Waste heat recovery: technologically and economically viable solutions for industrial businesses

A white book on industrial waste heat recovery

Fives 2017
Preface

Scarcity of resources and global warming are still two major issues for the early 21st century. To achieve sustainable development, the origin and the use of energy have to be addressed, and advanced energy technologies for both fossil and renewable energy carriers have to be developed, requiring significant progress in research and technology. Recent international crises leading to rising oil prices (even if in the last few years the relatively low cost has hidden this resource's impending depletion) and major natural disasters that climate change could be driving, have made the public aware and more sensitive to energy issues and the impact of global warming. The COP21 conference held in Paris at the end of 2015, which resulted in a global agreement between nations to take positive action against climate change, marked the birth of a new hope for mankind and a visible signal to increase efforts in researching safe, efficient, and sustainable systems.

Therefore, the scientific and engineering communities have to develop and prove the technical and economic availability of innovative energy technologies. However, there is no single solution, but rather a set or combination of measures, which have to be adapted at the local level: we should think globally but act locally. The scientific community not only has to design and develop advanced energy technologies, but also to contribute in improving the existing ones. Despite the fact that renewable energies and new energy carriers, such as hydrogen, are promising solutions, our society is still relying on fossil fuels as a primary energy source for many applications. Last but not least, energy conservation and energy efficiency must be promoted, and the best energy is the one that is not consumed. The only way to meet the sustainable energy challenge is to strengthen collaboration between the various sectors and to promote an exchange of knowledge and experience between countries.

CEA Tech, CEA’s entity involved in promoting applied technological research to industry, is obviously committed to this approach, and every action that contributes to the energy efficiency challenge is important. Fives has been promoting this approach for several years in various industrial applications. The Group’s multi-sector expertise allows them to offer this useful guide on technical issues to implement heat recovery and re-use into industrial processes. Through applied examples in relevant markets (cement, aluminium, steel, glass), this white book on industrial waste heat recovery presents energy stakes and technological challenges that will be able to guide any professional concerned by energy, from the global to the local level. Some of the answers are already or almost available (Heat exchangers, Sorption Systems, Organic Rankine Cycle), but even if technological and environmental breakthroughs change the stakes in the near future, the finding and methods presented by Fives in this white book will still be relevant. As such, there is no doubt that the whole scientific and industrial community concerned by the energy efficiency of industrial processes will welcome this initiative.

Patrice Tochon

CEA Tech

Directeur of the Thermal, Biomass and Hydrogen Technologies Department

The French Alternative Energies and Atomic Energy Commission (CEA) is a key player in research, development and innovation in four main areas: defence and security, nuclear energy (fission and fusion), technological research for industry, fundamental research in the physical sciences and life sciences.

Drawing on its widely acknowledged expertise, the CEA actively participates in collaborative projects with a large number of academic and industrial partners.
About Fives

Fives is an industrial engineering Group with a heritage of over 200 years of engineering excellence and expertise. Fives designs and supplies machines, process equipment and production lines for the world’s largest industrial groups in various sectors such as aluminium, steel, glass, automotive, logistics, aerospace, cement and energy, in both developing and developed countries.

In all of these sectors, Fives designs and manufactures equipment and innovative solutions, which better anticipate and meet the needs of its customers in terms of performance, quality, safety and respect for the environment.

In 2015, Fives achieved a turnover of 1.7 billion euros and employed about 8,000 people in over thirty countries.

In 2012, Fives created a think tank: the Plants of the Future Observatory. This Observatory is committed to initiating an open discussion about the industry of tomorrow and to disseminating these views to the public. More on www.plantsofthefuture.com.
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Table of contents

Preface p.1
About Fives p.2
Authors & Contact p.3

Enhancing energy efficiency in industrial processes p.5
1. Introduction
2. Waste heat recovery, the next challenge of energy-intensive industries
3. Energy conversion technologies

Challenges & solutions by industrial sector p.14
1. Cement p.15
2. Aluminium p.21
3. Glass p.27
4. Steel p.32
5. Recommendations for making an investment in waste heat recovery p.40

Appendices p.42
Key references p.43
Glossary p.44
Definitions p.45

Each focus per industrial sector provides insight into the context, the industry-specific challenges as well as the solutions that can be developed to recover waste heat. Also, quantified case studies illustrate the potential gains.
Enhancing energy efficiency in industrial processes
1. Introduction

As global competition rises, developed countries strive to remain competitive, protect their industry and keep their manufacturing jobs. Some of these economies, such as Germany, France, the US and China, have launched programs to help their national industries achieve the transition that will ensure their long-term sustainability, competitiveness and attractiveness. However, the challenges of reinventing industry once more are substantial, both economically and socially, as well as in terms of environmental impacts.

Industry is responsible for 32% of worldwide greenhouse gas emissions, i.e. about 16 billion tonnes of CO₂ equivalent, including indirect emissions due to electricity used in industrial plants¹. At a time when natural resources are stretched and climate change is the opponent, the environmental aspect is now a crucial factor of performance in the business world. As a matter of fact, industrialists are now looking for ways to generate a smaller footprint and set new objectives for the energy transition.

Fives, an industrial engineering group, designs technologies for industries that are exposed to environmental challenges and some of the most energy-intensive industries (production of aluminium, cement, steel, glass, etc.). As a participant in a more sustainable industrial future, Fives aims for exemplarity in terms of energy efficiency and environmental performance for all of its products and, in 2012, created an internal eco-design program called Engineered Sustainability®. Thus, the Group supplies equipment that enhance energy efficiency, such as high efficiency furnaces for various industries, compact heat exchangers, burners adapted to alternative fuels (biomass, waste, industrial gases), smart control systems enabling maximum energy efficiency and flexibility, as well as energy storage technologies and waste heat recovery systems and their integration into industrial processes.

As a manufacturer & designer of industrial equipment and plants, Fives brings strong process knowledge to its customers. This process expertise not only allows Fives to minimize heat losses and re-use energy within the process; but also to recapture residual energy losses using external energy recovery systems. The latter is called waste heat recovery (WHR) and is the next frontier in terms of energy efficiency for energy-intensive industries.

Fives is committed to overall optimization, meaning that when its teams design a WHR system, they make sure that it does not lead to energy losses or operational issues in other parts of the customer’s process. As such, Fives’ robust and competitive solutions meet the challenges associated with waste heat recovery systems, such as production continuity and variability of energy supply. A multi-industries player, Fives also benefits from experience acquired in various energy-intensive sectors meeting similar challenges, and provides unbiased advice regarding WHR technology choice.

This white paper aims to provide a better understanding of the industry-specific challenges faced by the Aluminium, Cement, Glass and Steel sectors. It also illustrates some WHR solutions offered by Fives for these industries, and the associated gains. These solutions are new, or are adaptations of state-of-the-art designs that lead to higher performance.

¹ According to IPCC. 2010 data
2. Waste heat recovery, the next challenge of energy-intensive industries

Given their share in the world’s greenhouse gas emissions, reduction of emissions from industries is critical to achieving the world’s commitment to fight climate change. Reducing the use of raw materials such as steel, aluminium and glass, whose production is highly energy- and CO₂-intensive, is a viable option supported by recycling and circular economy programs but will not be sufficient. Another way to decrease CO₂ emissions of processes that are energy intensive and intrinsically CO₂ generators such as the cement process is to substitute the high energy footprint component (the clinker in that case²).

An increase in demand for primary materials is actually expected: more aluminium (lighter than steel) will be used to build cars and planes³, demand for high quality cement and glass will increase to build energy-efficient buildings, high quality steel is needed to build wind turbines... This increased demand goes along with a need for enhanced quality: materials must be lighter, stronger, and have a longer lifetime. Industry players are working on new industrial processes able to achieve the challenge of meeting quality specifications like these without using more energy.

Improving energy efficiency has already been a focus of manufacturers’ Research & Development efforts for decades and notable progress has been made. For instance, the energy intensity (amount of energy required to produce one tonne of steel) in the US steel industry is now only 30% of what it used to be in the 1980s⁴.

More recently, new emphasis has been put on using renewable and recycled fuels in industrial processes. That includes biomass plants generating power for an industrial process, waste upgraded as fuel (e.g. tires burned in cement plants), as well as recycling gas generated on-site as a by-product (coke-oven gas or blast furnace gas) in steel furnaces.

Figure 1
Energy efficiency and measures for cutting greenhouses gases in an industrial plant

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² Clinker can be partially substituted with industrial waste such as blast furnace slag, or with gypsum - from desulphurization (sulfo-gypsum) or from the fertilizer industry (phosphor-gypsum).
³ +22% demand in aluminium for transport in 2050, in IEA’s BLUE Map scenario compared to « business as usual » (source: Energy technology transitions for Industry, International Energy Agency, 2009, chapter 8. BLUE Map scenario corresponds to dividing world’s CO₂ emissions by two in 2050)
Once a process has been made more efficient and its inputs have been substituted with low-impact sources, the next thing that can be improved is the process outputs, i.e. minimizing losses (Figure 1). In an industrial process, losses can be materials as well as wasted energy (Figure 2). Recovery and re-use of waste energy (which is most often heat) will be the focus of this white book.

Special emphasis is given to re-using waste energy in another part of the plant or outside the plant. Re-use within the equipment (e.g. recirculation of a furnace’s flue gases inside the furnace) is already commonly implemented and this document will focus on solutions to recover remaining waste heat once all opportunities for internal re-use have been exploited.

![Figure 2](image2.png)

**Figure 2**
Definition of industrial waste heat recovery

According to the International Energy Agency (see Figure 3 below), energy efficiency and fuel and feedstock switching (use of renewable energy and materials) will make the biggest contributions to fighting climate change along with carbon capture and storage (CCS). Energy / waste heat recovery together with recycling is expected to bring 9% of the necessary emissions reduction. The world cannot afford to neglect the contribution of waste heat recovery, especially as CCS is taking off slower than expected.
Approximately 4,000 TWh of heat are wasted every year in the world, which corresponds to emissions of 2,800 million metric tonnes of CO₂ (source: US Department of Energy and ADEME). The European organization Energy Efficiency in Industrial Processes (EE-IP) has estimated that waste heat recovery has a CO₂ emission reduction potential of 250 million tonnes/year in Europe\(^5\). This corresponds to half of the emissions generated annually by the worldwide aluminium industry.

Another challenge that manufacturers will need to address is flexibility. Today, as market conditions, customer requirements, technological opportunities and even climate conditions rapidly change, constant production over decades is no longer the norm for industrial plants. Factories need to become more flexible and capable of delivering an output that varies in nature and quantity. Energy flexibility is one aspect of this need, and industrial plants will increasingly make use of demand response and energy storage in order to be less vulnerable to the fluctuations of energy markets and take advantage of them instead.

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3. Energy conversion technologies

Recovery of wasted energy can be achieved using energy conversion technologies. These technologies can be classified depending on the type of energy input (thermal energy or waste heat, which will be the focus of this document, and other types such as pressure or motion), and on the type of energy output.

Waste heat recovery technologies include:

- Heat exchangers and heat storage solutions, which do not convert energy but simply transfer it to another medium or store it to make it available upon demand
- Heat pumps, which increase the temperature of a heat source
- Steam boilers, that use waste heat to produce steam for use in the plant (widely implemented in industrial processes)
- Classic thermodynamic cycles, based on the phase change of a fluid, to produce electricity with a turbine or directly drive a rotating machine in the plant (mechanical drive)
- Alternative technologies to produce electricity without rotating machines and phase change fluids (e.g. thermoelectricity)
- Cold power production, by converting heat into cold by means of various physics phenomena
- Feeding an endothermic chemical or biological reaction, to sell the end-product or to perform energy storage in case of a reversible reaction.

Technologies to recover energy that is not in the form of heat include:

- Hydraulic turbines, taking advantage of a pressure decrease on a fluid
- Energy harvesting devices recovering kinetic energy or the energy of electromagnetic waves.

All of the technologies listed above do not have the same degree of maturity; a short description of each technology is provided in the table below. Typical conversion efficiencies have not been provided, on purpose, in order to stress that it should not be the only driver of technology choice as waste heat is ‘free’. Moreover, it is not as relevant because other factors have an impact on the efficiency of the overall system such as:

- minimum temperature of the waste heat source (usually determined by the acid dew point of flue gases\(^6\)): energy is hardly recoverable below this point because of acid corrosion and exchanger blockage. The residual energy will remain wasted in general as it is too expensive to recover\(^7\).
- energy losses in equipment used to recover and transport heat: heat exchangers, intermediate heat transfer loop in case it is necessary, pumps and coolers used in the cold source.

Capital expenditure (CAPEX) investment and operating expenses (OPEX) savings, as well as variations in the process (inducing benefits or disruption) and other elements such as maintenance, size, safety and environmental impact are strong criteria for industrial manufacturers to select the most suited WHR solution.

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\(^6\) See definitions of ‘acid dew point’ and ‘flue gases’ in the Definitions section at the end of this document

\(^7\) Some technologies under development (e.g. heat exchangers made of plastics) will make recovery of energy below the acid dew point possible
### A/ Waste heat recovery technologies using classic thermodynamic cycles

<table>
<thead>
<tr>
<th>Output</th>
<th>Technology</th>
<th>Principle</th>
<th>Fluid</th>
<th>Heat source power and temperature range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heat</td>
<td>Thermodynamic heat pump</td>
<td>External energy input (usually electricity) to increase temperature of waste heat source</td>
<td>Refrigerant fluids</td>
<td>Up to 100°C with high-temperature heat pumps</td>
</tr>
<tr>
<td></td>
<td>Rankine Water-steam cycle</td>
<td>Cycle using a fluid undergoing a phase change</td>
<td>Water</td>
<td>&gt; 400°C from 1 MWth to &gt; 100 MWth for high power, combination of smaller modules is possible</td>
</tr>
<tr>
<td></td>
<td>Micro Rankine cycle*</td>
<td></td>
<td>Water or organic fluid</td>
<td>&gt; 100°C 100 kWth to 10 MWth</td>
</tr>
<tr>
<td></td>
<td>Organic Rankine Cycle (ORC)</td>
<td></td>
<td>Hydrocarbons or refrigerant fluids</td>
<td>100-400°C 1 MWth to 10 MWth</td>
</tr>
<tr>
<td>Electricity or Mechanical drive</td>
<td>Stirling “hot air engines”</td>
<td>Heating of a fluid placed in a regenerator between two pistons No phase change, closed cycle</td>
<td>Air, hydrogen, helium or CO₂</td>
<td>Very large range: 150-800°C Small modules from 500 Wth to 75 kWth</td>
</tr>
<tr>
<td></td>
<td>Ericsson</td>
<td>Heating and compression of ambient air No phase change, open cycle, no fluid</td>
<td>Air</td>
<td>700°C</td>
</tr>
<tr>
<td></td>
<td>Brayton (gas turbine)</td>
<td>Closed cycle gas turbine: gas turbine using waste heat instead of a combustion chamber</td>
<td>Air or helium</td>
<td>&gt; 500°C</td>
</tr>
<tr>
<td></td>
<td>Supercritical cycles (Rankine and Brayton)</td>
<td>Same as Rankine and Brayton cycles but without phase change as fluid is in supercritical state</td>
<td>Water, H₂, N₂, hydrocarbons or CO₂</td>
<td>Same as Rankine or Brayton cycles but with better efficiency</td>
</tr>
</tbody>
</table>

*use a biphasic turbine capable of operating with low admission pressure (~2 bar) and weak flowrates (~5t/h)
## B/ Waste heat recovery technologies without rotating machines

<table>
<thead>
<tr>
<th>Output</th>
<th>Technology</th>
<th>Principle</th>
<th>Conversion medium</th>
<th>Heat source power and temperature range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electricity</td>
<td>Thermoelectricity</td>
<td>Conversion of a heat gradient into electricity (Seebeck effect)</td>
<td>Semi-conductor</td>
<td>From 200°C, best above 500°C Up to 500 We</td>
</tr>
<tr>
<td></td>
<td>Heat exchanger</td>
<td>Transfer of heat from one fluid to another</td>
<td>n/a</td>
<td>Any temperature</td>
</tr>
<tr>
<td>Heat</td>
<td>Heat storage</td>
<td>Storage of heat in an adequate material for later use or for transforming</td>
<td>Sensible heat: rock, ceramic Latent heat: paraffin, molten salt</td>
<td>Up to 300°C with latent heat storage</td>
</tr>
<tr>
<td>Steam</td>
<td>Steam boiler</td>
<td>Water evaporation</td>
<td>Water</td>
<td>Interesting starting from 150°C to &gt; 500°C</td>
</tr>
<tr>
<td>Cold power</td>
<td>Absorption machines</td>
<td>Absorption then desorption of a refrigerant fluid (e.g. water) into a LiBr solution</td>
<td>LiBr or NH₃</td>
<td>From 70°C to 110°C 10kWₜ to 10 MWₜ for high power, combination of smaller modules is possible</td>
</tr>
<tr>
<td></td>
<td>Adsorption machines</td>
<td>Similar to absorption but uses a solid adsorbent</td>
<td>Zeolites, silica gel</td>
<td>from 55°C to 100°C 10 kWₜ to 500 kWₜ for high power, combination of smaller modules is possible</td>
</tr>
<tr>
<td>Other</td>
<td>Thermochemical conversion</td>
<td>Feeding of an endothermic chemical or biological reaction, to manufacture a valuable product</td>
<td>Variable</td>
<td>Depends on the reaction Up to 550°C for heat storage (lime humidification)</td>
</tr>
<tr>
<td></td>
<td>Thermal water desalination</td>
<td>Multi-stage distillation of seawater</td>
<td>Membrane</td>
<td>70-80°C (MED process)</td>
</tr>
</tbody>
</table>

As a general rule, it is possible to combine several modules to reach a higher power. The module size can be the maximum (power limit of the technology), or a standard size to lower the cost.

The charts below give an approximate representation of the technologies’ operating ranges (power and temperature).
Figure 4
Waste heat recovery technology for electricity production depending on hot source power and temperature
(Fives, CEA)

Figure 5
Waste heat recovery technologies depending on hot source power and temperature for cold production
(Fives, CEA)
Challenges & solutions by industrial sector
1. Cement

Among energy-intensive industries, cement is the one where waste heat recovery (WHR) has been most developed. As early as the 1980s, Japanese companies spearheaded the introduction of WHR power systems in the cement industry and it is now considered a proven technology. However, WHR uptake has remained limited except in China. There are over 850 WHR power installations in the world, including 739 in China, mainly classic Rankine-cycle steam-based installations (source: IIP and IFC, Waste Heat Recovery for the Cement Sector, 2014).

![Figure 6](image_url)

**Figure 6**
Current WHR installations in cement industry
(OneStone Research / CemPower 2013, Latest Waste Heat Utilization Trends, quoted by IIP & IFC)
In areas where electricity supply is not reliable, even if the price of electricity is low, WHR can be advantageous as it allows the plant to be more self-sufficient.

Progress made on the energy efficiency of the clinker production process resulted in a decrease in temperature of cement kilns’ exhaust gases. The waste heat temperatures of new cement plants are too low to use classic steam cycles, while interest in Organic Rankine Cycles (ORC), which work at lower temperatures, is on the rise.

**Waste heat sources**

There are two main waste heat sources in the cement production process: flue gases from the pre-heater, and exhaust air from the clinker cooler. The former are often used to dry raw materials when necessary, thus only the second source (clinker cooler exhaust air) may be available in humid countries.

Temperatures and flow rates are shown on the illustration below for a typical cement plant:

![Figure 7](image)

**Figure 7**

Waste heat sources in the cement process

*(source: Fives data & references)*

**Industry-specific challenges**

Waste heat sources are gases with high dust content, which can be as high as 150 g/Nm³. Dust on the pre-heater side is sticky, and dust at the clinker cooler exhaust is abrasive. This aspect has an impact on the heat exchangers used for waste heat recovery. In addition, sulfur contained in those gases can condensate, which limits the amount of waste heat that can be recovered.
Lastly, cooling water required in water-steam and ORC cycles can be an issue in some water-stressed areas and the quest for energy efficiency should not lead to creating another environmental problem.

**Integration challenges**

The clinker production process depends on seasonal variations of ambient temperature, which calls for careful design of the WHR unit.

Fives has developed new patented arrangements of the clinker production process overcoming those challenges and allowing optimal integration of waste heat recovery into the process. Depending on local characteristics, those arrangements can involve boosting the temperature of waste heat sources without any major loss of kiln efficiency, clinker cooler modifications, and heat storage.

The goal of such process modifications is to integrate WHR while maintaining quality of production and plant availability, and to optimize the overall energy efficiency of the plant (which matters more than local optimization of the WHR system).

**Waste heat uses**

In most plants, all hot flue gases are used to dry raw material and solid fuel (pet coke, coal, RDF - refuse derived fuel). Afterwards, the temperature of flue gases is taken down to about 195°C. The vast majority of WHR installations in the Cement industry are oriented towards electricity production; secondly, water desalination can be considered. However, other ways to use waste heat can make sense, such as converting waste heat into cold power, to cool plant buildings.

**Case study**

**Issue:** For modern cement plants, WHR is profitable only in the long-term.

Fives proposes to introduce slight modifications in the clinker production process to make WHR easier on new generation cement plants.

WHR is widely used in the cement industry and most systems are water-steam cycles installed on relatively old plants or new plants with average efficiency and ‘hot’ exhaust gases.

Options for new generation plants with high efficiency are Organic Rankine Cycles, or water-steam cycles with a design adapted to the lower temperature of the exhaust gases.
**Water-steam cycle (best for waste heat at T > 400°C)**

The “water-steam cycle” is based on a Rankine thermodynamic cycle using water as fluid (see above): the working fluid enters a boiler in liquid phase where it is heated and evaporated at constant pressure by the external heat source. The steam produced is super-heated by the external heat source in order to avoid too many droplets forming into the turbine (resulting in higher maintenance costs), and the steam is then expanded. The turbine is connected to a generator to produce electricity. At the end of the turbine, wet steam at low pressure enters a condenser to become a saturated liquid at constant pressure before being pumped back to the boiler at high pressure.

The efficiency of the cycle mainly depends on the cold source temperature (which can be either air or water) and on the pressure difference obtained at turbine level (which depends on heat source temperature). A first oil loop can be installed before the cycle in order to properly recover the heat sources or because of footprint constraints, resulting in a slight decrease in efficiency. The net efficiency takes into account the consumption of auxiliaries such as the main pump, cold source and oil loops. Many arrangements can be made to super-heat the steam several times and produce electricity at high, medium and low levels in order to get the maximum power.

**Sources: Aqylon (illustrations)**

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**Organic Rankine cycle (best for waste heat at T < 400°C)**

The “Organic Rankine Cycle” (ORC) is based on the same principle as the “water-steam cycle” except for the fact that the working fluid used is organic with a high density and lower evaporation temperature (~ 50°C). Also, super-heating after evaporation is not required thanks to the organic fluid’s “wetting fluid” behavior (see above). Thus a lower heat source (power and temperature) can be exploited and still be advantageous in terms of electric power production. Examples of organic fluids are benzene, propane, butane, R245fa… which are chosen depending on their properties to get the best efficiency of the cycle.

The cycle efficiency mainly depends on the cold source temperature (which can be air or water), the heat source temperature and the chosen fluid. Net efficiency takes into account consumption of all auxiliaries (main pump, cold source, oil loop). In that case more thermal energy into the cycle doesn’t mean more electrical power and an optimal point has to be found to get the best net efficiency.

In some cases, a first oil loop is also placed before the ORC in order to correctly recover energy from the heat source (particularly with high fluctuating heat sources) or because of footprint constraints. This will slightly decrease the efficiency of the cycle. A regenerator can be integrated in order to improve the efficiency.

Sources: Aqylon (illustrations)
Classic water-steam cycle (state of the art configuration)

Traditional “water-steam” systems, based on Rankine/Hirn thermodynamic cycle, are made up of an exchanger on the preheater flue gases and another one on the clinker cooler exhaust air to produce steam. Each exchanger includes a high pressure boiler:
- preheater flue gases: vaporizer and superheater
- clinker cooler exhaust air: economizer, vaporizer and superheater.

The electric production is obtained through a steam turbine coupled with an electric generator. On a typical cement plant with a capacity of 5,000 tonnes per day, the flue gas flow rate is 300,000 Nm³/h with a temperature of 330°C and around 2/3 of exhaust air - “quaternary air” - representing 116,000 Nm³/h, which can be picked in order to get 330°C. In that case, superheating barely reaches 305°C at 25 bars. The steam turbine may produce a net electrical power of 7.5 MWₑ with an overall efficiency of 25.4% which is typical for a “water-steam system” at this temperature.

“Boosted” water-steam cycle (Fives design)

Fives has developed a new design (patented) to “boost” superheating. It consists of extracting a small part of the tertiary air “thermal energy” to reach a higher steam temperature. The steam of the “classical design” is sent through a standard superheater near the tertiary air duct or the smoke chamber to be superheated (Figure 8).

Thus, with the same hot sources characteristics, and with a superheating increased to 400°C at 23.5 bars, the system can produce net electric power of 10.2 MWₑ with an overall efficiency of 30.7%.

To obtain these figures, the thermal power taken from the tertiary air is equal to 2.4 MWₑ, and the temperature of the air arriving in the precalciner is thus around 890°C. Therefore, the Fives design increases the electric production up to 2.7 MWₑ by taking only 2.4 MWₑ on the thermal power.

This configuration offers both economic and environmental benefits in cement plants where alternative / renewable fuels are used in the precalciner and electricity is expensive, and if electricity from the grid is of fossil origin.

Fives cost estimation - assuming an installation as part of a new turnkey plant - takes into account the total investment cost of WHR: in addition to the “water-steam module” described above, it includes the cost of air/steam heat exchangers, boost exchanger, the cold source, installation-related costs (transport, insurance, civil works, erection...), as well as operating costs for the WHR system and auxiliaries. With all these items included, we obtain a payback time of 4 years, with €100/MWh of electricity and free alternative fuel. If alternative fuel cost goes up to €50/ton, which is a typical value, payback is increased by only a few months.

This result corresponds to a 1-year reduction compared to a classic water-steam cycle (without boosting) with the same scope (payback = 5 years in that case). Also, it is in line with the average costs quoted in IFC report on WHR for the Cement Sector⁹. It has to be noted that the lowest payback times given in the IFC report assume operating costs of 2.5% of total investment for the water-steam system (per year), and 7% of investment for auxiliaries; whereas Fives accounts for more realistic estimates of 5% for the WHR system and 9% for auxiliaries, and carefully accounts for all subelements and installation costs.

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⁸ Reference conditions for normal cubic meter (Nm³): Temperature: 0°C, Pressure: 1.01325 barA (absolute pressure)
⁹ Waste Heat Recovery for Cement Sector, IFC – Institute for Industrial Productivity, Jun 2014
Figure 8
Waste heat recovery of flue gases, tertiary & quaternary air for electric production in the cement sector

Cement case study results ("Boosted" water-steam cycle):

<p>| | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Cement production</strong></td>
<td>5,000 tonnes/day</td>
<td>Functioning 85% of the time</td>
</tr>
<tr>
<td><strong>Waste heat source</strong></td>
<td>31 MW&lt;sub&gt;th&lt;/sub&gt; at ~ 330°C</td>
<td>With a 'water steam cycle' with net production (eg. oil loop consumption, cold source, 'boost' fan on tertiary air, primary pump, additional ID fan consumption)</td>
</tr>
<tr>
<td><strong>Electricity production</strong></td>
<td>69 GWh/year&lt;br&gt;9.2 MW&lt;sub&gt;th&lt;/sub&gt;, net</td>
<td>As part of a new turnkey plant</td>
</tr>
<tr>
<td><strong>CAPEX</strong></td>
<td>€20 M</td>
<td>Additional fuel consumption with “Boost” solution</td>
</tr>
<tr>
<td><strong>OPEX</strong></td>
<td>€680 k</td>
<td>Compared to no heat recovery, with free alternative fuel</td>
</tr>
<tr>
<td><strong>Process changes</strong></td>
<td>2.4 MW&lt;sub&gt;th&lt;/sub&gt;</td>
<td></td>
</tr>
<tr>
<td><strong>Payback</strong></td>
<td>4 years with €100 /MWh electricity price</td>
<td></td>
</tr>
</tbody>
</table>
2. Aluminium

A very energy-intensive industry that uses massive amounts of electricity and even makes decisions about where to locate its plants based on availability of cheap electricity, the aluminium industry has made notable progress over the past decades to improve its energy intensity (Figure 9).

Figure 9
Aluminium Manufacturing - Historical and Forecasted Industry Energy Intensity
Improvements in the energy efficiency of the electrolysis process (also called smelting), which is at the heart of the aluminium production process, have driven this progress as well as aluminium recycling: 75% of aluminium ever produced is still in use\textsuperscript{10}!

Even though there is potential for waste heat recovery in the aluminium process, it has to be kept in mind that the amounts of energy recovered will remain negligible compared to the massive quantity of electricity needed for smelters (Figure 10).

\begin{figure}
\centering
\includegraphics[width=\textwidth]{figure10.png}
\caption{Aluminium Manufacturing – Total Energy Used and Waste Heat in the Value Chain \textit{(Frost & Sullivan, 2010)}}
\end{figure}

Some initiatives to recover waste heat are already being implemented in aluminium plants, as shown on the graph below, but there is still unused potential even at high temperature:

\begin{figure}
\centering
\includegraphics[width=\textwidth]{figure11.png}
\caption{Aluminium – Overall Waste Heat Schematic \textit{(Frost & Sullivan, 2010)}}
\end{figure}

Waste heat sources

The graph below provides more details on waste heat sources and focuses on primary aluminium, as opposed to secondary aluminium which is recycled metal.

Electrolysis generates large amounts of heat (1.6 MW per electrolysis pot, for AP30 pots at 380 kA and 4.2 V) among which only half is useful. The remaining heat is evacuated through the walls, in the hot gases and in the anode rodding shop. Aluminium producers like Hydro and Rio Tinto have patented various ways to recover heat directly on the walls of electrolysis cells, by using the wall insulation as a heat exchanger.

Exhaust gas from electrolysis pots is available at relatively low temperatures but massive flowrates (millions of Nm³/h). It is easier to recover by the means of a heat exchanger that is adapted to the composition of those gases (see below).

Furnaces in the casthouse are another source of waste heat, as they generate fumes at high temperature but with a low flowrate.

Finally, the carbon sector (anode production) also provides opportunities for waste heat recovery.

Temperatures and flow rates of main waste heat sources are provided below, in the case of a modern and energy-efficient aluminium plant producing about 600,000 tonnes / year and located in the Gulf area.

![Figure 12: Waste heat sources in the primary aluminium process](source: Fives data and references)
Industry-specific challenges

The gas coming out of electrolysis pots contains components that are very specific to the aluminium industry: sulfur dioxide (SO₂, typically contained in electrodes used in electrolysis cells) and hydrogen fluoride (HF; fluoride is used in electrolysis cells to lower the temperature of reduction process). It also contains dust (200 to 500 mg/Nm³) and fouling of heat exchangers is an issue that led Fives to design specific heat exchangers for this application, in partnership with Hydro and NTNU.

Exhaust fumes from anode baking furnaces are also characterized by high fouling and acid corrosion properties. Unlike exhaust gas from electrolysis pots, their temperature is highly variable. Exhaust gases from holding and melting furnaces are more conventional in terms of composition (traditional combustion gases with, in case of secondary aluminium, low concentration of polyaromatic hydrocarbons coming from the scraps) but also subject to high variability. Energy contained in those gases can be recovered to preheat combustion air with regenerative burners.

Green anode plant exhausts are pitch fumes at around 50-60°C which is very low for energy recovery. They are mainly composed of highly polluting polyaromatic hydrocarbons, which are captured and treated by a Pitch Fumes Treatment System (PFTS).

Integration challenges

The first integration challenge is the large dimension of aluminium plants, which makes it difficult to link waste heat sources (e.g. from electrolysis pots) to heat-consuming equipment (e.g. in the carbon sector). Also, temperatures of heat-generating sources and heat-consuming equipment do not match.

Exhaust gas from electrolysis pots is collected and depolluted in Gas Treatment Centers (GTC). The gas needs to be cooled in order to ensure proper functioning of filters. Basic cooling systems such as dilution with ambient air are widely used but are very poor in terms of energy efficiency: no heat recovery, use of ambient air which is rather hot in many aluminium-producing countries, and increased gas volume that results in oversized filters and exhaust fans in the GTC. Cooling with heat exchangers connected to a system producing electric or cold power has not taken off yet for economic reasons: as cooling, and not heat recovery, is the primary function of the system, the installation of a full conventional cooling system as a back-up is required, which increases CAPEX and OPEX.

Waste heat uses

For primary aluminium plants, electricity production does not always appear to be the best way to use waste heat. For plants located in hot ambient air temperature countries, production of cold power makes sense as well as production of desalinated water or connecting to an external process in an ‘industrial ecology’ scheme. The low temperature of exhaust gas from electrolysis pots corresponds to the thermal needs of desalination (thermal processes such as multiple-effect desalination) and phosphate production processes, both of which are needed and present in the Middle East. For plants located in cold countries, heat may be used on-site provided that distances make it possible.

Case study

Issue: Gas entering Gas Treatment Centers (GTC) is commonly cooled by air dilution, which does not allow recovery of the cooling energy. Moreover, aluminium plants are installed in areas where...
electricity is affordable, making conversion of waste heat into electricity for external sale uneconomic.

Fives proposes to replace conventional cooling systems with WHR systems that produce freshwater through desalination processes – a need in water-stressed areas.

Studies led by Fives covered all waste heat sources and resulted in focusing on recovering exhaust gas from electrolysis pots (at the inlet of Gas Treatment Centers) to desalinate water. It appeared as the most interesting WHR solution for regions like the Middle East, where seawater desalination is extensively used. Reverse osmosis, which uses massive amounts of electricity, is a commonly used process. Thermal processes for seawater desalination are also available and are especially relevant when waste heat is available. One of these processes is known as multiple-effect distillation (MED): it uses heat rather than electricity, and is well suited to small to medium capacities (< 30,000 m³/day of desalinated water). 8% of the world’s desalinated water is produced this way.

Seawater is introduced in the first stage, heated and evaporated in tubes using a heat source. This steam flows to the next stage where it condensates, producing pure water, while evaporating the same amount of seawater, and so on (Figure 13). In theory, the same initial amount of energy is reused at each distillation stage, but thermal losses limit the number of stages. The number of distillation stages is optimized depending on the characteristics of the heat source and cost expenditure. The optimum heat source temperature for desalination is around 70-80°C.

![Figure 13](image-url)

*Figure 13*

Principle of multiple-effect desalination

*(CEA - French Alternative Energies and Atomic Energy Commission)*
The chosen case study focuses on an aluminium plant in a Gulf country, with an electricity price of 43€/MWh and a water price of €1.18/m³. Two Gas Treatment Centers are equipped with 8 heat exchangers each, which recover 16 x 2.6 MW of waste heat.

In our case study, waste heat from the aluminium plant could feed an MED desalination plant with the following characteristics and allows a payback time of 4.3 years with a pure water production of 5,800 m³ per day:

**Aluminium case study results**

| Aluminium case | 300,000 tonnes / year | 365 days per year for GTC |
| Desalinated water produced | ~5,800 m³/day | 4 effects |
| CAPEX | ~€7.5 M | This CAPEX includes integration costs of the WHR system. |
| OPEX | €505 k/year | Electricity price: €43/MWh |
| Water savings | €2,260 k/year | Water price: €1.18/m³ |
| | €3,830 k/year | Water price: €2/m³ |
| Payback | 4.3 years | water price €1.18/m³ |
| | 2.3 years | compared to air coolers alone |

accounts for OPEX savings on air cooling | Water price €2/m³ | compared to air coolers alone |
3. Glass

Like other energy-intensive industries and despite its conservative reputation, the glass industry has been recycling used products and actively working on reducing energy consumption since the mid-1970s. Typical specific energy consumption dropped by more than 60% between 1930 and 1980.\(^{11}\)

A few industrial references for waste heat recovery units on glass plants exist, both on flat glass and hollow glass production lines. Although some of them are reported to have stopped (e.g. AGC’s oldest plant in Cuneo, Italy: equipped with an ORC in 2012 to produce power from the furnace exhaust gases, the plant was stopped due to market reasons), this situation is not due to issues in operating WHR systems and interest in WHR is growing in the industry.

This section will focus on float glass, which represents 80% of the world’s flat glass production and is used in applications such as buildings and cars.

Waste heat sources

Glass is formed in a glass melting furnace, which is a chemical reactor that transforms sand mixed with soda and limestone and recycled glass (cullet) into glass, before being extended and cooled down. A furnace can produce up to 1,000 tonnes of molten glass at 1,550°C per day without interruption for 15 years.

\(^{11}\) Glass Worldwide, Furnace waste heat recovery – the alternatives?, Richard Sims, 2014 (issue 54)
Modern glass melting furnaces are already equipped with built-in heat recovery: a regenerator stores heat then releases it to preheat combustion air, however gases exiting the regenerator are still very hot (~450°C). On the 400 glass plants installed with a typical power of 30-40 MWth, around 10 MWth are lost into flue gases representing the main waste heat energy of the process (Figure 14). The furnace’s specific consumption of 6.5 GJ per tonne of glass can firstly be improved by working on tank design features. An example of an improved melting furnace design is Fives’ recently installed ‘low energy melter’ (LEM®), which proves that a specific consumption as low as 5.5 GJ/tonne glass can be achieved. This corresponds to 15% less losses in flues gases and is made possible thanks to a series of improvements: the main one is patented and consists in reducing the melt recirculation in the charging section, which leads to a consecutive reduction of the tank size (reduction of wall losses).

An alternative to the melting furnace with regenerator is the oxycombustion furnace: combustion is performed with pure oxygen instead of air. In that case, resulting exhaust gases have a higher temperature and a lower volume. This option results in less nitrogen oxides (NOx) emissions and in potentially easier waste heat recovery, but cost and environmental impact of oxygen production needs to be carefully assessed.

In the float glass process, glass is then poured into a molten tin bath. A glass ribbon is formed and slowly cooled until it becomes sufficiently rigid (620°C) to be transported on metallic rollers to the annealing lehr. The lehr is an insulated tunnel where controlled cooling is performed in order to stabilize the glass ribbon’s residual strains. Water and air used respectively for cooling in the tin bath and the annealing lehr offer waste heat recovery potential.

Typical temperatures and flow rates of waste heat sources are provided below:

![Figure 14](source:Fives data and reference)
Industry-specific challenges

The high temperature and stability of waste heat sources in glass plants make waste heat recovery interesting. However, any kind of process innovation in the glass industry is very challenging due to a specificity of glass manufacturing: a glass melting furnace is never stopped throughout its entire lifetime. This makes it challenging to perform WHR on the furnace’s flue gases. Less energy is wasted in the tin bath and annealing lehr but these sources are easier to use as it is clean air.

Integration challenges

Internal re-use of waste heat to pre-heat raw materials appears as a very good WHR opportunity in the glass industry, and viable solutions to historical technical barriers have been developed recently. This solution maximizes waste heat utilization and increases maximum melting capacity in the furnace, but requires extensive expertise in the glass melting process.

Waste heat uses

Efficiency of the melting furnace can be improved by preheating raw materials (called ‘batch’). Internal re-use of waste heat from the furnace exhaust gas to perform batch preheating makes a lot of sense for glass plants and companies like Fives have been carrying out extensive work to overcome technical barriers (agglutination of raw materials and dusting causing blockage and quality issues in glass). The combustion flue gases are at around 350-500°C depending on the burner technology. They can be exhausted to produce steam at high quality (21 bars up to 42 bars depending on the flue gases temperature) and/or electricity with a water-steam or organic Rankine cycle. For a plant producing 700 tonnes of glass per day, depending on steam production needs and WHR solution availability - mainly impacted by blockage problems which is a key point as explained above - the electricity production is around 2.5 MW. (Scheuten Osterweddingen plant)12. For steam production, payback time can be less than 2 years, depending on the fuel price.

Use of the furnace exhaust gas to perform high-temperature chemical reactions, such as hydrogen production via methane reforming, has also been proposed13. However, additional heat input is required to obtain a temperature of 800-900°C in the reformer. Air exiting the working end is very hot (1,000°C) and might be better suited to that application, although the amount of energy available is lower.

On existing plants, where modifying the furnace to perform batch preheating is not possible, other ways to use waste heat may be preferred, such as electricity or steam production.

Waste heat from the tin bath and annealing lehr can also be used for electricity production; an example is given in the case study below.

Case study

Issue: Each section of the glass cooling section produces too little energy and no WHR is possible on one of the main cooling source (tin bath).

---

12 Siemens. Glass Focus. Well Equipped for the Future. New technologies for innovation and energy efficiency. 2010
13 By HyGear and CelSian
Fives has developed a profitable solution to make WHR possible on the cooling section (including tin bath), which also improves glass quality; it consists in switching the cooling medium and combining several heat sources.

Tin bath cooling is traditionally performed with water by means of a roof monotubular exchanger (Figure 15). Fives proposes to replace water with clean air, which allows better recovery of cooling energy as it results in air exiting the tin bath at a temperature between 350°C and 650°C, instead of water at 50°C which is hardly usable in a glass plant. This solution called Hot air cooler™ also improves cooling quality and process control, hence is beneficial to the quality of the glass.

![Figure 15](image)

**Figure 15**
Water cooling of tin bath

*Air cooling + Organic Rankine Cycle on a single heat source*

The air temperature of the air exiting the tin bath end - around 300°C - is suitable for electricity production with an ‘Organic Rankine Cycle’ (for the definition, see Cement case study p.17). Cooling this air below 150°C would increase the risk of acid and water condensation of flue gases into circuits.

For a typical glass plant of 800 tonnes per day, the thermal power available is 1 MWth, this would allow an electricity output of 140 kW, (14% efficiency) which is typical for an ORC at this temperature. Considering an electricity price of €100/MWh, and considering CAPEX of the WHR system and its installation as well as OPEX of auxiliaries, payback time of this solution compared to water cooling would be around 4.5 years.

*Air cooling + Organic Rankine Cycle on multiple heat sources combination (Fives design)*

Fives proposes to improve the heat recovery potential, by combining the air of tin bath end at 350°C with both the air flow of tin bath start cooling at 650°C and the air flow at 1,000°C from the conditioning section without disrupting the process. This would double the available thermal power for heat recovery with an air temperature around 480°C (Figure 16).

With a standard Organic Rankine Cycle design, air enters the system at around 480°C (because of the first oil loop exchanger pinch) and still exits at 150°C. This would result in an electricity output of 435 kW, (taking into account auxiliary consumptions) with a higher efficiency of 22%, which is typical for an Organic Rankine Cycle in this temperature range.
Assuming that the tin bath is equipped with HAC®, additional investment cost for heat recovery have been estimated, including cost of integration (first oil loop, transport, civil works, insurance...) as well as the cold source and fans. Taking into account the water-steam module OPEX and consumption of auxiliaries, and since the system works without interruption like the glass melting furnace, payback time becomes more attractive since it goes down to 3.6 years with an electricity price of €100/MWh. Ongoing development of micro-steam turbines, particularly suited to the waste heat temperatures in this application, offer perspectives for future cost reduction.

**Glass case study results**

<table>
<thead>
<tr>
<th>Glass production</th>
<th>800 tonnes/day</th>
<th>365 days/year, 24h / day</th>
</tr>
</thead>
<tbody>
<tr>
<td>Waste heat source</td>
<td>1.9 MWh at ~ 480°C</td>
<td></td>
</tr>
<tr>
<td>Electricity production</td>
<td>3.9 GWh/year</td>
<td>With an ORC (net production)</td>
</tr>
<tr>
<td>CAPEX</td>
<td>€1.9 M</td>
<td>With Hot air cooler™, WHR system No cooling system (existant) and no backup</td>
</tr>
<tr>
<td>OPEX</td>
<td>€60 k</td>
<td>With Hot air cooler™ additional fan consumption compared to water cooling system consumption alone and taking into account WHR OPEX (maintenance)</td>
</tr>
<tr>
<td>Payback</td>
<td>3.6 years with €100/MWh electricity price</td>
<td>Compared to a water cooled solution Lower if benefits on the process and glass quality are taken into account *</td>
</tr>
</tbody>
</table>

* Benefits of air cooling with HAC®:
  - HAC® on head cooler: 200/400 k€ per year of production savings, 1% more production output
  - HAC® on end cooler: 1 M€ per year improved glass sales, 35% reduction of cleaning inspection
4. Steel

The Steel industry is very energy-intensive and has made big progress in reducing its energy intensity. As an example, evolution of energy intensity (kWh per kg of steel produced) in the United States is displayed on the graph below.

Such progress was first achieved by continuous casting and blast furnace optimization, and then through steel recycling and replacement of fossil fuels with recycled gas (e.g. coke-oven gas or blast-furnace gas burned in furnaces downstream in the process).

In-situ waste heat recovery has been implemented wherever possible, for instance by recirculating hot flue gases inside the furnace where they were created to lower external energy demand, or by using hot flue gases to preheat combustion air or fuel. Such energy efficiency improvements still leave residual waste heat recovery opportunities, e.g. to produce steam for other parts of the process or to sell electricity.

**Waste heat sources**

The steelmaking process is complex and involves many waste heat recovery opportunities (Figure 18):

- on the upstream plants that produce raw materials (coke oven plant and sinter plant)
- on the blast furnace itself and on the next process step called a basic oxygen furnace (BOF),
- on furnaces used to re-melt recycled steel: electric arc furnaces (EAF),
- on the downstream process (hot rolling and cold rolling).

![Waste heat sources diagram](http://ietd.iipnetwork.org/content/top-pressure-recovery-turbines)

In the upstream process, some significant sources of waste heat are the following:

- Blast furnace gas is the main source of waste heat. Its level of pressure (up to 3 bar\(^1\)) offers an opportunity to use this gas in a turbine – referred to as Top-pressure Recovery Turbine (TRT) – to generate electricity. Blast furnace gas might then be burnt, despite its low heating value, and used as a substitute to natural gas in the downstream process.

\(^1\) http://ietd.iipnetwork.org/content/top-pressure-recovery-turbines
- BOF flue gas has an energy content of 0.5 to 1 Gigajoules per tonne steel depending on flow rates. Most of the time, as it is rich in carbon monoxide (CO), it can be used as a substitute to natural gas.
- EAF flue gas production is much more variable since it is a cyclical process with variable scrap content (recycled steel). About one quarter of EAF energy input is released as waste heat, representing around 200 kWh/tonne steel. Those flue gases are traditionally treated and cooled down to 250°C in a flue gas treatment center before being rejected. This cooling operation can be combined with energy recovery to produce high quality steam or electricity. There are recent references where 15 to 25 kWh of electricity per tonne of steel are produced with an ORC.

Typical temperatures and flow rates of waste heat sources are provided below, for a modern and energy-efficient steel plant with around 30% steel production through EAF route.

In the downstream process, waste heat sources are located as follows:

- On the reheat furnace, which brings steel slabs, coming out of a storage section (at ambient temperature) or from continuous casting (800°C), back to about 1,250°C before entering the hot...
rolling mill. Both exhaust gases and cooling water coming out of the reheat furnace contain residual heat.

- In the heat treatment line which processes coils coming from the hot rolling mill or the cold rolling line. The heat treatment line is a succession of heating and cooling operations performed on a steel strip to obtain the required mechanical properties. Heat integration between heating and cooling sections is already performed to a certain extent and further optimization is still possible. As an example, the steel strip is traditionally cooled by atmosphere, which is in turn cooled by water. This results in high amounts of energy being lost in a hot water discharge at a low temperature (50°C), making it hardly usable: Fives is working on alternative designs of the cooling system that avoid such losses.

In addition to heat wasted in exhaust gases from furnaces, other types of waste heat recovery opportunities are possible:

- Recovery on hot solid products: hot steel is transported under different forms all along the process and recovery of radiation energy is possible with cooling tunnels, to produce steam or electricity using thermoelements.
- Pressure recovery with expansion turbines, e.g. on blast furnace exhaust gas as explained earlier.

**Industry-specific challenges**

Unlike waste heat recovery on EAF, which is being more and more implemented thanks to a high amount of energy losses and very hot gases, waste heat sources in the downstream process (reheat furnace, processing lines) are more challenging. Beyond the fact that energy losses as well as temperatures are much lower, the main difficulty is that the output from a steel plant is not a constant production with the same quality but a ‘product mix’ with different grades of steel for various applications. Furthermore, production is highly dependent on market needs and load typically fluctuates between 70% and 100% of maximum capacity and may be subject to daily stoppage. Heat treatment equipment is therefore designed to be highly flexible, and its exhaust gases are in turn subject to strong flow, temperature and composition variations.

**Integration challenges**

As in all industries covered in this document, waste heat recovery should in no instance disrupt the steel production process. This is challenging in the case of the steel process, especially its downstream part, as the parameters of reheating, heat treatment and annealing furnaces are finely tuned to achieve specific mechanical properties of steel. This means that additional heat exchanges for waste heat recovery purposes may have an effect on steel quality and must be designed by qualified experts.

**Waste heat uses**

Depending on the plant needs, waste heat can be used to produce steam at different quality levels for internal use in the plant, e.g. for degreasing steel strips, or to produce mechanical power for direct drive of rotating equipment or for conversion into electricity.

**Case study**

**Issue:** On reheating furnaces, high variability of production and low power of wasted energy make WHR difficult to implement.
Fives proposes to combine several heat sources to offset their variability, and to design on real furnace capacity instead of maximum capacity to ensure better profitability.

The reheating furnace is a key equipment of the hot rolling section. Its function is to continuously heat billets, slabs or blooms of different sizes and grades up to around 1,250°C. Most of the new reheat furnaces are “Walking beams furnaces” (WBF). In a WBF, heating is performed over and under the products which are handled from charging side to discharging side by means of insulated and cooled beams (skids). A key performance criterion for reheating furnaces is heating homogeneity.

20 to 30% of the energy input is typically wasted, and split between several thermal losses:

- Furnace exhaust gas (available at about 250-300°C between the combustion air recuperator and the stack if natural gas is used as a fuel ; available at a higher temperature in the case of a fuel with a lower calorific value).
- Water loop: Water is used to constantly cool the product handling system, which is composed of skids that are in contact with a very hot atmosphere in the furnace. This water loop typically enters at 40°C and is heated by 15°C before being directed to a dedicated cooling system.
- Wall and doors losses, hardly recoverable.

![Figure 18](image)

**Figure 18**
Skid cooling system in a reheat furnace

State-of-the-art on skid cooling system (case A)

Several industrial sites already perform waste heat recovery on the skid cooling system by producing high quality steam when it is needed in the plant for other purposes. As such, this installation reduces losses through the skid system thanks to the use of water-cooled pipes used at higher temperature. If steam from the reheat furnace section is not needed within the plant, an Organic Rankine Cycle (adapted for such temperatures ~200°C) could be installed on the steam circuit to produce electricity. This installation has the benefit of being easily and safely operable especially in the context of highly variable energy losses, thanks to the constant temperature brought by the water phase change.
State-of-the-art on exhaust gases (case B)

An electricity production system can be proposed to recover energy from exhaust gases. Depending on the waste heat temperature, solutions such as a water-steam cycle (adapted to low efficiency furnaces) or an ORC (for furnaces with better efficiency) are available. Cases where the reheating furnace production is highly variable (e.g. fluctuations every couple of minutes, which affects the heat content of exhaust gases entering the WHR system) have to be studied with caution. An ORC is a rather flexible system that can accommodate input variations up to a certain point: it can typically operate down to 30% of its nominal capacity, and automatically shuts down when the heat input goes below that threshold. However, the economic aspect is affected as electricity production will decrease as well, hence the difficulty in making the investment profitable.

Combination of both sources + Organic Rankine Cycle (Fives design)

This situation could be improved thanks to the Fives solution (Patent pending) which combines heat from the skid cooling loop operated at higher pressure and temperature – in order to produce a mixture of steam and water at around 215°C in a closed loop – and heat from exhaust gases. The two heat sources are recovered separately thanks to organic heat fluid loops, then they are combined to form a common heat source.

Fluctuation of exhaust gases resulting from furnace load variations (capacity or product type variations) are balanced thanks to the constant temperature and power of the heat coming from the skid cooling system (which is less sensitive to load variations). As a result, operation of the system is easier and makes the combined heat source more stable especially in case of high fluctuations.

There are several ways to combine and optimize the two energy sources. In this case study, the two organic fluid loops are recovered in parallel and then combined into a common heat source at around 215°C (Figure 21). This temperature is suitable for an ORC application (see Cement case study p.17 for description of the technology).

As explained earlier, a reheating furnace does not function at full capacity all year long so the WHR system should be sized according to the actual production mix. The present case study assumes a furnace operated 90% of the time at 70% load, and 10% at full capacity.

An existing furnace can be equipped with an ORC sized on 70% of the furnace capacity instead of 100%, thanks to combined recovery of both waste heat sources. In this configuration, extra losses generated over 70% of maximum capacity are dispatched to the backup feed water cooling of the skid system. With this configuration, the ORC system operates at its maximum efficiency all the time.

For a 450 t/h WBF with mixed gas19, the configuration proposed by Fives will:

- Reduce heat losses from the skid system by 2 MWth, thanks to new skid installation at 21 bars and water cooled skid pipes used at higher temperature
- Produce 2 MWn (11% net efficiency including auxiliaries) - typical for an ORC at this temperature
- Avoid energy consumption of the conventional skid cooling system 90% of the time

The ORC produces 16 GWh annually, which is 2 MWh more than what would be produced by an ORC sized on 100% capacity and used at suboptimal efficiency 90% of the time. Furthermore the ORC module is smaller so investment is lower. This configuration leads to a reduction in payback of 6 months to 1 year.

19 Mixed gas is a mixture between a rich fuel (eg. Natural gas) and a lean fuel recovery (eg. Blast Furnace Gas)
(depending on electricity and mixed gas2019 prices, assumed respectively from €60 to €100 /MWh and €0.012 to €0.03 /kWhth), compared to an ORC sized on maximum capacity.

![Sketch of a WBF with ORC electricity production](image)

**Steel case study results**

<table>
<thead>
<tr>
<th>WBF nominal capacity</th>
<th>450 tonnes / h</th>
<th>7400 h/year</th>
</tr>
</thead>
<tbody>
<tr>
<td>Load variations</td>
<td>90% of the time at 70% of maximum capacity</td>
<td>10% of the time at maximum capacity</td>
</tr>
<tr>
<td>Waste heat source @ 70% capacity</td>
<td>Steam: 9.4 MWth at 200-250°C</td>
<td>Water: 11 MWth at 55°C</td>
</tr>
<tr>
<td>Electricity production</td>
<td>16 GWh/year (~ 2.2 MWth) with an ORC</td>
<td></td>
</tr>
<tr>
<td>CAPEX</td>
<td>€6.2 M</td>
<td></td>
</tr>
<tr>
<td>OPEX</td>
<td>€350 k</td>
<td></td>
</tr>
<tr>
<td>Process benefits</td>
<td>Less losses through skid system with steam use (~2 MWth)</td>
<td>Better operability of the skid cooling system</td>
</tr>
<tr>
<td>Payback</td>
<td>3.4 years with electricity price of €100 /MWh</td>
<td>Compared to a conventional installation with a water-cooled skid system, without heat recovery</td>
</tr>
</tbody>
</table>

20 Mixed gas is a mixture between a rich fuel (eg. Coke Oven Gas) and a lean fuel (eg. Blast Furnace Gas)
21 Mixed gas is a mixture between a rich fuel (eg. Natural gas) and a lean fuel recovery (eg. Blast Furnace Gas)
Taking into account total investment - i.e. ORC module, additional price for steam production in the skid system, oils loops and exchangers for heat recovery, additional backup cold source, installation of the solution (transport, insurance, civil works as well as additional consumption of auxiliaries, savings made on fuel consumption and cooling and finally ORC operating expenses – the Fives configuration has a payback of 3.4 years with an electricity price of €100 /MWh€ and a fuel (mixed gas\(^{22}\)) cost of €0.03 /kWhth.

Recovering energy on the two combined sources and sizing the ORC on the furnace’s real capacity reduces the payback time by:

- 1.3 years compared to an ORC recovering only the exhaust fumes and sized on 100% capacity (case B)
- 9 months compared to an ORC recovering only the energy wasted in the skid cooling system (case A) and WHR sized on 100% capacity.

The table below summarizes the different configurations observed depending on relative values of steam and electricity. The case study detailed above corresponds to the bottom right hand corner and is relevant for a situation where steam cannot be re-used in the plant.

In some configurations, emerging technologies such as heat storage may offer an interesting alternative. Heat storage solutions adapted to daily variations are becoming available for industrial applications and could be used in combination with an ORC to flatten its production. Oil is, for instance, an appropriate heat storage medium at that temperature level. Economic benefits need to be assessed on a case by case basis.

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\(^{22}\) Mixed gas is a mixture between a rich fuel (eg. Natural gas) and a lean fuel recovery (eg. Blast Furnace Gas)
5. Recommendations for making an investment in waste heat recovery

As a conclusion of this white book, Fives has defined a set of recommendations for industrial manufacturers who might be considering implementing a WHR project. The figure below lists important matters and questions to address when designing a WHR project.

One major takeaway of WHR studies carried out within Fives is the following: **Choosing a WHR system offering maximum energy efficiency, or looking for the highest energy recovery rate of the energy source, is not always the best economic option.** The most viable solution is an economic & technological compromise. Although counterintuitive, we believe this approach is the best way to maximize chances that industrial waste heat recovery becomes largely implemented.

We recommend that industrials pay attention to the global profits instead: **focus on overall efficiency at the plant boundaries even if that means leaving behind some energy that will still be wasted, select and design the waste heat recovery system on real load instead of maximum or theoretical capacity, and use modules that are already on the market to get the lowest cost.**

This approach offers the best technical & economical compromise and thus the most attractive solution.

Fives’ multisector process expertise and engineering capabilities can help industrialists to get the best out of the waste heat recovery system by providing unbiased advice regarding technology choices, adapted and complete integration of the WHR solution without any compromise on operational issues.

You can contact Fives experts at fives.innovation@fivesgroup.com
<table>
<thead>
<tr>
<th>Map the situation</th>
<th>Identify sources of waste heat and their characteristics</th>
<th>Such as temperature, pressure, flowrate, composition (abrasiveness, dew point...), as well as their variability.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Evaluate</td>
<td>Evaluate recoverable waste heat</td>
<td>All available energy is usually not recoverable (e.g. because of condensation below 100-150°C).</td>
</tr>
<tr>
<td>alternatives to</td>
<td>Assess constraints and opportunities of the process</td>
<td>Assess performance criteria, available space, maximum/design load vs. actual load, available cooling sources, unmet energy needs...</td>
</tr>
<tr>
<td>waste heat</td>
<td>Compare existing equipment with the BAT</td>
<td>Depending on the plant’s remaining lifetime, especially for existing plants, replacement by a more modern and energy-efficient equipment should be first considered as an alternative to waste heat recovery.</td>
</tr>
<tr>
<td>recovery first!</td>
<td>(Best Available Technology)</td>
<td>Identify internal uses e.g. for pre-heating air, fuel, or products.</td>
</tr>
<tr>
<td>Review the</td>
<td>Identify energy needs around the equipment</td>
<td>The following order of priority should generally be considered: in the equipment, in the process, in the plant’s auxiliary buildings, in a nearby plant, then for external use (e.g. electricity production).</td>
</tr>
<tr>
<td>best uses for</td>
<td>Select the use of waste heat that has the highest added value</td>
<td>Compare the value of the different possible WHR outputs (e.g. electricity vs. cold power, desalinated water, etc.), also depending on the plant location.</td>
</tr>
<tr>
<td>recovered waste</td>
<td>Consider the combination of several waste heat sources</td>
<td>It may lower the level of investment and widen the scope of possible WHR solutions.</td>
</tr>
<tr>
<td>heat</td>
<td>Consider switching to a more adapted WHR carrier</td>
<td>Using another medium (e.g. air instead of water for cooling) can make WHR easier.</td>
</tr>
<tr>
<td>Design the WHR</td>
<td>Consider the whole process and be ready for potential process changes</td>
<td>The overall efficiency of the whole process should be assessed to ensure environmental &amp; economic viability of the plant, as addition of local optima does not always lead to overall optimum. Adopt a « life cycle » mindset (e.g. when using additional energy to increase temperature of waste heat).</td>
</tr>
<tr>
<td>system</td>
<td>Iterate to determine how much energy should be recovered</td>
<td>Converting all recoverable energy is not always the best option, as it may be too costly and jeopardize the whole project.</td>
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<tr>
<td></td>
<td>Take into account the external benefits of WHR</td>
<td>WHR sometimes comes along with process benefits such as improved cooling, enhanced quality of the plant’s final product, less maintenance, reduction of health hazards (e.g. legionellosis). Such process benefits can considerably improve economics of a WHR project.</td>
</tr>
<tr>
<td></td>
<td>Anticipate variability of the production process</td>
<td>Behavior and economics of the WHR system are impacted by the variability of the heat source (e.g. when the plant is operated below its maximum production). Think in terms of flexibility.</td>
</tr>
<tr>
<td></td>
<td>Think of a back-up system</td>
<td>Continuous production must be ensured, even when the WHR system is unavailable.</td>
</tr>
<tr>
<td>Define optimal</td>
<td>Calculate CAPEX and OPEX of the plant with WHR</td>
<td>CAPEX should include integration costs and other external items (e.g. heat exchangers) around the WHR module. OPEX savings should be taken into account, and may include more sophisticated indicators than payback time (e.g. a discount rate). If relevant, revenues from CO2 markets may have a positive impact.</td>
</tr>
<tr>
<td>business model</td>
<td>Identify financing options</td>
<td>Governmental incentives for energy efficiency projects or financing schemes offered by suppliers of WHR systems may be available.</td>
</tr>
</tbody>
</table>
Key references


**ADEME** (French Environment & Energy Management Agency), La chaleur fatale industrielle, 2015 (in French)

http://www.recuperation-chaleur.fr/: website developed by ADEME and CETIAT, consulted in March 2016 (in French)


**DECC** (UK Department of Energy and Climate Change), Industrial Decarbonisation & Energy Efficiency Roadmaps to 2050 – Glass, March 2015
<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
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</thead>
<tbody>
<tr>
<td>BOF</td>
<td>Basic Oxygen Furnace</td>
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<tr>
<td>CAPEX</td>
<td>Capital Expenditure</td>
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<tr>
<td>CCS</td>
<td>Carbon Capture and Storage</td>
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<tr>
<td>EAF</td>
<td>Electric Arc Furnace</td>
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<tr>
<td>EE-IP</td>
<td>Energy Efficiency in Industrial Processes</td>
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<tr>
<td>GTC</td>
<td>Gas Treatment Center</td>
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<tr>
<td>IEA</td>
<td>International Energy Agency</td>
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<tr>
<td>IFC</td>
<td>International Finance Corporation</td>
</tr>
<tr>
<td>IIP</td>
<td>Institute for Industrial Productivity</td>
</tr>
<tr>
<td>MED</td>
<td>Multiple Effect Distillation</td>
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<tr>
<td>OPEX</td>
<td>Operating Expenses</td>
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<tr>
<td>ORC</td>
<td>Organic Rankine Cycle</td>
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<tr>
<td>WHR</td>
<td>Waste Heat Recovery</td>
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<tr>
<td>WBF</td>
<td>Walking Beam Furnace</td>
</tr>
</tbody>
</table>
Definitions

**Acid dew point**

The acid dew point of a flue gas (see above) is the temperature, at a given pressure, at which any gaseous acid contained in the flue gas will start to condense into liquid acid.

It is very important not to cool a flue gas below its acid dew point because the resulting liquid acid condensed from the flue gas can cause serious corrosion problems in the equipment used for transporting and cooling the flue gas.

(*source: ChemEngineering*)

**Flue gas**

Mixture of gases resulting from combustion of fossil fuels. Flue gases are mainly composed of nitrogen (N₂), carbon dioxide (CO₂) and water (H₂O vapor), as well as corrosive products such as sulfur dioxide (SO₂).

**Payback time**

The payback time is the period of time required to recoup the funds expended in an investment, or to reach the break-even point. It is calculated as the total CAPEX divided by the total revenues from the investment – such as savings made for example on electricity – less the total cost of operation of the system. It is calculated in years.