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

A white book on industrial waste heat recovery

Fives 2016
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 two 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 last year, 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 valorization 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
Director of the Thermal, Biomass and Hydrogen Technologies Department

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.
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.
Authors & Contact

Lead author: Pauline Plisson, Innovation & Sustainability Program Manager, Fives

Contributors:
- Guillaume Denis, Sébastien Devroe, Aurélie Gonzalez, Aliénor Guiard, Claire Mathieu (Fives)
- Cement: François Boudot, Yannick Guimard (Fives FCB)
- Aluminium: El-Hani Bouhabila, Adélaïde Faux (Fives Solios)
- Glass: Wolf Kuhn, Bertrand Strock (Fives Stein)
- Steel: Patrick Giraud (Fives Stein)
- CEA: Benjamin Boillot (Liten Institute)

If you have any questions or want to get in touch with industry experts at Fives, please write to fives.innovation@fivesgroup.com
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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. Actually, an increase in demand for those materials is expected: more aluminium (lighter than steel) will be used to build cars and planes, 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 1980s.

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](image_url)

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

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2. 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.

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.

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

**Figure 3**
Technologies for reducing direct CO2 emissions in industry
(*IEA, Technology transitions for Industry, 2009*)
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 Europe⁴. This corresponds to half of the emissions generated annually by the worldwide aluminium industry.

Another way to decrease CO₂ emissions for processes that are energy intensive and intrinsically CO₂ generators such as the cement process is to substitute the high energy footprint component (the clinker). This can be done by using industrial waste such as blast furnace slag for clinker or gypsum from desulphurization (sulfo-gypsum) or fertilizer industry processes (phosphor-gypsum). Another challenge that manufacturers will need to address is flexibility. Today, as market conditions, customer requirements, technological opportunities and even the 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 (thermoelectricity, thermoacoustics)
- 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\(^5\)): 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\(^6\).
- 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 expenditure (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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\(^5\) See definitions of ‘acid dew point’ and ‘flue gases’ in the Definitions section at the end of this document

\(^6\) Some technologies under development (e.g. heat exchangers made of plastics) will make recovery of energy below the acid dew point possible
### 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 1 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 pistionnes 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>

*uses 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>Heat</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 a variable heat source into a stable one</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 10kWₑ to 10 MWₑ for high power, combination of smaller modules is possible</td>
</tr>
<tr>
<td>Cold power</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 kWₑ to 500 kWₑ for high power, combination of smaller modules is possible</td>
</tr>
<tr>
<td>Electricity, heat or Cold power</td>
<td>Thermoacoustics</td>
<td>Amplification of pressure waves (ie acoustic power) using waste heat*. Can be used as an engine for heat or electricity production, or as a refrigerator if used in reverse mode</td>
<td>Pressure waves (sound) in air, nitrogen, argon or helium</td>
<td>Any temperature (only temperature gradient matters)</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>Other</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>

* mimics a Stirling cycle without using rotating machines nor phase-change fluid

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: Current WHR installations in cement industry](OneStone Research/CemPower 2013, Latest Waste Heat Utilization Trends, quoted by IIP & IFC)
However, WHR remains uneconomic in numerous countries, especially in areas where low electricity prices do not make the conversion of waste heat into electricity of interest. Where electricity supply is a problem (because of uncertainties regarding electricity voltage), even if the price of electricity is low, WHR can be advantageous as it allows the plant to be more self-sufficient. Also, 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: exhaust air from the clinker cooler, and flue gases from the pre-heater. The latter are often used to dry raw materials when necessary, thus only the first source (clinker cooler exhaust air) may be available in humid countries.

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

![Waste heat sources in the cement process](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/(n)m³. 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, water required for cooling 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 valorization routes 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 (maintenance cost issue) into the turbine where the steam is then expanded. The turbine is connected to a generator to produce electricity. At the end of the turbine, at low pressure, the wet steam 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 depends mainly on the cold source temperature (which can be either air or water) and 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 constrains, decreasing the efficiency slightly. The net efficiency takes into account the consumption of auxiliaries such as the main pump, cold source functioning, oil loops.

Many arrangements can be made to super-heat the steam several times and produce electricity a high, medium and low levels in order to get the maximum power.

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). Furthermore super-heating after evaporation is not necessary required (to avoid too many droplets into the turbine after) 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 depends mainly on the cold source temperature (which can be air or water), the heat source temperature and as well the fluid choice. The net efficiency takes into account all auxiliaries consumption (main pump, cold source, oil loop). In that case the more thermal energy into the cycle doesn’t mean the more electricity power. 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 the energy from the heat source (particularly with high fluctuating heat sources) or because of footprint constrains. This will decrease the efficiency of the cycle slightly. 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 4,000 tonnes per day cement plant, the flue gas flow rate is 300,000 (n)m³/h with a temperature of 330°C and around 2/3 of exhaust air - “quaternary air” - representing 116,000 (n)m³/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 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 MWₜ, 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 MWₜ on the thermal power.

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

With €100/MWh of electricity and free alternative fuel, typical payback time given by the cement industry⁸ - for ‘water-steam’ systems like these with electricity production of 10 MWₑ - is close to 4 years. This is obtained by accounting for a “WHR cost” of 2,000 USD/kWₑ, with 7% of investment for auxiliary equipment and 2.5% of investment for the “water-steam system” OPEX.

By contrast, Fives estimation takes into account the total investment cost of WHR: in addition to the “water-steam module” quoted above, payback has to include the cost of the heat exchangers, the cold source, integration to the plant (transport, insurance, civil works, erection...) as well as OPEX and auxiliaries consumptions. With these adjustments, the real payback of WHR system like this is closer to 5 years; this corresponds to a 1-year reduction compared to a classic water-steam cycle with the same scope (payback = 6 years).

If alternative fuel costs go up to €50/ton, which is a typical value, payback is increased by only a few months.

---

⁷ Reference conditions for normal cubic meter ((n)m³): Temperature: 0°C, Pressure: 1.01325 barA (absolute pressure)
⁸ Waste Heat Recovery for Cement Sector, IFC – Institute for Industrial Productivity, Jun 2014
Cement case study results ("Boosted" water-steam cycle):

<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cement production</td>
<td>4000 tonnes/day</td>
<td>functioning 90% of the time</td>
</tr>
<tr>
<td>Waste heat source</td>
<td>31 MW&lt;sub&gt;th&lt;/sub&gt; at ~ 330°C</td>
<td></td>
</tr>
<tr>
<td>Electricity production</td>
<td>72 GWh/year - 9.2 MW&lt;sub&gt;th&lt;/sub&gt;, net</td>
<td>With a ‘water steam cycle’ with net production (e.g. oil loop consumption, cold source, ‘boost’ fan on tertiary air, primary pump, additional ID fan consumption)</td>
</tr>
<tr>
<td>CAPEX</td>
<td>€25 M</td>
<td>With ‘water-steam’ system &amp; cold source, ‘Boost’ exchanger, integration to the plant</td>
</tr>
<tr>
<td>OPEX</td>
<td>€600 k</td>
<td>With ‘water-steam’ OPEX (maintenance)</td>
</tr>
<tr>
<td>Process changes</td>
<td>2.4 MW&lt;sub&gt;th&lt;/sub&gt;</td>
<td>Additional fuel consumption with ‘Boost’ solution</td>
</tr>
<tr>
<td>Payback</td>
<td>5 years with €100 /MWh electricity price</td>
<td>Compared to no heat recovery, with free alternative fuel</td>
</tr>
<tr>
<td></td>
<td>9 years with €60 /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](image)

**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!  

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).

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:

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**Figure 10**
Aluminium Manufacturing – Total Energy Used and Waste Heat in the Value Chain
*(Frost & Sullivan, 2010)*

**Figure 11**
Aluminium – Overall Waste Heat Schematic
*(Frost & Sullivan, 2010)*

---

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. Aluminium producers like Hydro and Rio Tinto Alcan have patented various ways to recover heat directly on the walls of electrolysis cells, by using the wall insulation as a heat exchanger.

Exhaust air from smelters is available at relatively low temperatures but massive flowrates (millions of (n)m³/h). It is easier to recover by the means of a heat exchanger that is adapted to such gas composition (see below).

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

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

Typical temperatures and flow rates of waste heat sources are provided below, for a modern and energy-efficient aluminium plant producing 585,000 tonnes/year:

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

Although the gas coming out of smelters is referred to as “air”, it 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; fluorine is used in electrolysis cells to lower the temperature of aluminium formation). It also contains dust (200 to 500 mg/(n)m³) 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 gases from anode baking furnaces are also characterized by high fouling and acid corrosion properties. Unlike smelters exhaust air, 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.

Green anode plant exhausts are pitch fumes at around 50-60°C. They are mainly composed of highly polluting polyaromatic hydrocarbons, which are captured and treated by a Pitch Fumes Treatment System (PFTS). Pitch fumes condensation appears at just below 50°C, which is very low for energy recovery, and creates sticky condensates, making the energy recovery hardly possible.

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 smelters) to heat-consuming equipment (e.g. in the carbon sector).

Smelters exhaust air is collected and depolluted in Gas Treatment Centers (GTC). The air 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 air volume that results in oversized filters 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.

Energy contained in the exhaust gases of melting furnaces in the cast houses is in many cases recovered to preheat combustion air with regenerative burners. Treatment of combustion gases is optimal at 130°C and most of the time those gases are diluted with ambient air to reach this temperature. As for GTC, this has a negative impact in terms of energy efficiency and leads to oversized fumes treatment centers.

Waste heat uses

For primary aluminium plants, electricity production does not appear to be the best way to use waste heat. For plants located in hot 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 smelter exhaust air 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: Energy from GTC gas is very often dissipated by dilution and lost. Moreover, in areas where aluminium are installed, additional production of electricity is not needed.

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

Studies led by Fives covered all waste heat sources and resulted in focusing on recovering smelter exhaust air (at the inlet of Gas Treatment Centers) to desalinate water. It appeared as the most interesting WHR solutions in aluminium-producing areas.

Freshwater is scarce in the Middle East, where seawater desalination is extensively used. Reverse osmosis, which uses massive amounts of electricity, is the most widely used process.

Another competing thermal process for seawater desalination is available and is relevant when waste heat is available. 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
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 5,524m³ per day:

**Aluminium case study results**

<table>
<thead>
<tr>
<th>Aluminium case</th>
<th>300,000 tonnes / year</th>
<th>300 days per year</th>
</tr>
</thead>
<tbody>
<tr>
<td>Desalinated water produced</td>
<td>5,524 m³/day</td>
<td></td>
</tr>
<tr>
<td>CAPEX</td>
<td>~€6.8 M</td>
<td>This CAPEX includes air coolers as a back-up solution to cool the smelter exhaust air, in case the desalination plant is not operating. It also includes integration costs of the WHR system.</td>
</tr>
<tr>
<td>OPEX</td>
<td>€527 k/year</td>
<td>Electricity price: €43/MWh</td>
</tr>
<tr>
<td>Water savings</td>
<td>€1956 k/year</td>
<td>Water price: €1.18/m³</td>
</tr>
<tr>
<td>Payback</td>
<td>4.3 years</td>
<td>Compared to air coolers alone</td>
</tr>
</tbody>
</table>

**Fives – A white book on industrial waste heat recovery**
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.\textsuperscript{10}

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.

\textsuperscript{10} 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**
Waste heat sources in the float glass process
(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 MWₑ. (Scheuten Osterweddingen plant)¹¹. 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 proposed¹². 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 valorize 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).

¹¹ Siemens. Glass Focus. Well Equipped for the Future. New technologies for innovation and energy efficiency. 2010
¹² 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.

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 kWₑ (14% efficiency) which is typical for an ORC at this temperature. Considering an electricity price of €100/MWh, and considering CAPEX of the HAC® and the WHR installation as well as auxiliary OPEX, payback time of this solution compared to water cooling would be around 9 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 kWₑ (taking
into account auxiliary consumptions) with a higher efficiency of 22%, which is typical for an Organic Rankine cycle in this temperature range.

With the assumptions mentioned above and taking into account the total cost of integration (first oil loop, transport, civil works, insurance...), cold source, additional investment for heat recovery (HAC®, fan), water-steam module OPEX and the 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 5.5 years with an electricity price of €100/MWh for electricity price.

Figure 16
Waste heat recovery of cooling air
for electricity production in the glass sector

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>3.9GWh/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 (existent) 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>Process benefits</td>
<td>Better process control</td>
<td></td>
</tr>
<tr>
<td>Payback</td>
<td>5.5 years with €100 /MWh 9.5 years with €60 /MWh</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>

* Air cooling with HAC® is performed at a higher temperature than water cooling allowing less salt condensation on the exchanger tubes. Thus there is less need to clean exchanger tubes (less maintenance cost) and less risk of “drops” falling onto the glass.
4. Steel

The Steel industry has made the biggest 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.

![Energy Intensity for Steel Production](Figure_16)

*Figure 16*
Steel Manufacturing - Historical and Forecasted Industry Energy Intensity
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 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),
- on the upstream plants that produce raw materials (coke oven plant and sinter plant).

![Figure 17](image-url)

Steel Manufacturing – Total Energy Used and Waste Heat in the Value Chain for USA

*(Nippon Steel Corporation quoted by Frost & Sullivan)*
At the steelmaking level, there are two main sources of waste heat, which are commonly recovered for steam production:

- For primary steel production, BOF flue gases represent 250 MJ per tonne of steel lost at 1,200°C and are most of the time redirected to a waste heat boiler to produce 80 to 100 kg of steam per ton of steel.\(^{13}\)
- For secondary steel production, EAF flue gas production is much more variable since it is a cycling process with scrap content variation. EAF waste heat gas represents 26% of its energy input at 1,250°C. Those flue gases are traditionally treated and cooled down to 250°C in a flue gases treatment center before being rejected. 85% of this energy content can be recovered to produce steam at 25 bars. It is also possible, by installing an adapted heat exchanger on the flue gas treatment center and a thermal stabilizer, to produce electricity with a water-steam cycle or an Organic Rankine Cycle. ORC seems better suited to that application because of process fluctuations. 15 to 25 kWh\(^{15}\) of electricity per tonne of steel can be produced that way.

Typical temperatures and flow rates of waste heat sources are provided below, for a modern and energy-efficient steel plant:

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\(^{13}\) Ecpolants solutions and energy recovery in steel plants, C. Fröhling, K.-P. Hemmling, J. Rotarius, SMS group, Germany.

\(^{14}\) Danieli’s Green Steel vision: an environmentally sustainable approach for steel industry development, N. Santangelo, L. Tomadin, A. Bertolissio, Danieli & C. Officine Meccaniche S.p.A., Italy.

\(^{15}\) Danieli’s Green Steel vision: an environmentally sustainable approach for steel industry development, N. Santangelo, L. Tomadin, A. Bertolissio, Danieli & C. Officine Meccaniche S.p.A., Italy.
In the downstream process, waste heat sources are located as follows:

- Reheat furnaces bring steel slabs, coming out of a storage section thus from ambient temperature or from continuous casting from 800°C, back to about 1,250°C before supplying the hot rolling mill. Both exhaust gases and cooling water coming out of the furnace contain residual heat.
- The heat treatment line, which processes coils coming from the hot rolling mill or the cold rolling 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, especially as heat treatment processes become increasingly complex and flexible in order to produce very high quality steel.

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, recovery of radiation energy is possible with thermoelectricity or cooling tunnels.
- Recovery of expansion energy: blast furnace gas exhausts the blast furnace at a pressure of 3 to 4 bar, energy recovery with expansion turbines is possible.

**Industry-specific challenges**

Unlike waste heat recovery on EAF or BOF which are emerging 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 the temperature are much lower, the main difficulty is that the output from a steel plant is not a constant product with the same quality but a ‘product mix’ with different grades of steel for various applications. Furthermore, production is highly dependent on market needs: it typically fluctuates between 70% and 100% of maximum capacity and may have day stoppage. Heat treatment equipment is therefore 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 (different parts of the process are usually operated as separate plants). Waste heat from BOF and EAF are increasingly used for that purpose, as was explained earlier. Steam production in processing lines is also possible, for example at the annealing furnace level where the addition of a flue gas process atmosphere gas exchanger on exhaust gas at 450°C can supply a convective heat section and produce steam at 4 bars with the remaining heat.
To produce mechanical power for direct drive of rotating equipment or to be converted into electricity sold to the grid and for back-up electricity supply.

Case study

Issue: High variability of the production and the low power of wasted energy released by the reheating furnace make the WHR difficult to implement.

Fives takes into account the variability of the heat source into the design of the WHR solution and combines several heat sources in order to stabilize waste heat source and make WHR profitable.

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 1,250°C. Most of the new reheat furnaces are “Walking beams furnaces” (WBF). On the WBF the heating is done 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 divided between several thermal losses:

- the temperature of the exhaust gas between the combustion air recuperator and the stack is at 250°C-300°C with natural gas fuel and higher with lower calorific value fuel
- the product handling systems inside the furnace with skids and post cooling system (Figure 20)
- wall and doors losses, hardly recoverable.
Water is used to constantly cool the skid system which is 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.

**State-of-the-art on skid cooling system**

Several industrial sites already perform waste heat recovery on the skid cooling system by producing steam when it is needed in the plant for other purposes. On its own, this installation reduces losses through the skid system thanks to the use of water cool pipes used at higher temperature. If steam is not needed by the customer, an ‘Organic Rankine Cycle’ (adapted for such temperatures ~ 200°C) could be installed on the steam circuit to produce electricity (see Cement case study p.17 for description of the Organic Rankine Cycle). This installation has the benefit of being easily and safely operable especially with high variability of the losses thanks to the constant temperature brought by the water phase change. Most of the time this technology is not installed because of long payback (see next section to have an example of payback value); meanwhile, most of the time the energy contained in exhaust gases is wasted.

**State-of-the-art on exhaust gases**

An electricity production system can be proposed to recover energy from exhaust gases. Depending on the heat source temperature, either a ‘water-steam cycle’ (with low efficiency furnace) or an ORC (with better efficiency) are available. Most of the time those technologies are not installed because of their long payback (see next section to have an example of payback value).

**Double sources combination + ‘Organic Rankine Cycle’ (Fives design)**

This situations 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 and then combined to form a common heat source.

The heat fluctuation from the exhaust gases (temperature and volume are modified) in case of furnace power variations (production or product variations) are balanced thanks to the constant temperature of the heat coming from the skid cooling system. Thus operation of the system is easy and makes the global heat source more stable especially with 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 220°C (Figure 21). This temperature is suitable for an ORC application (see Cement case study p.17 for description of the technology).

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. Here the case study presents a furnace which is operated 90% of the time at 70% load and 10% at full capacity.

Thus an existing furnace can be equipped with an ORC sized on 70% capacity of the furnace instead of 100% based on the recovery of both flue gases and skid cooling sources. In this configuration, extra losses over 70% of maximum capacity are dispatched to the backup feed water cooling of the skids system. The ORC system can only produce up to its maximum power design; in this case the ORC will be operating at its maximum efficiency all the time.
For a case study of a 450 t/h WBF with mixed gas, the configuration proposed by Fives would:

- Reduce heat losses through a skid system by 2 MW\textsubscript{th} thanks to new skid installation at 21 bars and water cooled skid pipes used at higher temperature
- Produce 2 MW\textsubscript{e} (11% net efficiency including auxiliaries) - typical for an ORC at this temperature
- While avoiding conventional skid cooling system 90% of the time

The ORC produces 16 GWh annually, which is 2 MWh more than 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 (depending on electricity and mixed gas prices respectively from €60 to 100 /MWh\textsubscript{e} and 0.012 to €0.03 /kWh\textsubscript{th}), compared to an ORC sized on maximum capacity.

![Figure 21](image)

Sketch of a WBF with ORC electricity production

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 OPEX – the Fives configuration has a payback of 3.6 years with an electricity price of €100 /MWh\textsubscript{e} and a fuel (mixed gas) cost of €0.03 /kWh\textsubscript{th}. This result comes in comparison with a conventional installation (skid system with water cooling solution and no recovery on the flue gases).

The energy recovery on the two sources combined with the ORC dimensioning on the furnace's real capacity reduces the payback time from:

- 1.2 to 1.5 years compared to a recovery with ORC on only the exhaust fumes and a dimensioning on 100% capacity
- 6 months to 1.5 years compared to a simple recovery with ORC only on the steam (water cooling solution on the skid system) and a dimensioning on 100% capacity

depending on the electricity and mixed gas prices of, respectively, €60 to 100 /MWh\textsubscript{e} and €0.012 to 0.03 /kWh\textsubscript{th}.  

Fives – A white book on industrial waste heat recovery
### 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></td>
</tr>
<tr>
<td></td>
<td>10% of the time at maximum capacity</td>
<td></td>
</tr>
<tr>
<td>Waste heat source @ 70% capacity</td>
<td>Steam: 9.4 MW(_{th}) at 200-250°C</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Water: 11 MW(_{th}) at 55°C</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Flue gases: 7.6 MW(_{th}) at 280°C</td>
<td></td>
</tr>
<tr>
<td>Electricity production</td>
<td>16 GWh/year (~ 2.2 MW(_{el}))</td>
<td></td>
</tr>
<tr>
<td>CAPEX</td>
<td>€6.4 M</td>
<td></td>
</tr>
<tr>
<td>OPEX</td>
<td>€350 k</td>
<td></td>
</tr>
<tr>
<td>Process benefits</td>
<td>Less losses 2 MW(_{th}) through skid system with steam use</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Operability of the waste heat recovery system on the skid cooling system</td>
<td></td>
</tr>
<tr>
<td>Payback</td>
<td>3.6 years electricity price of €100 /MWh and mixed gas price of €0.03 /kW(_{th})</td>
<td></td>
</tr>
<tr>
<td></td>
<td>7 years with electricity price of €60/MWh and mixed gas price of €0.012/kW(_{th})</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Compared to a traditional skid system water cooling</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Compared to traditional skid system water cooling (compensation between additional consumptions on exhauster and heat recovery loops, ORC OPEX and skid system cooling savings)</td>
<td></td>
</tr>
</tbody>
</table>

As presented above, the reheat furnace production can fluctuate in few minutes, which affects the heat content of exhaust gases entering the waste heat recovery system. The ORC is a rather flexible system that can accommodate such variations up to a certain point. An ORC 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.

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.
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 which 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
| Map the situation | Identify sources of waste heat and their characteristics | Such as temperature, pressure, flowrate, composition (abrasiveness, dew point...), as well as their variability. |
| Evaluate recoverable waste heat | | All available energy is usually not recoverable (e.g. because of acid condensation below 100-150°C). |
| Assess constraints and opportunities of the process | Assess performance criteria, available space, maximum/design load vs. actual load, available cooling sources, unmet energy needs... |

| Evaluate alternatives to waste heat recovery first | Compare existing equipment with the BAT (Best Available Technology) | 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. |
| Assess possible uses of waste heat into the equipment itself | | Identify internal uses e.g. for pre-heating air, fuel, or products |

| Review the best uses for recovered waste heat | Identify energy needs around the equipment | 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). |
| Select the valorization mode that has the highest added value | | Compare the value of the different possible WHR outputs (e.g. electricity vs. cold power, desalinated water, etc.) also depending on the plant location. |

| Design the WHR system | Consider the combination of several waste heat sources | It may lower the level of investment and widen the scope of possible WHR solutions. |
| Consider switching to a more adapted WHR carrier | Using another medium (e.g. air instead of water for cooling) can make WHR easier. |
| Consider the whole process and be ready for potential process changes | The overall efficiency of the whole process should be assessed to ensure environmental & economic viability of the plant, as addition of local benefits does not always lead to overall optimum. Adopt a « life cycle » mindset (e.g. when using additional energy to increase temperature of waste heat). |
| Iterate to determine how much energy should be recovered | Converting all recoverable energy is not always the best option, as it may be too costly and jeopardize the whole project. |
| Take into account the external benefits of WHR | 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. |
| Anticipate variability of the production process | 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. |
| Think of a back-up system | Continuous production must be ensured, even when the WHR system is unavailable. |

| Define optimal business model | Calculate CAPEX and OPEX of the plant with WHR | 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. |
| Identify financing options | Governmental incentives for energy efficiency projects or financing schemes offered by suppliers of WHR systems may be available. |
Appendices
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>
</tr>
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<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>
</tr>
<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>
</tr>
<tr>
<td>GTC</td>
<td>Gas Treatment Center</td>
</tr>
<tr>
<td>IEA</td>
<td>International Energy Agency</td>
</tr>
<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>
</tr>
<tr>
<td>OPEX</td>
<td>Operating Expenditure</td>
</tr>
<tr>
<td>ORC</td>
<td>Organic Rankine Cycle</td>
</tr>
<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 (i.e. a combustion product gas) is the temperature, at a given pressure, at which any gaseous acid 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 for the equipment used in transporting, cooling and emitting the flue gas.

(source: ChemEngineering)

Flues gases

Product of gas combustion which occurs in all Fives processes. Flue gases are mainly composed of nitrogen (N₂), air, 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.