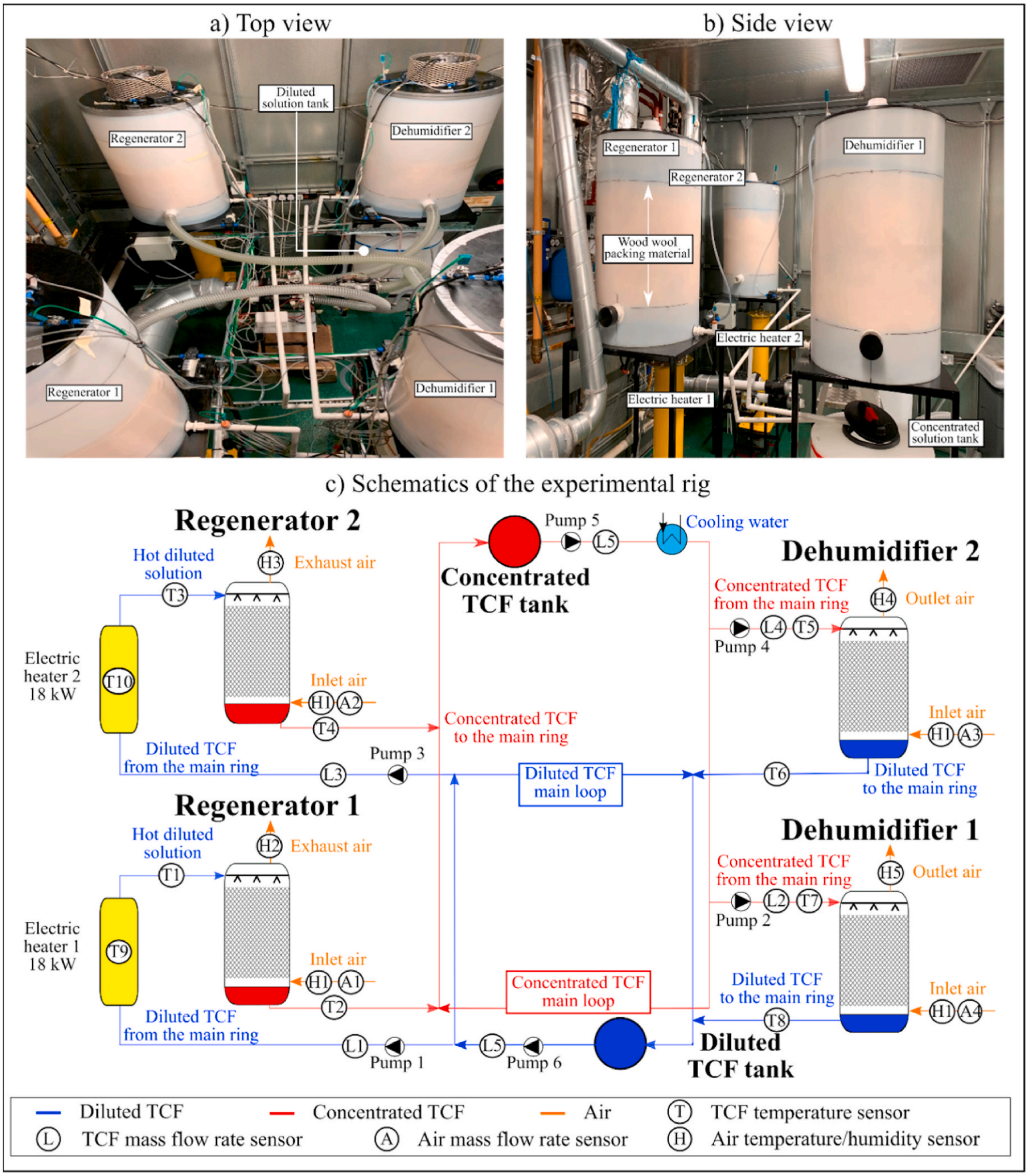

Fig. 4. Photographs of the (a) top and (b) side view of the experimental thermo-chemical district network together with (c) experimental apparatus schematics.

Table 3
Specifications of measurement devices.

Parameter	Device	N[a]	Operational range	Accuracy
Air dry-bulb temperature and relative humidity	HTM2500LF humidity and temperature transducer	5	$-40<T_{air}<85$ °C $0<RH_{air}<100\%$	RH ±3%
Air mass flow rate	Mass air flow (MAF) sensor meter	4	$1<m_{air}<5$ V	V ±2%
TCF volumetric flow rate	Pump flow rate calibration	6	$0<V_{TCF}<V_{MAX}$	n/a
TCF temperature	Thermocouples Type K	10	$0<T_{TCF}<350$ °C	±1.5 °C

[a] Number of devices.

Table 4
Emulation capability of operational cases with new experimental test network rig.

Potential operation	Experimental procedure
Alternative energy sources	•The waste heat supply from heat source profiles similar to those of CHP and use for TCF regeneration was tested •The waste heat supply from heat source profiles similar to those of PV-T and use for TCF regeneration was tested
Alternative energy demands	•The dehumidification performance required by different end-users, such as indoor pools, gyms, data centres and museums, was evaluated
Steady state and transient state operation	•The regeneration performance for steady state and transient heat sources was tested
Different atmospheric and seasonal conditions	•Tests were carried out to emulate different European outdoor air conditions showing hot (Rome), intermediate (Amsterdam) and cold (Newcastle) climate conditions •Tests were carried out to emulate different seasonal conditions

Table 5
Operational cases emulated by the thermo-chemical experimental rig on the demand side.

Application	Working principle	Demand	Ref.
Indoor pool	Temperature control is required to reduce evaporation and to improve the comfort of swimmers as they leave the water. Humidity control is required to prevent condensation, protect the building fabric and provide a comfortable ambient for users.	T = 23–24 °C RH = 55–65%	[42]
Gym	Temperature and humidity control is required for client's thermal comfort, allowing for evaporative cooling.	T = 18–20 °C RH = 40–60%	[43]
Museum	Temperature control is required for occupants' comfort. Humidity control is required to avoid dryness and fungi growth. Reducing the fluctuation of RH is also important.	T = 16–20 °C RH = 40–70%	[44]
Data centre	Temperature and humidity control is required for optimal performance, reliability and longevity of the computers.	T = 20–24 °C RH = 55–65%	[45]

The next step of the analysis was the study of a heat source with a transient profile similar to that of a PV-T system. The PV-T transient load behaviour was obtained from NASA POWER Data Access Viewer [47] for summer conditions in Newcastle. In the experiment run, the temperature of the electric heater was configurated to follow the transient load profile by LabVIEW control. To emulate summer conditions in Newcastle, the temperature of the inlet air was set at 21.05 °C and the RH at 82.86%. Fig. 11 shows the performance of the regeneration process driven by the transient load heat.

It is clear from Fig. 11 that as soon as the temperature of the transient profile reaches 50 °C (i.e., the LiCl solution reaches approximately 45 °C), the TCF starts the regeneration process driven by the available solar heat. Compared to the process shown in Fig. 10, the increase in the temperature of the PV-T heat is less sudden than the load on/off of the CHP system, resulting in the TCF reaching faster the conditions required for its regeneration. Similar to the previous case, Fig. 12 shows the experimental performance of the regeneration process driven by the transient heat load similar to PV-T profiles in summer in Amsterdam [47]. To emulate summer conditions in Amsterdam, the temperature of the inlet air was set at 23.07 °C and the RH at 82.8%.

As shown in Fig. 12, the higher humidity of the outdoor air in the experiment requires the TCF to be at a higher temperature than the case shown in Fig. 11, as a temperature higher than 60 °C is required to start the TCF regeneration process.

4.4. Energy and economic performance

To conclude, an investigation of the energy and economic benefits that could be achieved by the implementation of thermo-chemical district networks was conducted. Based on the results of the case studies, Table 7 was produced to show the potential end-user applications of the thermo-chemical district network and identify possible scenarios of use (reported in terms of the ability of the dehumidifier 1 and 2 to supply the temperature and humidity control for the various demands at different outdoor air conditions).

As shown in Table 7, the air produced by the experimental thermo-chemical network could be used for different application scenarios in Newcastle and Amsterdam, while for the case study emulated in Rome

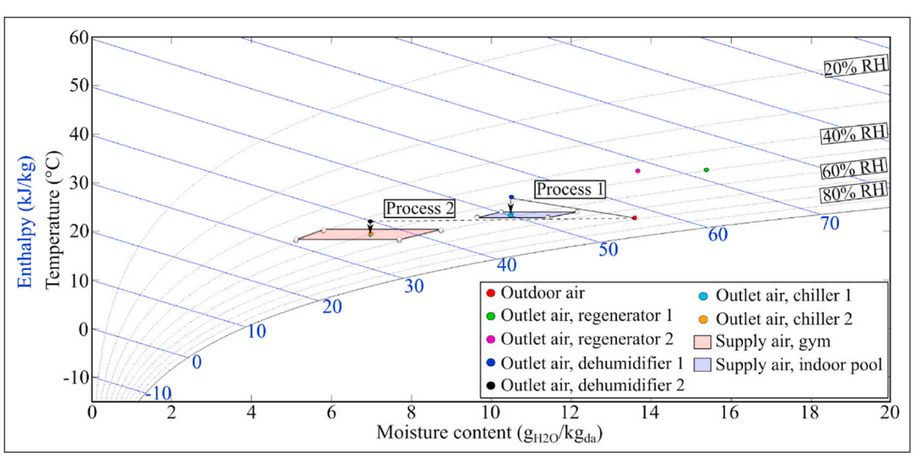

Fig. 5. Moisture-enthalpy diagram of the experimental average performance of thermo-chemical district network emulated for summer condition in Newcastle.

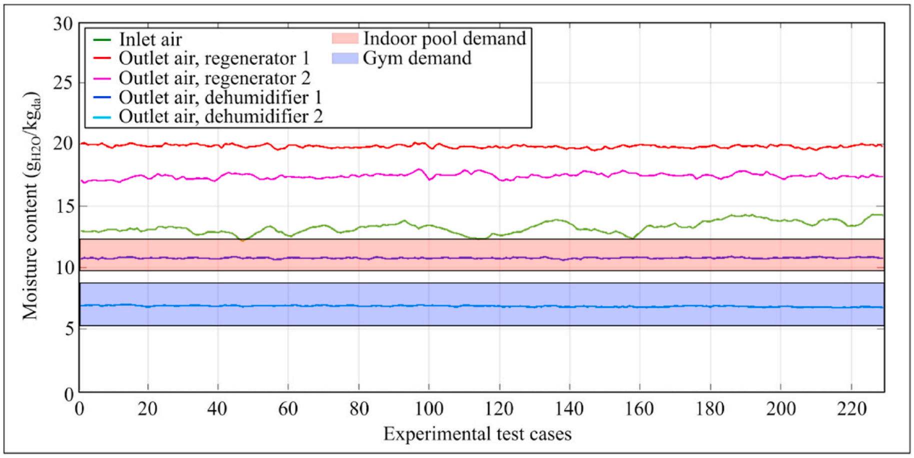

Fig. 6. Dehumidification and regeneration performance of experimental thermo-chemical district network emulated for summer condition in Newcastle.

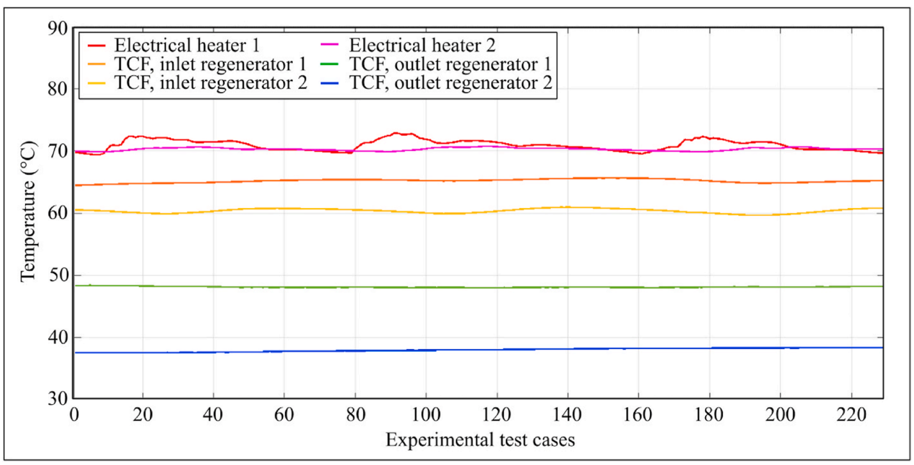

Fig. 7. Temperature of electrical heaters and TCF inlet and outlet of regenerator 1 and 2.

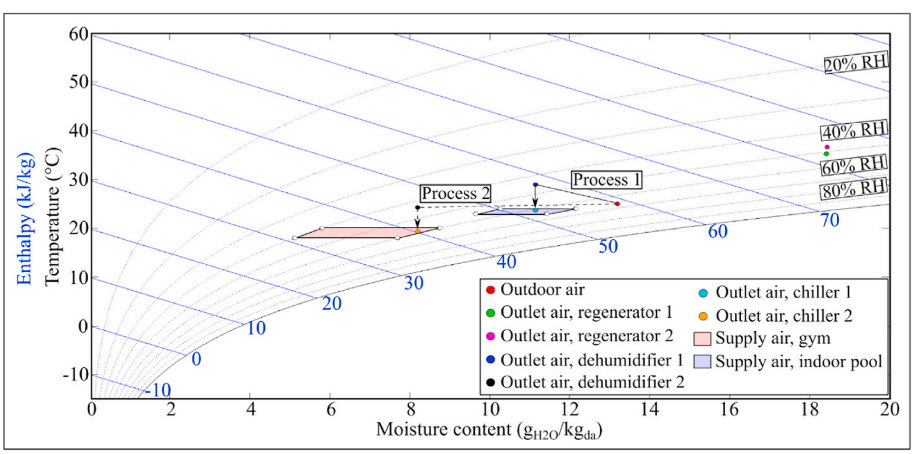

Fig. 8. Moisture-enthalpy diagram of the experimental average performance of thermo-chemical district network emulated for summer condition in Amsterdam.

the experimental rig would not be able to fully remove the latent loads and an improvement of the performance of the test rig is required. Based on the results of Table 7, Table 8 calculates the energy consumption and economic savings achievable for different scenarios of application of the thermo-chemical district network. For the calculation, the following assumptions were considered: (i) the supply air demand is 10,000 m^3/h for each application, (ii) the annual operating hours of the system are 2000, (iii) the COP of the conventional electrically driven cooling system is 2.4 and (iv) the cost of the electricity and natural gas are assumed as £0.11 per kWh and £0.025 per kWh, respectively. In addition, the CAPEX of the liquid desiccant system depending on the volumetric air flow rate is estimated using [48], while the annual OPEX of the system is assumed as 5% of the CAPEX [48]. These values were used to calculate the payback period for the different application scenarios illustrated in

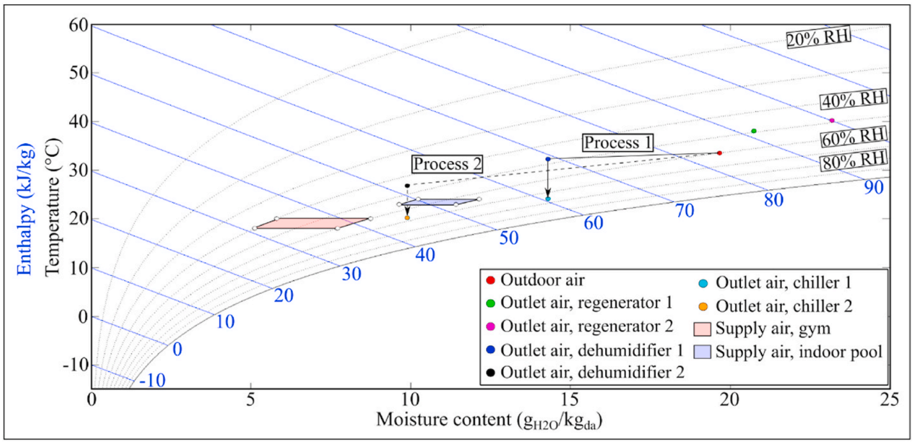

Fig. 9. Moisture-enthalpy diagram of the experimental average performance of thermo-chemical district network emulated for summer condition in Rome.

Table 6
Full range of experimental results and performance of dehumidification and regeneration process for different climatic conditions.

	Newcastle	Amsterdam	Rome
Experimental test cases	229	63	1133
$\omega_{air,in}$ (g_{H2O}/kg_{da})	12.1–14.3	12.5–14.1	18.6–20.6
$T_{air,in}$ (°C)	22.25–23.54	24.72–25.54	32.06–35.28
$\omega_{Deh1,out}$ (g_{H2O}/kg_{da})	10.6–10.9	10.8–11.9	13.3–15.4
$T_{Deh1,out}$ (°C)	27.32–27.58	27.97–30.29	30.48–33.34
ΔH_{Deh1} (kJ/kg)	3.31–4.18	−0.51–2.13	13.07–18.38
$\omega_{Deh2,out}$ (g_{H2O}/kg_{da})	6.7–7	8–8.3	8.7–11
$T_{Deh2,out}$ (°C)	22.95–23.4	24.14–24.51	24.1–28.55
ΔH_{Deh2} (kJ/kg)	17.29–18.3	11.69–16.46	29.08–36.76
$\omega_{Reg1,out}$ (g_{H2O}/kg_{da})	16.8–18	17.9–18.8	18.6–22.4
$T_{Reg1,out}$ (°C)	34.49–34.77	35.07–35.33	35.51–39.09
$\omega_{Reg2,out}$ (g_{H2O}/kg_{da})	19.5–20.1	18.2–18.7	21.3–24.3
$T_{Reg2,out}$ (°C)	37.38–37.88	36.31–36.7	37.06–41.23

Table 8, as shown in Fig. 13. The full equations used for the estimation of the CAPEX of the liquid desiccant technology and the calculation of the payback period are reported in the Appendix.

Table 8 shows how significant energy and economic savings are achievable for temperature and humidity control applications using thermo-chemical district networks. All the considered scenarios presented a reduction of the energy cost higher than 40% (ranging between 42.7% and 64.63%). This is mostly due to the ability of TCFs to deal with moisture and the inefficiency of conventional technologies to remove the latter. Better energy and economic performance are obtained for Newcastle, where the lower outdoor air temperature reduces the sensible cooling demand after the TCF dehumidification process. As shown in Fig. 13, the payback period ranges between 6.6 and 9.7 years for the identified application cases. Even though these prices might not seem like they would be particularly enticing as an investment, it is crucial to remember that these calculations were made considering projects of retrofitting, which did not include the CAPEX of the conventional electrical chiller. Therefore, new projects for thermo-chemical district networks in combination with a future reduction of the CAPEX of liquid desiccant systems could potentially offer a more favourable economic return.

5. Conclusion

Thermo-chemical energy networks could represent an alternative to 5th generation district networks capable of (a) recovering low-grade heat sources (about or lower than 60 °C), (b) providing various applications, such as space heating and cooling, drying and humidity control, (c) storing thermal energy in thermo-chemical form, (d) transporting the thermo-chemical energy over long distances with limited losses, (e) shifting the energy supply over mid-term storage period and (f) being managed by a centralised network control strategy. To this end, a first-of-a-kind experimental thermo-chemical district network was developed, which implemented a smart control strategy to manage demand and supply side response and evaluated the effect of alternative energy sources and demands, load profiles and outdoor air conditions on the performance of the network. This work experimentally demonstrated the feasibility of the design concept of such a network, which would be managed by centralised control, regenerated by steady or transient heat

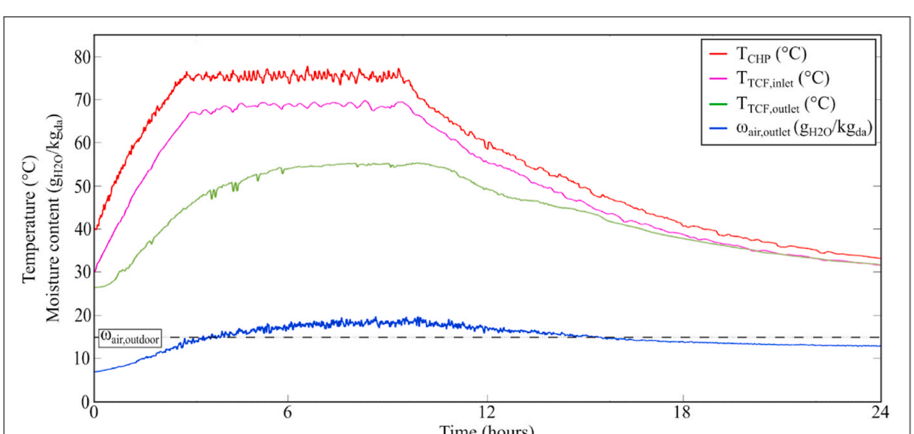

Fig. 10. Regeneration performance of thermo-chemical district network driven by CHP system (load on/off) during typical summer outdoor air condition.

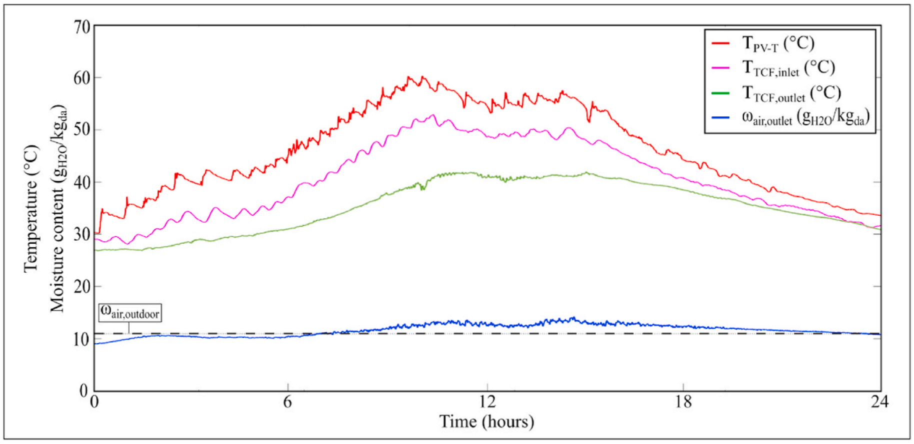

Fig. 11. Regeneration performance of thermo-chemical district network driven by PV-T heat transient load profile during summer condition in Newcastle.

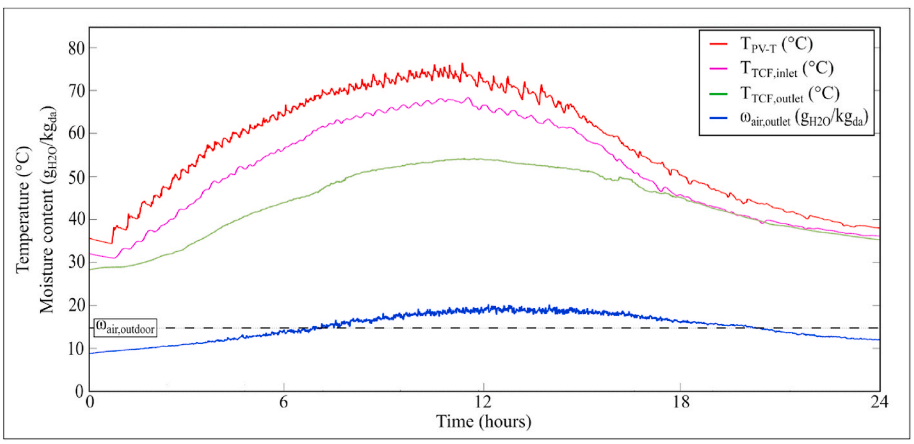

Fig. 12. Regeneration performance of thermo-chemical district network driven by PV-T heat transient load profile during summer condition in Amsterdam.

Table 7
Potential end-user applications for thermo-chemical district networks.

Demand side			Outdoor air condition					
			Newcastle		Amsterdam		Rome	
Application	T(°C)	ω (g_{H2O}/kg_{da})	Deh1	Deh2	Deh1	Deh2	Deh1	Deh2
Indoor pool	23–24	10.2–12.1	Yes	No	Yes	No	No	Yes
Data centre	20–24	8–12.1	Yes	No	Yes	Yes	No	No
Gym	18–20	5.1–8.7	No	Yes	No	Yes	No	No
Museum	16–20	4.5–10.2	No	Yes	No	Yes	No	Yes

Table 8
Estimation of achievable energy and economic savings for the application scenarios with thermo-chemical district networks.

S[a]	City	Application 1	Application 2	Energy savings (kWh/y)	Economic savings (£/y)	Economic savings (%)
1	Newcastle	Pool	Gym	169,125.3	10,291.7	−64.63%
2	Newcastle	Pool	Museum	151,193.2	9361.6	−62.59%
3	Newcastle	Data centre	Gym	142,803.2	8893.4	−53.07%
4	Newcastle	Data centre	Museum	124,871	7963.2	−50.43%
5	Amsterdam	Pool	Data centre	114,269.7	7025.8	−57.1%
6	Amsterdam	Pool	Gym	164,182.3	9646.6	−55.72%
7	Amsterdam	Pool	Museum	145,817.4	8724.1	−53.34%
8	Amsterdam	Data centre	Gym	138,078.1	8259.8	−45.53%
9	Amsterdam	Data centre	Museum	119,713.2	7337.3	−42.7%

[a] Scenario.

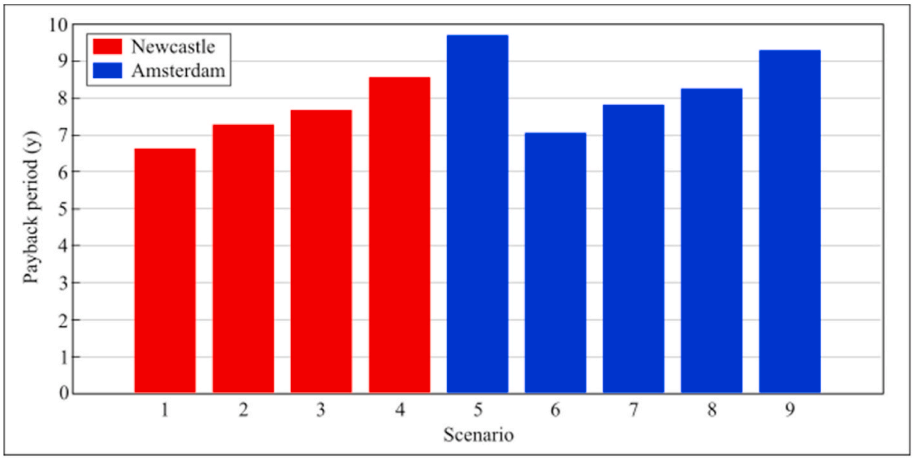

Fig. 13. Payback period of the identified application scenarios for thermo-chemical district networks.

loads and able to supply various demands. When operating with transient heat loads and variable outdoor air conditions, the operation of the thermo-chemical network can be adjusted to keep the value of the concentration of the TCF concentration approximately constant for the concentrated and diluted solution loop of the network or to supply the air within the optimal temperature and demand range for the specific application on the demand side. The potential energy and economic savings resulting from the use of the network were also calculated, identifying application scenarios for temperature and humidity control where energy savings could be higher than 60% compared to conventional operation and with payback periods in the range between 6.6 and 9.7 years.

Credit author statement

Alessandro Giampieri: Conceptualization, Methodology, Software, Investigation, Writing – original draft Sumit Roy: Methodology, Investigation, Writing – review & editing K.V. Shivaprasad: Investigation, Writing – review & editing Andrew J. Smallbone: Conceptualization, Methodology, Supervision, Writing – review & editing, 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.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.rser.2022.112869.

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