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Thermal energy storage (TES) for industrial waste heat (IWH) recovery: A review

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HIGHLIGHTS

- Industrial activities have a huge potential for waste heat recovery.
- TES systems overcome the intermittence and distance of the IWH source.
- More than 35 IWH case studies of on-site and off-site TES systems are reviewed.
- On-site TES systems in the basic metals manufacturing are the most recurrent option.
- Water, erythritol and zeolite are the TES materials more used in IWH recovery.

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ABSTRACT

Industrial activities have a huge potential for waste heat recovery. In spite of its high potential, industrial waste heat (IWH) is currently underutilized. This may be due, on one hand, to the technical and economic difficulties in applying conventional heat recovery methods and, on the other, the temporary or geographical mismatch between the energy released and its heat demand. Thermal energy storage (TES) is a technology which can solve the existing mismatch by recovering the IWH and storing it for a later use. Moreover, the use of recovered IWH leads to a decrease of CO_2 emissions and to economic and energy savings. Depending on the distance between the IWH source and the heat demand, TES systems can be placed on-site or the IWH can be transported by means of mobile TES systems, to an off-site heat demand. Around 50 industry case studies, in which both on-site and off-site recovery systems are considered are here reviewed and discussed taking into account the characteristics of the heat source, the heat, the TES system, and the economic, environmental and energy savings. Besides, the trends and the maturity of the cases reviewed have been considered. On-site TES systems in the basic metals manufacturing are the technology and industrial sector which has focused the most attention among the researchers, respectively. Moreover, water (or steam), erythritol and zeolite are the TES materials used in most industries and space comfort and electricity generation are the most recurrent applications.

Contents

Abbreviations: AA-CAES, advanced adiabatic compressed air energy storage; BTES, borehole thermal energy storage; CAES, compressed air energy storage; CHP, combined heat and power; D-CAES, distributed compressed air energy storage; DH, district heating; DHC, district heating and cooling; EAF, electric arc furnace; HTF, heat transfer fluid; HT-BTES, high temperature borehole thermal energy storage; IWH, industrial waste heat; LD, Linz and Donawitz; M-TES, mobile thermal energy storage; NACE, nomenclature statistique des activités économiques dans la Communauté Européenne; PCM, phase change material; PTES, pit thermal energy storage; TCM, thermochemical; TES, thermal energy storage.

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1. Introduction

Energy consumption is an important parameter which reflects the influence of a certain sector on the economic growth and environmental pollution of a region [1]. Existing reports from different energy statistics agencies [2–4] show that both industrial activities and energy sectors (power stations, oil refineries, coke ovens, etc.) are the most energy consuming sectors worldwide and, as a consequence, the responsible for the release of large quantities of industrial waste heat (IWH) to the environment by means of hot exhaust gases, cooling media and heat lost from hot equipment surfaces and heated products [5]. Recovering and reusing IWH would provide an attractive opportunity for a low-carbon and less costly energy resource [6]. Moreover, reducing the environmental impact and costs could, at the same time, improve the competitiveness of the sector.

Despite the fact that some work has been done to review and categorize the existing methods to estimate IWH potential as well as to highlight the importance of well explained and transferable IWH recovery estimations [5,7], the biggest amount of the IWH is underutilized. The technological, production process, financial and administrative as well as information barriers of IWH utilization was discussed and weighted in an expert meeting in 2010 [8]. They conclude that the five most relevant barriers to develop IWH recovery and reuse are:

- Technological barriers:
  - o No nearby heat sink
  - o No information about heat sinks nearby
- Production process barriers:
  - o Disturbance of the operation
- Financial and administrative barriers:
  - o Too high rate of return expectations
  - o Uncertainty of the economic future for the investing company

Once the IWH source is identified, the following step is to choose the most suitable technology to recover it. Accordingly, Brueckner et al. [9] categorized the available technologies to recover IWH as passive technologies, whether the heat is being

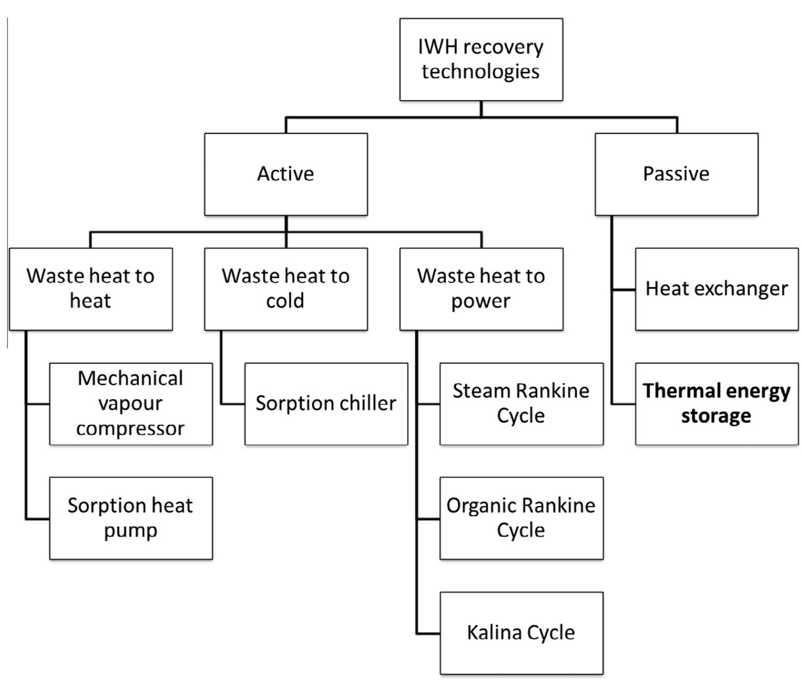

Fig. 1. Categorization of IWH recovery technologies, based on [9].

Table 1
Typical parameters of TES systems, based on [13].

TES technology	Storage period (hours, days, seasonal)	Capacity (kW h/t)	Cost (€/kW h)
Sensible (hot water)	Days/seasonal	10–50	0.1–10
Phase change materials (PCM)	Hours/seasonal	50–150	10–50
Chemical reactions	Hours/days	120–250	8–100

used directly at the same or at lower temperature level, or as active technologies, whether it is transformed to another form of energy or to a higher temperature level (Fig. 1).

Among the available technologies, this review focuses only on thermal energy storage (TES), which strengths are the possibility of solving the problem of matching the discontinuous IWH supply with the heat demand and achieving a better capacity factor, allowing the process components to be designed for a lower maximum output, for avoiding start-up and partial load losses, and for reducing investment cost in combination with cost intensive components (such as refrigerators or Organic Rankine cycle engines) [10,11]. Moreover, already in 2014, the IEA [4] highlighted the use of thermal energy storage for waste heat utilization as a key application to achieve a low-carbon future due to the temporal and geographic decoupling of heat supply and demand. Depending on the temporal range of this decoupling (hourly, daily, weekly or seasonally [12]), the storage capacity and estimated storage costs, sensible, latent and thermochemical (TCM) TES storages need to be considered and studied in order to choose the most suitable technology. Therefore, the storage period as well as the heat capacity and cost of different TES candidates are presented in Table 1.

Thus, the scope of this review focuses only on industrial and energy production activities (commercial, domestic and service-related activities are excluded) as they are the most energy consuming sectors; therefore, their energetic and economic savings are expected to be significant. The exhaust gases or streams that scape from the processes of these activities are considered without taking into account recovering technology which is already implanted, such as recuperators or regenerators. As the main drawback of those activities are their intermittence and the temporal and geographical mismatch between their heat release and the later use heat demand, TES systems have been proposed to overcome them.

In this article, the case studies in which TES systems were proposed to reuse and recover IWH are reviewed. As search terms

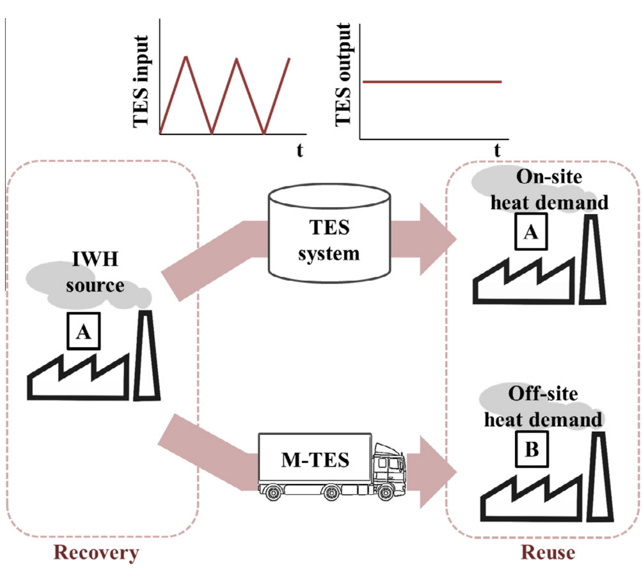

Fig. 2. Schematic of on-site and off-site reuse of IWH.

in scientific databases, the different nomenclatures of waste heat (waste heat, surplus heat, and excess heat) are considered. Moreover, scientific communications in conferences and other dissemination sources are reviewed. Patents are not included in the search. Based on this analysis, the most representative characteristics of the TES systems and their applications have been identified and their economic, environmental and energy savings are discussed. In addition, the trends and the maturity of the cases reviewed are considered. Last but not least, this review is aimed to identify research niches in the topic.

In order to present the industrial cases reviewed, the structure of this article is divided with regard to the location of the heat demand (Fig. 2): on-site or off-site. On-site is considered, when both the IWH source and the heat demand are in the same site. This section is then divided regarding to the type of industrial activity which generates the IWH. Off-site is considered, when the IWH source and heat demand are not on the same location but separated a certain distance. Therefore, mobile TES (M-TES) systems are required to transport the IWH from the location in which the heat is generated to the heat demand. In this section, the case studies are listed according to their maturity level.

2. On-site IWH reuse

Most of the case studies reviewed in this article proposed the IWH to be reused at the same location in which it is generated. The on-site reuse of this heat presents an opportunity to lower the energy intensity (total costs per amount of output product) of the site and, therefore, to reduce the energy costs and the costs derived from the CO_2 emissions.

This section is composed of two main groups: the manufacturing industry and other industrial activities. The manufacturing industry is the group which includes most references and covers metallic and non-metallic industries, chemical industry, paper industry and food processing industries. Power plants, vehicle engines, incineration plants and other TES systems applied to unspecific IWH sources are included in Section 2.2.

2.1. Manufacturing industry

Among the different industrial activities considered, the manufacturing industry is the one which has attracted most attention among the research community because, on the one hand, it is one of the most energy consuming sectors and, on the other hand, some of their process and combustion exhaust temperatures are significantly high which provides versatility of use (the higher the waste heat temperatures, the broader the possibilities to match them to different application).

Table 2
Exhaust temperature of some processes in the manufacture of basic metals [9].

Process	Exhaust temperature (°C)
Iron- and steelmaking	1450–1550
Steel electric arc furnace	1370–1650
Nickel refining furnace	1370–1650
Aluminium reverberatory furnace	1100–1200
Cooper refining furnace	760–820

2.1.1. Manufacture of basic metals

This subsector includes the activities of smelting and/or refining ferrous and non-ferrous metals from ore, pig or scrap, using electrometallurgical and other process metallurgic techniques [3]. In this subsector the highest temperatures (and, therefore, the highest potential) can be found (Table 2). Within this subsector, foundries and steelworks activities are the processes which have been most analysed by the researchers.

Three studies have been found regarding foundries. First, Anderson et al. [14] reported the development of a high temperature borehole thermal energy storage (HT-BTES system) to take advantage of the IWH from the foundry ovens of a Swedish pump manufacturer. This system aimed reducing the dependence of the manufacturing plant from external energy sources for its space heating. In this study, it was estimated that the unused waste heat from the foundry ovens was approximately 10 GW h/y and it was proposed to be recovered it by chilling the exhaust waste heat using water and pumping it to a borehole thermal energy storage (BTES) in combination with a heat pump. It was estimated that 3800 MW h of surplus heat could be yearly stored in the HT-BTES at 60–65 °C representing a mitigation of carbon dioxide of 1500 t/y. In the second study, researchers within the ongoing German project IAST [15] are analysing the recovery of discontinuous IWH from a foundry furnace in order to be stored in a 10 MW h capacity TES system. This system is composed of a dual-TES media with a packed bed in direct contact with a heat transfer fluid (HTF) at temperatures up to 300 °C. Their objective is to use the stored energy as input heat for different furnace processes and for space heating at temperatures up to 100 °C. The third study was recently carried out by Selvaraj et al. [16], who focused on the use of sand moulds with aluminium shots as TES system to recover the potential waste heat from the solidification process of metal castings. It consisted of preparing sand moulds with aluminium shots surrounding the mould cavity. Most of the shots were close to the cavity and could absorb the heat liberated during the solidification. Afterwards, the heated shots were separated from the mould and passed through a conveyor to an insulation box where they heated by conduction the scrap material. This scrap was further used as input at the furnace, which reduced the energy consumption. It was estimated that at least 6.4% of the waste heat could be recovered and reused by this method.

The IWH recovery from the steelmaking processes has focused the attention within the research community since the late 70s, when the first assessments were started to be published. In 1978, a research work [17,18] studied the IWH recovery and reuse

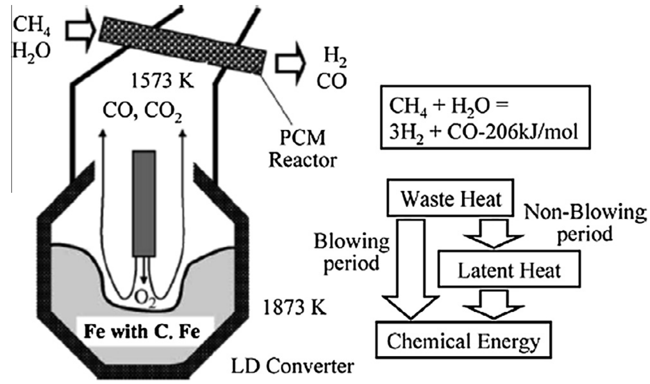

Fig. 4. Schematic diagram of the process consisting of the LD converter and the PCM storage by Maruoka et al. [21].

potential from the exhaust hot gases in the primary fume evacuation system from the electric arc steel remelting furnaces of an American scrap metal refining plant. Two packed bed sensible heat TES systems were proposed in order to be used at a temperature range from 315 to 1500 °C in both the operational periods, so to time average the widely fluctuating temperature of the energy source, and in the peaking periods, so to hold energy until the demand arises (Fig. 3). The system proposed was expected to save 0.0227 MW per ton of produced steel.

In 2000, Aliyama et al. [19] identified the possibilities of recovering and reusing high temperature IWH from blast furnace slags, Linz and Donawitz (LD) converter slags, electric furnace slags and LD gas. A thermo-chemical TES system was proposed, in which nine endothermic reactions candidates were proposed to generate steam and hot water from an exergy point of view. Two years later, Maruoka et al. [20] studied the implementation of a TES system consisting of copper balls encapsulated by a nickel film as to store discontinuous IWH at temperature above 1600 °C from the exhaust gas of a steelmaking LD converter. The stored IWH was further supplied to a coke oven gas to induce an endothermic reaction of methane steam reforming to produce methanol and for the reforming reaction from methane to hydrogen and carbon monoxide (Fig. 4). In a later work, Maruoka and Akiyama [21] estimated the potential of the implementation of this TES system [20] to the Japanese methanol industry. Even they do not reported energetic or environmental savings, they found a reduction of the exergy loss of 28% (compared with the conventional process) and that this

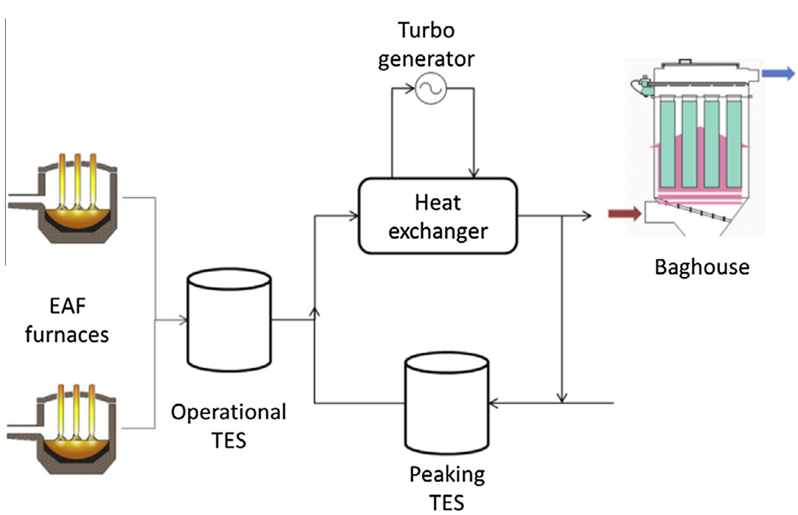

Fig. 3. Steel electric arc furnace (EAF) energy recovery and storage system, based on [18].

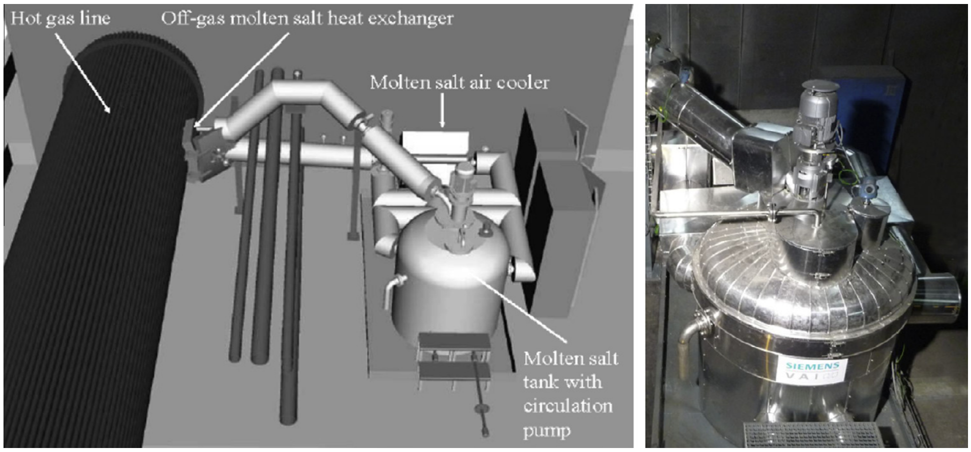

Fig. 5. Schematic view of the design of the pilot plant [23] (left); and picture of the real molten salt tank [24] (right).

implementation would allow producing $6.6 \cdot 10^5$ ton of methanol annually, corresponding to 20% of the total country demand.

Zhang and Akiyama [22] reviewed different recuperation techniques in the Japanese steelmaking industry at temperatures up to 1427 °C. Among them, the authors identified nine thermochemical reactions and a PCM (sodium acetate trihydration salt) were identified as TES systems candidates for IWH recovery. However, the authors did not calculate the environmental or energetic savings but the differences in the exergy losses if compared to a conventional system. Results showed that when the temperature is well controlled significant reductions in exergy losses could be achieved.

Steinparzer et al. [23] numerically analysed the intermittent exhaust gas recovery of an electric arc furnace (EAF) as IWH from a steelmaking industry with different TES systems (steam accumulators, PCM, molten salts and concrete) in order to be reused as heat for other processes or to be transformed into electricity. The authors estimated in 370 kW h per ton of liquid steel. However, only up to 24% of the energy existing in the exhaust gas could be recovered to generate process steam or electricity for on-site use. Therefore, energy consumption could be reduced between 60 and 80 kW h per ton of liquid steel, and CO_2 emissions could be reduced by up to 45 kg per ton of liquid steel. Later on, a test rig using 1500 kg of molten salts at 430 °C [24] was designed (Fig. 5, left) and implemented (Fig. 5, right) to experimentally test the concept proposed by Steinparzer et al. [23]. So far, there are not published results about its performance.

Recently, Raine et al. [25] investigated the potential uses of intermittent IWH (0.5 PJ/y) from three steelmaking industries in the United Kingdom using a thermal energy steam accumulator as TES system to be further reused for various processes on-site by means of an internal district heating (DH) network. Four IWH sources at a temperature range of 600–1500 °C were identified: steam from arc furnace flue gas, hot water from arc furnace flue gas, hot water recovered from reheat furnace flue gas and cooling water. High pressure steam accumulators and regenerator ceramic materials were proposed as TES system. The estimated annual CO_2 savings as a result of implementing these TES systems were 22,482 tCO_2.

Table 3
Exhaust temperature of some processes in the manufacture of non-metallic minerals [9,28].

Process	Exhaust temperature (°C)
Cement sintering	1450
Glass melting furnace	1300–1540
Calcining of limestone in the kiln	900
Calcination of magnesia	600–800
Cement kiln	450–620

Table 4
Heat sources in the cement production identified by Beshore et al. [29].

IWH sources	Description	IWH source maximum temperature (°C)
Clinker cooler	Waste air	177–232
Kiln system exhaust gas	Exhaust gas from the kiln or preheater, considered before entering the precipitator	382–816

Finally, from the point of view of recovering IWH from metal molten slags, Barati et al. [26] estimated a worldwide amount of IWH recovered from the slags at temperatures in the range of 1200–1600 °C of 792 PJ/y. Moreover, they reported the possibility of using the molten slags both as heat carrier and TES medium.

2.1.2. Manufacture of non-metallic mineral products

This subsector includes activities related to mined or quarried sand, gravel, stone or clay as well as the manufacture of glass and glass products, tiles and baked clay products, ceramic products, concrete and cement and plaster, from raw materials to finished products [3]. The production of this sector, especially for cement, has grown in the last years. Together with the high exhaust temperatures found in the sector (Table 3), this sector has attracted the attention of some researches, such as Miró et al. [27] who estimated based on CO_2 emissions the IWH potential of this industrial sector at European scale for the period 2007–2012 in 134 PJ/y. Within this subsector, TES systems for recovering IWH have been only proposed in precast and aerated concrete and in cement manufacture.

The earliest work reporting the use of TES systems in the non-metallic mineral industry was performed by Beshore et al. [29] in the late 80s. They analysed some American dry process cement plants in order to identify and quantify IWH sources (Table 4) and possible TES systems (Fig. 6) to recover IWH at a temperature range of 177–816 °C to be further reused for electricity production. They proposed two TES systems proposed were the rock bed, which consisted of two rock bed storage modules charged independently depending on the temperature (Fig. 6, left), and the molten draw salt, which consisted of a thermocline tank coupled with a kiln system (Fig. 6, right). The authors estimated an annual saving of 24.5 PJ/y in the American cement industry.

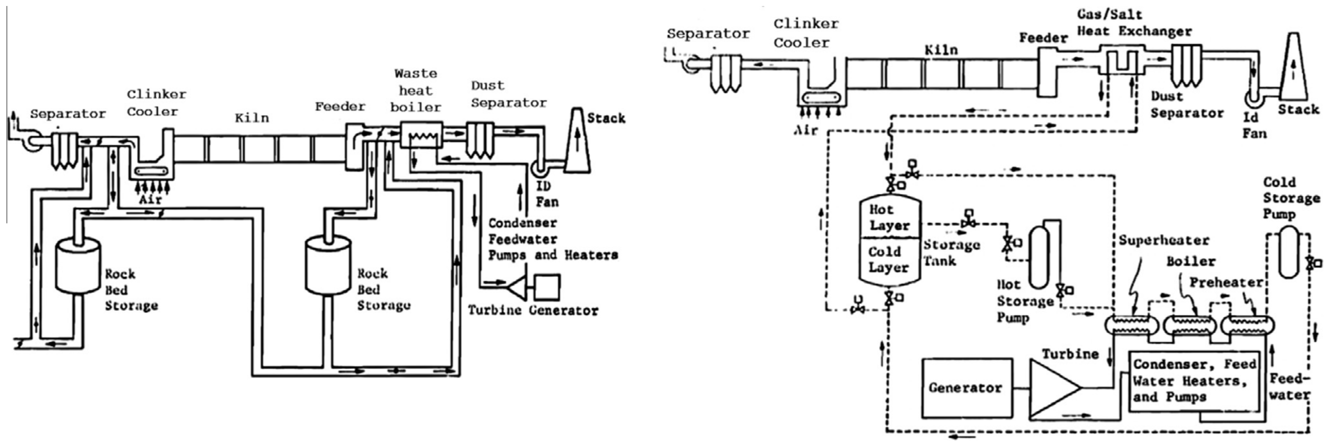

Fig. 6. TES system proposed by Beshore et al. [29] in a cement plant: rock beds (left), and draw salt thermocline (right).

Table 5
Exhaust temperature of some processes in the manufacture of non-metallic minerals [9,28].

Process	Exhaust temperature (°C)
Furnace black process	1200–1900
Ammonia catalyst reaction	510
Paint and varnish depolymerisation	288–343
Plastic and rubber	90–200

Regarding the concrete manufacturing industry, Steinmann [28] proposed to recover the IWH from the hardening of the aerated concrete using a latent heat TES tank based on the sandwich concept (with graphite) using an eutectic mixture of KNO_3 and $NaNO_3$ as PCM to further provide saturated steam. This concept was successfully demonstrated and tested at high scale by developing a battery mould for reinforced concrete slabs as heat exchanger interacting with a latent heat TES system. Under inputs of 100 kW using 2000 kg of PCM saturated steam at approximately 3 bar (between 120 and 250 °C) could be obtained. Even though there are no public results regarding the energy or emissions savings, the authors expected a reduction of the investment cost to below 50 €/kW h. Recently, the ENBELAT project [30] is studying the IWH recovery complemented with latent heat TES storage composed of reinforced concrete slabs and paraffin from a concrete manufacturing industry to further be reused in different internal prefabricated concrete manufacturing processes. This project aims to obtain a decrease of 45% on the energy consumption and a reduction of 15,000 tCO_2/y.

2.1.3. Manufacture of chemicals and chemical products

According Eurostat [3], this subsector includes the transformation of organic and inorganic raw materials by a chemical process and the formation of products, for example, industrial gases, dyes, pigments, etc. as well as explosives and pyrotechnic products, glues, essential oils and other chemical products such as photographic chemical materials and composite diagnostic preparations. Unlike other subsectors, this is a very heterogeneous subsector which is composed of many different processes working at different temperatures (Table 5).

Only two studies regarding the integration of TES systems in the heat recovery in the chemical industry have been found in the literature. In the first one, De Boer et al. [31] designed three different TES systems, within operating temperatures between 110 °C and 160 °C, to store the IWH recovered from the exothermic reaction generated during the manufacturing process of organic surfactants in a Dutch facility. The stored IWH was further reused to preheat products which were used in the same manufacturing process. It was estimated that the implementation of TES systems could save up to 70% of the energy consumption without any other modification on the process manufacturing. Table 6 summarizes the main characteristics of the three TES systems. The first one consisted of encapsulated PCM, with a melting temperature of 140 °C, in 10 cm diameter metal balls. The second and third ones were based on two different concrete blocks with a bundle of 1800 HTF tubes embedded inside which differ in their storage capacity.

The second study was carried out by Anastasovski et al. [32], who studied on the one hand, the recovery of IWH from bioprocess plants which produced yeast and ethyl-alcohol in a semi-continuous mode, and on the other hand, the design of a TES system based on two water storage vessels to store the IWH at a temperature range of 25–40 °C. Results showed an on-site decrease in the heating and cooling demand of 3% and 2%, respectively.

Table 6
General description of the three TES systems proposed by de Boer et al. [31].

Characteristics	Units	PCM	Concrete block 1	Concrete block 2
TES material volume	[m^3]	8.3	24.9	58.3
Storage capacity ($\Delta T = 20$ °C)	[MJ]	4600	611	1440
Energy consumption savings	[%]	56	50	70

2.1.4. Pulp and paper products

The paper and paper products subsector includes the manufacture of pulp, paper and converted paper products. It also includes further processing of paper and paperboard by coating, covering and impregnation, the manufacture of creped or crinkled paper, the manufacture of handmade paper, newsprint and other printing or writing paper [3].

In the late 70s, an American paper and pulp processing facility was chosen to evaluate the potential energy savings as a result of implementing a TES system to recover IWH from its internal processes [17,33]. The authors proposed a 173 m^3 water tank to store the excess steam from a hog fuel boiler when operating at a higher base load to be further reused in the same process during higher demand periods (Fig. 7). Hence, the author estimations lead to a decrease on the demand of fossil fuels by 50%. This implementation was expected to save $1.2 \cdot 10^9$ l/y of fuel oil per year.

2.1.5. Food products and beverages

This subsector includes the processing of the products of agriculture, forestry and fishing into food for humans or animals

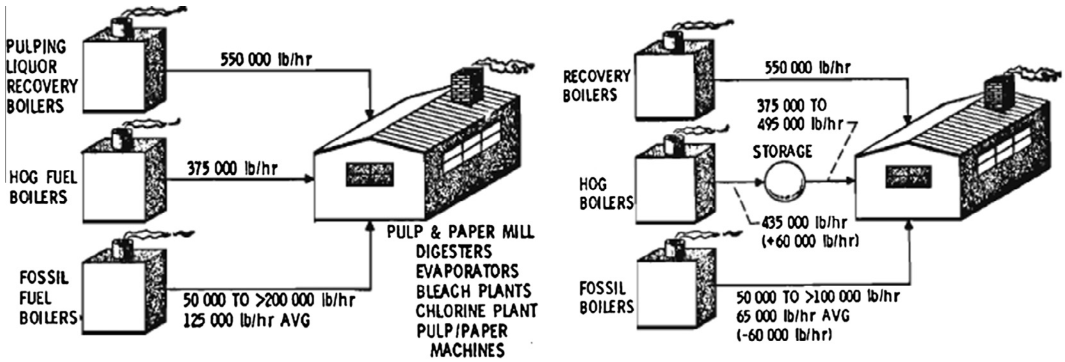

Fig. 7. Paper and pulp energy diagram without (left) and with (right) TES storage [17].

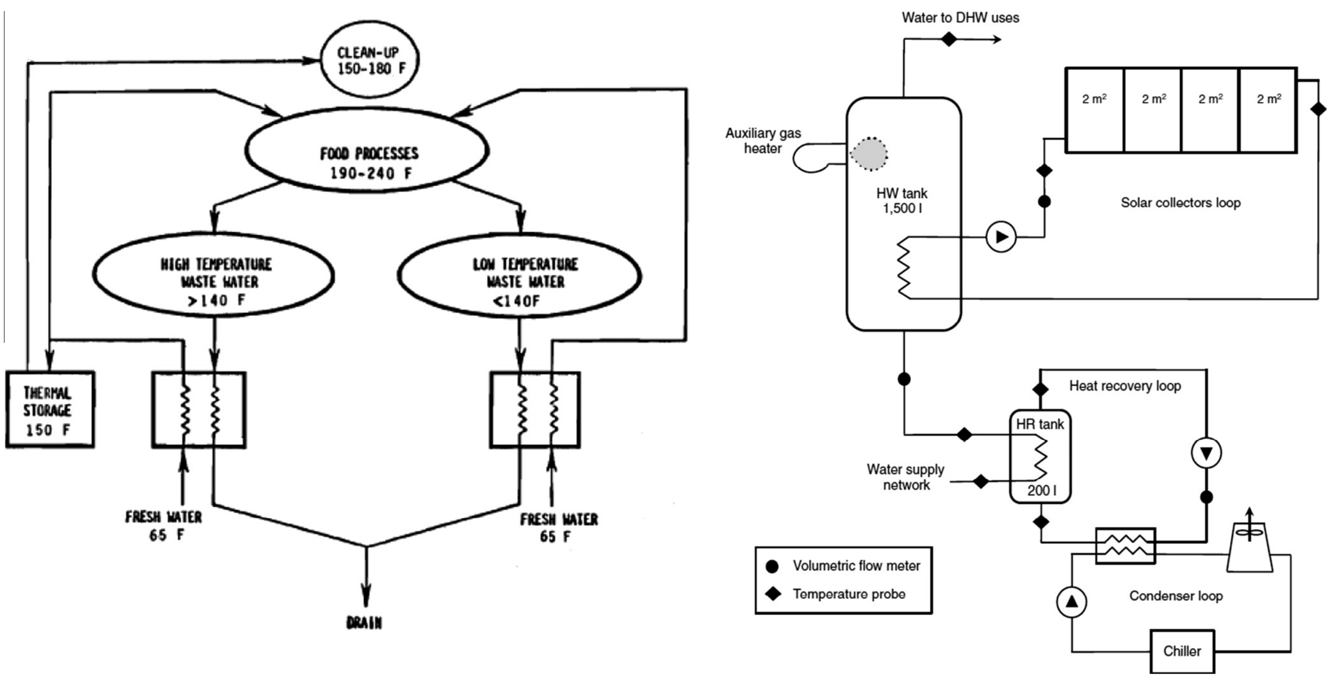

Fig. 8. Energy recovery and TES systems in food processing plants. System proposed by Wojnar et al. [17] (left), and system proposed by Biglia et al. [36] (right).

as well as alcoholic and non-alcoholic beverages mainly through fermentation or distillation [3]. This subsector is a major user of low-temperature (mostly below 120 °C) process heat and it is estimated that 85% of the fuel utilized by the industry produces process steam and hot water for cooking, sterilizing, and washing and sanitizing equipment and work areas [17].

Duscha and Masica [17] and Wojnar et al. [34,35] estimated up to 6% of energy consumption savings of an American food factory as a result of recovering the IWH from its internal processes, storing it at 65 °C in a storage tank (using water as TES material) and later on reusing it for heating the make-up water boiler, heating the fresh water for the different food processes and heating the factory clean-up water (Fig. 8, left). A similar concept was proposed and implemented by Biglia et al. [36] in an Italian chocolate industry where a 1500 L multi-source water TES tank stored the IWH from the debacterisation and cleaning processes to be further supplied to the hot water network (Fig. 8, right). The real system is under monitoring and the savings are not still available.

Other authors have focused on the refrigeration systems commonly used in the food processing industry and the potential energy savings by implementing TES system to store the IWH from their internal processes [37,38]. Reindl and Jekel [37] identified four potential locations within an industrial ammonia refrigeration system suitable for recovering IWH: oil cooling/heat rejection (fluid-cooled screw compressors), head cooling (reciprocating compressors), high-stage discharge gas stream (reciprocating compressors or screw compressors) and booster discharge gas stream (minimal opportunity). They stated the importance of TES if there is a mismatch between the demand and supply. Lohrenz [38] proposed taking advantage of the IWH rejected from the refrigeration systems in grocery stores to store it in a TES system consisting of a ground heat exchanger. It can be operated as a thermal storage for both short term energy storage and seasonal energy storage in order to further be reused for space conditioning and hot water needs.

Finally, Table 7 summarizes the available information from the studies reported in the literature regarding the manufacturing industry. In this table, the studies are classified according the manufacturing sector, the scale of the study (numerical, laboratory or pilot plant scale), the location, the characteristics related to the IWH source, the TES system proposed and its main characteristics, the heat demand covered with the IWH recovery, the demand applications and the savings achieved.

As expected, the activities in which researchers proposed the use of TES systems coincide with the most energy-consuming

Table 7
Summary of the TES systems proposed in the manufacturing sector for on-site IWH recovery and reused.

Manufacturing sector	Country	Scale of the study[a]	IWH source			TES system		Heat demand		Savings	Ref.
			Source	Yearly potential (MW h)	Exhaust temperature (°C)	TES material	Storage capacity (MW h)	Heat sink	Temperature (°C)		
Basic metals	Sweden	N	Foundry	$10 \cdot 10^3$	n.a.	Water	3800	Space heating	40–60	1500 tCO_2/y	[14]
	n.a.	N	Foundry	n.a.	300	Dual-TES media	10	On-site processes and space heating	<100	n.a.	[15]
	n.a.	N, L	Foundry	n.a.	n.a.	Aluminium shots	n.a.	Furnace input scrap material	n.a.	On-site reuse of 6.4% of the IWH	[16]
	USA	N	Steelworks	n.a.	315–1500	Packed bed with refractory brick, slag or scrap steel	n.a.	Steam for power generation	n.a.	2.27 kW/t of product	[17,18]
	n.a.	N	Steelworks	n.a.	n.a.	Endothermic reactions	n.a.	Steam and hot water	n.a.	n.a.	[19]
	Japan	N, L	Steelworks	n.a.	>1200	Copper	n.a.	Endothermic reaction	n.a.	n.a.	[20,21]
	n.a.	N	Steelworks	n.a.	<1427	Sodium acetate trihydration salt	n.a.	n.a.	n.a.	n.a.	[22]
	Germany	P	Steelworks	$370 \cdot 10^{-3}$ per ton of liquid steel	430	Molten salts	90 kW h/m^3	On-site processes and steam for power generation	n.a.	60–80 kW h/t of energy consumption and 45 $kgCO_2$/t of product	[23,24]
	UK	N	Steelworks	$138 \cdot 10^3$	600–1500	Steam	n.a	On-site processes and DH	n.a.	22,483 tCO_2/y	[25]
	n.a.	N	Metal casting	$220 \cdot 10^6$	1200–1600	Molten slag	n.a	n.a	n.a	n.a	[26]
Non-metallic minerals	USA	N	Cement production plant	$23.6 \cdot 10^{12}$	177–816	Rock beds and draw salts	n.a.	Steam for power generation	n.a.	$6.8 \cdot 10^6$ MW h of energy consumption	[29]
	Spain	N, L	Concrete production plant	n.a.	n.a.	Eutectic mixture of KNO_3 and $NaNO_3$ with graphite	n.a.	Steam generation	120–250	n.a.	[28]
	n.a.	N	Concrete production plant	n.a.	n.a.	Reinforced concrete slabs and paraffin	1.25	On-site processes	n.a.	45% in energy consumption and 15000 t CO_2/y	[15]
Chemicals and chemical products	Netherlands	N	Organic sulfactants plant	n.a.	110–160	(1) Metal encapsulated PCM (2)–(3) Concrete	(1) 1.28 (2) 0.17 (3) 0.40	Preheat on-site processes	n.a.	Steam supply (1) 56%, (2) 50% and (3) 70%	[31]
	n.a.	N	Yeast and ethyl-alcohol plant	n.a.	25–40	Water	n.a.	On-site heating and cooling	n.a.	Heating and cooling demand of 2–3%	[32]
Pulp and paper products	USA	N	Paper and pulp processing facility	n.a.	n.a.	Water	n.a.	Steam	n.a.	Fuel consumption $1.2 \cdot 10^9$l/y	[17,33]
Food products and beverages	USA	N	Food factory	n.a.	65	Water	n.a.	Water preheating	n.a.	Energy consumption 5–6%	[17,34]
	Italy	N	Chocolate industry	n.a.	n.a.	Water	n.a.	Hot water network	n.a.	n.a.	[36]

n.a.: not available.
[a] N: numerical scale, L: laboratory scale, P: pilot plant scale.

sectors. Also, in those sectors the IWH produced is higher. However, and as it can be seen in Table 7, the studies found in the literature do not report enough information for a deeper analysis and comparison. Even though not all cases report the location of the IWH source, most of the analyses were developed in Europe and USA. The basic metal subsector is the one which has most potential and has attracted most attention in the scientific community. This can be observed considering that there are both laboratory and pilot plant prototypes tested in the literature (and not only numerical studies). This may be due to the high exhaust temperatures of the activities (Table 2) which allow a wide variety of subsequent uses of this heat. In this subsector, the two main IWH sources identified in this sector are foundries and steelworks which use different TES material types depending on the subsequent use. For power generation molten salts, metals and ceramic materials were proposed. In the case of on-site processes and space heating purposes, lower temperature TES materials like water are used. Both laboratory scale and real scale prototypes were proposed in this sector.

Besides, in the cement and concrete production plants from the non-metallic mineral subsector the specific heat sources were identified (clinker cooler and kiln system exhaust gas), and, depending on the exhaust temperature the different types of TES materials (molten salts and ceramic materials) were proposed for power generation and on-site production processes. In just one case, a laboratory scale prototype was developed.

Fewer cases were identified for the rest of the manufacturing sector. In the case of the chemical activities only numerical studies were published in which different TES materials were used for on-site processes and climate control. Regarding both pulp and paper and food industrial activities, only numerical case studies using water as TES material were identified. Since the exhaust temperature for these sectors is as high as in the previous mentioned subsectors, the feasible subsequent uses are the pre-heating of other water flows in the process.

2.2. Other industrial activities

This section includes other industrial sectors found in the literature which cannot be included in the manufacturing industry: vehicle engines, power plants, incineration plants as well as Compressed Air Energy Storage (CAES) systems and other systems applied to unspecific industrial sources.

2.2.1. Vehicle engines

Engines are essential elements in both transportation and conventional power generation units. In fact, nearly two-thirds of the input energy in engines is wasted through the exhaust gases and cooling streams [6]. For example, in a four stroke diesel engine, the temperature of the exhaust gas is approximately 400–500 °C at full load conditions. Hence, it is possible to recover a large quantity of useful heat from these exhaust gases which are released to the ambient. However, in many situations the operation of the engines may not be continuous. In such situations, TES systems are suitable to both recover the waste heat and bridge the mismatch between the energy supply and demand.

From a general point of view and without any specific application for the recovered IWH, three different studies were performed in the same experimental setup in order to analyse the coupling of TES systems in diesel engines [39–42] and its most suitable configuration. The experimental setup consisted of a water cooled diesel engine coupled to an electrical dynamometer, and integrated to a recovery heat exchanger, which was connected to the TES system (Fig. 9, left). The TES system consisted of a cylindrical vessel made of stainless steel (Fig. 9, right). In the first study [39,40], 55 kg of castor oil and 15 kg of paraffin embedded in 48 cylindrical capsules were selected as sensible and latent TES material, respectively. Results showed up to 15.2% of savings in the fuel consumption if compared to the same setup without TES system. In the second study, Raja et al. [41] tested the thermal behaviour of the TES system with paraffin operating at various engine load conditions (25%, 50%, 75% and 100%). A direct relation between the charging rate and charging efficiency depending on the load was found. Moreover, nearly 15% of total heat was recovered with this system. Finally, in the third study, Chinnapandian et al. [42] replaced the initial TES system by two TES tanks arranged in a cascaded mode. The first TES tank used 19 kg of d-sorbitol filled in 48 capsules as TES material and the second TES tank used 15 kg of paraffin filled in 48 capsules as TES material, while 55 kg of castor oil were used as HTF. Results showed the suitability of the selected TES and HTF for the application proposed and the benefits of the cascaded mode as the total waste heat recovery increased in relation to the previous single tank configuration [39,40] up to 20%. The authors already highlighted the expectations of achieving fiscal benefits when using TES systems for vehicle applications.

A similar setup was later used by Prabu and Asokan [43] and Gopal et al. [44]. The TES system consisted of a stainless steel vessel, which was filled with 40 spherical containers made of

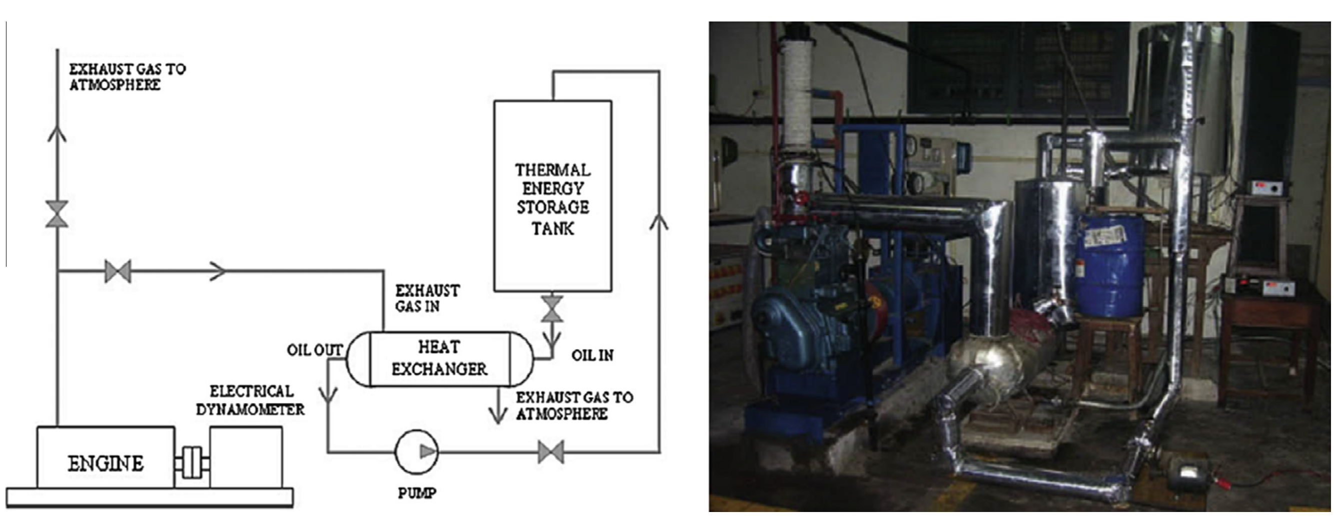

Fig. 9. Schematic diagram of the experimental setup (left) [39]; picture of the experimental setup (right) [41].

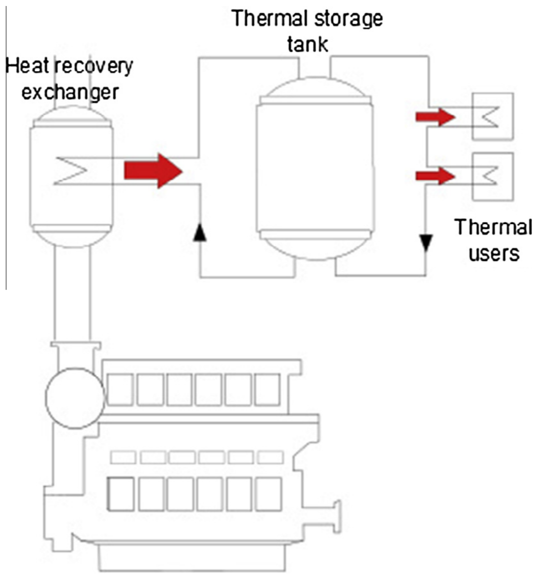

Fig. 10. TES system coupled with an engine designed by Baldi et al. [47].

low density polyethylene encapsulating each one approximately 100 g of PCM (paraffin). In this system, water was used as HTF. Results showed that nearly 7% of the total exhaust heat was recovered and the energy efficiencies of the integrated system oscillated between 3.2% and 34.2%.

Regarding specific applications in vehicle engines, Kauranen et al. [45] analysed the advantages of adding TES to a diesel car engine in sub-zero outdoor temperatures. At those conditions, the engine usually need additional heating to maintain a desired operation temperature (above 70 °C) so the additional heater was replaced by a combination of exhaust gas heat recovery system and latent heat TES accumulator. 4 kg of a commercial PCM (Climsel C70) with a melting point at 75 °C was selected for the heat accumulator in a typical shell and tube configuration. In comparison with the original system, the response of the TES accumulator was faster and the cold start emissions were greatly reduced. Later on, Shon et al. [46] proposed storing waste heat from a hot engine coolant in a tank filled with 4.2 kg of xylitol with a heat capacity of 1300 kJ. The stored heat could be used to quickly warm the engine and heat the passenger compartment. Experimental results showed that the engine warm-up time was shortened 33.7%. In the case of shipping transportation, a TES system was designed and modelled by Baldi et al. [47] (Fig. 10) for the engine exhaust streams. A 1000 m^3 cylindrical storage tank filled with thermal oil was considered for the TES system. Numerical results showed that the fuel consumption from the boilers could be reduced by 80%.

Finally, Li et al. [48] numerically proposed a system consisting of a diesel engine combined with a CAES unit for electricity supply in remote areas. The flue gas from the engine and the compressed air from the reservoir are both fed into the heat exchanger and recovered (Fig. 11). The PCM proposed was a composite consisting of an inorganic salt melting at 210 °C and a ceramic matrix. Results showed that the fuel consumption of the integrated system was only 50% of fuel consumption of a single diesel unit covering the same demand.

2.2.2. Power plants

When steam is used to generate electricity, only about a third of the energy in the steam is used; the rest becomes waste heat that companies have to get rid of. Power plants either use cooling towers to dump this heat into the surrounding air, or they draw water from a nearby river or lake to cool down the steam [48]. In order to increase the total efficiency of these facilities their waste heat is recommended to be reused. Elminshawy et al. [49] proposed a desalination system driven by the IWH recovered from both a thermal power plant and solar collectors in Saudi Arabia. In a related experimental work, a test rig was built using a water tank as TES system to store the IWH coming from a steam turbine. Results transferred to a 47 MW industrial steam turbine showed fuel savings up to 1844 kg/h.

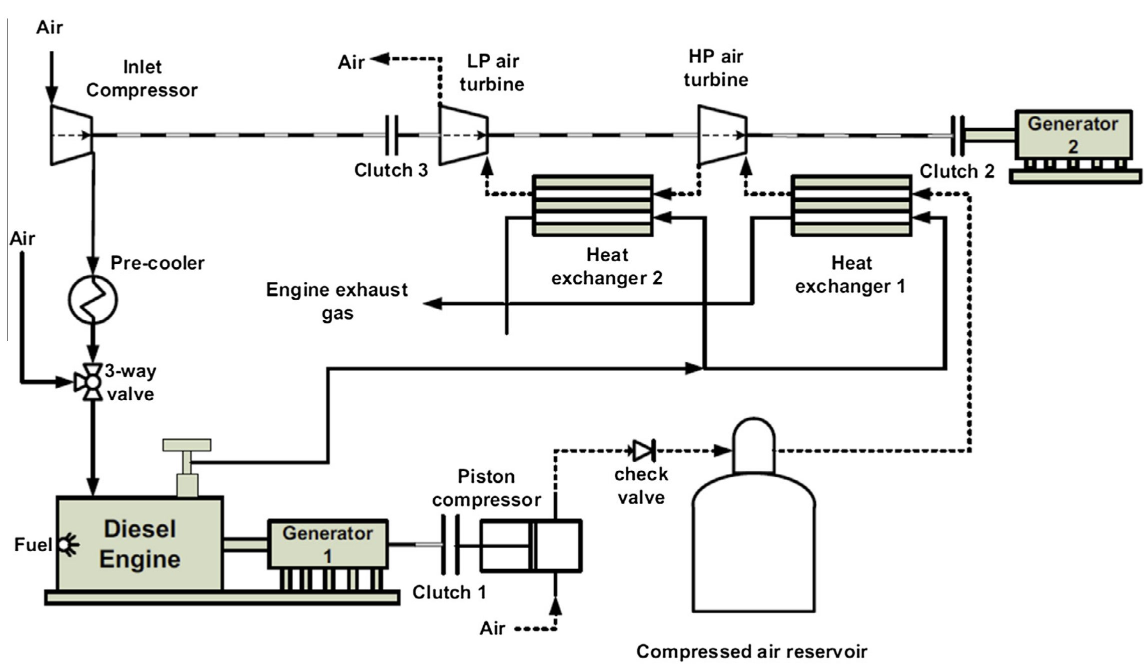

Fig. 11. Integrated TES and CAES system proposed by Li et al. [48].

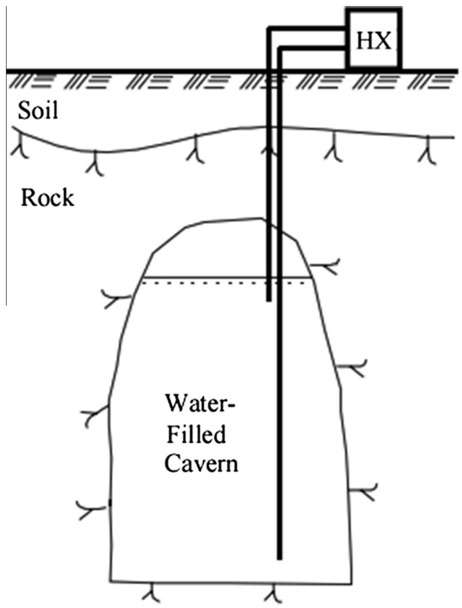

Fig. 12. Schematic draw of the water-filled rock cavern built in Avesta (Sweden) [52].

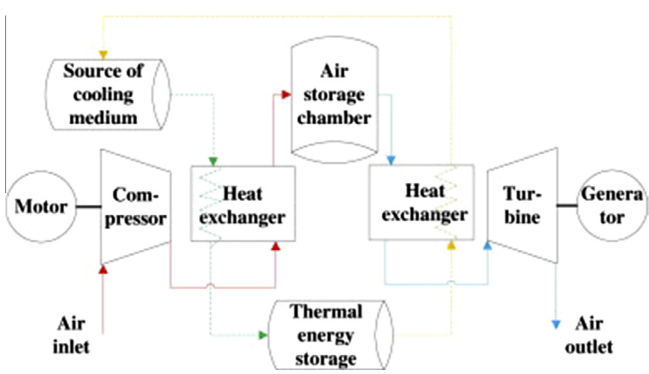

Fig. 13. Scheme of the AA-CAES system coupled with TES [54].

2.2.3. Incineration plants

Energy recovery from waste is the conversion of non-recyclable waste materials into useable heat, electricity, or fuel through a variety of processes. This process is often called waste-to-energy [50]. IWH recovery from incineration plants is considered to be the next logical step to make the most of optimising the use of waste and to reduce carbon emissions [51]. In 1981, a 15,000 m^3 rock cavern filled with water was built in Avesta (Sweden) for short-term TES of the IWH produced in a nearby incineration plant with the aim of being used for both research purposes and in the Avesta DH system (Fig. 12) [52]. In those systems, the power of injection is very high, so, in addition, they can be used to meet very high powers.

2.2.4. Other unspecific industrial activities

Other case studies have been found in the literature where an unspecific industrial waste source is recovered by means of TES. However, the authors focused in the TES system and not in the IWH source. That is the case of two CAES facilities and a desalination plant.

In a CAES plant, ambient air is compressed and stored under pressure in an underground cavern. When electricity is required, the pressurized air is heated and expanded in an expansion turbine driving a generator for power production [53]. The implementation of TES systems has been proposed to two different types of CAES systems: an advanced adiabatic CAES (AA-CAES) and a distributed CAES (D-CAES). The main difference of these systems to conventional CAES is the treatment to the heat of compression. While in conventional CAES plants the waste heat is dumped to the atmosphere in AA-CAES and D-CAES plants the waste heat is recovered and stored [53]. Zhang et al. [54] designed a system where the IWH from an AA-CAES compression process was recovered and stored in a water storage tank to be later reused in the expansion work to generate higher values of peak power (Fig. 13). Results showed that with this design, the AA-CAES system power and thermal efficiencies could be increased. Safei and Keith [55] simulated the IWH recovery from a D-CAES compression process in order to store it in a water storage tank to further be used to meet space and water heating loads in a DH network. The authors analysed the economic feasibility of the system in regards of many design parameters. However, they highlighted that the suitability of the system largely depends on the application and the market environment in which the plant is operating.

The process of desalination requires a significant amount of energy and significant capital costs. Therefore, Gude [56] analysed a variable energy source desalination plant (both solar and process waste heat) where the addition of TES could improve economics, better resource management and lower environmental emissions (Fig. 14). After a comparison and discussion of the TES materials, molten salts, concrete, PCM, steam and hot water were proposed for storing IWH and solar energy to be later reused in a thermal desalination plant. In this facility, molten salts, concrete, PCM and steam are proposed for multi stage flash, multi-effect evaporation, mechanical vapour compression and reverse osmosis desalination processes; while hot water is proposed for solar still, humidification-dehumidification, membrane distillation, and other low temperature desalination processes.

3. Off-site IWH reuse

The off-site IWH recovery consists of recovering the IWH from one or more industrial processes and transporting it to the heat demand to be later used, which is located at a certain distance from the IWH source. Depending on the distance between the IWH source and the heat demand, economical aspects and the characteristics of the heat sink, two different technologies can be used to transport the TES medium: district heating and cooling (DHC) and mobilized thermal energy storage system (M-TES). DHC is a suitable method to supply heat to dense populated areas with large heat demand because of its economic feasibility [57,58]. Even though some authors have highlighted the potential of coupling TES systems with DHC networks [59], only a study has been found in which a biomass trigeneration plant is combined with pit TES system and connected to a DHC network [60]. In this case, the authors stated a significant increase of the plant efficiency up to 65% and warn about the influence of the energy tariffs in the economic feasibility of this solution.

On the contrary, M-TES is suitable when the investment and maintenance costs of the infrastructure for DHC are high if compared to the heat demand and the distance between the IWH source and the heat sink [60]. In fact, a study estimated that the maximum transport distance for an efficient M-TES cycle was over 35 km when the transport is a truck, 200 km if it is a train and three days if it is a boat [61]. In order to ensure the technical feasibility of the M-TES system, the following considerations should be accomplished:

- High energy density: to store the highest amount of energy within the minimum volume. Hence all the auxiliary equipment should be introduced within the container.

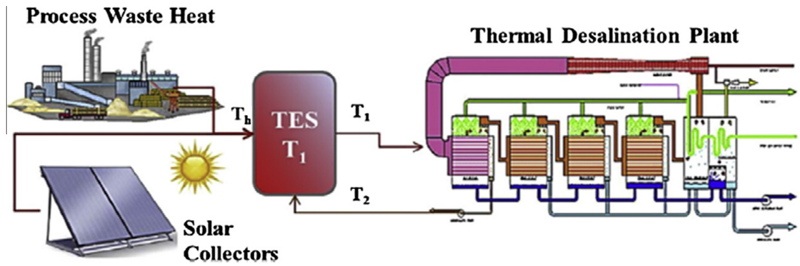

Fig. 14. Thermal desalination plant powered by both solar collectors and IWH [56].

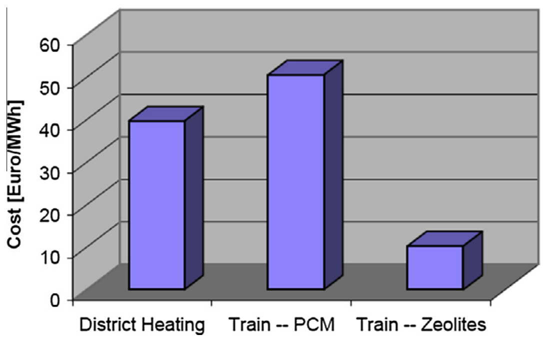

Fig. 15. Cost estimation for 30 km heat transport from steel making industry to utility plant [58].

- High charging and discharging energy rates: to be versatile with different IWH sources and heat demands.
- Ensuring the temperature stability: to avoid TES material problems within the container.
- Suitable operational strategy: number of cycles, storage mass, etc.

The reviewed literature of this section is presented taking into account its degree of development: first, economic and environmental analyses. Afterwards, numerical simulations, and finally lab-scale and real-scale prototype tests. Notice that some of them combine different scales of study, e.g. lab-scale prototypes and numerical simulations.

Guo et al. [57] performed a study analysing the potential of transporting IWH from a steelwork industry to a utility plant in Sweden. Three methods for transporting the IWH were compared: (1) a conventional DH solution requiring new underground piping, (2) transportation by train using PCM, and (3) transportation by train using the zeolite sorption technology. As shown in Fig. 15, the sorption alternative using zeolites (thermochemical materials, also known as TCM) was the most promising with regards to cost effectiveness.

Storch and Hauer [62], discussed the economic performance of a truck M-TES system considering two IWH sources (an aluminium factory and a waste incineration plant located at 10 and 7 km from the heat demand, respectively) and two TES materials (sodium acetate trihydrate as PCM and zeolite as TCM). Like in the previous case, results showed that the economic performance for the proposed sorption system was generally better than for the PCM storage, with energy costs of 15 €/MW h, which are well below than current oil and gas prices (40 €/MW h for oil and 28 €/MW h for natural gas). Li et al. [63] studied the economic cost of supplying heat with a M-TES system consisting of a 28 m^3 prototype container using erythritol as PCM to a heat demand located at a distance between 10 and 50 km from the IWH source, and compared it to other heat supply methods. Results show that the cost was in a range between 30 and 60 USD/MW h and it was observed that the cost variation was proportional to the transport distance, but inversely proportional to the heat demand. Moreover, the cost was more sensitive to the price of PCM than to other parameters, such as the cost of transportation. More recently, Deckert et al. [64] studied and proved the economic and technical feasibility of an available M-TES, highlighting that the profitability of the M-TES systems no only depends on technical parameters but also depends on the user behaviour and on the number of cycles per year. Finally, in the economic study presented by Chiu and Martin [65], the authors considered the transportation of IWH by maritime, rail and road means for a DH network. In this analysis, the possibility of partial charges of the TES system, the amount of trips per day, and the capital, operating and transportation costs were considered. The TES system consisted of a 12-m long container with erythritol. Results showed the high dependence of the economic viability to that of the transportation cost. The last analysis from an economic and environmental point of view was performed by the Sewerage Bureau of Tokyo Metropolitan Government [66], which developed a M-TES system using PCM in order to recover medium and low temperature IWH (from 70 to 350 °C) from a sludge incinerator to further control the air temperature in a civic gymnasium located at 2.5 km (Fig. 16). The system consisted of a tank filled with PCM and oil as HTF. Two PCM were used, one with the melting point at 58 °C for room heating and another one with the melting point at 118 °C for room cooling. Results showed that the use of a container can achieve a reduction between 68% and 95% in the energy consumption and a reduction between 71% and 93% in the CO_2 emissions.

From a another point of view, Kaizawa et al. [67,68] studied the exergy losses and CO_2 emissions of a 5.3 GJ truck M-TES (using erythritol as PCM) to further be reused to supply hot or cold water (Fig. 17). Some assumptions were considered: the temperature of IWH was 200 °C, the temperature of the water supplied was 50 °C or 7 °C (depending if it was for heat or cold water), and the distance between the IWH source and heat demand was 20 km. Results showed that when supplying hot water at 50 °C, the M-TES system had an energy requirement of 7.7%, exergy losses of 8.1% and CO_2 emissions of 20.2% if compared to on-site conventional systems using kerosene. When supplying cold water at 7 °C, the system had an energy requirement of 12.0%, exergy losses of 12.0% and CO_2 emissions of 26.6% when compared an on-site absorption chiller using natural gas heat source. A similar M-TES system containing 17.5 t of PCM was proposed by Nomura et al. [69] to recover the IWH from steelworks in order to deliver it to a chemical plant located at 10 km. In this study, NaOH was selected as PCM and the M-TES could supply 2.3 MW h per cycle at 250 °C. If compared to an on-site conventional system, the proposed M-TES system had only 8.6% of the energy requirements, 37.9% of the exergy losses, and 17.5% of the CO_2 emissions. Nomura et al. [70] used the same case study substituting the previous PCM for Na_2CO_3/NaOH. This system had energy requirements, exergy losses, and CO_2 emissions of 9.5%, 39.7%, and 19.6%, respectively, when compared to a conventional system using fossil fuel as energy input.

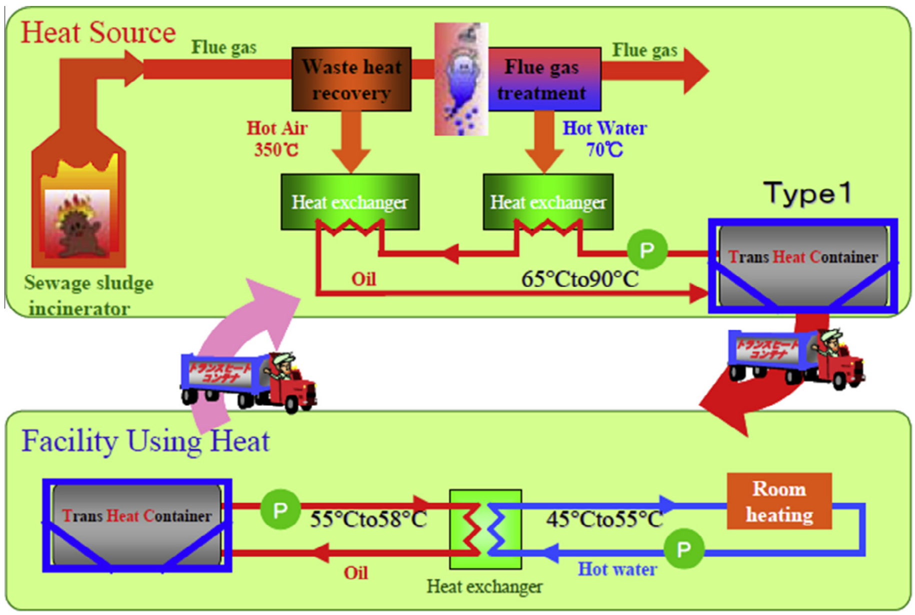

Fig. 16. Flow diagram of the M-TES recovery system proposed by Yabuki and Gabuno [66].

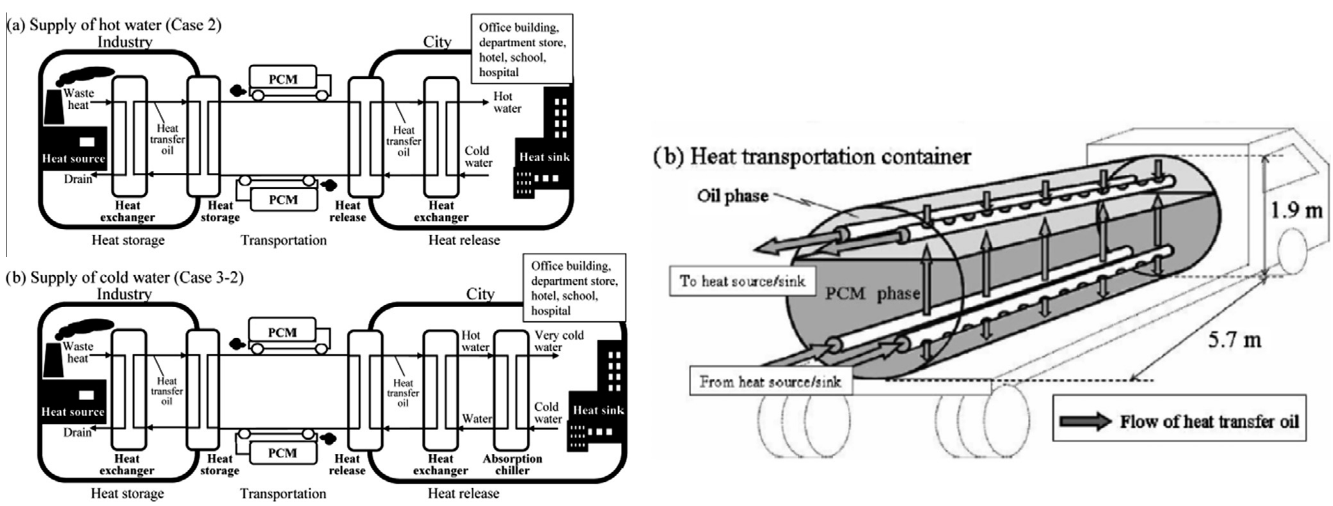

Fig. 17. Supply diagram (left) and scheme of the heat transportation container (right) proposed by Kaizawa et al. [67,68].

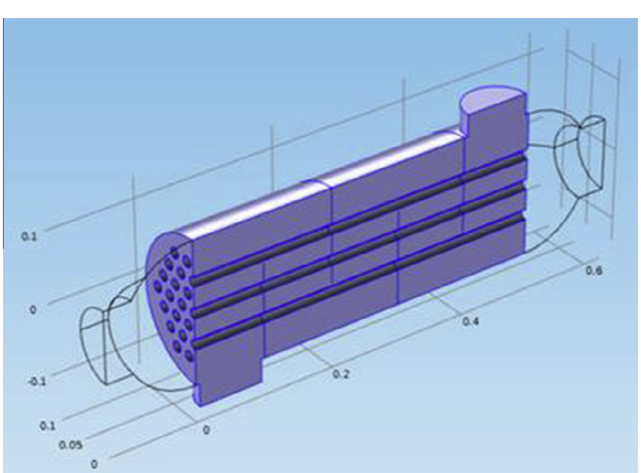

Fig. 18. 3D model used by Chiu and Martin [65].

Table 8
IWH source from a CHP plant, exit temperature and TES material proposed for an off-site IWH recovery and reuse system [72,73].

IWH source	IWH temperature (°C)	TES material proposed
Hot water from an accumulator	90	$CH_3COONa{\cdot}3H_2O$
Steam extracted from the high pressure steam turbine (HPST)	175	Erythritol
Steam extracted from the low pressure steam turbine	124	Xylitol, Mg $(NO_3)_2{\cdot}6H_2O$
Hot water extracted from the HPST	140	Erythritol

From the point of view of the design of the container, Chiu et al. [71] developed 2D and 3D numerical models of a M-TES container. They consisted of a submerged shell and tube heat exchanger and using erythritol as PCM (Fig. 18) in order to recover IWH to further be delivered to a DH network located at 48 km. In this work, the technical feasibility, storage design parameters and the storage

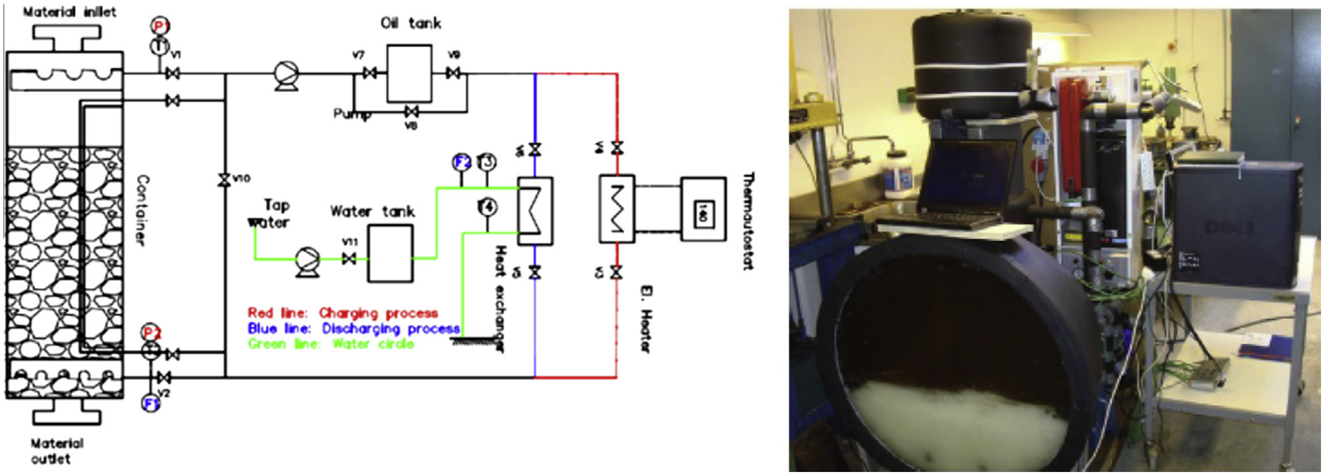

Fig. 19. Scheme (left) and picture of the experimental setup (right) proposed by Wang et al. [72].

performance were discussed, concluding that partial storage is an essential operating strategy to reach economical solutions in M-TES systems.

Wang et al. [72,73] presented a case study in Sweden in which the IWH from a combined heat and power (CHP) plant was recovered by means of the M-TES technology. This IWH was delivered to a DH network which was used to supply hot water during the summer and for space heating and tap water during the winter of a small village located 20 km far away from a CHP plant. Four potential IWH sources were identified in the CHP plant and, according to their exit temperature, a TES material was proposed for each stream (Table 8). Assuming a M-TES container energy efficiency of 85% and that two TES containers were charged and discharged every day, results showed that 224 MW h of heat could be delivered each month. This heat could cover the 42% of the total heat demand. Moreover, a, payback period of 6 years is calculated for the whole system.

Focusing on the studies at pilot plant scale, Wang [72] designed and tested a M-TES system (Fig. 19), in which an electrical heater simulated the IWH source during the charging process and a water cycle to simulate the heat demand. The prototype consisted of a 9.15 kW h direct contact system which used 74 kg of PCM (erythritol) and Thermia oil C as HTF. The behaviour of the M-TES prototype at different HTF flow rates (from 5 to 21 l/min) and at different time lengths (from 15 to 210 min) was analysed. Later on, three other studies experimentally analysed different improvements on this configuration. First, Guo et al. [57] investigated the mechanism of melting process to improve the charging performance. Results showed the influence of increasing the HTF flow rate in shortening the charging process time, with reduction of time up to 29%. On another study, Wang et al. [73] compared the direct and indirect contact container configurations. The charging times are 240 min and 600 min for the direct-contact container system and indirect-contact container system respectively. Finally, Guo et al. [74] analysed the effect of adding quick channels with electric heaters. This mechanism solves the blocking of the direct contact configuration by the deposited PCM at the initial stage of the charging process. The authors estimated that this system would use less than 5% of the energy stored in the container and recommended this method for systems with a low rate of heat release.

Kaizawa et al. [67] also studied at pilot plant scale the behaviour of a PCM and an HTF inside a 14 kW h M-TES prototype based on a two-dimensional, roundly sliced model (Fig. 20). The experimental setup contained 80 kg of erythritol as PCM and 23 kg of HTF. The authors recommended maximizing the heat storage density and the heat exchange rate. Moreover, the shape of the inlet pipes should be designed considering their position, the number of pipes and the nozzle angle using a sophisticated heat and fluid flow model.

At higher scales, only two complete studies could be found at the literature. In the first study, the Fraunhofer Institute [64,75]

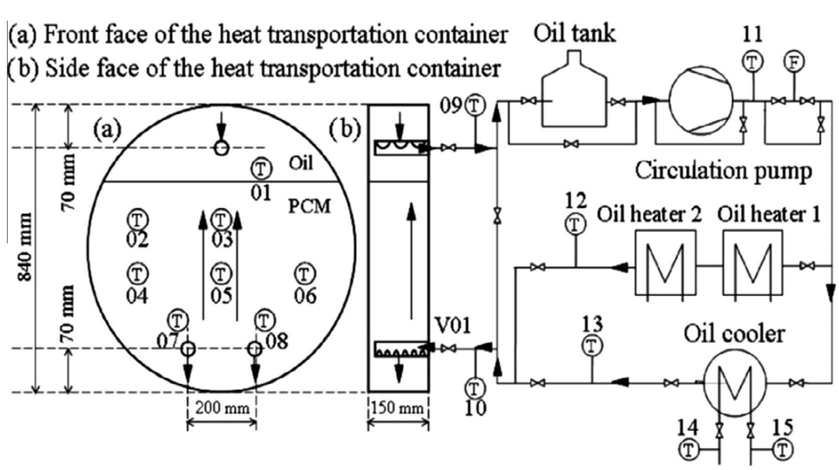

Fig. 20. Front and side face of the heat transportation container prototype used by Kaizawa et al. [67].

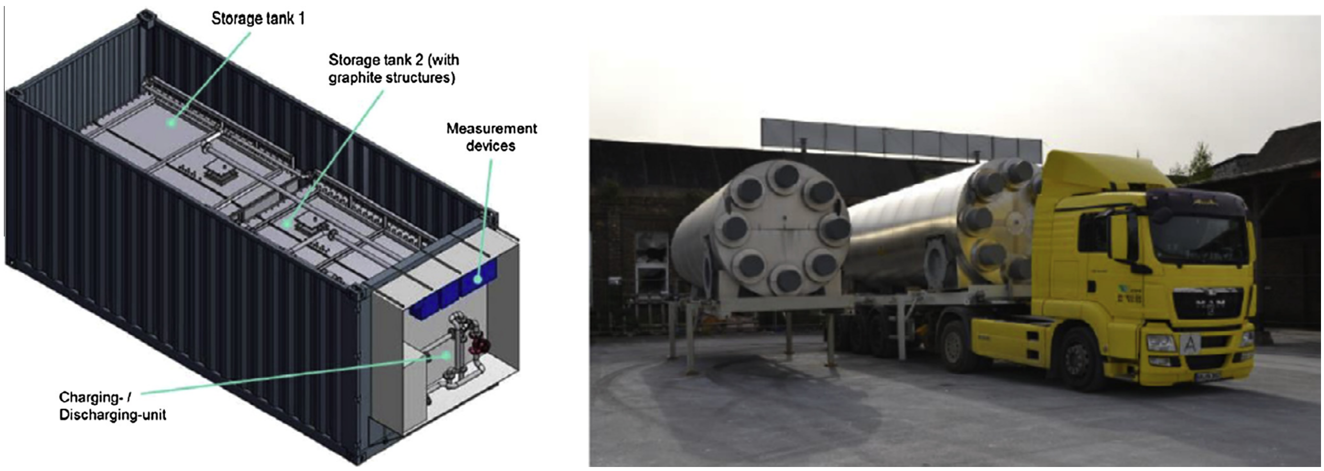

Fig. 21. 3D structure of the M-TES prototype proposed by Deckert et al. [64] (left), and M-TES prototype tested by ZAE Research Centre [76] (right).

Table 9
Summary of the M-TES systems for off-site IWH reuse.

Country	Scale of the study[a]	IWH source		TES system			Heat demand		Savings	Ref.
		Source	Exhaust temperature (°C)	TES material	TES material amount	Storage capacity (MW h)	Heat sink	Distance (km)		
n.a.	N	Steelworks	n.a.	(1) PCM (2) Zeolite	n.a.	n.a.	Utility plant	30	n.a.	[58]
Germany	N	Aluminium factory/ incineration	n.a.	(1) Sodium acetate trihydrate (2) Zeolite	15 t	(1) 2.4 (2) 3.4	Industrial drying, air conditioning and swimming pools	(1) 10 (2) 7	Energy costs drop to 15 €/ MW h	[62]
Sweden	N	n.a.	n.a.	Erythritol	n.a.	n.a.	n.a.	10–50	n.a.	[63]
Sweden	N	n.a.	n.a.	Erythritol	n.a.	n.a.	DH network	48	n.a.	[65]
Japan	N	Sludge incinerator	70–350	(1) PCM (melting at 58 °C) (2) PCM (melting at 118 °C)	n.a.	2	Civic gymnasium	2.5	Energy consumption: 68–95% CO_2 emissions: 71–93%	[66]
Japan	N	n.a.	200	Erythritol	17.5 t	1.5	Hot and cold water	20	Energy consumption: 88–92.3% CO_2 emissions: 73.4–79.8%	[67,68]
Sweden	N	Steelworks	250	Sodium hydroxide	17.5 t	2.3	Chemical plant	10	Energy consumption: 91.4% CO_2 emissions: 82.5%	[71]
Japan	N	Steelworks	250	Sodium carbonate/sodium hydroxide	17.5 t	1.9	Chemical plant	10	Energy consumption: 90.5% CO_2 emissions: 81.4%	[69]
Sweden	N	CHP plant	n.a.	Erythritol	n.a.	224	DH network	20	n.a.	[72,73,81]
Sweden	N, P	n.a.	n.a.	Erythritol	74 kg	$9.15 \cdot 10^{-3}$	n.a.	n.a.	n.a.	[57,72–74]
Japan	P	n.a.	n.a.	Erythritol	80 kg	$14 \cdot 10^{-3}$	n.a.	n.a.	n.a.	[67]
Germany	R	n.a.	n.a.	Sodium acetate trihydrate	16.6 t	2	n.a.	6	n.a.	[64,75]
Germany	R	Incineration plant	n.a.	TCM:Zeolite	14 t	2.3	Industrial drying process	7	616 kg CO_2/cycle	[76,77]

n.a. non available.
[a] N: numerical scale, P: pilot plant scale, R: real scale.

designed and tested a M-TES prototype consisting of two real scale 6-m-long container with a storage capacity of 2 MW h in order to recover the IWH from a biogas plant to further reuse it in a small DH network at 6 km distance (Fig. 21 left). The prototype contained 16.6 t of sodium acetate trihydrate, acting as PCM, and was equipped with 24 internal tubes extended with graphite structures operating as tube heat exchangers. This heat transfer enhancement let the system to a reduction in charging and discharging times up to 37%. In the second study, the ZAE Research Centre also studied and developed a 2.3 MW h M-TES system based on an open sorption system, with a 14 t packed bed zeolite working as adsorbent. It was used in order to recover the IWH from an incineration

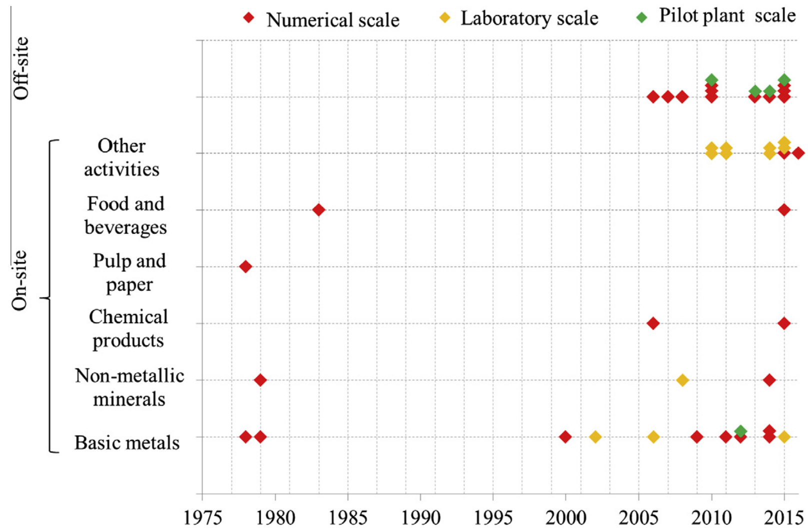

Fig. 22. Maturity and trends of the TES systems reviewed.

plant located 7 km far away from the heat demand (Fig. 21, right) [76,77]. The M-TES prototype was built, operated and monitored over one year using at the heat sink discharging system exhaust air from the dryer with 60 °C and 0.09 kg/kg humidity. However, the power released was not the desired because of misdistribution through the packed bed of zeolite. This system was able to save 616 kg of CO_2 per cycle and the TES material showed no degradation during the different tests. Other M-TES prototypes have been developed, in Germany [78], China [79], Austria [80], and Japan [58,72] but very few information could be obtained.

Table 9 summarizes the M-TES studies reported in this literature review and specifies, when available, the scale of the study, the characteristics related to the IWH source (source, temperature and location), to the TES system proposed (TES material, amount of TES material and storage capacity), to the heat demand (activity and distance from the IWH source) and to the economic and environmental savings when compared with conventional heating system.

The heat sources in which M-TES were proposed to be applied are incineration plants, CHP and basic metal production. All cases were developed in Germany, Sweden and Japan. PCM and TCM were the two types of TES material proposed and erythritol (PCM) is proposed in almost half of the studies. Even though most of the cases correspond to numerical studies, two of them were developed at pilot plant scale and another two at real scale, using a truck as the transport method. Due to the possibility of geographically transporting waste heat, potential subsequent uses of this heat can be in applications like industrial processes, DH networks or climate control. Moreover, reported distances between heat source and heat sink range from 2 to 50 km. The obstacles which were found by the researchers when developing this technology are the limitations of working with big amounts of TES materials (for example, heat transfer problems) and that its economic suitability depends of factors like the price of fuels, which are not easy to predict.

4. Discussion

The lack of studies found in the literature may be due to different factors. First, to the maturity level of TES systems. Second, to the industry production processes and the financial barriers (see the Introduction section). Finally, to the commercial confidentiality in these sectors. Regarding to the technology maturity, and according to the IEA Energy Storage Roadmap [82], only residential hot water heaters with storage, UTES, cold water storage and PTES (pit thermal energy storage) are the thermal storage technologies in commercialisation maturity level. The rest are still in early or middle stage of development and will require further attention before their potential can be fully realised.

Therefore, both trend and maturity can be seen in Fig. 22 in which the case studies found in the literature are plotted depending on the year in which they are published, the industrial activity they belong and the maturity (which is related to the scale of the study). In general, a clear lack of pilot plant and real scale studies can be seen and all of them are very recent, which indicates a trend and a possible research niche. Moreover, first cases published regarding this topic were done in the 80s and focused in the manufacturing industry. However, until almost 20 years later the topic has not been studied again, which coincides with the period when the environmental awareness has gained more relevance because of the environmental policies worldwide. Finally, the interest in transporting IWH by means of M-TES has increased in the last decade as a result of the widespread use and commercialisation of TES materials and systems.

The weakness of this review lies on the fact that in some cases not all the information regarding the characteristics of the heat source, the TES system and the heat demand is published. That makes a deeper discussion and comparison not possible, which is especially stressed regarding the economic and environmental savings in which not enough information was available to normalise and quantify the absolute savings. Moreover, it is known that in many countries industry is a very secretive economic sector [83] which also can affect the widespread use of recovered IWH.

5. Conclusions

Industry is one of the most consuming sectors worldwide. The IWH recovering and reuse could decrease both the CO_2 emissions and the energy costs, which would lead to more efficient and more competitive industrial activities. However, the IWH is nowadays barely used mainly due to technological and financial barriers for applying conventional heat recovery methods and to the fact that this heat is, in some cases, intermittently generated and not coincident (neither geographically nor temporally) with the heat demand.

Among the different technologies available to take advantage of IWH, TES is a powerful thermal management tool that allows the geographically and temporarily match of the energy supply and the energy demand, which is especially interesting considering the discontinuous supply nature of the IWH and the distance between the IWH source and the heat demand. Thus, TES systems can be used for on-site IWH recovering and reuse, if both the IWH source and the heat demand are located at the same place, or off-site, if the IWH source and the heat demand are separated within a kilometres distance range. If the demand is on-site, TES systems are used to store the IWH which is later used in other internal processes, such as preheating incoming water or combustion air, preheating furnace loads, etc. If the demand is off-site, M-TES system are proposed to transport the IWH from the source to the heat demand.

The main objective of this paper is to review and compare the case studies where TES technologies are implemented to recover and reuse IWH. Among the studies, it has been identified the industrial and energetic sectors, where the implementation of TES technologies is most rooted and the most used TES materials and systems. Finally, it is discussed their economic and environmental savings as well as their maturity and trends. Therefore, scientific and conference articles as well as divulgation sources have been here considered and no geographical or temporal limit is considered.

In the literature revision more than 50 cases were identified. More case studies regarding on-site than off-site reuse and recovery of the IWH were found. On-site recovery and reuse of IWH was identified in the following activities: energy-intensive manufacturing industry (basic metals, non-metallic minerals, chemicals, paper, and food), vehicle engines, power plants, incineration plants and other unspecified IWH sources to be reused in desalination plants and CAES facilities. Among the energy-intensive manufacturing subsectors, the basic metals subsector is, by far, the one which has drawn most attention and the only one with pilot plant scale studies. That may be due to the high exhaust temperatures of these industrial activities. In general, water (or steam) storage tanks have been the most used on-site TES systems while power generation and space heating and cooling have been the most recurrent applications for the on-site reuse of IWH. The first studies regarding the use of TES in these sectors were published in the late 70s however until 2006, when the environmental awareness in the society increased, the topic has not been of interest again. In addition, a clear lack of pilot plant and real scale studies was observed.

Up to now, the off-site recovery and reuse of IWH by means of M-TES has been addressed in the last decade mostly in numerical studies and almost no public information has been found of the existing real prototypes. From the literature review, the most recurrent TES materials have been erythritol (PCM) and zeolite (TCM). The reported distances between source and sink are from 2 to 50 km and mainly to transport heat to other industries or to DH networks.

The savings obtained as a result of the implementation of TES systems have been mainly reported from the point of view of economics and environmental parameters, such as CO2 mitigation and reduction of the fuel consumption. However, the lack of a detailed description of the TES systems proposed made impossible to normalise and quantify the absolute savings of the different activities.

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