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Application cases and economic benefits of thermo-chemical networks

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Abstract

Thermo-chemical potential of absorption and desorption is highly promising to capture and use residual heat at low-temperature ranges. Due to loss-free transport and storage of the captured energy potential, medium- to long distance transport and medium-term storage offer interesting potentials to utilise residual heat. As such, there is an opportunity to develop networks at scales up to district heating level which utilises thermo-chemical fluids rather than water as the main working medium. This paper will give an introduction to the technology that can provide heating, cooling and drying in one multiservice network and examine its economic dimension. The humidification/dehumidification properties of liquid desiccants and how they can be applied to the heating and cooling of residential and commercial buildings are described. In addition, the characterisation of the free-loss storage capacity of this technology is undertaken and presented in terms of how this system can employ the utilisation of low-grade heat from industrial processes and low-temperature renewable energies. Finally, an economic assessment of conventional versus thermo-chemical solutions for heat storage and transfer is offered. The conventional technologies for heating, cooling and drying applications form the background for an economic comparison. The aim of the economic comparison is to show the benefits of the thermo-chemical technology for the key stakeholders involved in such a network, providing evidence that thermo-chemical network technology offers a commercially viable opportunity Among the several possible employments of the technology, it has been estimated that particularly for residential heating/cooling, industrial drying and greenhouses the thermo-chemical networks result to be feasible systems with a payback period relatively small (between 2 and 5 years).

Keywords: Liquid desiccant technology; thermo-chemical storage; district network

Nomenclature

$CaCl_2$	Calcium chloride
$CaNO_3$	Calcium nitrate
CO_2	Carbon dioxide
LiBr	Lithium bromide
LiCl	Lithium chloride
$MgCl_2$	Magnesium chloride
$MgSO_4$	Magnesium sulphate
TCF	Thermo-chemical fluid
TEG	Tri-ethylene glycol

1 Introduction

Nowadays, an increasing attention is placed on reducing the energy consumption required for heating, cooling and drying with a resulting mitigation of the CO_2 production. As a matter of fact, a massive quantity of fossil fuel is used as primary energy source for space heating, air-conditioning and industrial operations causing a conversion to CO_2 that is swiftly rising and expediting the global climate change. For example, it has been determined that the energy depleted for heating and cooling of buildings (residential or in the service sector) and industrial processes accounts for 50% of the EU's annual energy consumption [1]. This is mostly due to the fact that almost half of the buildings in the EU are older and have poor efficiency, renewable energy is narrowly used in these sectors and a huge amount of heat produced by industrial processes is dissipated into the atmosphere or into water, usually missing the opportunity for its recovery [2]. Through the development of an optimized, more efficient and more cost-effective utilisation of the energy, it will be possible to achieve a decrease in the energy imports, obtaining a reduction in cost and, at the same time, an environmental benefit, represented by a reduction in the emission of greenhouse gases (including CO_2) [3]. District heating is considered to be one of the possible solutions in the direction of this purpose because it promotes the better use of the energy sources, particularly renewable energy. Nevertheless, this technology carries several drawbacks, such as the temperature required that can preclude the utilisation of some technologies that work with lower temperatures, notable heat losses occurring during the transportation in pipelines and the need for integration with storage systems in order to obtain balance between the demand and the sources in time and location [4]. A feasible opportunity for the implementation of district network characterised by small amounts of heat losses is the utilisation of liquid desiccants (solutions of MgCl2, CaCl2, LiBr, LiCl, etc.) as TCFs for energy storage systems [5]. The employment of liquid desiccants as working fluids in HVAC applications represents an alternative to compression-based technology that is well known since the early century [6, 7] While the ability of these solutions to store and transport energy has been already discussed [8, 9], their employments with thermo-chemical district network results to be an innovative technology.

Therefore, this paper will be addressed to the description of Intelligent Hybrid Thermo-Chemical District Networks, a novel type of district network based on the employment of TCFs instead of water as energy carrier and storage medium. Through this technology, it will be feasible to obtain an energy-efficient exploitation of the resources, particularly opportunities for low-grade industrial heat and thermal renewables, leading to the achievement of a more sustainable energy system. Moreover, through the use of liquid desiccant as TCF in order to obtain a loss-free long-distance transport and a medium-term storage, it will be possible to obtain significant cost reductions. The paper is structured as follows. *Section 2* starts with a description of the liquid desiccant technology. *Section 3* reports the characteristics and the main advantages arising from the integration of the TCF with the district network. The last two sections of the paper address the subject from an economic point of view, identifying the cost factors and the potential business models for this kind of system (*Section 4*) and the associated economic savings related to the different applications (*Section 5*).

2 Liquid desiccant technology

Desiccant-based TCFs have the potential to provide simultaneous and multiple on-site functions and services, such as heating, cooling, de/re-humidification, energy storage and energy transport. Liquid desiccants exploit the hygroscopic properties of a salt solution for the removal of the moisture from the ambient outdoor air, until the attainment of a situation of equilibrium of its vapour pressure with that of the incoming air. For this reason, the dehumidification capacity of the desiccant can be evaluated through its equilibrium vapour pressure. For example, an industrial process waste-heat driven air-conditioning system is shown in Figure 1 in a counter-flow packed bed configuration.

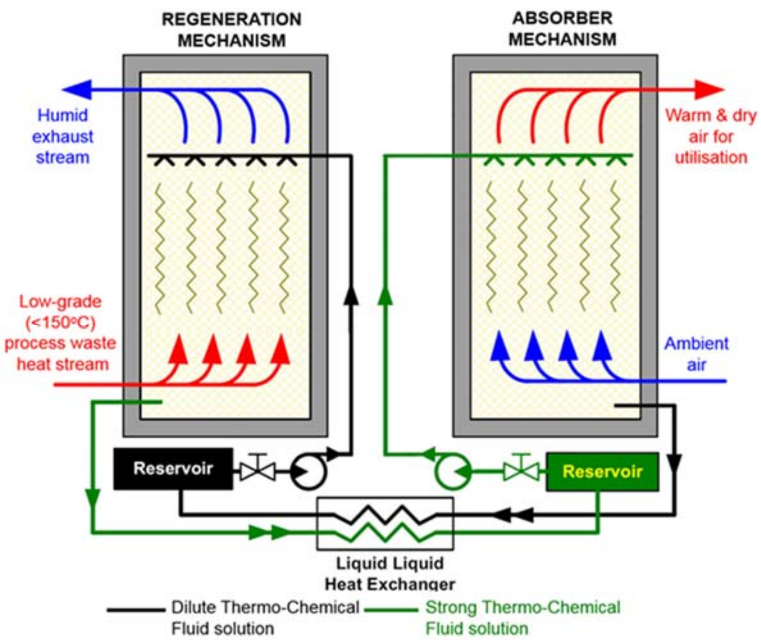

Figure 1: Liquid desiccant air-conditioning system [10, modified version].

In the absorption process, the TCF-solution with a higher concentration of salt (strong) is sprayed at the top of the absorber, while ambient air (or gas) enters the absorber at the bottom and transfers its moisture to the TCF. In this way, heat is liberated and the TCF-solution's temperature rises. This heat exchange process typically takes place over a packed bed/spray tower or gravity driven wetted wall column designed with the minimum pressure drop [10] with output humidity controlled by the temperature and concentration of the TCF solution. The dehumidified air exits at the top of the absorber and can be used to meet plant specific energy demands. The warm but now diluted TCF solution leaves the bottom of the absorber and it is pumped for regeneration. The regeneration process has typically the same configuration as the absorber and it is driven by the incoming industrial process excess heat gas stream or renewable energies; the now diluted TCF is sprayed over this stream and water in the TCF solution evaporates, reducing the gas temperature and increasing its humidity. A similar design is possible for waste heat transported by liquids (e.g. from cooling circuits). The TCF solution (now with a higher salt concentration) is pumped back to the absorber to restart the air-conditioning process.

Industrial manufacturing plants (and other energy consumers) typically have multiple demands for services to be provided on thermo-chemical basis in their locality; the previously described system can exploit the low-grade process waste heat to supplement (or even replace) such demands:

- Industrial Drying, because the exhaust air from a drying process can be de-humidified, thus turning latent into sensible heat, that can be re-directed into the drying chamber;
- Humidification, through the extraction of the moist from the outdoor air to humidify an air stream;
- Heating, since latent heat incorporated in air humidity can be re-converted in sensible heat either in air circulation mode or air exchange heat recovery mode. This is especially interesting at buildings with high attendance or high internal humidity sources. Furthermore, urban greenhouses can be conceptualised, to provide additional amounts of humid air based on solar energy. Along desiccant regeneration at the origin of residual heat supply, the ambient air is heated as it passes through the regenerator, which yields a warmer and more humid gas stream that can be used locally with corresponding savings in energy demands;
- Dehumidification, through the absorption by the desiccant of water from the air;
- Cooling, by utilising the dry air as the input into an evaporative cooling system, an additional re-humidification stage can be used to produce a cooling effect and thus to supplement local air-conditioning loads;
- Loss-Free Energy Storage, since through the transformation of heat to TCF potential is possible to transport and store heat and TCF potential in the hybrid district network with drastically reduced energy loss. As there is significant potential for thermal energy storage thus meeting/offsetting hourly, daily and, to some extent, seasonal energy supply/demand.

3 Thermo-chemical network technology

The aim of a Hybrid Thermo-Chemical District Network is to broaden the application of district networks through the realization of a multifunctional optimized system, able to simultaneously fulfil heating, cooling and drying operations and also to be integrated with existing thermal district networks, leading to the achievement of a more sustainable process.

Integrated storage: Through the recovery of industrial excess heat and the exploitation of low-temperature energy sources, it is possible to obtain via the regeneration process a TCF with high energy potential (in the state of TCF-concentrate). This potential serves as loss-free thermo-chemical energy storage medium. This is a notable advantage and offers the opportunity to offset available heat and demand, enabling longer distance transport of energy that can be as long as 50 km [4] mainly limited on transport costs. This feature, together with the increased energy density of the TCF (twice to eight times higher than the thermal capacity of water, employed in the conventional district heating system) can potentially open-up opportunities currently not considered viable from an economic point of view. Moreover, the promising characteristics of transport and low-cost by means of reduced or unnecessary insulation and cheap plastic pipes enable deployment into the regions with lower heat demand that are currently difficult to cover with conventional district network technology.

Low cost TCF materials: Another advantage is that the salts used in the solution as liquid desiccants are in most of the cases cheap (ranging from about 150 USD/m^3 for the $MgCl_2$ and 560 USD/m^3 for $CaCl_2$ to 7300 USD/m^3 for the LiBr [11]) and, for the characteristics of open system, they have to be as much as possible non-toxic and environmental harmless. Particularly, the $MgCl_2$, produced as a by-product from sea-water processing, and the $CaCl_2$, produced from industrial processes, result to be extremely cheap and easily available. If used for recovery of low-temperature heat (30-60°C), the drying potential is comparable with high cost TCFs, that would need higher temperatures in regeneration to explore their entire drying potential.

Environmental benefits: These benefits are mainly represented by the reduction in the primary energy consumption and in the related CO_2 production. The key for this reduction is the far better exploitation of applied primary energy. Furthermore, the simpler pipeline infrastructure, which is characterised by the utilisation of recyclable plastic pipes without any anti-frost protection, will allow to significantly reduce the transport costs. The system allows to reduce heat emissions into the environment like surface water heating and can help to reduce the urban heat island effect. If replacing cooling towers using water, the danger of legionella emissions into the neighbourhood can be prevented.

Hygiene: Lastly, the liquid desiccants present hygiene properties that can ensure humidity control of the process air, leading to an amelioration of the indoor comfort and forestalling the maturation of mould fungus. The technology avoids hygienic problems of competing technologies, such as mould problem in vapour compression-based dehumidification and germ growth in warm water-based humidification systems.

4 Economic evaluation of the utilisation of hybrid district networks

The attainment of benefits across financial, technological and environmental features are the main conditions for the deployment of a thermo-chemical district network. For the purpose of understanding the major expenses involved in the construction and utilisation of the hybrid district network, a cost factors analysis has been performed. The most significant cost factors are:

1. **Heat source and regenerator:** The heat sources used for desiccant regeneration range from low-grade waste heat within energy and industrial processes (CHP stations, air-conditioning units, data centres *etc.*) to heat generated by renewable sources. The recovery of low-grade heat with temperatures between the ambient air up to 150 °C (*e.g.* waste streams of warm/hot air or exhaust gases discharged into the environment without being treated) is considered complex and in the majority of cases not economically viable. However, in some cases such as regions suffering from water shortage, the desiccants could be used as a substitute for water in cooling operations, leading to a decrease in the costs when compared to the alternative solutions (i.e. high cost of water or dry cooling). Despite this, financial incentives (such as heat valorisation) are still needed to boost recycling excess heat. Moreover, the employment of the TCF-concentrate improve the efficiency of a fossil energy-based process, leading to the obligation of an incentive scheme to broader the utilisation of TCFs. The calculation has shown a price for waste heat between 0.5 and 1.5 cents per kWh. For the renewable energies, the adoption of various financing policies for promoting their use is contributing to a cost reduction, making them appropriate for the use in hybrid district network.
2. **Desiccant storage:** heat sources are usually temporally unsteady and non-uniform in temperature, hence problematic for integration into conventional district networks. To overcome this problem, through the employment of TCF-concentrates, regenerated during off-peak hours and stored for use during peak demand hours, largely creates a wider window of opportunity for this low-cost storage system. The energy storage with thermo-chemical fluid is the thermal storage technology currently less-developed and with less available cost data. However, through a cost comparison with other energy storage systems is possible to evaluate its related costs. It can be noted that quite clearly a strong relationship exists between size and cost where (in 2014) domestic level water-based (sensible) heat storage units where costed at 500€/m^3, dropping to 32€/m^3 at scales equivalent to 75000m^3 for underground pit stores [13]. Based on this evaluation, prices for thermochemical storage can be considered ranging between 150 and 300 €/m^3, depending on the total size of the storage system.
3. **Transport:** is the most challenging cost to evaluate because it is greatly reliant on the distance between the source and users, the energy demand, the energy source, the number of heat sources and most importantly the site-specific, market-dependant installation and commissioning rates. Three principle means for transportation have been identified:

   On-road transportation: If the regeneration and the demand side are not far, the desiccant transport by heavy duty truck can potentially be realized. This transport means is generally expensive and limited by the distance, nevertheless, it does represent an opportunity in roll-out of a network. The cost is around 160€ per 1000 t*km (tonne-kilometre).

   Water transportation: For areas close to water streams, it is feasible to transport the desiccant through a waterway vessel, obtaining the reaching of longer transport distance (25 km)~~.~~ It has been estimated that the waterway vessel cost is 20 € per 1000 t*km.

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   Pipeline: Its variable cost strongly depends on the pipeline capacity, the site of utilisation, its accessibility and local economics. In 2016, the rough calculation for the cost of machine excavation, earthwork support, laying and jointing pipes and accessories at a depth of up to 1.5m, backfilling and compaction and finally the disposal of surplus soil for uPVC pipework is 55-65€/m (100mm dia. Pipe) and 69-83 €/m (160mm dia. Pipe) [14]. For a heat source neighbouring the dehumidification unit very low costs relative to small pipelines have to be considered. A feasible transport way is the employment of longer pipelines (up to 50 km) in full-developed district networks with high heat demand and pipeline transport, the cost is 5€ per 1000 t*km. Finally, it is viable to concurrently utilise the two transport types, leading to the attainment of a longer transport and in more remote areas.

4.1 Potential business model

The main requirement for the development of the technology is to achieve profitability and efficiency for both suppliers and consumers and converting costs into revenues. The implementation of such a network would offer different benefits to different stakeholders:

End-users (Demand): Residents could profit from a significant monthly and yearly cost reduction for the utilisation of an environmentally friendly and energy-effective heating and cooling strategy, simultaneously achieving a better indoor comfort, ensured by the humidity control of the thermo-chemical system. Moreover, this could lead to a reduced variation in energy costs not related to the fluctuating price of the fossil-fuelled primary energy sources, because the network is based on the utilisation of renewable energy as well as excess heat from industry.

Producers (Supply): The supply side would benefit in the employment of district thermo-chemical networks in obtaining a sustainable energy-efficient process, able to decrease its net energy consumption. Areas with a desiccant network may provide a higher general value of ground as allowing cost reductions in industrial processes or may attract specific (e.g. drying intensive) industries. This advantage may play a role in more general economic calculations including the development of the ground values of an area. Concurrently, by avoiding fossil fuel consumption, this technology could lead to improvements of CO_2 and air pollution (particulates, nitric and sulphur dioxides *etc.*), contributing to local improvements in the related health problems.

In order to estimate the possible economic advantages resulting from the employment of the technology for different stakeholders, an analysis based on the study of business cases involved on the utilization of excess heat has been performed [12]. The main four identified sectors were: Built Environment Business to Customer (B2C), Built Environment Business to Business (B2B), Industry, and Horticulture. The Built Environment B2C (Figure 2) is the business model that mostly could exploit support from public parties to implement this technology. The channels involved are housing corporations, utility companies and municipalities, which usually have a previously established relationship with the business cases implicated in the model (new buildings and offices, renewal of utility buildings, utilisation of TCFs into an already existing district network). The SPV (Special-Purpose Vehicle) links the upstream and downstream supply chain. For this case, the utilisation of waste heat and renewable energies would have an environmental and economic positive impact, particularly in the case of connection with an already existing built environment, but only with an even division of the profit between the channels and the end-users.

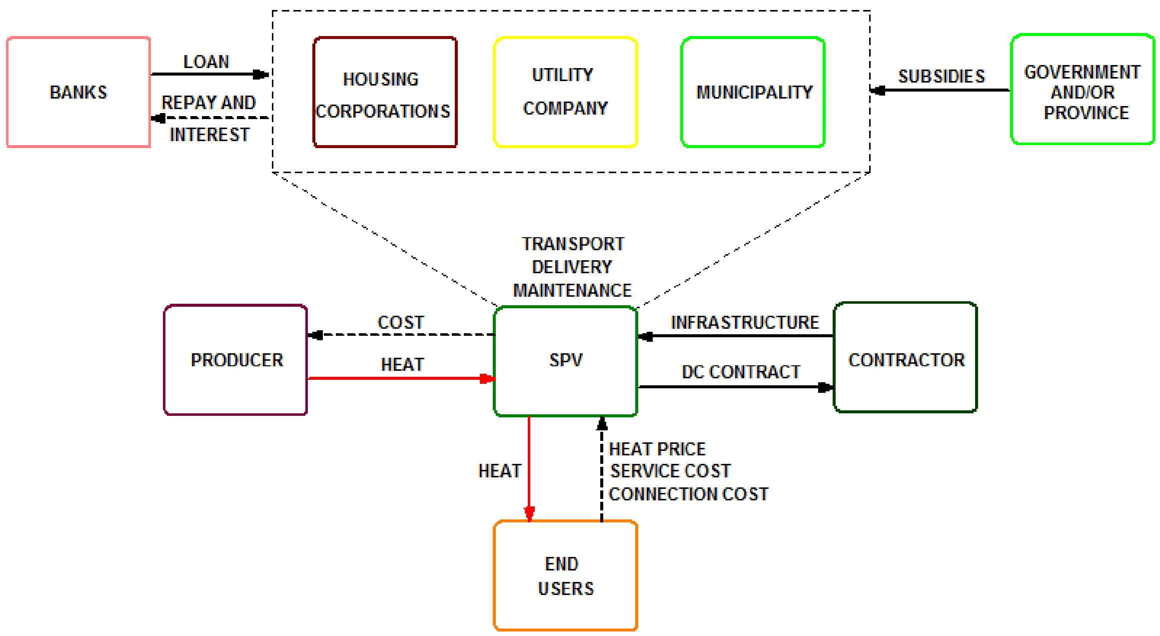

Figure 2: Example of Built Environment B2C business model [12, modified version].

The B2B model results similar to the previous case, with the addition of the involvement of energy distribution companies, interested in an improvement of their branding, represented by an amelioration in the public opinion obtained through a sustainable eco-friendly process. Industries, especially energy-intensive sectors, also concerned with the development of a branding image of sustainable company, are believed to be the most interesting sector in terms of economic gains because of the possible high revenues with the delivery of high-quality heat (steam), while the horticulture sector, characterised by the lack of an organization that acts as a channel with its customers spread over a wide area, is considered the least interesting in terms of implementation of a hybrid district network.

5 Application examples

In conclusion, some application examples have been discussed to estimate the possible financial savings related to the use of TCFs and hybrid district networks.

5.1 Drying application

One representative application case is an industrial laundry equipment. The analysis evaluates the economic savings related to the use of the energy potential of TCFs respect the conventional fossil-fuelled systems for drying processes. The system works through the absorption process accomplished by the TCF of the air released by the laundry dryer. This operation leads to the recovery of the thermal energy of the hot humid exhaust air that otherwise would be got lost and involves a significant reduction of it in the absorber. For the example at issue, it has been considered a comparison between a conventional and a TCF system with both a drying performance of 54 kW (Figure 3) [4].

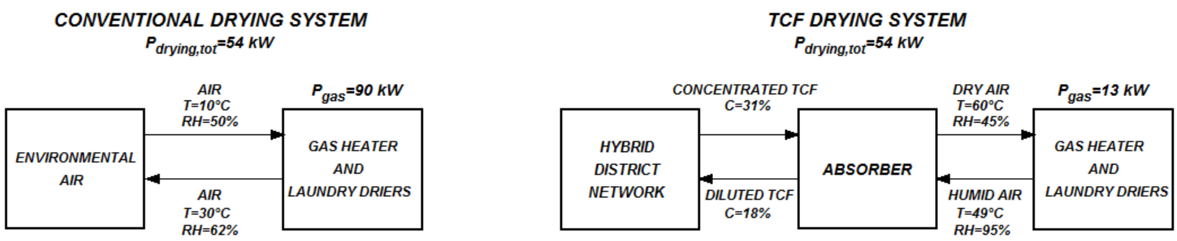

Figure 3: Comparison between conventional and TCF-based industrial laundry drier [4, modified].

This confrontation shows a significant difference in the amount of gas energy consumed for the heating. This is because while the fossil-fuelled system only uses natural gas and outdoor air for the drying process, the innovative system can exploit the thermo-chemical potential of the TCFs for exclusively employ the gas burner to warm-up the system and compensate the thermal losses. The calculation has been carried out considering a mean daily operation of 22 h/d, which yields a time operation of 5500 h/a (hours/year), assuming a price for the gas of 0.09 €/kWh and for the desiccant of 0.025 €/kWh [15], and a 54 kW "TCF-power" at a capturing rate of 79% of residual heat. The financial savings are around 28700 €/a with a resulting reduction of about 235 ton in the CO_2 production [16].

5.2 Heating/cooling application

The example refers to a building heating air-conditioning system, including an urban rooftop greenhouse for solar production. This technology can employ TCFs for the de/humidification of the process air, depending on the concentration and temperature of the TCF and on the ambient conditions of air, ensuring indoor comfort. The thermal energy needed for the process is obtained by the capture of solar energy through urban greenhouses (façades, roof greenhouses or greenhouses near buildings) that act as a low-temperature solar collector. From a cost saving viewpoint, it is estimated that for a family house of 150 m^2 with an energy requirement of 40 kWh/m^2 (6000 kWh/a) about 80% of the heating demand can be ensured by the TCF energy potential and the greenhouse, whereas just during the coldest period of the winter additional thermal energy is needed, this causing a yearly reduction in the energy consumption of 4800 kWh. Another cost-effective opportunity for this system is the humidity control in large greenhouses located in Botanic Gardens, where a low-grade heat source is employed to recover a liquid desiccant used for the dehumidification of the greenhouse humid air. Afterwards, this dry and warmer air is sent back to the greenhouse. The higher temperature reached by air can provide support to the heating system of the greenhouse.

5.3 Desiccant network

For the economic evaluation of the hybrid district network, the case of small (less than 4 km) and medium (about 25 km) distance has been considered. For the case when the regenerator and the user are located very close (Figure 4), it has been accounted the transport with a small truck (15 t of load) with a cost of 0.85 €/km and a daily covered distance of 80 km.

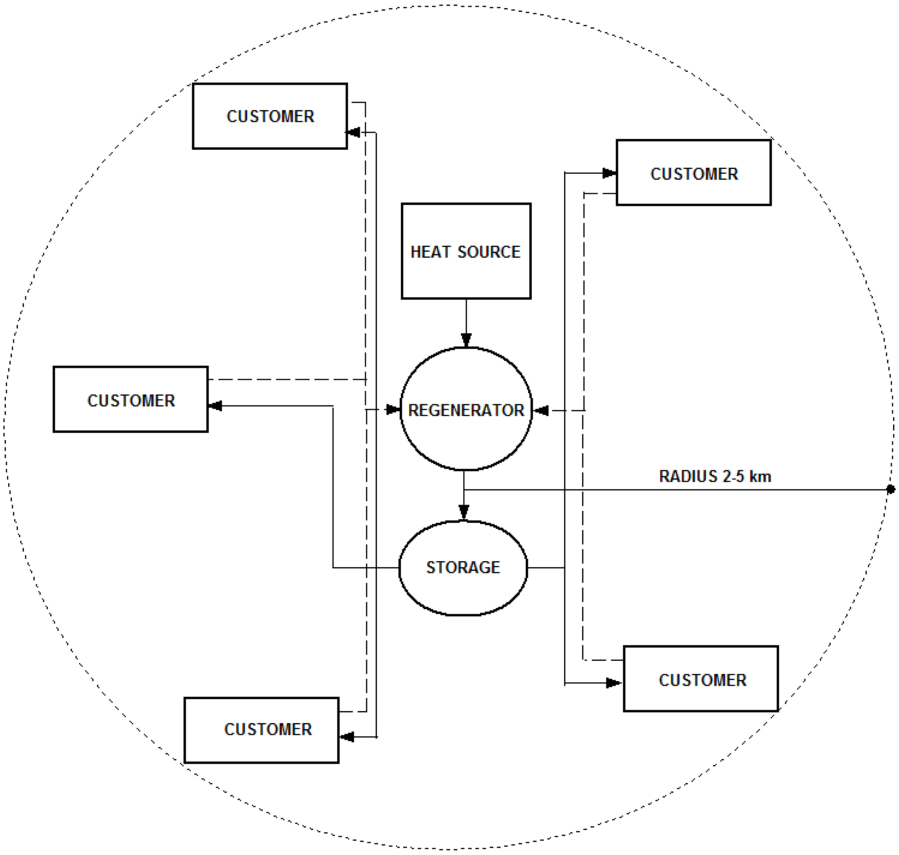

Figure 4: Example of small-scale hybrid district network within a neighbourhood.

The energy source is a waste heat of 6 MW, working half of the time, and the storage system has a 2-days capacity, sized to 3 MW constant load. The delivery by truck results to be fairly expensive but this is offset by the small distance. Basing the economic evaluation of the maximum thermal load, it is obtained that the cost for the waste heat is 0.01 €/kWh while the desiccant is sold at 0.025 €/kWh, making the investment feasible with 2.41 years of payback period (Table 1).

Table 1: Economic analysis of a small-scale hybrid district network within a neighbourhood.

Investment costs/a (in 5 years)	Value (€)
Regenerator unit	45.616
Desiccant storage	88.000
Running costs/a	
Transport costs	55.488
Cost of waste heat (0,01 €/kWh)	241.778
Total annual costs	430.881
Income from product (0,025 €/kWh)	680.000
Total net income	249.119
Return of Investment (years)	2,41

For a more remote heat source of 15 MW, a transport by water vessel (Figure 5) and a storage capacity of 3 days is considered.

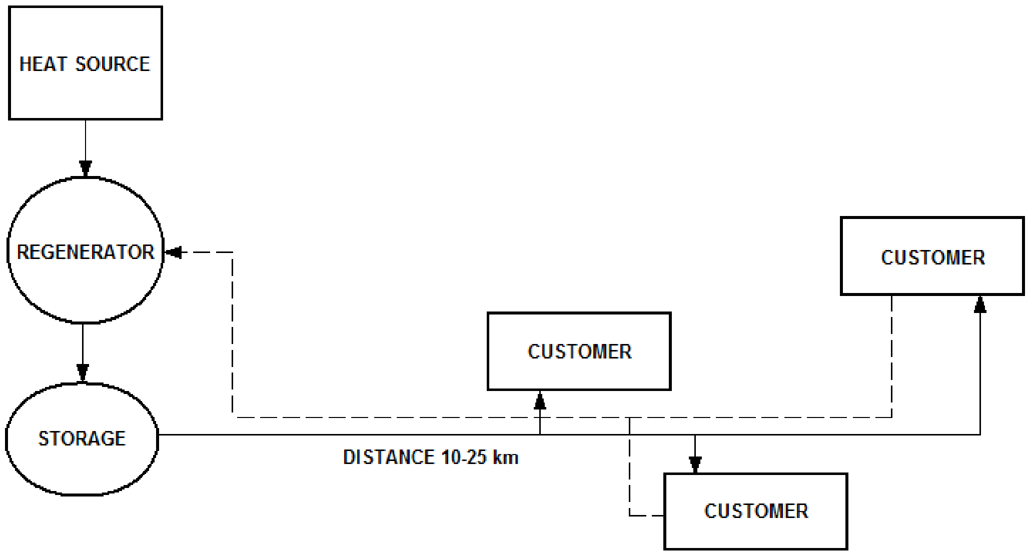

Figure 5: Example of small-scale network with a remote heat source with 15 MW waste heat.

Considering the same cost of the previous case for the waste heat and the sale of desiccant at 0.03 €/kWh, also here the investment is feasible with a payback period of 2.44 years (Table 2).

Table 2: Economic analysis of a small-scale network with a remote heat source (15 MW).

Specific costs (benefits)	Value (€)
Investment costs	3.440.000
Amortization regenerator unit	375.000
Amortization desiccant storage	270.000
Transport costs	816.000
Cost of waste heat (0,01 €/kWh)	1.044.480
Total annual costs	2.505.480
Income from product (0,03 €/kWh)	3.916.800
Total net income	1.411.320
Return of Investment (years)	2,44

Another opportunity is the employment of large-scale desiccant network that uses excess heat from a remote power station with a desiccant pipeline (40 km) to serve a city. Nevertheless, this system presents a payback period of 10.51 years, making this technology far from being realized.
Other developing technologies concern the utilisation of near surface seasonal heat storage as heat and cold source (2.13 years of payback period) and the utilisation of CSP (Concentrated Solar Power) unit in a closed greenhouse, which results to be a very promising technology in terms of revenues considering a 15-years lifetime of the system.

6 Conclusions

To the extent of an energy-efficient sustainable process of heating, cooling and drying the employment of thermo-chemical fluids into a district network results to be a promising technology. It allows a primary energy consumption reduction through the utilisation of low-temperature industrial excess heat and renewable energies while obtaining a reduction in the carbon footprint. Thermo-chemical fluids, through their hygroscopic property, have the potential to absorb/desorb water from the process air, obtaining a humidification/dehumidification process. Moreover, they can be employed as loss-free energy-storage medium, able to store the thermal energy in the form of TCF-concentrate that can be used when low-grade energies sources are unavailable. This can lead to the opportunity of bridging power mismatches between energy demand and supply and of obtaining a long-distance transport (up to 50 km), that only uses latent heat potential, making possible the realization of smaller plastic pipelines without insulation with resulting material and construction cost savings. An economic analysis through some application cases of the main cost factors (heat source and regenerator, desiccant storage and transport), and of the possible related monetary savings has led to the discernment of the economic feasibility of the process that in some cases have a relatively short payback (less than 2 years). To conclude with, the hybrid network is an opportunity for obtaining an efficient sustainable less-consuming process. That withstanding the solution needs to be developed, implemented and optimized in order to obtain a cost-effective network able to access residual heat sources and low-temperature renewable energies.

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