Applied Energy 151 (2015) 157–167

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

Industrial waste heat recovery technologies: An economic analysis of heat transformation technologies

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HIGHLIGHTS

- Potential of industrial waste heat for heating and cooling applications is studied.
- An economic analysis with maximum feasible investment cost as output.
- Different consumer types are defined: "Enthusiast", "Real estate" and "Industry".
- Absorption chillers are profitable when applied for at least 2500 h per year.
- Electric heat pumps are profitable for more than 4000 h/a, absorption heat pumps with 3000 h/a.

ARTICLE INFO

Article history:
Received 30 April 2014
Received in revised form 23 November 2014
Accepted 16 January 2015
Available online 15 May 2015

Keywords:
Industrial waste heat
Economic analysis
Heat transformation technologies

ABSTRACT

In this paper, the potential of industrial waste heat for heating and cooling applications is investigated. Therefore, heat transformation technologies are presented and their technical and economic potential are discussed. First, different industrial processes and their operating temperatures are presented as possible waste heat sources as well as low temperature processes, which can be supplied with waste heat. Then, a general economic analysis is performed for three different cases of waste heat use: an absorption chiller producing cold and heat production with a compression and an absorption heat pump. The maximum acceptable investment cost for each technology is estimated and compared with the current investment cost depending on the operating hours of the system. For this, three different consumer types, Enthusiast, Real Estate and Industry, are defined to represent different expectations in interest rate, payback period and the resulting annuity factor. Instead of judging if a technology is profitable or not, it is calculated how much the system is allowed to cost in order to be competitive for certain operating hours. Combined with present day cost of the technology, this serves as a rough judgment of the market deployment process. Finally, a sensitivity analysis of the initial assumptions for the economic analysis is performed, revealing a strong influence of the annuity factor. For the present day technology cost, absorption chillers were found to be profitable for two of the three consumer types when operated for at least 2500 h per year. Electric heat pumps are profitable for all consumer types when exceeding 4000 operating hours per year while absorption heat pumps start at 3000 h of operation per year to be profitable for all consumer types.

1. Introduction

In this article, the potential of industrial waste heat recovery for heating and cooling applications is investigated. For that, an economic analysis using the maximum acceptable investment cost is used. This method differs from commonly economic feasibility ones which use payback period or interest rate, both variable figures. This method analyses three different consumer types (in order to represent different expectations in interest rate and payback period, relatively constant figures) and it shows the economic feasibility of the technology according the consumer type and the technology operating hours, creating a more general approach. The method was developed and first presented by the IEA task 42/24 for storages [1].

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http://dx.doi.org/10.1016/j.apenergy.2015.01.147
0306-2619/

Before that, some definitions concerning waste heat recovery and the available technologies to be used are presented.

1.1. Definition of waste heat

You cannot make an omelet without breaking eggs, and you cannot perform work without waste heat: wherever goods are produced and machines are operated, waste heat is produced and released either via radiation, cooling fluid, exhaust gas or air. But even though these heat streams are considered waste, they often contain large amounts of exergy and would be able to perform work through one of the many waste heat usage technologies. In this paper, waste heat is considered as all forms of heat (latent as well as sensible) that are not the purpose of the system. Therefore, for example, heat from combined heat and power plants is not considered as waste heat. Sources for waste heat in industries can be furnaces, waste water from washing, drying or cooling processes, but also refrigeration systems, motors or the exhaust air from production halls [2]. Nonetheless, in the present paper, only waste heat that is released in a heat carrier medium like exhaust gas, cooling fluids or steam is considered.

1.2. Definition of waste heat potential

When considering different technologies to use the industrial waste heat potential it is necessary to first distinguish, which potential type is considered [3]: the theoretical or physical potential [4], the technical potential or the economic feasible potential [5] (Fig. 1). The theoretical potential only considers physical constraints: the heat has to be above ambient temperature, bound in a medium, etc. Thus, heat that is released diffusive, for example by radiation, is usually not assessed. In addition, whether or not it is possible to extract that heat from the carrier fluid or whether there is any way of using it, is not considered. These constraints define the technical potential. The technical potential also depends on the technologies considered. Technical constraints are for example the required minimum temperature. Whether or not it is profitable to use the technology is only considered in the economic potential or sometimes called feasible potential.

As mentioned above, the theoretical potential only considers physical boundary conditions like an above ambient temperature level of the exhaust gas or air. To analyze the potential of a waste heat application technology the waste heat potential of larger regions is of interest. In [3] different methods to estimate the waste heat potential are presented. In [7] waste heat estimations for different regions are evaluated. For the theoretical potential the results range from 50.4 PJ/y for the Basque Country (Spain) [8] and 51 PJ/y for North Rhine Westphalia (Germany) [9], and 1933.2 PJ/y for the United States of America [10].

The technical potential to use waste heat is defined by two major constrains: in addition to the boundary conditions of the technology itself, a heating or cooling demand is necessary. Therefore, before explaining the technological constraints of the heat transformation technologies, the theoretic size of industrial heating and cooling demands are described as possible cases to use industrial waste heat (Section 1.5).

1.3. Overview of waste heat recovery technologies

Technologies to use waste heat from industry can be categorized as passive or active technologies. This depends on whether the heat is being used directly at the same or at lower temperature level or whether it is transformed to another form of energy or to a higher temperature (Fig. 2). Heat exchangers and thermal energy storages are the two dominant passive technologies. These technologies can be used for recycling or reusing waste heat within an industry to heat or preheat other processes. Sorption systems, mechanically driven heat pumps and organic Rankine cycles (ORC) are active technologies.

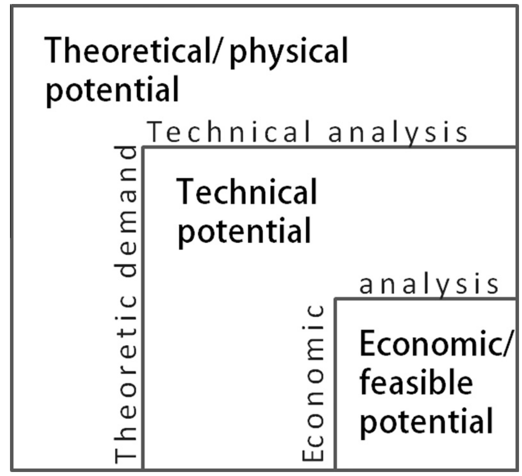

Fig. 1. Types of potential, graph based on [3,4,6].

Active applications of waste heat are categorized into three types: to provide heat (WHTH), cold (WHTC) or electricity (WHTP). Among the active technologies, WHTH and WHTC are considered heat transformation technologies as they modify the inlet temperature upgrading or downgrading it (marked with an asterisk in Fig. 2). For these technologies an economic analysis is presented later on.

1.4. Industrial waste heat sources

Industries consume a large portion of the total energy demand: in Europe, for example, the energy consumption from industries constituted about 62% of the total energy consumption in 2011 [6]. The largest amounts of waste heat in industries are usually found in food and tobacco and pulp and paper, basic metals, chemical industry, and non-metallic minerals.

To take advantage of this industrial waste heat potential there are different technologies available. Some processes with lower temperature may not be a useful source of industrial waste heat directly, but the heat can be upgraded. Temperature is one of the most important criteria when considering if the process would either produce valuable waste heat or could use waste heat as an energy source. Typically, high temperature waste heat has more potential to be reused. Fig. 3 shows the distribution of high (HT > 400 °C), medium (MT 100–400 °C) and low temperature (LT < 100 °C) applications in different sectors in Germany for 2005 [11]. High temperature waste heat holds a large share of the processes in the metal production and mineral processing sectors. On the other hand, the food and tobacco industry has only negligible amounts of high temperature heat demand.

A more detailed picture of possible waste heat sources is given in Table 1. Here exhaust gas temperatures of different processes from 30 to over 1600 °C are given. Those are not to be mistaken for process temperatures, which will be even higher.

1.5. Theoretic demand

1.5.1. Process heat demand

Europe industry heat consumption accounted for 4433 PJ in 2009 [15]. Among this heat, process heat can be a source of waste heat as well as a possible consumer, when waste heat from other processes is used to replace other fuels. Blesl et al. [6] suggest distinguishing supply and demand processes by a dividing

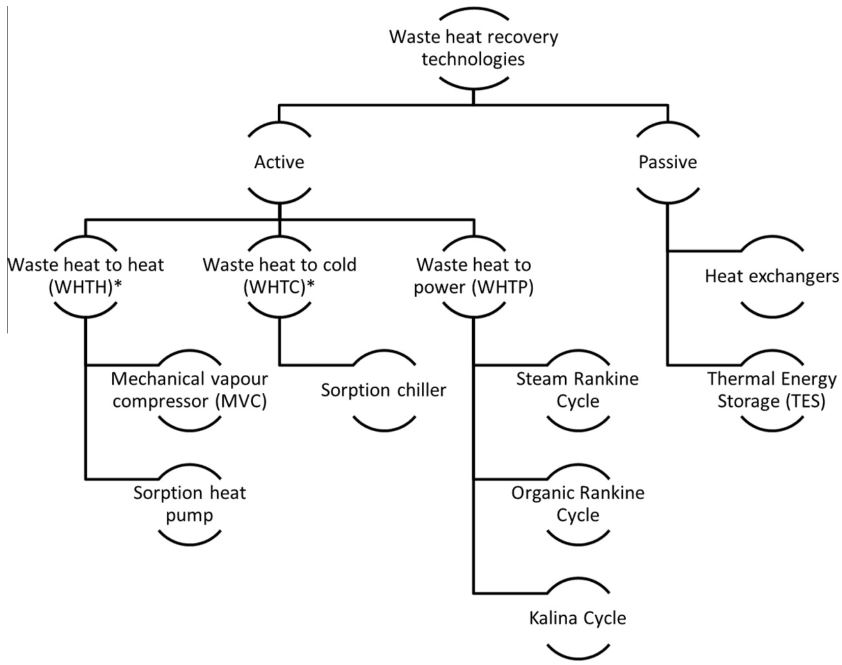

Fig. 2. Categorization of waste heat recovery technologies.

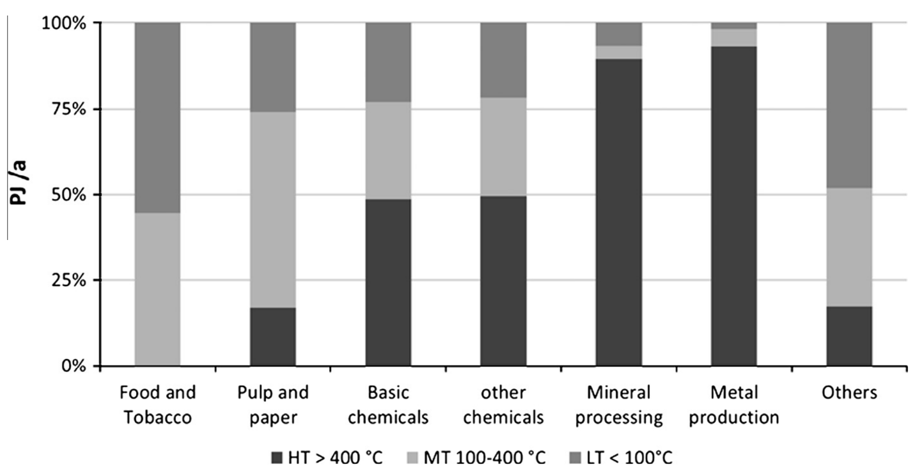

Fig. 3. Process heat demand by temperature (high (HT), medium (MT) and low (LT)) of different sectors, figure based on data from [11].

temperature of 200 °C. Processes with an input temperature above 200 °C are to be considered as possible waste heat sources since their exhaust gas temperature is likely to be at a usable level. Processes with input temperatures below 200 °C, according to their assumption, will only produce waste heat at ambient temperature or little above. In Table 1, industrial processes and their exhaust gas temperature are shown as possible sources. In Table 2 on the other hand, low temperature processes of the different sectors and their process temperature are given. Those processes could be supplied with waste heat from other processes and therefore function as a heat sink. Note that the presented temperatures are input temperatures.

1.5.2. Cooling demand

According to Oro et al. [19] the cooling demand in Europe is ~2207 PJ/y, and 78% is generated by industrial cooling applications (~1721 PJ/a). The Deutscher Kälte- und Klimatechnischer Verein (DKV) (German Society of Refrigeration and Air Conditioning) [20] evaluated the cooling demand in Germany for 1999: ~277 PJ/y. The majority of the cold, 86%, was generated by electric power. Related to the total final energy consumption of Germany, cooling applications consumed 14%, which corresponds to 5.8% of the primary energy demand. From the industrial cooling demand, the highest demand is in the food and beverage sector [20]. According to DKV the development cores in the upcoming years should be in the food and beverages, vehicle climatization, domestic cooling and chemical sector.

1.6. Technical analysis: heat transformation technologies

In order to evaluate the technical potential, the technical constraints of using the waste heat for the considered technology have to be considered. As mentioned above this paper focuses on heat transformation technologies. The latter are presented in the following with their possibilities, working principles and constraints.

Heat transformation technologies can be divided into two main types, mechanically and (closed cycle) thermally driven heat pumps, here particularly absorption heat pumps. Both have the same basic working principle, which is to transfer heat from a low temperature heat source to a high temperature heat sink.

Table 1
Exhaust gas temperatures of different processes [12–14].

Process	Exhaust gas temperature (°C)
Iron- and steelmaking	1450–1550 [12]
Nickel refining furnace	1370–1650 [12]
Steel electric arc furnace	1370–1650 [12]
Glass melting furnace	1300–1540 [12]
Basic oxygen furnace	1200 [12]
Aluminum reverberatory furnace	1100–1200 [12]
Steel heating furnace	930–1040 [12]
Copper reverberatory furnace	900–1090 [12]
Glass oven without regenerator	900–1300 [13]
Iron cupola	820–980 [12]
Cooper refining furnace	760–820 [12]
Reheating furnace without regenerator	700–1200 [13]
Hydrogen plants	650–980 [12]
Fume incinerators	650–1430 [12]
Coke oven	650–1000 [12]
Glass oven with regenerator	600–800 [13]
Cement kiln	450–620 [12]
Heat treating furnace	430–650 [12]
Melting oven	400–700 [13]
Gas turbine exhaust	370–540 [12]
Reciprocating engine exhaust	320–590 [12]
Reheating furnace with regenerator	300–600 [13]
Blast furnace stoves	250–300 [14]
Drying and baking ovens	230–590 [12]
Steam boiler exhaust	230–480 [12]
Finishing soaking pit reheat furnace	200–600 [14]
	300–400 [14]
Steam boiler	200–300 [13]
Coke oven	190 [14]
Stack gas	
Container glass melting	160–200 [14]
	140–160 [14]
Flat glass melting	160–200 [14]
	140–160 [14]
Ceramic kiln	150–1000 [13]
Drying, baking, and curing ovens	90–230 [12]
Cooling water from annealing furnaces	70–230 [12]
Cooling water from internal combustion engines	70–120 [12]
Exhaust gases exiting recovery devices in gas-fired boilers, ethylene furnaces, etc.	70–230 [12]
Conventional hot water boiler	60–230 [13]
Process steam condensate	50–90 [12]
Condensing hot water boiler	40–50 [13]
Hot processed liquids/solids	30–230 [12]
Cooling water from air conditioning and refrigeration condensers	30–40 [12]
Cooling water from air compressors	30–50 [12]
Cooling water from furnace doors	30–50 [12]

Table 2
Process temperatures of low temperature processes [13,16,17,18].

Industry	Process	Working temperature (°C)
Food and beverages	Cleaning	60 [16]
	Cooking	110–115 [16]
	Pasteurizing	65 [16]
		80–110 [13,18]
	Whitening	85 [16]
	Drying	30–90 [18]
		30–120 [13]
		50–90 [17]
	Washing	40–85 [18]
		40–80 [13]
	Sterilizing	140–150 [18]
		80–90 [17]
	Boiling	95–105 [13,18]
	Heat treatment	40–60 [13,18]
	Drainage	38–104 [13]
Textile	Dry heating	88 [16]
	Ironing	100 [16]
	Washing	40–80 [13,18]
	Bleaching	60–100 [13,18]
	Dyeing	100–160 [18]
	Drying	75–250 [13]
	Steaming	100–130 [17]
Chemical	Boiling	95–105 [18]
	Distilling	110–300 [18]
		90–130 [17]
	Various chemical processes	120–180 [18]
Paper industry	Pulp drying	95–120 [13]
	Paper drying	95–120 [13]
		50–120 [17]
Non-metallic mineral processes	Drying of rocks, bricks, sand and other minerals	35–150 [13]
Wood	Drying	70–90 [17]
Other	Metal cleaning	60–90 [16]
	Painting drying	80–120 [16]

Depending on whether the "supplied cold" at the heat source or the heat provided at the heat sink are considered as useful, the machine is referred to as a refrigerator/chiller or a heat pump, respectively.

Heat transfer between different temperature levels is based on the variable boiling point of a certain refrigerant. Mechanically driven heat transformers utilize the dependency of boiling point on pressure; thermally driven heat transformers additionally make use of the boiling point elevation of the refrigerant caused by a solute.

The main components of both cycles include an evaporator and a condenser. The difference between mechanically and thermally driven machines is how the gaseous refrigerant is moved from the evaporator to the condenser.

1.6.1. Mechanical driven heat pump

Fig. 4 shows the simplified working principle of a common mechanically driven heat pump (MDHP); depicted is the pressure (p) versus the saturation temperature (T); Q_0 is the low temperature (T_0) heat that is lifted to a higher temperature level (T_1) in the heat pump and (additionally to the driving energy W_{el}) released as Q_1.

In addition to evaporator and condenser, a MDHP consists of a mechanical compressor and an expansion valve. The refrigerant evaporates at a low temperature and pressure, taking up the heat from the low temperature heat source at the evaporator. The vapor is polytrophic compressed by means of mechanic energy to a higher pressure and therefore higher temperature. The compressor is typically powered by electric energy. When the gaseous working fluid condenses it releases heat to the heat sink at the condenser at the higher temperature level.

The external temperature levels determine which working fluids are appropriate for a certain application and which kind of compressor should be used. Here critical temperatures and vapor pressure curves of the refrigerant as well as pressure ratios of the compressors have to be considered besides other thermo-physical properties.

The maximum delivery temperature would be between 120 and 140 °C due to material constraints caused by temperature and pressure. Common systems typically operate up to a maximum of 80 °C. Due to the limited pressure ratio the lowest temperature at the low temperate heat source can be about −35 °C for single-stage machines operating with CO_2 as refrigerant, but this is strongly depending on condenser temperature. If the rejected heat at the condenser can be released below 0 °C, heat at temperatures of about −50 °C and below could be used at the evaporator.

The temperature lift (T_1–T_0) is limited by the compression ratio (the ratio of the pressure before and after compression) of the compressor and the temperature–pressure dependency of the chosen

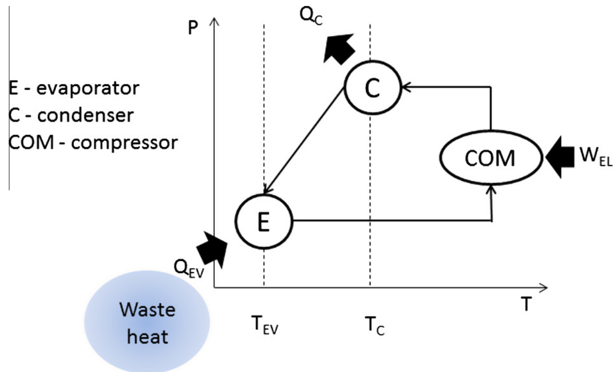

Fig. 4. Simplified scheme of a mechanically driven heat pump (MDHP).

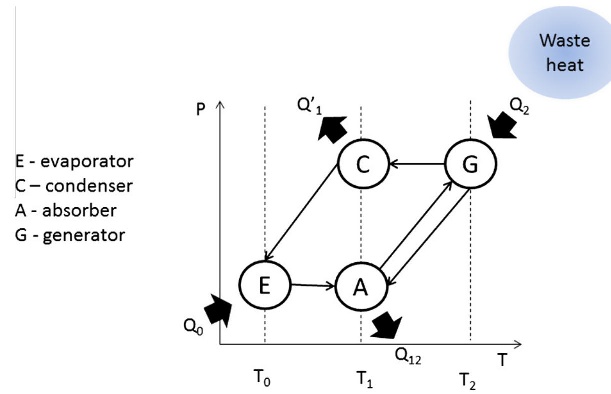

Fig. 5. Simplified scheme of a thermally driven heat pump (TDHP).

working fluid [21]. Experimental set-ups demonstrate that the maximum possible lift is about 90 K; typically these machines are operating with a lift below 60 K.

The theoretical efficiency for a refrigerator can be calculated using the Energy Efficiency Ratio (EER_{th}) in Eq. (1) and for a heat pump using the Coefficient of Performance (COP_{th}) in Eq. (2):

$$EER_{th} = \frac{T_0}{T_1 - T_0} \quad T\ in\ K \tag{1}$$

$$COP_{th} = \frac{T_1}{T_1 - T_0} = EER_{th} + 1 \quad T\ in\ K \tag{2}$$

Due to losses, especially within the compressor, properly designed plants can reach up to 0.7 times the theoretical efficiency; this number is usually called efficiency factor. Common plants show an efficiency factor of about 0.6 during nominal operation. The real efficiency usually is referred to as electrical efficiency COP_{el} (Eq. (3)) or EER_{el} (Eq. (4)), respectively, and is defined as:

$$COP_{el} = \frac{\dot{Q}_1}{W_{el}} \tag{3}$$

$$EER_{el} = \frac{\dot{Q}_0}{W_{el}} \tag{4}$$

Common mechanically driven heat pump systems show an overall COP_{el} up to 4 during nominal operation, while mechanically driven refrigerators will reach an overall EER_{el} of about 3.

With increasing temperature lift EER and COP decrease strongly. Therefore the capacity of a given MDHP decreases with increasing temperature lift, too. This is mainly caused by losses increasing with the pressure ratio at the compressor.

1.6.2. Absorption heat pump

Absorption heat pumps (AHP) are driven by high temperature heat instead of mechanical energy. Fig. 5 shows the simplified working principle of a common single stage absorption heat pump in a diagram analog to Fig. 4.

Evaporator and condenser operation is analogous to a MDHP, however the compression of the gaseous refrigerant is done by a solution cycle where the working fluid is absorbed into the solvent at evaporator pressure (releasing the absorption heat Q_{12}, usually on a similar temperature level as the condenser) and desorbed at condenser pressure (receiving desorption heat Q_2 at high temperature). The rejected heat for an absorption heat pump is therefore the sum of heat transferred at absorber and condenser (neglecting losses, this is equal to the sum of transferred heat at evaporator and generator, respectively). In addition to the temperature lift for thermally driven heat pumps, (T_2–T_1), is designated as temperature drive.

Due to the similar thermo-physical behavior of different solute/sorbent systems [22], it is possible to estimate the internal temperature of either evaporator (T_0), generator (T_2) or absorber and condenser (T_1) as long as the other two temperatures are known. The empirical equation Eq. (5) gives an estimation of the relationship among the internal temperature levels:

$$1.15 \times (T_1 - T_0) \cong (T_2 - T_1) \tag{5}$$

Using these internal temperatures a theoretical thermodynamic efficiency, EER_{th} (Eq. (6)) and COP_{th} (Eq. (7)), can be derived from the second law of thermodynamics analog to those for mechanically driven heat pump systems:

$$EER_{th} = \frac{T_0}{(T_1 - T_0)} * \frac{(T_2 - T_1)}{T_2} \quad T\ in\ K \tag{6}$$

$$COP_{th} = \frac{T_1}{T_1 - T_0} * \frac{(T_2 - T_0)}{T_2} = EER_{th} + 1 \quad T\ in\ K \tag{7}$$

Defining the real thermal efficiency as quotient of useful cold and driving heat, common absorption chillers can reach about 0.7 for nominal operation. For heat pumps the quotient of useful and driving heat will reach 1.7 for properly designed plants. Discussing the electrical efficiency (especially to compare TDHP with MDHP), it can be said that optimized systems can reach an overall EER_{el} for refrigeration (defined analogous to MDHP) of up to 20 or, depending on the application, even higher. Nowadays well designed absorption chiller systems show an EER_{el} of about 12. As the rejected heat of an absorption system is about 2.5 higher than the low temperature heat input, and such systems do not need coolers to release the rejected heat to the environment, the overall COP_{el} for properly designed absorption heat pump systems is about 40 and can reach values higher than 60.

If temperature levels of a certain application are considered there will be driving temperature differences at each heat exchanger which have additionally to be taken into account. These depend on the heat transfer media of the external cycles and the degree of capacity utilization of the plant. For external cycles with liquid heat carriers these driving temperature levels usually are between 5 and 10 K at full load. To calculate the dependency of capacity on the external temperatures there is a so called characteristic equation [23], which can be formulated with either the driving temperatures of each heat exchanger or solely using external temperature levels. If the temperatures t_i are the external mean temperatures at each heat exchanger, it can be shown that the cooling (or heating) output of an absorption chiller is directly proportional to a total driving temperature difference ($\Delta\Delta T$) (Eq. (6)):

$$\Delta\Delta T = (t_G - t_A) - R(t_C - t_E) \quad (8)$$

R is a correction factor which shows the influence of the different slopes of the vapor pressure curves of pure refrigerant and solution. Usually R amounts to about 1.1–1.2. This is valid for not too large temperature differences [23].

At present, there are only two common working pairs, water/aqueous lithium bromide solution (LiBr) and ammonia/water. Absorption chillers with water/LiBr usually show a higher efficiency. However, without certain additives to the refrigerant, these plants are limited to low temperature heat sources above 6 °C to avoid freezing.

There are also different kinds of two stage absorption heat pumps available. Double-effect absorption chillers use higher driving temperatures to increase efficiency (up to a real EER_{th} of about 1.25) while keeping the temperature of low temperature source and reject heat constant. These systems are often used in conjunction with co-generation units in order to utilize high temperature exhaust. Double-lift absorption heat pumps – which are less common – accept a reduction of efficiency to either reduce the needed temperature of driving heat or increase the temperature lift.

Fig. 6 shows roughly the possible operational areas for different absorption heat pump systems in common applications.

The areas given in Fig. 6 have to be shifted according to Eqs. (5) and (8) for different loads or temperature levels. Shown in the figure are areas of operating temperatures for plants with a rejected heat temperature level of 35 and 60 °C. Examples for the first case with 35° rejected heat are cooling applications (thus absorption chillers). To keep the chart clear only double effect systems with water/aqueous lithium bromide and single effect systems with ammonia/water are shown for the upper temperature level. As depicted, increasing rejected heat temperature generates a shift to the upper right of each area. Customized or gas driven plants can exceed beyond the areas given in Fig. 6, examples are given in [24].

1.6.3. Other sorption technologies

Besides (closed cycle) thermally driven heat pumps, there are some other configurations of sorption systems to supply heat and cold. This include open cycle vapor recompression systems, absorption heat transformers, compression-absorption heat pumps, and adsorption and desiccant systems [17,25–27]. These technologies do not have large market shares [28–30] and are not as well developed with the exception of closed cycle adsorption heat pumps.

From a thermodynamic point of view, closed cycle adsorption systems work identically to absorption systems. These machines are distinguished by the sorbent; while absorption heat pumps use liquid sorbents, adsorption heat pumps use solid sorbents. Common pairs for adsorption systems are water/silica gel and water/zeolite. In real application, the efficiency usually is lower than that of absorption systems, showing a thermal efficiency based on refrigeration capacity of about 0.5–0.6.

1.6.4. Comparison of systems

It can be said that heat pumps in general offer potential to provide heat and cold in an efficient way. Compared to mechanically driven heat pumps, it is further possible to reduce electrical energy input – especially with absorption heat pumps – as these machines can utilize waste heat as driving energy. As MDHP are already an established technology and the specific investment costs of AHP are usually higher, up to date, the MDHP have a much higher market share.

Table 3 shows a brief comparison of mechanically driven heat pumps and absorption heat pumps; in each case only single stage plants are considered.

While comparing these technologies one has to keep in mind, that in order to use absorption heat pumps for waste heat applications an industrial waste heat source at a high temperature level is necessary to drive the machine. Furthermore, a low temperature heat source that is upgraded to a higher (though not as hot as the first source) temperature to meet a given heat demand. If no high temperature heat source is given, the demand could be met by using a low temperature heat source and a mechanically driven heat pump.

2. Economic analysis

2.1. Applied method

Above different technologies to deploy waste heat sources are presented with their technical limitations and application rates. However, a technically feasible solution is not enough. To actually

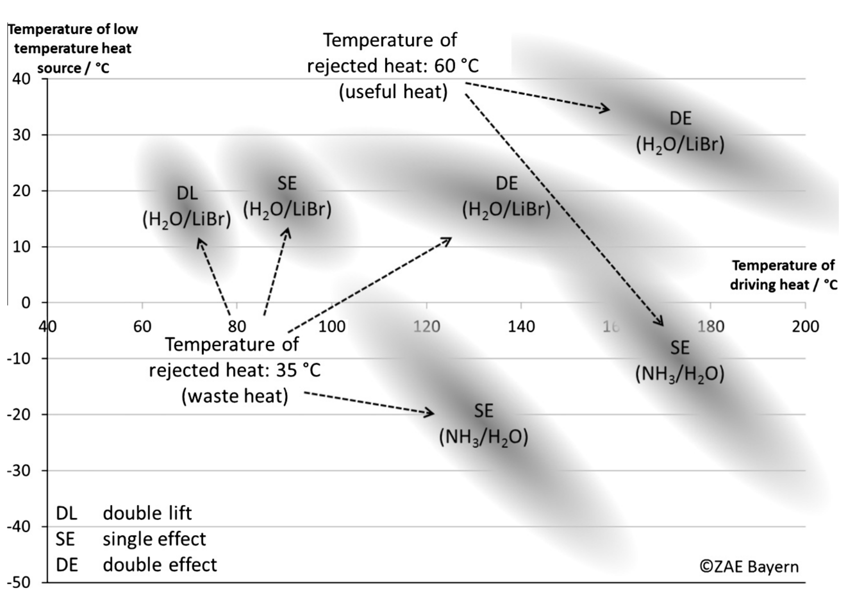

Fig. 6. Possible temperatures for low temperature heat sources (Q_0) vs. needed driving heat (Q_2) temperature level for different absorption heat pumps.

Table 3
Comparison of MDHP and absorption heat pumps.

	MDHP	Absorption heat pumps and chillers
Market share	High established technology	Low compared to MDHP
Driving energy	Mechanical energy (usually electrical energy)	Thermal energy, different temperature levels possible
Efficiency (electrical)	Relatively high, decreases strongly with increasing temperature lift	Very high if system is well designed, low dependence on temperature lift and drive
Efficiency (thermal)	–	Nearly constant for a large range of temperature lift
Volume	Compact machines	Comparatively large volumes needed
Controls	Requirements well known	Complex compared to MDHP

be applied a technology has to be economically competitive and attractive. But when is a technology economically attractive and to whom? To answer this question for storage systems the experts working at the IEA Task 42/24 [1] developed a new approach, the maximum acceptable cost.

Commonly economic feasibility is evaluated by the payback period or interest rate. Both figures are used by companies for investment decisions. They depend on investment cost, operating cost and operating hours. Unfortunately all of these figures are variable: investment cost decreases by technical learning, operating cost depend on energy market prices and operating hours depend on each individual application case. Therefore, the evaluation method is inversed in the maximum acceptable cost method presented in this article: since the expectations on interest rate and payback period are relatively constant, three cases (named consumer types) are defined and taken as input parameters. Thus, a function for economic feasible investment cost can be defined depending on operating hours, creating a more general approach. Moreover, the main advantage of this approach is that it does not require detailed information about the technology or its implementation. The analysis neglects operating costs and changes in the cost of energy production over the time period. Nevertheless, it illustrates the most important feature in energy economics, the relationship between acceptable storage costs, the frequency of use, and the cost of energy.

The different consumer types with different desired interest rates and desired payback periods are defined:

1. Industry
   For an application in the industrial sector, a technology has to have a high interest rate and a low payback period. It is therefore the most ambitious application. Here, an interest rate of 10% and a payback period of 5 years were assumed.
2. Real estate
   When a technology is applied in a commercial building it also has to satisfy certain economic criteria, but they differ from the industrial case: the payback periods may usually be longer but it should still have a fair interest rate. Thus, an interest rate of 5% and a payback period of 15 years were assumed. This is also the typical lifespan of conventional technical building equipment like boilers.
3. Enthusiast
   As an optimistic case, the enthusiast consumer type was defined: it represents the application mostly in the private sector by early adopters, who want to get the new technology and are content if it does not cause additional cost. The assumed interest rate is 1% and the payback period is equal to the life span of most technologies of 25 years.

These parameters are important to translate future costs and savings to present values. This is done over an annuity factor (Eq. (9)) [31]:

$$\mathrm{AF} = \frac{q-1}{1-q^{-t}} \tag{9}$$

With $q = 1 + i$ and
q: interest rate factor.
i: interest rate, in %.
t: payback period, in years.

In Fig. 7 the annuity factor for the three cases over the payback period is displayed.

Matching the chosen payback periods with these results, leads to an annuity factor of 0.26 (26%), 0.09 (9%) and 0.045 (4.5%). A summary of these parameters is given in Table 4.

For calculating the maximum acceptable investment cost, it is distinguished between the supply of heat and cold.

2.1.1. Heat supply

For heat, the maximum acceptable investment cost can be calculated over the cost difference between a unit of conventionally supplied heat and the cost per unit of the investigated technology. This holds the advantage that the comparison is independent of the conventional technology used. In this paper, a heat price of 0.04 €/

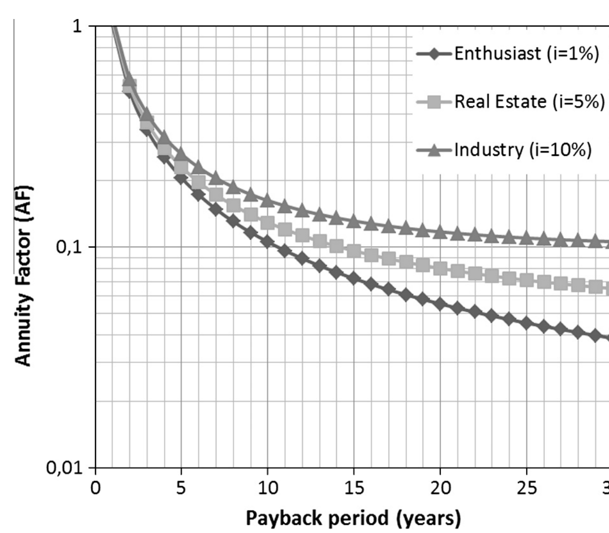

Fig. 7. Annuity factor for the three consumer types.

Table 4
Consumer types considered.

	Industry	Real estate	Enthusiast
Interest rate, i (%)	10	5	1
Payback period, t (a)	5	15	25
Annuity factor (%)	26	9	4.5

kW h is assumed. The maximum acceptable investment cost (Inv_max) can then be calculated as shown in Eq. (10):

$$\text{Inv\_max} = \text{operating hours} * \frac{\Delta\text{cost}}{\text{unit heat}} * \frac{1}{\text{AF}} \tag{10}$$

To determine the cost difference between a unit of conventionally supplied heat and one supplied with a heat pump Eq. (11) is used. For the heat supplied by a heat pump, the cost is assumed to only depend on the electricity used by the heat pump. The waste heat is assumed to be free of charge.

$$\frac{\Delta\text{cost}}{\text{unit heat}} = \frac{\text{cost of heat}}{\text{kW h\_th}} - \frac{1}{\text{COP\_el}} * \frac{\text{cost of electricity}}{\text{kW h\_el}} \tag{11}$$

For the cost of electricity the average industry price in EU 27 zone in 2012 [32] of 0.117 €/kW h is considered. This price might of course vary by country or for private consumer. Therefore a sensitivity test is presented in chapter 2.6. The input parameters used in this study for an electrical heat pump and for an absorption heat pump are summarized Table 5.

2.1.2. Cold supply

For cold there is no average market price available, but on the other hand there is not a large variety of alternative production technologies. Therefore, for the maximum the cost are divided into fix cost and operation dependent savings. The maximum acceptable investment cost is hence the cost the standard alternative technology, in this case an electric compressor, plus the operational savings (Eq. (12)):

$$\text{Inv\_max} = \text{Inv}_{\text{con}}\ (\text{current technology}) + \frac{\text{operational savings (operating hours)}}{\text{AF}} \tag{12}$$

For the investment cost of the current technology 300 €/kW [33] are considered (for 100 kW). In the enthusiast case, a payback period of 25 years is considered. This is the estimated life time of an absorption chiller. However, since the mechanic compressor has more moving parts, its life span is shorter. Therefore, for the enthusiast case, 150% of the installation cost of the compressor is assumed. Assuming that the heat is true industrial waste heat and free of charge, the operational saving only depend on the electricity used in both systems (Eq. (13)):

$$\text{operational savings (operating hours)} = \text{operating hours} * \frac{\Delta\text{cost}}{\text{unit cold}} \tag{13}$$

For the two technologies the difference in cost can be calculated over the difference in their performance coefficient (Eq. (14)):

$$\frac{\Delta\text{cost}}{\text{unit cold}} = \left(\frac{1}{\text{EER}_{\text{Absorption}}} - \frac{1}{\text{EER}_{\text{compressor}}}\right) * \frac{\text{cost of electricity}}{\text{kW h\_el}} \tag{14}$$

For an electrical heat pump the input parameters are summarized in Table 6.

Table 5
Input parameters for an electric heat pump and an absorption heat pump.

	Electric heat pump	Absorption heat pump
COP_el	4	30
Cost of electricity	0.117 €/kW h	0.117 €/kW h
Cost of heat	0.04 €/kW h	0.04 €/kW h

Table 6
Input parameters for an absorption chiller.

EER_compressor	4
EER_absorber	12
Cost of electricity	0.117 €/kW h
Inv_con	300 €/kW or 450 €/kW (for 25 years)

2.2. Results and discussion

The presented general economic analysis calculates the maximum acceptable investment cost depending on different consumer types and operating hours. In comparing the results with present day technology cost the results give an idea of the "market readiness" of the investigated heat transformation technologies, namely absorption chillers, electric heat pumps and absorption heat pumps. The current investment cost of the three technologies range between 800–2000 €/kW, 150–500 €/kW and 330–830 €/kW, respectively [17,33–36].

From the resulting figures presented below two conclusions can be drawn. First of all, using the presented graph the maximum acceptable investment cost of a system in order to be profitable for a certain consumer type and operating hours can be derived. This is independent of the current price of the investigated technology. It is the answer to the question "how much may it cost?".

Second, the derived values for the maximum acceptable investment cost are compared to present day investment cost (grey area). This comparison of the maximum acceptable investment cost and the present cost gives an idea of the market readiness of the technology. Everything within or above the grey area is already economically profitable.

In the following paragraph the results of this economic analysis are described for the different heat transformation technologies. Even though these technologies have different normal operating hours, all of them have been detailed in the same operating hours range in order to make them easily comparable.

2.3. Case 1: Absorption chiller

For the above described economic analysis, the maximum acceptable investment cost per kW is plotted over the operating hours for the three consumer type cases. This is displayed in Fig. 8. In the figure, the grey area shows the present value of the investment cost for the investigated technology. Application cases within the grey area or above are therefore economically feasible. Values below mark the gap that is still to overcome for market readiness.

For example, an absorption chiller supplying round about 1000 h of cooling demand per year has a maximum acceptable investment cost of 370, 510 and 880 €/kW for Industry, Building

Fig. 8. Maximum acceptable investment cost for absorption chillers; grey bar: current investment cost considered for the absorption chiller case.

Real Estate and Enthusiast investor consumer type. Comparing these values with its current invest cost, which is between 800 and 2000 €/kW (grey area in Fig. 8), it can be seen that it is far from being economically feasible except for the enthusiast consumer type investor. If the cooling demand is required longer (longer operating hours) the maximum allowable investment cost would increase. For the Real Estate consumer type, absorption chillers are already economically feasible for more than 2500 h operating hours per year. However, for industrial application, the investment cost still need to decrease significantly in order to become economically interesting.

2.4. Case 2: Electrical heat pump

For electric heat pumps the results are quite different. As shown in Fig. 9, even for industrial applications the present day investment cost of 150–500 €/kW is matching the maximum acceptable investment cost for 4000 operating hours. For Real Estate or Enthusiast consumers, the maximum acceptable investment cost is already at or above the present day investment cost of the technology. In both cases the technology is economically feasible.

2.5. Case 3: Absorption heat pump

Absorption heat pumps are already profitable for all consumer types for more than 3000 operating hours per year (Fig. 10). For Real Estate and Enthusiast even 1000 operating hours and less are still economically feasible. Assuming 24 h operation per day, 3000 h equal 125 days. For an order of magnitude: average winters in Germany, for example, have about 250 heating days [17]. The application of an absorption heat pump would already be profitable here.

2.6. Sensitivity test on heat production

As electricity and heat price vary in different countries and over time, a sensitivity analysis of these factors is performed for the heat production (both electric and absorption heat pump). For cooling production, no sensitivity analysis is carried out since in the case of cooling the cost are directly proportional to the electricity price.

Fig. 11 shows the results of a 50% increase and decrease of the electricity and heat price respectively. It can be concluded, that the heat price the technology is compared to, has a much stronger influence than the electricity price. Therefore, an increase in the oil price and thus an increase in the heat price per kW h would move the absorption technology even further into the profit zone.

Other major parameters of the economic analysis are the electrical COP (COP_el), the operating hours and the annuity factor. Their influence has been tested by varying them between 25% and 200%. As a reference case the Real Estate consumer type with 2000 operating hours was selected. The results are shown in Fig. 12.

As expected, the operating hours have a linear effect on the results of the economic analysis. The electrical COP (COP_el) has little influence within a reasonable variation span.

However, the strongest influence comes from the annuity factor with an almost exponential increase in investment cost for a

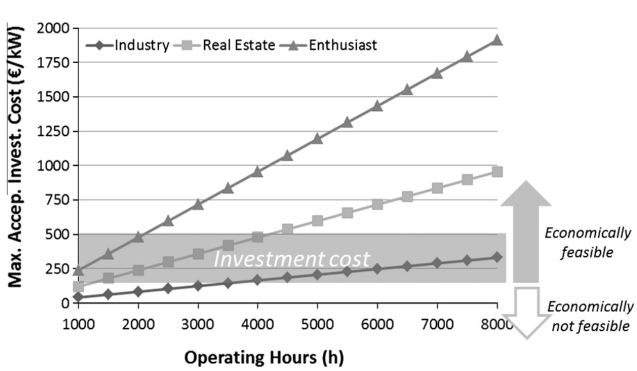

Fig. 9. Maximum acceptable investment cost for MVC, grey bar: current investment cost considered for the electrical MVC case.

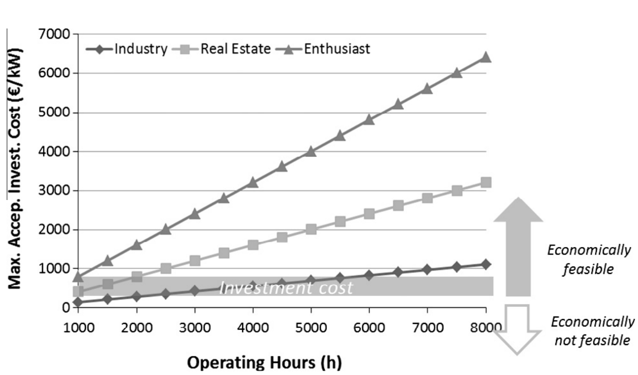

Fig. 10. Maximum acceptable investment cost for absorption heat pump, grey bar: current investment cost considered for the absorption heat pump case.

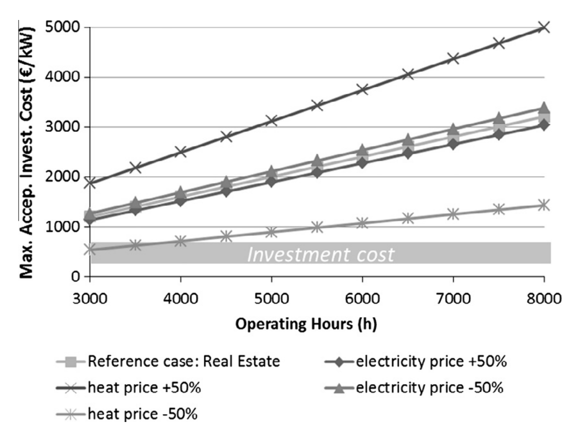

Fig. 11. Reference case: Real Estate consumer type with 2000 operating hours.

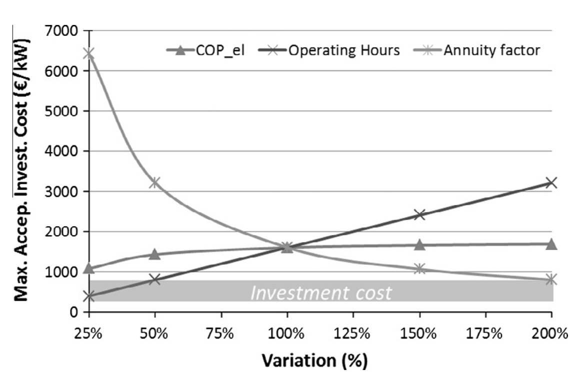

Fig. 12. Reference case: Real Estate consumer type with 4000 operating hours.

decreasing annuity factor. This supports the initial concept of defining different consumer types with different annuity factors.

3. Conclusions

In this paper the main technologies that can be used nowadays are described and compared for its use as waste heat recovery systems. For that, an overview of waste heat recovery potential including main definitions, available technologies, possible industrial waste heat sources and their temperatures and demand is also shown.

Moreover, a general economic analysis is presented for three different cases of waste heat use using heat transformation technologies (from the technologies reviewed, the ones able to produce heat or cold): an absorption chiller producing cold and heat production with a compression and an absorption heat pump. For each technology, the maximum acceptable investment cost is estimated and compared with the current investment cost depending on the operating hour of the system. In order to do that, three different consumer types (Enthusiast, Real Estate and Industry) are defined to represent different expectations in interest rate, payback period and the resulting annuity factor. Maximum acceptable investment cost for each technology is estimated by expressing the yearly operational savings in present value. This can then be compared with the present day market cost. The difference between the current investment cost of a technology and the calculated maximum acceptable investment cost is a measure for the market readiness: the bigger the difference, the further away is technology from wide market adoption.

For the present day technology cost, absorption chillers are profitable for Real Estate consumer types and when operated for at least 2500 h per year for Enthusiast consumer types. More than 6500 h per year are needed in order to be profitable for Industry consumers. Besides, absorption heat pumps are profitable starting at 3000 h for Industry consumer types while for the rest even less operating hours are economically feasible. Finally, for Real Estate and Enthusiast consumer types, the maximum acceptable investment cost is already at or above the present day investment cost of the technology, and for Industrial consumer types when exceeding 4000 operating hours per year.

The sensitivity analysis on absorption heat pump showed a large influence of the annuity factor on the profitability of the technology. This supports the chosen design of the economic analysis to evaluate three different consumer types with different annuities.

In addition it was shown, that present day electrical COP are already good enough to reduce the influence of the electricity cost on the investment cost.

Further research for heat transformation technologies to recover waste heat should therefore focus on system integration, design and size as well as market implementation.

Acknowledgements

Thanks to Peter Zachmeier, Christian Wuschig, Richard Gurtner, Martin Helm and Andreas Krönauer from ZAE Bayern e.V (Germany) for contributing to this work with their expertise.

This work was partially funded by BMWi the German Federal Ministry of Economics and Technology (project FKZ 0327383B Mobile Sorption Heat Storage) and the Spanish government (project ENE2011-22722). The authors would also like to thank the Catalan Government for the quality accreditation given to their research group GREA (2014 SGR 123).

Sarah Brückner would like to thank Stiftung der Deutschen Wirtschaft for her research fellow-ship. Selina Liu would like to thank DAAD for her internship fellowship within the RISE Program. Laia Miró would like to thank the Spanish Government for her research fellowship (BES-2012-051861).

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