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Waste-to-energy technologies in continuous process industries

Arturo Villar · Juan José Arribas · Jorge Parrondo

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Abstract A range of new waste-to-energy (WtE) technologies in continuous process industries have been analyzed in terms of conversion, energy saving, heat recovery, electricity generation, transportation fuel, storing energy and fuel, environmental emissions, and recycling management. This new group of WtE technologies is an emerging technology group for energy-intensive industries apart from the wide concept of "clean energy technologies". The current state of WtE technologies has been examined for five representative sectors in continuous industrial processes: iron and steel, cement, primary aluminum production, metal casting, and glass industry. The purpose of the study was to seek synergetic interactions between continuous process industries, with special emphasis on the case of the iron and steel industry. For the purpose of a comparative analysis, waste heat recovery (WHR) technology has been included. A case study in the steel sector is illustrated as a real-world example for solid recovery using WHR in sintering process.

Keywords Waste-to-energy technologies · Continuous process industries · Iron and steel industry · Energy saving · Waste heat recovery

A. Villar (✉) · J. Parrondo
Departamento de Energía, Universidad de Oviedo, Edificio Zona Este, Campus Universitario de Gijón, 33271 Gijón, Spain
e-mail: arturovillarmenendez@gmail.com

J. J. Arribas
Global R&D ArcelorMittal, 33400 Avilés, Spain

Introduction

The WtE technologies have become a keystone and are increasingly interesting as viewed from both an energy supply perspective and waste management. Globally, energy-intensive industries still emit the largest share of industrial greenhouse gas (GHG) emissions (IEA 2008b). WtE combines several ways of reducing GHG emissions. The term WtE is often used in reference to the incineration of municipal waste. However, in this article, WtE refers to all technologies that convert, transport, manage, and recover or reuse energy from any type of waste (solid, liquid, gas, and heat) in a continuous industrial process. In addition, these technologies have the potential for increasing heat recovery, emissions reduction, electric efficiency, transportation fuel substitution, and storing energy and fuel (Münster and Lund 2009). To our knowledge, no work has been reported in the open literature on WtE technologies in continuous process industries.

On the one hand, the global crisis has shown the importance of sustainable development. Tomorrow's industries must simultaneously address economic, social, and ecological dimensions, with processes that are as lean and clean as possible. In the medium and long term, "zero waste" and "zero emissions" will be the goals for the "factories of the future". On the other hand, under the pressure of rising world population and increasing lifestyle aspirations, global energy consumption is expected to double from the present level of 15 TW by 2050, and to triple by 2100. Thus, this will put a massive strain on Earth's resources (EU 2010).

The overall objective of the work presented was to investigate synergies between large energy consumers to achieve environmental and energy-saving technologies. In other words, the focus of this article was the analysis of the optimal use of WtE technologies in continuous process industries. The core of the first part of the article is the application of WtE technologies in the steel sector. The second section presents a summary of WtE technologies for a branch of general manufacturing industries with continuous processes. Finally, this study brings about a synergetic interaction in a matrix analysis among energy-intensive industries and identifies potentially energy-saving R&D areas of new WtE technologies.

Iron and steel industry

The iron and steel industry provides the backbone for construction, transportation, and manufacturing, and has become the material of choice for a variety of consumer products. Moreover, markets for iron and steel are expanding. As a result, this sector is critical to the world-wide economy.

The production process for manufacturing iron and steel is energy-intensive and requires a large amount of natural resources. The iron and steel industry accounted for 19% of final energy use and about a quarter of direct CO_2 emissions from the industry sector (IEA 2007). Energy constitutes a significant portion of the cost of iron and steel production, up to 40% in some countries. The majority of emissions generated by iron and steel production are due to coal use and other energy resources as a key process input, which means that increasing energy efficiency is the most cost-effective way to improve environmental performance (APP 2008). The aggregate carbon dioxide (CO_2) emissions from the global iron and steel industry have reached roughly two billion tons annually, accounting for approximately 5% of global anthropogenic CO_2 emissions (APP 2007).

The sector is divided into two basic types of production. First, standard processes with coke-making, iron-making, steel-making, and subsequent forming and finishing operations, which are referred to as "fully integrated production". Alternatively, a second type of production without coke-making or iron-making operations is mainly associated to metal scrap by applying electric arc furnace (EAF) technology, and is commonly referred to as "mini-mills" (EPA 2011). The integrated mill accounts for two-thirds of steel production (IEA 2007).

The production of steel requires a number of steps which can include: agglomeration processes (sintering, pelletizing, and briquetting), coke-making, iron-making (blast furnace, direct reduction, and direct iron-making), steel-making (basic oxygen furnace or BOF, EAF), and forming and finishing processes (ladle refining, casting, rolling, forming and finishing) (APP 2007).

Coke, which is the fuel and carbon source at integrated mills, is produced by heating coal in the absence of oxygen at high temperatures in coke ovens. Pig iron is then produced by heating the coke, iron ore, and limestone in a blast furnace. In a BOF, molten iron from the blast furnace is combined with flux and scrap steel where high-purity oxygen is injected. Moreover, in an EAF the input material is primarily scrap steel, which is melted and refined by passing an electric current from the electrodes through the scrap.

The sector has multi-media impacts, including air emissions (carbon oxide or COx, nitrogen oxide or NOx, sulfur oxide or SOx, and particulate matter or PMx), wastewater contaminants, hazardous wastes, and solid wastes. The major environmental impacts from integrated steel mills are from coke-making and iron-making. Furthermore, the energy used by "mini-mills" generates GHG from power generation (EPA 2011).

WtE technologies in the iron and steel industry

The iron and steel industry is faced with a wide range of environmental concerns that are fundamentally related to the high energy requirements, material usage, and the by-products associated with generating enormous quantities of steel (Manning and Fruehan 2001).

Figure 1 presents a layout of the current state-of-the-art in WtE technology in the iron and steel industry as collected from Asia Pacific Partnership (2007) and Arcelor-Mittal (2011).

Table 1 describes one by one these WtE technologies (showed in Fig. 1) in terms of iron and steel processes, typical uses and key factors (energy saving, environmental emission, commercial status, and other benefits). Fundamentally, the data have been gathered from Asia Pacific Partnership (2007).

Continuous process industries

Cement industry

Cement is an essential material for social infrastructure and has played a vital role in economic development around the world. The nonmetallic mineral sub-sector accounts for about 9% of global industrial energy use, of which 70–80% is used in cement production. The cement industry uses energy-intensive production processes and energy typically represents 20–40% of the total production costs (IEA 2007). Fossil fuels (e.g. coal, oil, or natural gas) are the predominant fuels used in the cement industry. Consequently, the aggregate amount of CO_2 emitted from the global cement industry has reached about 2.2 billion tons, accounting for approximately 5% of global man-made CO_2 emissions. However, alternative fossil fuels such as natural

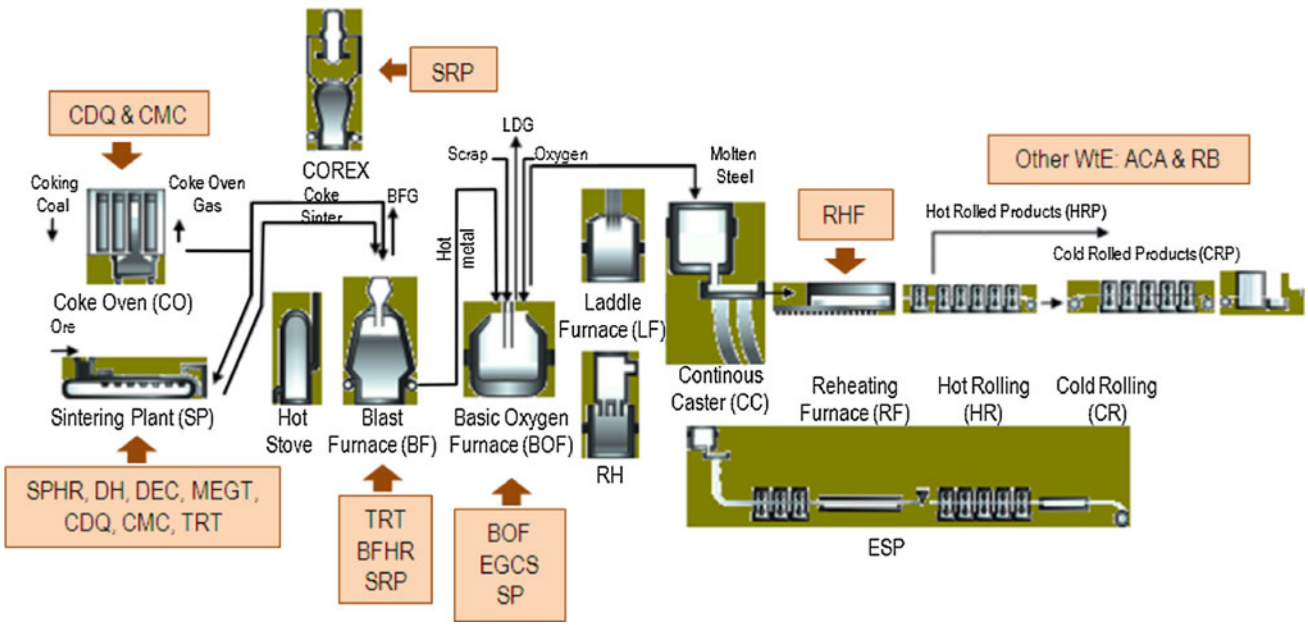

Fig. 1 Layout of WtE technologies in the iron and steel production processes

gas and biomass fuels have been increasingly used as a key factor to reduce CO_2 emissions in the recent years (IEA 2009).

The production of cement involves four steps: preparation of a material mixture, thermal formation of clinker in the cement kiln, clinker cooling, and finally grinding and mixing with additives to the cement quality required (Bolwerk 2005). Dry process kilns produce almost 80% of cement manufactured in Europe (EHS 2007). Table 2 exhibits the particular WtE technologies in the cement industry, which have mainly been obtained from International Energy Agency (2009).

Primary aluminum production industry

More than half of the energy used in nonferrous metals is for primary aluminum production (IEA 2007). Aluminum is the third most abundant element (following oxygen and silicon) and represents 8% of the Earth's crust (Balomenos et al. 2009). Because of its chemical reactivity, aluminum is never found in nature as an isolated element but always in its oxidized form as a component of a variety of minerals. The steps for primary aluminum production are: bauxite mining, production of alumina from bauxite, production of carbon anodes, electrolysis, and rolling. Electrolysis is the most energy-intensive step in the production of aluminum (IEA 2007) and is responsible for the generation of large amounts of CO_2 (Balomenos et al. 2009). The pre-eminent WtE technologies are outlined in Table 3.

Metal-casting industry

The metal-casting industry produces both simple and complex parts that meet a wide variety of manufacturing needs. Metal-casting foundries range in size from small job shops to large manufacturing plants that turn out thousands of tons of castings each day (ITP 2005). Cast metal products are found in 90% of manufactured goods and equipment, from critical components for aircraft, automobiles, defense equipment to power generation equipment, industrial machinery, and construction materials (Eppich and Naranjo 2007).

The most common process used for casting is green sand molding, accounting for approximately 60% of castings produced. The major energy-consuming processes in metal casting include melting metal (about 55% of energy consumption), core making, heat treating, and post-casting operations (Eppich and Naranjo 2007). Generation of waste is directly related to the type of material melted (cast iron, steel, brass/bronze, or aluminum) (ITP 2005). Major information (Table 4) has been collected from Industrial Technologies Program (2005).

Glass industry

The glass industry consists of five segments: flat glass, glass containers, pressed and blown glass, wool fiberglass, and products of purchased glass. Approximately, 57% of all glass melted is produced by the glass container segment.

Table 1 Matrix of WtE technologies, uses and benefits in the iron and steel industry

WtE technology	Iron and steel process	Typical uses	Key factors
Sinter plant heat recovery (SPHR)	Sintering	Preheat the combustion air for the burners and generate high-pressure steam	Fuel savings in steam and coke with increased electricity use. Reduction in emissions (NOx, SOx, dust), coke and recovered exhaust heat. Commercial status: mature
District heating (DH)	Sintering	Waste heat in the steel industry but also for sharing resources with nearby residential and commercial buildings	Method for saving energy. Low temperature heat and waste heat. Economical benefits and a great reduction in total fuel requirements. Commercial status: mature
Dust emissions control (DEC)	Sintering	By sending waste off-gas to Electrostatic Precipitators (ESPs) producing clean waste gas and increasing the quantity of steam recovery	Over 98% efficiency, reducing dust load in off-gas of a typical plant from 3,000 mg/m^3 to about 50 mg/m^3. ESPs removal of fine dust may reduce particulate matter emission levels at sinter plants to about 50–150 mg/m^3. ESPs cause increased energy consumption of about 0.002 to 0.003 GJ/t sinter. Commercial status: mature
Main exhaust gas treatment (MEGT)	Sintering	SOx, NOx, dust, and dioxins contaminants are processed, absorbed, decomposed, and/or collected as non-toxic by-products to increase the quantity of steam recovery, and improve total fuel savings	SOx is absorbed and recovered as useful by-product. NOx is decomposed to nitrogen, water and oxygen by ammonia. Dust is collected in activated coke. Dioxins are collected or absorbed in activated coke and decomposed at 400°C with no-oxygen. Commercial status: mature
Coke dry quenching (CDQ)	Sintering coke-making	The heat is used to produce steam, which may be used on-site or to generate electricity. Recovers the sensible heat of the coke. As an environmental control technology	Energy recovered is approximately 400–500 kg steam/t, equivalent to 800–1200 MJ/t coke. Others estimate energy conservation through steam generation (0.48 t/t coke). Decreased dust, CO_2 and SOx emissions. Increased water efficiency. Better quality coke production, improved strength of coke by 4%. Commercial status: mature
Coal moisture control (CMC)	Sintering coke-making	Waste heat from the coke oven gas to dry the coal used for coke-making. The coal can be dried using the heat content of the coke oven gas or other waste heat sources	Fuel savings of approximately 0.3 GJ/t. Coke quality improvement (about 1.7%). Coke production increase (about 10%). Shorter cooking times. Decrease in water pollution (ammonia reduction). Commercial status: emerging
Top-pressure recovery turbine (TRT)	Sintering iron-making	TRT is a power generation system, which converts the physical energy of high-pressure blast furnace top gas into electricity by using an expansion turbine	Generates electric power of approximately 40–60 kWh/t pig iron. Excellent operational reliability, abrasion resistant. Suitable for larger furnaces and higher temperature gases compared to bag filter systems. Commercial status: mature
Blast furnace heat recuperation (BFHR)	Iron-making	Recuperation systems, e.g., Hot Blast Stove, BFG (Blast Furnace Gas) Preheating System, etc., are used to heat the combustion air of the blast furnace. The exit temperature of the flue gases, approximately 250°C, can be recovered to preheat the combustion air of the stoves	Hot Blast Stove fuel savings vary between 80–85 MJ/t. BFG Preheating System has an economic recovery for low to medium temperature grade heat. Energy savings of 3–5% for boiler. Commercial status: emerging
Smelting reduction process (SRP)	Iron-making	The excess gas produced is used for power generation, production of direct reduced iron (an alternative iron input for scrap), or as fuel gas. Smelting reduction processes, including Aumelt Ausiron®, HIsmelt®, CCF, DIOS and COREX, involve the pre-reduction of iron ore by gases coming from a hot bath	Low capital and operating costs. Single furnace with direct waste energy recovery. Low environmental impact (reduced CO_2, SO_2, and NOx). Recycling of steel plant dusts and slag, making effective uses of coal energy. Commercial status: emerging
Basic oxygen furnace (BOF)	Steel-making	The sensible heat of the off-gas is first recovered in a waste heat boiler, generating high-pressure steam. The gas is cleaned and recovered	Energy savings vary between 535 and 916 MJ/ton steel, depends on the way in which the steam is recovered; with increased power of 2 kWh/ton the total primary energy savings is 136%. Commercial status: mature

Table 1 continued

WtE technology	Iron and steel process	Typical uses	Key factors
Exhaust gas cooling system (EGCS)	Steel-making	Recovers the latent heat and sensible heat of gas as steam through heat exchange. Exhaust gas treatment consists of an exhaust gas cooling system and a cleaning system	Two types of steam recovery boilers, a full boiler equipped with a super heater and coal economizer, and a half boiler without such equipment. Several types of dust removal machines, such as electrical precipitators (which are the most popular, wet and dry type), venturi scrubbers and bag filters. Commercial status: mature
Scrap preheating (SP)	Steel-making	Reduce the power consumption of EAFs through from using the waste heat of the furnace to preheat the scrap charge. Various systems have been developed and are in use at various sites in the U.S. and Europe, i.e., Consteel tunnel-type preheater, Fuchs Finger Shaft, and Fuchs Twin Shaft	Consteel Process. Productivity increase of 33%. Reduced electrode consumption of 40% and dust emissions. Commercial status: mature. Fusch Shaft Furnaces. Electricity savings of 120 kWh/t and fuel increases of 0.7 GJ/t. Up to 20% productivity increase. 25% reduced flue gas dust emissions (reducing hazardous waste handling costs). Commercial status: mature
Rotary hearth furnace (RHF) dust recycling system	Common system	Dust recycling in the rotary hearth furnace (RHF). Zinc and other impurities in the dust and sludge are expelled and exhausted into off-gas.	DRI (Direct Reduction Ore) pellets made from the dust and sludge have 70% metallization and are strong enough to be recycled to the blast furnaces. Waste reduction and decreased disposal costs. Recovery of unused resources (recycling iron, nickel, zinc, carbon, etc.). Commercial status: emerging
Activated carbon absorption (ACA)	Common system	Remove high pollutant concentrations	Eliminate the yellow brown color of coke wastewater. Significant reduction of COD (Chemical Oxygen Demand) of the secondary wastewater treatment plant to below 5 mg/ℓ. Heavy metals removal. Commercial status: mature
Regenerative burner (RB)	Common system	Recovers the waste heat of the furnace exhaust gas to heat-up the combustion air of the furnace	20–50% of energy reduction possible, depending on types of furnace and condition of fuel up to 50% NOx reduction possible with high-temperature combustion. Commercial status: mature

Table 2 Summary of WtE technologies in the cement industry

WtE technology	Cement process	Typical uses	Key factors
Preheater (PH) and Precalciner (PC) Multistage cyclone	Dry manufacturing	Heat produced by the kiln to preheat the raw materials as they move through the various stages of the tall preheater towers.	Fuel efficient than long kilns using up to 50% less energy. Lowest heat consumption (due to the high heat recovery from kiln gas in the cyclones, and the low kiln heat losses). Offers the highest production capacity (EHS 2007). Comparing with wet kiln there is no evaporation of water (EHS 2007)
Waste heat recovery (WHR)	Dry manufacturing	Recovery the waste energy that was discharged unused in waste gases, and uses it in a steam turbine to convert the energy to electricity. Preheating the combustion air in the cooler while at same time cooling the clinker, and by using the exhaust the gas energy after the rotary kiln for calcining and preheating the raw meal in the calciner and preheater (Bolwerk 2005)	No added fuel is required, so generation is cleaner and running cost lower. Waste heat recoverable (1,000 ton/day of clinker capacity) from various streams can be (AIT 1997): by-pass gas: 120–241 MJ/ton of clinker cyclone preheater exhaust gas: 388–457 MJ/ton of clinker clinker cooler exhaust gas: 345–457 MJ/ton of clinker
Grate cooler (GC)	Clinker cooling	An excess of heated cooling air is re-circulated back to the PH or PC kiln (ESTAP 2010)	Efficiency of 70–75%. Electricity consumption ranges from 4 to 8 kWh/ton of clinker. Economical lifetime more than 10 years (ESTAP 2010). Commercial status: mature

Table 3 Main WtE technologies in the primary aluminum production industry

WtE technology	Primary aluminum process	Typical uses	Key factors
Hall-Héroult (HH)	Electrolysis	High intensity energy conversion systems. Point-fed prebaked technology (IEA 2007)	Electricity consumption for pre-baked is in the range of 13–16.5 kWh/kg. Difference in efficiency between 20% attributed to different cell types (IEA 2007). Commercial status: mature New technology Inert Anode (Prebake Anode or PBANOD) would improve (Luo and Soria 2007): energy efficiency 10–25% Commercial status: availability is expected by 2020
Reverberatory furnace (RF)	Alloying and melting	Capture the waste heat in the stack gas to preheat incoming materials. Heat is transferred to the molten metal by convection and radiation (EERE 2007)	Increases energy efficiency and reduces the time required to melt the metal. Recuperated waste heat can also be used to preheat combustion air and cogeneration. Reduce fuel usage to less than 0.57 kWh/kg of aluminum (EERE 2007)

Table 4 WtE technologies in metal casting process

WtE technology	Metal casting process	Typical uses	Key factors
Cupola furnace (CP)	Melting	Melting cast iron because the molten droplets of metal directly contact the coke and flux during their descent, saturating the liquid iron with carbon and refining the metal product	Energy efficiency from 40 to over 70%. Air blast preheating offer energy saving with efficient off-gas combustion systems. Waste heat recuperators preheat the hot blast air up to 650°C (1,200°F). Oxygen-fuel burners increase energy efficiency with dust injection systems and provide a method of recycling plant-generated residues (cupola dust, finishing dust, and sand reclamation dust)
Stack furnace (SF)	Melting	Flue gases to preheat the charge materials	The hot exhaust gases preheat the incoming charge, improving the energy efficiency of the stack furnace by 40–50%. SF has waste gas control and preheating area
Heat recovery system (HRS)	Melting	Transfer thermal energy from the high-temperature effluent stream to a low-temperature input stream (make-up air or metal charge)	Waste-heat-conversion methods, as absorption refrigeration, thermoelectric and thermionic, utilize the elevated flue gas temperatures to drive energy conversion devices. This WtE is reused, it save up 20% of energy costs and reduce emissions
Preheating system (PS)	Melting	Preheat scrap for the second charge of the heat or the first part of the next heat. Shaft furnace technology and twin shell system	Scrap preheating reduce the energy for melting (by up to 50–75 kWh/ton) and electric energy by 30–60 kWh/ton

The remaining glass melting is roughly divided between the flat glass (24%) and pressed and blown glass (19%) segments (SOTA 1997).

More than half of energy consumption in the glass production process corresponds to the melting process. The main production steps found in virtually all glass plants are: raw materials selection, batch preparation (weighing and mixing raw materials), melting and refining, conditioning and forming, and post-processing—annealing, tempering, polishing or coating (IEA 2007). WtE technologies related to glass process are shown in Table 5.

Applications

Waste heat recovery technologies in energy-intensive industries

Between 20 and 50% of industrial energy input is estimated to be lost as waste heat in the form of hot exhaust gases, cooling water, and heat lost from hot equipment surfaces and heated products (ITP 2008). In fact, heating is considered to be the second largest energy-consuming operation (EERE 2007).

Table 5 WtE technologies related to glass industry

WtE technology	Glass process	Typical uses	Key factors
Oxy-fuel furnace (OFF)	Melting	Oxygen as a way to increase fuel efficiency and reduce emissions	Reduces NOx and CO_2 emissions substantially. Improves heat transfer characteristics and reduced volatilization of alkali vapors from glass melting. (Kobayashi and Van Hassel 2005)
Waste heat recovery boiler (WHRB)	Float and container	Residual heat of waste gases to preheat raw materials and cullet	The recovered waste heat is about 0.28 GJ/t where the overall energy consumption of the furnace is about 3.78 GJ/t. This corresponds in energy savings of 7.4% of the furnace fuel consumption (Wesselink and Deng 2009). It is estimated that 40% of the capacity in the container glass production can be retrofitted with batch WHRB systems in the next two decades (Wesselink and Deng 2009)
Recuperative furnace (RF)	Common system	Continuous preheat of combustion air by the waste gases	Metallic heat exchangers for heat recovery. Excess heat in the off-gas stream can be used to generate steam in a WHRB. Increase overall efficiency to 50–65% (Worrell et al. 2008)

Table 6 presents a current state of WHR practices in a variety of applications in energy-intensive industries as collected from International Technologies Program in U.S. industry (2008). The results from this investigation serve as a basis for understanding the current state of WHR in terms of commercialization status, technical, and economic feasibility in the U.S. industry.

New technologies are emerging as options for heat recovery such as the kalina cycle for low temperature power generation and thermoelectric devices (direct conversion technologies) (ITP 2008).

Case study in the steel sector

A case study for solid recovery using WHR in sintering process is illustrated (Fig. 2) as a real-world example.

The key points for solid recovery are: two hoods with two air/water tubular heat exchangers (50% of the cooler is covered), one bag filter for the dedusting of gas and two blowers. There is a reduction of 250 t/h of sinter from 500 to 50°C => 30 MW (theory) and emission reduction of 92% of the diffuse dust (ArcelorMittal 2010).

A first conclusion is that heat recovery can be used alone or with dedusting and good synergy exists between cooler dedusting and heat recovery. Moreover, heat can be used for district heating, but other applications are possible, such as preheating combustion air or sinter raw mix. Finally, heat recovery can lead to CO_2 emission reduction.

Synergetic interaction between continuous process industries

Table 7 describes the interaction between continuous process industries in terms of synergy (inter-industry collaboration), typical uses, and key factors.

R&D areas of new WtE technologies

Literature searches were conducted to obtain available information on R&D areas of new WtE technologies. The U.S.A. appears to be the top country in terms of relative amount of annual R&D intensities and number of scientists and engineers per million people (WBCSD 2010). Based on the report of the World Business Council for Sustainable Development (2010), which lists a wide range of WtE technologies in continuous industrial processes, there are two issues on R&D:

– The first issue is focusing on industrial reactions & separations related to: advanced water removal (500 TBtu), low-water-use industrial processes, advanced gas separations (60 TBtu), hybrid distillation (240 TBtu), energy-intensive conversion processes (200 TBtu), and is projected in the long-term (2030) savings of 1,000 TBtu and 75 $MMTCO_2$ (Chan 2010; Glatt 2010).
– The second issue is waste heat minimization & recovery related to: super Boiler (350 TBtu), ultra-high efficiency furnace (90 TBtu), waste heat recovery systems (260 TBtu), and is projected savings in 2030 of 700 TBtu and 50 $MMTCO_2$ (Chan 2010; Glatt 2010).

Top three R&D areas of new WtE technologies are: low-temperature waste heat recovery (steam generation, heat utilization), high efficiency thermoelectric for low temperature heat recovery, and combined heat & power (CHP): systems recover waste heat to generate electricity and heat at >80% efficiency.

Conclusions

This research has been conducted on the field of "WtE technologies", which represents an emerging technology

Table 6 WHR in the U.S. energy-intensive industries

	Iron and steel											
	Coke oven						Blast furnace					
	Coke oven gas			Waste gas			Blast furnace gas			Hot blast stove exhaust		
	Commercial	Technical	Economic	Commercial	Technical	Economic	Commercial	Technical	Economic	Commercial	Technical	Economic
Regenerator	–	–	–	+	+	+	–	–	–	n	n	–
Recuperator	–	–	–	n	–	–	–	–	–	n	n	–
Heat wheel	–	–	–	n	m	–	n	n	n	+	+	+
Passive air preheater	–	–	–	–	o	o	n	n	n	+	+	+
Thermal medium system	o	o	–	n	m	–	n	n	n	+	+	+
Waste heat boiler	–	–	–	–	–	–	n	–	n	n	–	–
Low T power cycle	–	–	–	n	m	–	–	n	n	–	m	n
Solid state generation	–	–	–	–	m	–	–	–	–	–	m	–
Load preheat												
Process specific/other[a]	o	o	–	o	o	–	o	+	–			

	Iron and steel						Glass industry					
	BOF			EAF			Glass melting					
	Basic oxygen a furnace gas			Electric arc furnace offgas			Gas-fired melting furnace			Oxyfuel melting furnace		
	Commercial	Technical	Economic	Commercial	Technical	Economic	Commercial	Technical	Economic	Commercial	Technical	Economic
Regenerator	x	x	x	x	x	x	+	+	o	–	o	–
Recuperator	x	x	x	x	x	x	+	+	+	–	o	–
Heat wheel	x	x	x	x	x	x	o	o	–	n	o	–
Passive air preheater	x	x	x	x	x	x	n	n	n	–	o	–
Thermal medium system	n	n	n	n	n	n	n	n	n	n	n	n
Waste heat boiler	o	+	o	n	–	n	o	+	–	o	+	–
Low T power cycle	x	x	x	x	x	x	x	x	x	x	x	x
Solid state generation	–	–	–	–	–	–	–	m	–	–	m	–
Load preheat				+	+	o	n	m	n	o	o	o
Process specific/other[a]												

Table 6 continued

	Cement			Primary aluminum						Metal casting		
	Cement kiln			Hall-Héroult Cells			Melting furnace			Iron cupola		
	Commercial	Technical	Economic	Commercial	Technical	Economic	Commercial	Technical	Economic	Commercial	Technical	Economic
Regenerator	n	n	n	–	–	–	+	+	o	n	n	n
Recuperator	n	n	n	–	–	–	+	+	o	+	+	+
Heat wheel	n	n	n	–	–	–	o	+	o	n	n	n
Passive air preheater	n	n	n	–	–	–	n	n	n	n	n	n
Thermal medium system	n	n	n	–	–	–	n	n	n	n	n	n
Waste heat boiler	+	+	+	–	–	–	n	n	n	n	n	n
Low T power cycle	o	+	o	–	–	–	x	x	x	n	n	n
Solid state generation	–	m	–	–	m	–	–	m	–	–	m	–
Load preheat	+	+	+	n	n	n	+	+	o			
Process specific/other[a]	+	+	+									

Key	Commercial status	Technical feasibility	Economic feasibility
	+ Frequently used in US	+ No technical barriers	+ Cost effective
	o Limited commercialization	o Proven in limited applications	o Application-specific
	– Not deployed	m May be feasible, not demonstrated	– Cost-prohibitive
		– Not technically feasible	
	n Not addressed in available literature		
	x Not applicable		

[a] "Process Specific" includes coal moisture control for coke-making, dry-type top-pressure recovery turbines for blast furnace, and recovery from cement clinker cooler

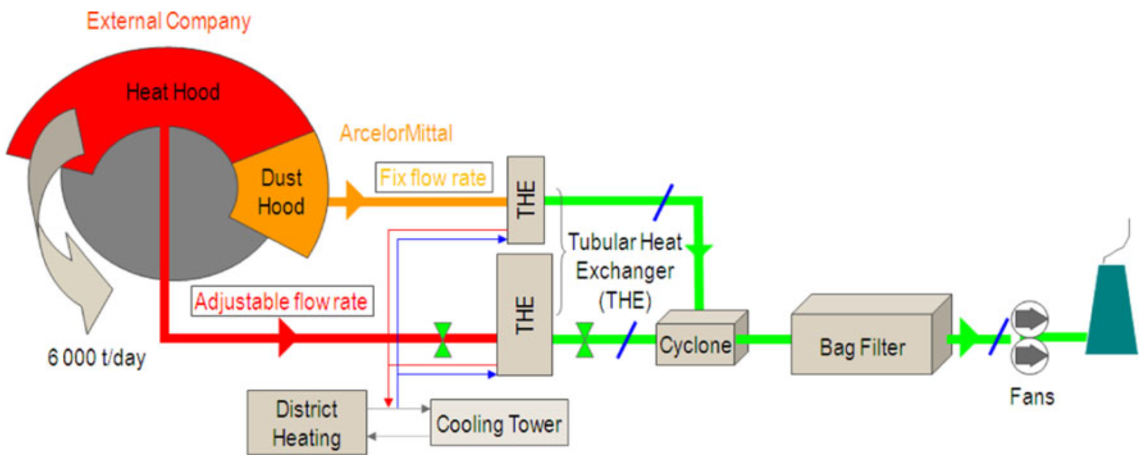

Fig. 2 Case study in the steel sector using WHR

Table 7 Synergetic interaction between continuous process industries

Synergy	Industry	Typical uses	Key factors
Iron and steel—Blast-furnace slag	Cement	About half of all blast-furnace slag is already used for cement-making. The main objective is replacing the clinker ingredient with less energy-intensive	The slag is water-cooled. Transport distances and costs are acceptable. If all blast-furnace slag were used, this would yield a CO_2 reduction of approximately 100 Mt CO_2 (IEA 2008a)
Iron and steel—Steel slag	Cement	The CemStar uses 15% charge of air-cooled steel slag pebbles in the rotary kiln feedstock mix. The main goal is replacing the clinker ingredient with other mineral industrial components, which less energy-intensive	CO_2 reduction of approximately 0.47 t/t steel slag added. Successfully applied in the United States (IEA 2008a)
Iron and steel—Steel slag	Metal casting	Slag can be recycled as a feed to cupola furnaces (gray iron production line)	The cupola furnace slag scavenges trace metals from the induction furnace slag. The resulting cupola slag may be rendered a nonhazardous waste
Cement—Rotary kiln	Primary aluminum	The kiln can be rotary (like a cement works) or, in more modern plants a fluid bed furnace	Lower capital costs because of smaller equipment. Lower temperatures resulting in lower NOx emissions and a wider variety of fuels can be used, as well as lower energy use
Glass—Oxy-fuel technology	Primary aluminum	Know-how of OFF in glass industry as a way to increase fuel efficiency and reduce emissions	Reduce the volume of the waste gases and the use of heat recovery systems is avoided
Metal casting—Stack furnaces	Primary aluminum	A modified reverberatory furnace where its efficiency is improved by better sealing of the furnace and the use of the flue gases to preheat the charge materials	Higher energy efficiency than reverberatory furnaces

group for energy-intensive industries apart from the wide concept of “clean energy technologies”. The current state of WtE technologies has been investigated for five representative sectors in continuous industrial processes: iron and steel, cement, primary aluminum production, metal casting, and glass industry. Goals for the “factories of the future” in all of those sectors are “zero emissions” and “zero material waste” (clean energy technologies) plus maximum efficiency in energy consumption, which requires the best specific technologies for waste energy recovery.

This new group of WtE technologies in continuous process industries has been analyzed in terms of conversion, transportation, management, and recovery or reuse energy from any type of waste (solid, liquid, gas, and heat). Such technologies have the potential for increasing heat recovery, emissions reduction, electric efficiency, transportation fuel substitution, and storing energy and fuel.

This article outlines the potential for technological advancement in the continuous industrial processes of the five sectors studied, as well as inter-industry energy-efficiency opportunities. The aim of the study has been to provide a practical classification of the typical uses and key factors of current WtE technologies. As an application, some synergetic interactions between continuous process industries have been identified, mostly related to WHR technologies, in addition to potentially energy-saving R&D areas of new WtE technologies.

WtE technologies for industrial processes represent a challenge that requires scientific innovation, process development, and manufacturing scale-up required to accelerate the commercialization of WtE technologies with potential cross-industry collaboration. In conclusion, WtE technologies are the key to success as energy-efficiency technologies to reduce energy use and GHG emissions in medium- and long-term approach.

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