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D 2.3 Report on estimation of energy, environmental and economic potential for heat recovery in EU28

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Contents

Introduction

Based on the outcome of the review realized in Task 2.1 (D2.1), the results of the audits in Task 2.2, and comparison of the proposed and conventional heat recovery technologies, projected energy and CO_2 emission savings from the application of the proposed heat recovery technologies in the EU28 is attempted to be determined in this report. The information is also used to determine target energy performance and capital and installation costs to make the technologies to be developed attractive for wide adoption by industry.

1. Iron and Steel industry

Iron and steel production is separated into different processes and each process has different temperature range and potential waste heat recovery. There are five main operation processes described as the sinter process, the pelletization plants/ induration process, the coke oven plants, the blast furnace, and the basic oxygen steel making. Temperature ranges in the iron and steel industry are in the high temperature range, with temperatures ranging from 900 to 1500 degrees Celsius between processes. Higher temperatures of the waste heat to be recovered correspond to a higher quality and economic efficiency of the heat, regardless of the method used (Qi, Xiaoyu, Hongyou, Tuanjie, & Li, 2017). To examine the technical and economic feasibility of the waste heat recovery system it is essential to match supply with demand (Oluleye, Jobson, Smith, & Perry, 2016).

1.1 Technologies

There are different methods employed to take advantage of the waste heat energy from the processes. Barati *et al.*, (2011) have classified heat recovery technologies into recovery as hot air or steam, conversion to chemical energy as fuel, and thermoelectric power generation (Barati, Esfahani, & Utigard, 2011). The methods are generally applied into three categories as described by Qi *et al.,* (2017) :

1. Direct utilizing; heat delivery to district heating or cooling or preheating
2. Power utilizing; electricity generation using generator
3. Cascade utilization; combine heating, cooling and power

- ### Direct utilization

Direct utilization can be achieved using heat exchangers. The heat exchangers are most commonly used for heat transfer from the combustion exhaust gases to the air entering the furnace; this process is known as preheating or recovery from hot air. The heat pump systems can be classified as suggested by Bruckner *et al.* (2015) in Mechanical driven heat pump, Absorption heat pump and Other sorption technologies; they include open cycle vapor recompression systems, absorption heat transformers, compression-absorption heat pumps, and adsorption and desiccant systems. The techniques used in the waste heat recovery of iron and steel industry and the process of which each technique is applicable are identified in table 1 (BCS, Johnson, Choate, & Davidson, 2008):

Table 1. Waste Heat Recovery Technologies, table reproduction from (BCS, Johnson, Choate, & Davidson, 2008)

	COKE OVEN		BLAST FURNACE		BOF	EAF
	Cove Oven Gas	**Waste Gas**	**Blast Furnace Gas**	**Hot Blast Stove Exhaust**	**Basic Oxygen Furnace Gas**	**Electric Arc Furnace Offgas**
REGENERATOR		+				
HEAT WHEEL				+		
PASSIVE AIR PREHEATER		+		+		
THERMAL MEDIUM SYSTEM	+			+		
WASTE HEAT BOILER					+	
LOAD PREHEAT						+

The convectional way to recover heat is with the use of water quenching (water quenching techniques have been studied by Lei *et al.* (2016). Molten slug exhausted is the most common heat recovery source of energy in the iron and steel industry and the systems/processes used are described by Hui *et al.* (2013).

The procedure of slag crushing is required to take advantage of the waste heat and it is certified into three physical methods; the mechanical crushing, the air blast and the centrifugal granulated method. A list of the all the processes is given below:

- Solid slag impingement process
- Mechanical stirring process
- Rotating drum process
- Air blast process
- Rotating cup atomizer (RCA) process
- Spinning disk atomizer (SDA) process
- Rotating cylinder atomizer (RCLA) process
- Direct electrical conversion devices
    - Heat recovery by phase change materials (PCMs)
    - Heat recovery by thermoelectric materials

• Power utilizing

Generating electrical power from waste heat energy is achieved by converting the heat energy to mechanical energy to drive an electric generator. The temperature of the waste heat is affecting and limiting the efficiency of the power generation and is only available to mainly high (as in the case of the iron and steel industry) and in some cases to medium temperature waste sources.

Generating power via mechanical work in the iron and steel industry can be achieved using the following principles:

- Steam Rankine Cycle
- Organic Rankine Cycle
- Kalina Cycle

- ### Chemical energy utilization

The chemical method is classified into two processes:

- The methane reforming reaction process
- The coal gasification process

The chemical processes, despite the sensible heat conversion of molten slag into chemical energy with high energy values, exhibit limitations. The gas product, for example, is hard to be purified and as raw materials for the chemical processes cannot be directly obtained from the iron and steel manufacturing plants, the process will have an increased cost. At the moment there is no available information of large scale applications in the iron and steel industry.

1.2 Performance and Potential

Different methods at different processes can yield different performance and energy recovery for a specific system. It would be more accurate to present the available performance potential of each system. The processes and the techniques have been discussed in the previous sections. The energy recovery from the granulation/ slag type and heat recovery rate are presented in Table 2.

Table 2. Summary for the granulation processes and heat recovery methods from Hui et al., (2013)

Granulation	Slag type	Heat exchanger	Heat recovery rate (%)	Ref
Solid impingement	BF slag	Fluidized bed	65	(Tiberg)
Mechanical stirring	BF slag	Partition wall type heat exchanger	~50	(Shun, 2009)

Mechanical stirring	BF slag	Partition wall type heat exchanger	~50	(Nakada, Nakayama, Fujii, & Iwahashi, 1983)
Single rotating drum	BF slag	Fluidized bed	60	(Sieverding, 1980)
Twin drum	BF slag	Partition wall type heat exchanger	40	(Yoshida, Nara, Nakatani, Anazi, & Sato, 1984)
Air blast	Steel slag	Partition wall type heat exchanger	41	(Ando, Nakahar, Onous, Tchimura, & Kondo, 1985)
Air blast	BF slag	Fluidized bed	48	(Zhou, 1990)
Rotating cup	BF slag	Fluidized bed	59	(Pickering, Hay, Roylance, & Thomas, 1985)
Spinning disc	BF slag	Packed bed		(Xie, Jahanshahi, & Norgate, 2010)
Spinning disc	BF slag	Chemical process		(Hadi & Tomohiro, 2005)
Rotating cylinder	BF slag			(Kashiwaya, In-Nami, & Akiyama, 2010)

The waste heat recovery potential of the iron and steel industry is presented in Table 3.

Table 3. Waste heat recovery potential (Element, 2014)

		Heat source	Heat Supply (KWh/ton)	Temperature (°C)
Coke Ovens	Sensible Heat in the Coke Ovens	Gas	82	980
Coke Ovens	Exhaust gas from combustion of CO gas	Gas	58	200
Coke Ovens	Heat Recovery from solid radiant coke	Solid	62	800
Blast Furnaces	Sensible heat in the blast furnace	Gas	28	100
Blast Furnaces	Exhaust gas from blast stoves	Gas	82	250
Blast Furnaces	heat recovery from slag	Solid	100	1300
BOS	Heat recovery from BOS gas	Gas	141	1700
BOS	Heat recovery from BOS slag	Solid	6	1500
EAF	Electric Arc Furnace	Gas	44	1200
Casters	Heat Recovery from hot slab	Solid	352	1600
Hot Rolling	Heat recovery from coil	Solid	1395	400
		Total	**2350**	**KWh/ton**

A case study of hot blast stove flue gas sensible heat recovery and utilization has been presented by Lingen *et al.* (2015). An absorption heat pump was firstly run using the flue gas, and later was used to preheat the Blast Furnace gas. The system performance was optimized using the energy saving rate and the profit rate by the authors. The results indicated that the system could achieve an energy saving of 16.5% and a reduction of CO_2 at 16.5%. Lemmens & Lecompte (2017) have also investigated the economic effect of flue gas heat recovery using organic Rankine cycle (ORC). The flue gas has a maximum temperature of 240–250 °C that amounts to approximately 2.8 MW of thermal power. The IRR of the project was calculated at 12.6%, which is higher than the discount rate scenarios, yielding hence a positive NPV value. A sensitivity analysis was conducted by the authors stating that the project results altered most by changes in the electricity price and the annual load hours of the system. Arash *et al.* (2017) have presented a comparative thermodynamic analysis of two waste heat recovery cycles, organic Rankine cycle and Kalina cycle for a cogeneration system. The authors have observed that optimum pressure value for the ORC is much lower than that of the Kalina, which leads to lower cost levels for materials and sealing of ORC. Additionally, the Kalina cycle requires a lower turbine size than that of the ORC. Another study on the performance between ORC and Kalina cycles has been investigated by Yufei *et al.* (2017) using multi-stream waste heat recovery techniques. The authors have presented the calculated results with maximum waste stream temperature of 180 °C, concluding that for straight and concave waste heat with R not less than 0.2, Kalina cycle is better than ORC, while for convex waste heat, ORC is preferable.

A study contacted in Japan (NEDO, 2008) has presented the economic analysis of the waste heat recovery devises and is presented in Table 4.

Table 4. Economic analysis of waste heat recovery devices

Waste heat recovery Device	**Investment cost (EUR)**		**Economic Effect (EUR million/ year)**	**Estimated Payback Period**	
	Equipment cost	**Construction cost**		**Equipment**	**Construction**
Sintering machine cooler	25 million	4 million	1.1	22.1 years	25.8 years
Hot stove	1.2 million		0.5	2.8 years	
Blast furnace top-pressure recovery turbine	3.3 million	3.3 million	8	1.4	1.8
Converter gas	4.8-9 million		0.6	8.3–15.2 years	
Converter gas sensible	4.85 million	0.8 million	0.7–1 million/year	5.6–7.8 years	

2. Food and Drink Industry

In the food industry, heat has an important influence on food processing because it is the most convenient way of extending the shelf life of foods. Indeed, heat will destroy enzymatic or microbiological activity or remove water to inhibit deterioration. So, there is a lot of processing by application of heat (baking, pasteurization, heat sterilization, blanching) or by removal of heat (chilling, freezing, freeze drying). But processing temperature is usually low, not too high to destroy food quality product. So, many end uses are in the 60–140°C temperature range, well adapted to the level of temperature reached by heat pumps (Thekdi and Nimbalkar, 2015).

Industrial heat pumps, using waste process heat as the heat source, deliver heat at higher temperature for use in industrial process heating (Hita *et al.*, 2011). However, the installation of a heat pump corresponds to an additional investment cost and leads to savings on operating costs. The profitability depends on the initial investment cost and energy prices.

Hita *et al.* (2011) carried out a study to assess the potential of heat recovery in food and drink industry by the use of the TIMES model. TIMES is an energy prospective model usually applied to the analysis of the entire energy sector, but it may also be applied to study in detail single sectors, like the food and drink industrial sector in this case.

In industry, it is possible to find heat source in the temperature range of 30–60 °C on several equipment like air compressors, chillers and other thermal end uses. This heat is at too low temperature (30–60 °C) to be recovered by an exchanger and used directly in industrial processes. So, this heat is currently wasted and heat pumps represent a way to recover it. The price of a heat pump is very dependent on their working conditions. Standard machines for temperatures of up to 100 °C or up 140 °C cost 1500 €/kW and 1800 €/kW respectively.

The TIMES model calculated the amount of heat that can be recovered from different processes as follows:

- Heat recovered in air compressors = 50% * input energy
- Heat recovered in the chillers = 70% *(2.5+1) * input energy
- Heat recovered in thermal end uses = 15% * input energy

Mukherjee *et al.* (2016) carried out a study on food processing and technology focusing on the baking processes in the food manufacturing sector that use gas fired ovens. Only about one-third of the total energy used in these ovens adds value to the final product. The remaining two-thirds is discharged with the exhaust gases at 150–250 °C and thus represents an opportunity for heat recovery. However, the low temperature range, fouling and presence of corrosive materials in the exhaust streams make heat recovery technically challenging and uneconomical. The existing low grade heat recovery technologies mostly use gas to liquid heat transfer to produce hot water for use in other areas of the manufacturing plant. The design enables recovery of up to 50% of the energy available through the exhaust stack, increasing the energy efficiency of the overall process to 60% and reducing food manufacturing costs by one third.

Lundberg and Christenson (1979) carried out an analysis to evaluate the potential of waste heat recovery in the food processing industry. Five selected survey industries were studied by selecting two case study factories to analyze the technical aspects of potential waste heat recovery systems and the economics of installing them. The five industries deal with the canned specialties, the canned fruits and vegetables, the ice cream and frozen desserts, the frozen specialties and the frozen foods and vegetables. These five industries are represented in the two survey sites, the Pittsburgh Factory and the Lake City Factory. The Pittsburgh Factory specializes in foods processed with steam and hot water. The factory's main products are baby foods and juices, canned soups and canned bean products. The Lake City Factory deals with the preparation of dessert products that are quick-frozen as the last step in the process.

2.1 Technologies and Processes

The typical waste heat sources and their characteristics for food processing, in particular for snack manufacturing and similar operations, as presented by Thekdi and Nimbalkar (2015), are shown in Table 5.

Table 5. Waste Heat Sources, Recovery Opportunities and Barriers for the Food (Snack) Manufacturing Industry.

Waste Heat Source	Heat Recovery Opportunities	Barriers or Limitations – Currently Available Equipment
Clean exhaust gases from boilers, corn products dryers, oil heaters, and other sources	Low-temperature (< 500°F or 260°C) heat recovery from combustion products with moisture content of 20–40%.	No major technical barriers. Economics of heat recovery system installation and use of recovered heat within the plant are two major barriers. Electricity generation using heat from these sources using low-temperature systems (i.e. ORC) is uneconomical at the current state of technology.
Exhaust gases from fryers. These gases contain moisture and oil vapors.	Recovery of sensible heat, use of heating value content of oil vapors and latent heat of moisture.	Presence of oil vapors prevents use of conventional heat recovery (e.g., recuperates, heat wheels, condensing heat exchangers).

Hot wash water (120–180°F or 50–82°C) from various sources.	Sensible heat of water	Presence of particulates, economics of heat recovery, and lack of use of low-grade heat in the forms of warm water or air in the plant.
Waste material with organic content or heat value and moisture.	Recovery and use of heating value content of the waste material.	Economic justification, availability of combustion equipment that can burn or process such waste economically.

According to the Agriculture and Agri-Food Canada (2011) the amount of waste heat available in a plant varies widely from sector to sector in the food industry, owing to the different processes and energy requirements involved. The actual amount of potentially useful waste heat can only be revealed by a comprehensive audit of the plant's energy consumption.

- ### Red meat processing

In a slaughterhouse, the major energy use is for refrigeration of carcasses. In beef slaughtering, another major energy consumer is the clean-up operation, which uses large quantities of hot water. In hog slaughtering, the hair removal process (scalding, dehairing, singeing) uses a large amount of energy. Recovery of waste heat from refrigeration systems and by-product dryers is practical, while that from rendering cookers is possible but more difficult because of the grease in the cooker's exhaust. Recovered energy could be employed for heating hot water used for clean-up, or for preheating boiler feed water or intake air for dryers.

- ### Poultry processing

In poultry processing, large quantities of energy are required for scalding, cooling and freezing. The scalders and chillers have continuous overflow, and thus large amounts of energy are lost. However, recovery of heat (or cooling capacity) from scalders (or from chillers) is feasible, and the energy can be returned to the scalders (or chillers). Heat can also be recovered from refrigeration system condensers and used to preheat boiler makeup water or wash water.

- ### Fruit and vegetable processing (freezing and canning)

In freezing plants, the major source is the refrigeration system condensers. Heat is available from the hot refrigerant and should be easily recoverable. A second source is wastewater; however, waste heat from it is of low quality and solid particles in the wastewater might cause fouling problems in heat exchangers. In canning plants, the major waste heat sources are retort vents and wastewater.

- ### Dairy processing

Dairy processing plants usually use energy efficiently. Heat transmitted to milk products during pasteurization is normally rejected to incoming cold milk in the regenerator. A large percentage of waste energy is in the heat rejected by the refrigeration condensers. It can be used in generating hot water for use in clean-up, in preheating boiler feed water, or in heating culture tanks for some unit operations.

- ### Biscuit Manufacturers

Flue gases from ovens, fryers, pan washers and boilers are major heat loss sources. Hot water can be produced from these sources for use in pan and plant clean-up. Recovery of low-grade heat from oven exhaust for lower temperature heat requirements (e.g., proofing, fermentation) is another possibility.

- ### Egg processing

As in the dairy industry, heat received by egg products during pasteurization is transmitted to the cold incoming egg product inside a regenerator. Principal sources of waste heat depend very much on the type of product the plant is producing, but they are generally refrigeration systems, wastewater from egg washing, and exhaust air from drying operations.

2.2 Case studies and economic data of heat recovery systems

- ### Case study: The Pittsburgh Factory

At the Pittsburgh Factory, the hot waste water is the main waste heat source, while at the Lake City Factory the refrigeration system condensers represent the waste heat source.

The waste heat recovery system at the Pittsburgh Factory: The high temperature streams (i.e., those above 140 °F) are collected in the high temperature accumulator (HTA) while all low temperature streams are channeled to a low temperature accumulator (LTA) – Figure 1. The estimated cost of the system is shown in Table 6, where – including the engineering costs – the total was $413300.

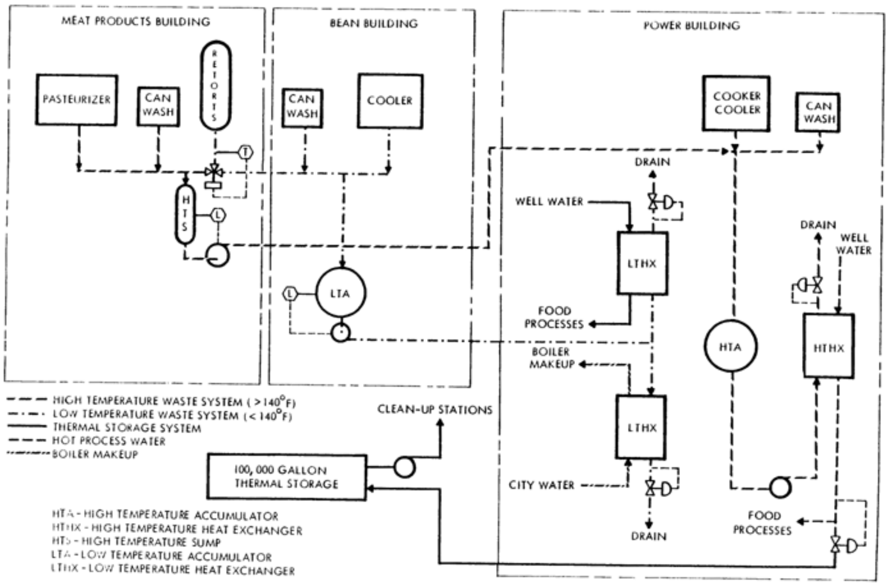

Figure 1.The waste heat recovery system at the Pittsburgh Factory.

Table 6. The estimated costs of the heat recovery system in the Pittsburgh Factory.

Item	Materials cost ($)	Installation ($)
Tanks	90000	-
Heat exchangers	44400	6700
Pumps	13400	6000
Strainers	10000	4000
Valves	15500	12800
Piping	27300	92200
Instrumentation/Controls	17800	19300
Total:	218400	141000
Total Materials and Installation: $359400		

- ## Case study: The Lake City Factory

The waste heat recovery system at the Lake City Factory: Two independent systems have been evaluated. First, a refrigeration waste heat from the compressors heats fresh water for later use during third shift clean-up operations (Figure 2). The total system cost, including engineering, was $36900 (Table 7). The system displaces natural gas at the rate of nearly 1900 MCF annually. This reduction in fuel consumption is valued, at 1979 fuel prices, at $3870 per year and it was expected to reduce the factory's total energy input (gas and electricity) by 7% and its natural gas consumption by 13%. The second system (Figure 3), is to warm freezer floor air. The total system cost, including engineering, was $17700 (Table 8). The system displaces natural gas at the yearly rate of 1390 MCF (valued at $2880) and reduce the factory's natural gas and total energy consumption by 10% and 5%, respectively.

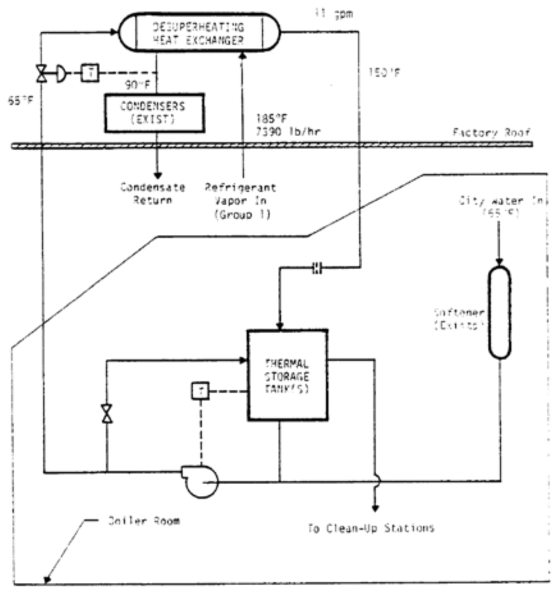

Figure 2. The waste heat recovery system for water heating at the Lake City Factory.

Table 7. The estimated costs for the waste heat recovery system for water heating in the Lake City Factory.

Item	**Materials cost ($)**	**Installation ($)**
Thermal Storage Tank 6000 gal	8300	3000
Heat Exchanger	3500	1200
Pump	500	500
Water Flow Control Valve	1100	200
Temperature sensor and transmitter	3500	400
Piping	2300	5000
Total:	19200	10300
Total Materials and Installation: $29500		

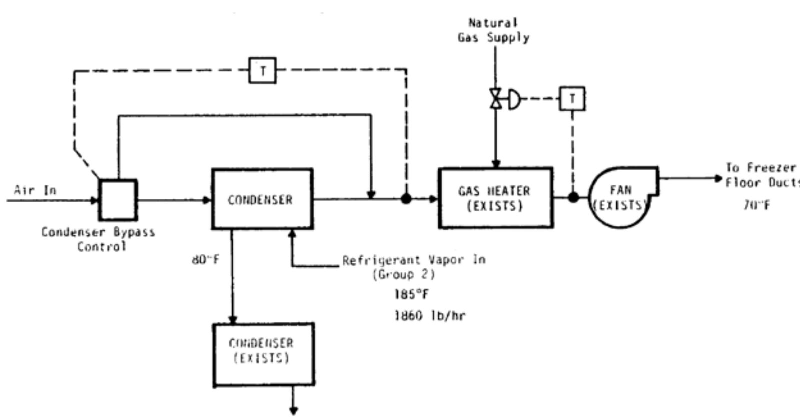

Figure 3. The waste heat recovery system for air heating at the Lake City Factory.

Table 8. The estimated costs for the waste heat recovery system for air heating in the Lake City Factory.

<table>
<tr><th>Item</th><th>Materials cost ($)</th><th>Installation ($)</th></tr>
<tr><td>Condenser</td><td>2800</td><td>1800</td></tr>
<tr><td>Piping</td><td>600</td><td>1100</td></tr>
<tr><td>Air Ducting</td><td rowspan="2">3000</td><td>1200</td></tr>
<tr><td>Controls</td><td>800</td></tr>
<tr><td>Fan Motor</td><td>500</td><td>-</td></tr>
<tr><td>Total:</td><td>6900</td><td>4900</td></tr>
<tr><td colspan="3">Total Materials and Installation: $11800</td></tr>
</table>

- ## Case study: Rendering cookers – Canadian meat processing plant

In the meat processing industry, rendering cookers (Figure 4) provide a good opportunity for heat recovery because of the high temperatures and the large volume of steam involved. The system recovers heat by passing vapor at atmospheric pressure through a steam-condensing heat exchanger. Each 3630 kg capacity steam-jacketed cooker exhausts 2105 kg of vapor during each 2.4 hour batch-cooking process. The average demand for hot water at 93 °C for production and sanitation during the production shift is 480 L/min. The spiral type heat exchanger selected provides a high degree of turbulence, ease of inspecting and cleaning, and permits sub-cooling of the vapor to 57 °C, allowing recovery of some of the sensible heat. The financial analysis of the spiral heat exchanger for the Canadian meat processing plan is shown in Table 9.

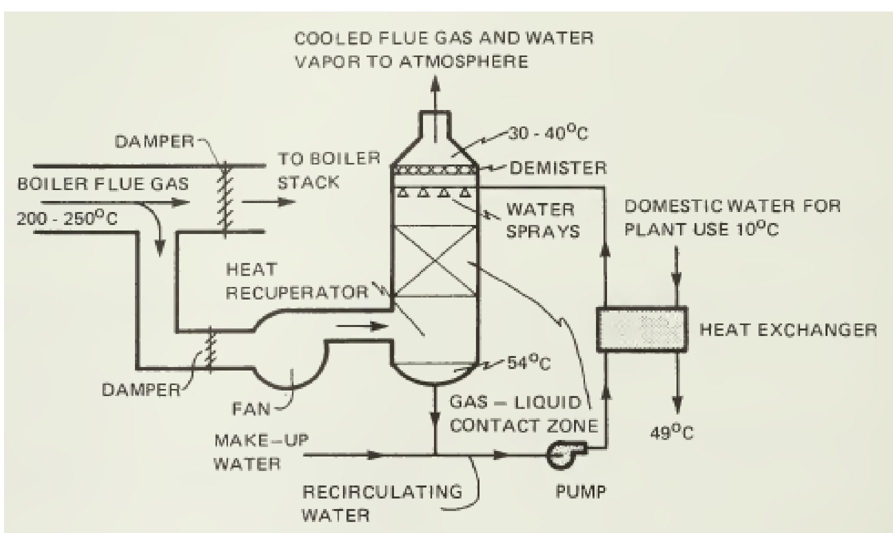

Figure 4. Rendering cookers heat recovery system.

Table 9. Financial analysis of the spiral heat exchanger for the Canadian meat processing plant.

Year	Cost $	Rate of real price increase 2%	Annual savings in current $	Discount Factor (10%)	Present value annual savings $	Accumulated present value annual savings $	Net present value savings-costs $
0	124290						
1		1.0200	50034	0.90909	45486	45485	–78804
2		1.0404	51035	0.82645	42177	87663	–36627
3		1.0612	52055	0.75131	39110	126773	2483
4		1.0824	53096	0.88301	36266	163036	38749
5		1.1041	54158	0.62092	33628	196667	72377
6		1.1262	55242	0.56447	31182	227849	103559
7		1.1487	56346	0.55316	28915	256764	132474
8		1.1717	57473	0.46651	26812	283576	159286
9		1.1951	58623	0.42410	24862	308438	184148
10		1.2190	59795	0.38554	23054	331491	207201

- ### Case study: Steam plant flue gases - Canada Packers

Canada Packers has installed a new and very efficient heat exchanger in its Winnipeg plant. A direct contact heat recuperator is used to reclaim heat from the steam plant flue gases. The flue gas flows upward through the recuperator into which cold water is sprayed. The water is recirculated with a very small amount of makeup water.

Under optimum conditions, water leaving the recuperator will have been heated to 54 °C. Flue gases will cool from 215 to 30–40°C. Dampers are installed to divert flue gases to a main stack in the event of a system failure.

The recirculated water flows through a plate heat exchanger and back to the recuperator. The clean, cold process water is preheated to 50 °C in the exchanger. Process water can be further heated with steam for use as plant hot water.

The financial analysis of the Canada Packers case study for the steam plant is shown in Table 10.

Table 10. Financial analysis for case study: Canada Packers.

Project Costs	
Recuperator and controls	$225000
Installation and auxiliaries	$175275
Total installed cost	$400275
Operating costs	
Pre-demonstration annual fuel costs	$1489600
Post-demonstration annual fuel costs	$1311000
Annual fuel savings	$178600
Added incremental annual costs	$27900
Net annual savings	$150700
Simple payback period	2.7 years

- ## Case study: Poultry scalder and desuperheater - Gold Kist

The case of Gold Kist in Elligay, Georgia, illustrates an interesting application in the poultry processing industry. The poultry scalder overflow is at 53 °C at a rate of between 75–115 L/min and contains a high level of suspended solids. The exchanger selected was a plate heat exchanger consisting of stainless steel plates. It was selected because of its compactness, high heat transfer coefficients and ease of cleaning. The researchers calculated a simple payback period in an analysis of actual operating costs, see Table 11.

Table 11. Financial analysis for case study: Gold Kist.

System	Energy savings (MJ/h)	Capital cost installed ($)	Energy cost installed ($)	Simple payback period (years)
Overflow heat recovery system	664	13287	16921	0.78
Refrigeration heat recovery system	443	29038	11515	2.5
Combined systems	1107	42325	28436	1.5

- ## Case study: The Danish Technological Institute - Industrial cleaner

Law *et al.* (2011) presented the Danish Technological Institute - Industrial cleaner, as a case study for waste heat recovery system showing the data below:

- Heat source: Humid air leaving the cleaner
- Heat sink: Hot water input to the system

- COP: 4
- Small scale: 25 kW output per unit
- Energy consumption to unit cut by 50%
- Payback time: 1.5 to 3 years (only four month into demonstration)
- Saving 49 tons of CO_2 per unit, per year

3. Non-metallic minerals

Non-metallic mineral industry includes industries such as cement, ceramics, glass, etc. (European Commission, 2017). According to Brückner *et al.* (2015), non-metallic mineral industry is one of the leading industries among others in waste heat amounts and, therefore, there is a large potential for technologies referring to Waste Heat Recovery (WHR).

WHR is most useful and has a higher potential in high temperature processes rather than in lower temperature processes. As stated by Al-Rabghi *et al.* (1993) the highest potential savings are possible at temperatures in the range of 200 °C and above. Table 12 shows the temperature ranges in different processes related to the non-metallic mineral industry (Brückner *et al.*, 2015).

Table 12. Temperature rangers of high and low temperature processes in the non-metallic mineral industry (Brückner et al., 2015)

PROCESS	EXHAUST GAS TEMPERATURE [°C]
GLASS MELTING FURNACE	1300 – 1540
GLASS OVEN WITHOUT REGENERATOR	900 – 1300
GLASS OVEN WITH REGENERATOR	600 – 800
CEMENT KILN	450 – 620
CONTAINER GLASS MELTING	160 – 200
FLAT GLASS MELTING	160 – 200
CERAMIC KILN	160 – 200
DRYING OF ROCKS, BRICKS, SAND AND OTHER MINERALS	35 – 150

According to Brückner *et al.* (2015) a high temperature process is defined when the process reaches temperatures above 400 °C, a middle temperature process at temperatures ranging from 100–400 °C and a low temperature process at temperatures below 100 °C. Hence, most of the processes in the non-metallic mineral industry may be defined as medium to high temperature processes, showing the high potential of WHR.

3.1 Technologies

Different technologies exist for WHR purposes in non-metallic mineral industry. Ammar *et al.* (2012) stated that high-grade heat and low grade-heat are the two main definitions in WHR applications. They defined that a high-grade heat recovery technology is used when the heat is available to be captured within the process. On the other hand, a low-grade heat recovery system is used when the heat is released to the environment and is not available to be captured within the process. The latter needs a heat transfer medium to transfer the wasted heat from the source to the WHR system. The medium is a working liquid and such liquids could be cryogens (liquified nitrogen, oxygen, liquified natural gas etc.), CO_2, ethanol, thermal oil and others. Most of the non-metallic mineral industries may be categorized as low-grade heat industries and mostly WHR technologies for low-grade heat capture are usually used for power generation with the aid of the Ranking Cycles.

A report published by the U.S. Department of Energy in 2008 (U.S. Department of Energy, 2008) distinguished the different WHR technologies used in different industrial sectors. Particularly, in Glass manufacturing regenerators, recuperators are mostly used for WHR, whereas in Cement industry WHR technologies are mainly used for power generation and meal preheating. In general, WHR technologies available in the non-metallic mineral sector are listed below, with related literature discussed in the following section.

- Regenerators
- Recuperators
- Heat exchangers
- Air Bottoming Cycle
- Waste Heat Recovery Steam Generator
- Ranking Cycles (Organic Ranking Cycles, Steam Ranking Cycles, Kalina Ranking Cycles)

The last one is a common technology as it is found to be a promising technology in terms of WHR rates, efficiency and payback period. Among other common WHR technologies are the thermoelectric generation and the piezoelectric power generation, which are referred to as solid state generation. However, these are emerging technologies that have not been applied in a large scale and it is difficult to find applications using these techniques (Lu *et al.*, 2016). Table 13 summarizes the different statuses of the WHR technologies used in the Cement and Glass manufacturing.

Table 13. Status of Conventional and Emerging Waste Heat Technologies reproduced from (U.S. Department of Energy, 2008)

	GLASS		CEMENT
WHR TECHNOLOGY	**Gas fired Melting Furnace**	**Oxyfuel Melting Furnace**	**Cement Kiln**
REGENERATOR	✓	✓	N/A
RECUPERATOR	✓	✓	N/A
HEAT WHEEL	✓*	✓	N/A
PASSIVE AIR PREHEATER	N/A	✓*	N/A
WASTE HEAT BOILER	N/A	✓	✓
LOW TEMPERAT. POWER CYCLE	N/A	N/A	✓
SOLID STATE GENERATION	N/A	N/A	N/A
LOAD PREHEAT	N/A	✓	✓

* Application specific
N/A: Not addressed

3.2 Case Studies

Peris *et al.* (2015) used Organic Ranking Cycle (ORC) technology in a ceramic industry for low grade heat recovery. The recovery facility consists of a recuperator, a heat exchanger and a heat transfer loop for transferring heat from the furnace (heat source) to the ORC unit. A gross electrical efficiency and a net electrical efficiency of 12.47% and 10.94%, respectively, were achieved. A feasibility study of the application was also carried-out and showed an annual electricity generation of 120886 kWh, a Net Present Value (NPV) for 15 years of €138286, an Internal Rate of Return (IRR) of 22.88% and a Payback Period (PBP) of 4.63 years.

Forni *et al.* (2012) studied the application of the ORC in industries such as Cement and Glass. In the cement industrial plant, two heat sources were used for the heat recovery system. The waste heat streams were the gas of the kiln after the pre-heating of the raw material and the clinker cooler, which cools the final product (clinker) once it exits the kiln. Thermal oil is used for transferring the waste heat to the ORC module. For the cement plant, the results showed a net electricity generation of 36.340 kWh/year, an IRR of 9% for 10 years, an NPV of €1.050.000 for 10 years and a PBP of 9.2 years. In the glass industrial plant, WHR during the float glass production process was studied. Specifically, the waste heat from the exhaust gas of the float glass furnace is transferred to the ORC with the aid of a heat exchanger and a thermal oil. The results in this application showed a net electricity production of 8.910 kWh/year, an IRR of 11% for 10 years, a NPV of €500.000 for 10 years and a PBP of 8.2 years.

Casci *et al.* (1981) used ORC technology in a ceramic production plant, during the ceramic firing process in a tile tunnel kiln. Using the exhaust gases at middle range temperatures the heat was transferred to the ORC engine using thermal oil as the heat transfer liquid. The schematic of the recovery technology is shown in Figure 5.

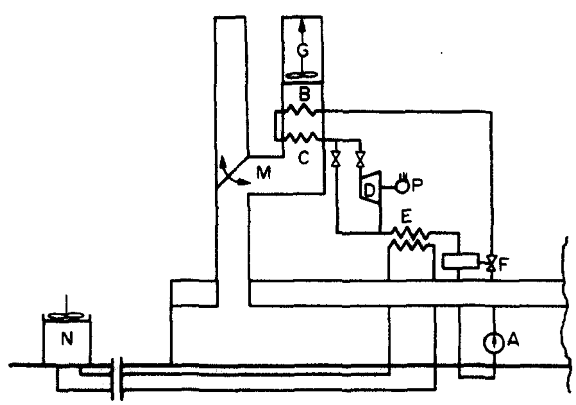

Figure 5: "Simplified scheme of the recovery plant: A = Feed pump; B = Pre-heater; C = Vaporizer; D = Turbine; E -- Condenser; F = Constant level hotwell; G = Auxiliary fan; H = Stack; L = By-pass stack; M = By-pass valve; N = Cooling tower; P = Alternator" (Casci et al., 1981)

The test results showed that an overall efficiency of 80% was achieved. Finally, the economic analysis showed a minimum and maximum PBP of 2.86 and 4 years for an operational time of 7000 hours/year, and a minimum and maximum PBP of 2.5 and 3.5 years for an operational time of 8000 hours/year. An IRR of 18% is also possible for a life expectancy of 5 years.

Korobitsyn (2002) proposed the application of an Air Bottoming Cycle (ABC) in a Glass industrial plant, during the glass-melting process, in a glass-melting furnace. The author's interest on ABC module is due to its simplicity and low operational and maintenance costs. As mentioned in the study, the temperatures in glass-melting furnaces such as regenerative, recuperative and oxy-fuel furnaces may reach 600, 900 and 1200 °C, respectively. Thus, there is a significant potential for waste heat recovery. Figure 6 shows the simple architecture of the proposed system.

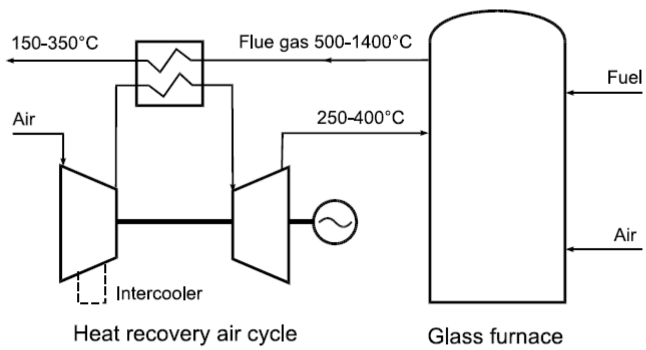

Figure 6: Waste heat recovery by ABC (Korobitsyn, 2002)

The results for each type of furnace (regenerative, recuperative and oxy-fuel) showed that: (1) the electrical power generated was 430 kW, 1085 kW and 934 kW, respectively; (2) the heat recovery efficiency was 10.9%, 21.2% and 25.9%, respectively; (3) the exergy was 17.4%, 28.1% and 31.1%, respectively; (4) the payback period was 3.7 years, 3.4 years and 3.4 years, respectively; (5) the NPV was €390000, €1130.000 and €970000 (considering today's currency rate), respectively; (6) the IRR was 18.7%, 21.6% and 21.6%, respectively.

Engin & Ari (2005) studied the case of heat recovery in a dry type cement rotary kiln systems by proposing a Waste Heat Recovery Steam Generator (WHRSG). The schematic is shown in Figure 7.

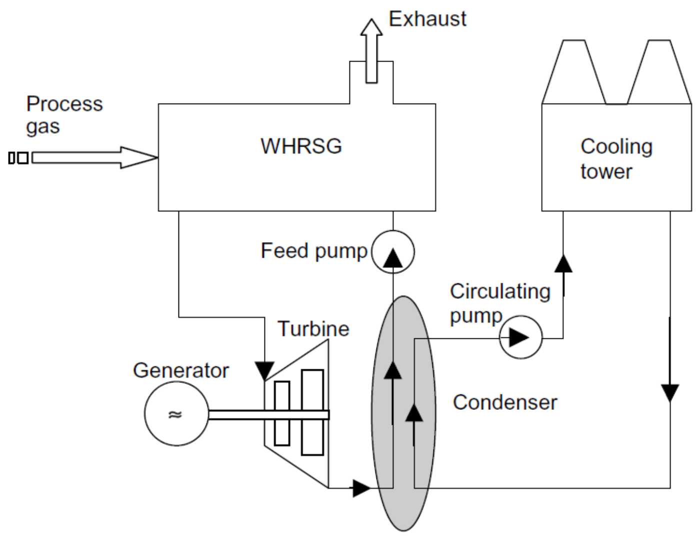

Figure 7: "Process schema of a typical WHRSG application" (Evgin and Ari, 2005)

The heat streams used in the proposed scheme were the waste heat from the clinker cooler and the kiln exhaust gas, which have an average temperature of 215 °C and 315 °C, respectively. Both streams are supplied to the circulating water inside the WHRSG unit, so that steam is produced that subsequently drives a turbine, resulting to the generation of electrical energy. The authors calculated the savings and found that up to 8 GWhr/year could be saved, resulting to a total savings of 560000 $/year and a PBP of 17 months, assuming a total implementation cost of $750000.

Rasul *et al.* (2005) assessed the benefits of the energy conservation of the heat recovery from both the kiln exhaust gas and the cooler exhaust gas in a cement plant in Indonesia. The waste heat from the kiln exhaust gas was utilized for drying the raw materials in the clay dryer and drum dryer, resulting to savings of 74497 $/year (using today's currency rate). The waste heat from the cooler exhaust was used for preheating the primary air to the kiln system, which showed that an additional annual saving of $5054 (using today's currency) on top of the heat recovery technique from the kiln exhaust gas was possible.

Khurana *et al.* (2002) reported that the waste heat loss of a cement plant in India was about 35%. As a result, the authors studied the potential of increasing the efficiency of the system through a waste heat recovery technique, known as WHRSG. The heat recovery unit was used for generating electrical energy that improved the total primary energy efficiency of the plant by 10%. Results showed that the 30% of the total electrical energy used by the plant was completely covered by the electrical energy generated from the recovery unit. The overall recovering scheme is shown in Figure 8.

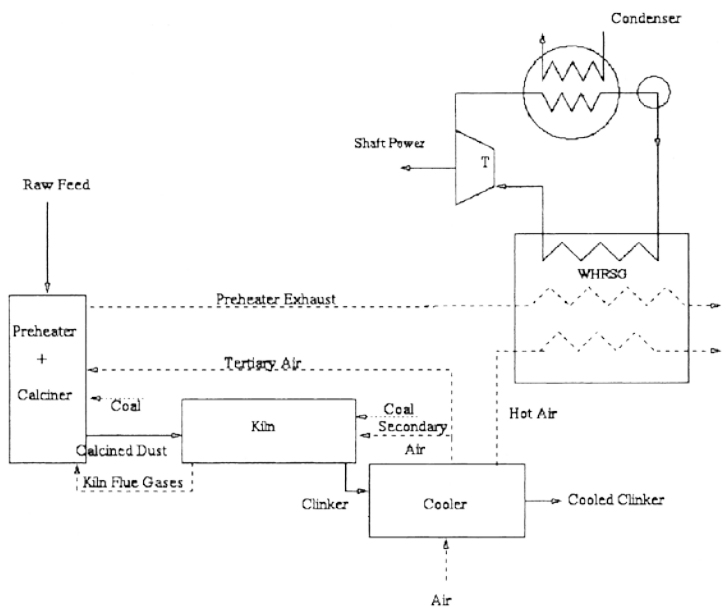

Figure 8: "Schematic for the power generation system" (Khurana et al., 2002)

The feasibility study showed that $1020000/year (using today's currency) was saved with an estimated PBP of 2 years.

Based on the literature presented waste heat recovery technologies are very important for non-metallic industry as they achieve significant savings as well as the improvement of the overall efficiency of the plant. Table 14 summarizes the results of the different case studies presented above.

Table 14. Summary results of literature

REFERENCE	INDUSTRY	PROCESS	WHR TECHNOLOGY	EFFICIENCY [%]	ANNUAL ELECTRICITY GENERATION [kWh/YEAR]	NPV [€]	IRR [%]	PBP [YRS]
Peris et al. (2015)	Ceramic	Furnace	ORC	10.94	120886.00	138286	22.88	4.63
Forni et al. (2012)	Cement	Kiln & clinker cooler	ORC	n/a	36340.00	1050000	9	9.2
	Glass	Float glass furnace	ORC	n/a	8910.00	500000	11	8.2
Casci et al. (1981)	Ceramic	Tile tunnel kiln	ORC	80(1)	n/a	n/a	18	4
Korobitsyn (2002)	Glass	Glass-melting furnace (regenerative)	ABC	10.9	430(3)	390000	18.7	3.7
		Glass-melting furnace (recuperative)		21.2	1085(3)	1130000	21.6	3.4
		Glass-melting furnace (oxy-fuel)		25.9(2)	934(3)	970000	21.6	3.4

Engin & Ari (2005)	Cement	Dry-type rotary kiln	WHRSG	48.7(2)	8000000	n/a	n/a	1.38
Rasul et al. (2005)	Cement	Kiln & cooler	n/a	51.2(2)	n/a	n/a	n/a	n/a
Khurana et al. (2002)	Cement	Preheater, Calciner, Kiln, Cooler	WHRSG	10(5)	4400	n/a	n/a	2

(1) Overall efficiency (2) Heat recovery efficiency
(3) Electrical Power (4) Of total primary energy efficiency

4. Cement Industry

Cement manufacturing is one of the largest energy consumers and CO_2 emitters, with an estimated 1.9 Gton of CO_2 emissions from thermal energy consumption and production processes in 2006 (International Energy Agency, Energy Technology Transitions for Industry, 2009). If Best Available Technologies can be adopted in all cement plants, this would result in CO_2 savings of around 119 Mton (International Energy Agency, Tracking Clean Energy Progress, 2012).

There are four main operation processes of cement production, namely the mining and quarrying, the raw material preparation, the clinker making and the finish grinding (KEMA, 2005). Clinker production in the kiln reaches temperatures of around 1500 °C and it is responsible for 90% of the total industry energy use. In modern plants, hot exhaust gases are used for pre-calcination, for pre-heating the raw meal and may also be used for additional energy recovery, thereby helping to reduce energy consumption (Worrell, Kermeli, & Galitsky, 2013).

The waste heat recovery technologies commonly used in cement industry are briefly presented below together with associated case studies.

4.1 Waste Heat Recovery for Power Generation

Waste heat from cement kilns is usually used for drying of raw materials and fuel. Depending on the humidity of the raw materials and the technology of the cooler, additional waste heat is available from the kiln gases (preheater exit gas) and cooler exhaust air. This heat can be used for electricity production. Power can be produced by using a steam cycle, an organic Rankine cycle (ORC), or the Kalina process. While in modern power plants the electric efficiency comes up to 45%, the relatively low temperature level of the waste heat in cement plants (200–400 °C) limits the efficiency to a maximum of 20–25%. However, 25–30% of the plant's power demand can be met through generating power from waste heat (Industrial Efficiency Technology Database), (CSI/ECRA, 2009) (Amiri & Vaseghi, 2015), (Gorbatenko, Sharabaroff, Hedman, & Shah, 2014). Worrell *et al.* have presented that heat recovery for cogeneration can result in significant electricity savings of up to 30%, primary energy savings of up to 10% and electricity savings of 20 kWh/ton clinker (Worrell, Kermeli, & Galitsky, 2013).

Steam turbine heat recovery systems were first developed and implemented in Japan and have by now been widely adopted in Europe and China (Hebei Quzhai Cement and SDIC Hainan Cement Co., Ltd.). Kawasaki Heavy Industries (KHI) put the first waste heat recovery system into operation at Sumitomo Osaka Cement (1980), with a capacity of 15 MW, at Taiheiyo Cement's Kumagaya plant. China installed its first system in 1998, and by 2012 over 700 units were operating in that country (Gorbatenko, Sharabaroff, Hedman, & Shah, 2014). Installation costs for steam systems range from \$2–4/annual ton cement capacity with operating costs ranging from \$0.2–0.3/annual ton cement capacity (U.S EPA, 2010). Generally, only long dry kilns produce exhaust gases with temperatures high enough to make heat recovery for power economical. Heat recovery installations in Europe and China include long dry kilns with preheaters (U.S EPA, 2010).

A 4100 ton/day cement plant in India (OCL India Limited), installed a waste heat recovery power plant using the exhaust from the preheaters and clinker cooler. The power plant was rated at 8

MW. Capital investment was $18.7 million, and CO_2 emission reductions were reported to be 49000/year (U.S EPA, 2010).

Moreover, 9 of the 24 existing cement plants in Pakistan have installed waste heat recovery systems representing 100 MW of capacity. Eight of nine systems are based on conventional steam technology. FLSmidth, which has an exclusive global license for the Kalina cycle in the cement and lime industries, has installed an 8.5 MW Kalina unit on a 7000 ton/day clinker line at D.G. Khan Cement's Khaipur plant (Gorbatenko, Sharabaroff, Hedman, & Shah, 2014).

The Philippines cement industry has installed 3 waste heat recovery power generation systems with a total capacity of 17.5 MW. For example, Cemex Antipolo Plant with 8000 ton/day capacity has since 2012 a 6 MW waste heat recovery power generation system, with a total installed cost of $18.6 million (Gorbatenko, Sharabaroff, Hedman, & Shah, 2014).

4.2 Optimized Heat Recovery in Clinker Cooler / Optimize Grate Cooler

The clinker cooler drops the clinker temperature from 1200 °C down to 100 °C. Heat recovery can be improved through reduction of excess air volume, control of clinker bed depth and new grates such as ring grates. Control of cooling air distribution over the grate may result in lower clinker temperatures and high air temperatures. A recent innovation in clinker coolers is the installation of a static grate section at the hot end of the clinker cooler. This has resulted in improved heat recovery and reduced maintenance of the cooler. Modification of the cooler would result in improved heat recovery rates of 2–5% over a conventional grate cooler. Savings of 0.05–0.16 GJ/ton clinker through the improved operation of the grate cooler is reported. Investments are estimated at $0.1–0.3/annual ton clinker capacity with an estimated payback period of 1–2 years (Industrial Efficiency Technology Database), (Worrell & Galitsky, 2008).

4.3 Heat Recovery for Water Preheating

As much as 80–93% of the electrical energy used by an industrial air compressor is converted into heat. In many cases, a heat recovery unit can recover 50–90% of this available thermal energy for space heating, industrial process heating, water heating, makeup air heating, boiler makeup water preheating, industrial drying, industrial cleaning processes, heat pumps, laundries or preheating aspirated air for oil burners. Heat recovery for space heating is not as common with water-cooled compressors because an extra stage of heat exchange is required and the temperature of the available heat is lower. However, with large water-cooled compressors, recovery efficiencies of 50–60% are typical. Payback period is less than one year (Worrell, Kermeli, & Galitsky, 2013), (Worrell & Galitsky, 2008).

Table 15. Summary for the case studies applying waste heat recovery technologies in cement industry

Waste Heat Recovery Technology	Fuel Savings (MBtu/ton cement)	Electricity Savings (kWh/ton cement)	Waste heat recovery Efficiency (%)	Estimated Payback Period (years)	Capital Costs ($/annual ton cement capacity)
Heat Recovery for Power Generation	-	**18** (Worrell, Kermeli, & Galitsky, 2013), (Worrell & Galitsky, 2008) **7–20** (U.S EPA, 2010) **8–22** (Industrial Efficiency Technology Database)	**20–25** (U.S EPA, 2010) **22.7** (Priyadarshini & Sivakumar, 2014) **25–30** (Thekdi & Nimbalkar, 2015)	**2–14** (Worrell, Kermeli, & Galitsky, 2013)	**2–4** (U.S EPA, 2010)
Optimized Heat Recovery in Clinker Cooler/ Optimize Grate Cooler	**0.06–0.12** (Worrell & Galitsky, 2008) **0.04–0.13** (Worrell, Kermeli, & Galitsky, 2013)	**0– -1.8** (Worrell & Galitsky, 2008) **0– -1.7** (Worrell, Kermeli, & Galitsky, 2013)		**1–2** (Worrell & Galitsky, 2008) **2–7** (Worrell, Kermeli, & Galitsky, 2013)	**0.11–0.33** (Industrial Efficiency Technology Database)
Heat Recovery for Water Preheating		**0–2** (Worrell, Kermeli, & Galitsky, 2013)	**50–60** (Worrell & Galitsky, 2008)	**< 1** (Worrell & Galitsky, 2008) **< 3** (Worrell, Kermeli, & Galitsky, 2013)	

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