Emerging Energy-Efficiency and CO_2 Emissions-Reduction Technologies for Industry: A Review of Technologies for Alternative Ironmaking and Pulp and Paper Industry

Ali Hasanbeigi and Lynn Price, Lawrence Berkeley National Laboratory
Lingbo Kong, South China University of Technology
Marlene Arens, Fraunhofer Institute for Systems and Innovation Research

ABSTRACT

Iron and steel and pulp and paper manufacturing are among the most energy-intensive industries. The steel industry accounts for the largest share, approximately 27 percent, of global carbon dioxide (CO_2) emissions from the manufacturing sector. Globally, the pulp and paper industry accounted for approximately 5 percent of total world industrial energy consumption in 2007, and contributed 2 percent of direct CO_2 emissions from industry. The ongoing increase in world steel and paper demand means that these industries' energy use and CO_2 emissions will continue to grow, so there is significant incentive to develop, commercialize, and adopt emerging energy-efficiency and CO_2 emissions-reduction technologies for steel and paper production. Although studies from around the world have identified a wide range of energy-efficiency technologies applicable to the steel and paper industry that have already been commercialized, information is limited and/or scattered regarding emerging or advanced energy-efficiency and low-carbon technologies that are not yet commercialized. This paper presents the work on compiling the available information on emerging alternative ironmaking technologies and emerging technology for the pulp and paper industry, with the intent of providing a well-structured database of information on these technologies for engineers, researchers, investors, companies, policy makers, and other interested parties. For each technology included, we provide information on energy savings and environmental and other benefits, costs, and commercialization status. The methodology of the study and some of the important technologies will be discussed in details.

Introduction

Iron and steel manufacturing is one of the most energy-intensive industries worldwide. In addition, use of coal as the primary fuel for iron and steel production means that iron and steel production has among the highest carbon dioxide (CO_2) emissions of any industry. According to the International Energy Agency (IEA), the iron and steel industry accounts for the largest share – approximately 27 percent – of CO_2 emissions from the global manufacturing sector (IEA 2007). Annual world steel demand is expected to grow from approximately 1,410 million tonnes (Mt) of crude steel in 2010 (USGS 2012) to approximately 2,200 Mt in 2050 (Bellevrat and Menanteau 2008). The bulk of this growth will take place in China, India, and other developing countries in Asia. This significant increase in steel consumption and production will drive a significant increase in the industry's absolute energy use and CO_2 emissions.

Globally, pulp and paper manufacturing is the fourth largest industries in terms of energy use, using 6.87 exajoules (EJ) of final energy in 2007, which is 5 percent of total world industrial energy consumption (Kong et al. 2013). However, unlike the iron and steel industry, the pulp and paper sector is one of the least carbon-intensive industries as a result of the large share of biomass. According to IEA, the pulp and paper industry emitted 183 Mt of direct CO_2, accounts for only 2 percent of direct CO_2 emissions from the global manufacturing sector (IEA 2011). World paper production is expected to grow from about 394 Mt in 2010 (FAOSTAT 2012) to approximately 700 Mt (low estimate) and 900 Mt (high estimate) in 2050 (IEA 2009). The bulk of this growth will take place in China, India, and other developing countries. This significant increase in paper production will cause a corresponding significant increase in the industry's absolute energy use and CO_2 emissions.

Many studies from around the world have identified sector-specific (AISI 2010; APP 2010; EIPPCB 2001, 2013; FOE 2005; Kramer et al. 2009; Martin et al. 2000a; U.S. EPA 2010a, 2010b; Worrell et al. 2010;) and cross-cutting (NEDO 2008; U.S. DOE/AMO 2012) energy-efficiency technologies for the iron and steel and pulp and paper industry that are already commercially available. However, information is limited and not easily accessible regarding emerging or advanced energy-efficiency and low-carbon technologies for the industry that have not yet been commercialized. This paper consolidates the available information on alternative emerging ironmaking technologies and emerging energy efficiency technologies for the pulp and paper industry to assist engineers, researchers, investors, iron and steel companies, policy makers, and other interested parties.

We have identified the commercialization status of each technology. The commercialization status of each technology is as of the writing of this paper and uses the following categories:

- Research stage: The technology has been studied, but no prototype has been developed.
- Development stage: The technology is being studied in the laboratory, and a prototype has been developed.
- Pilot stage: The technology is being tested at an industrial-scale pilot plant.
- Demonstration stage: The technology is being demonstrated and tested at the industrial scale in more than one plant but has not yet been commercially proven.
- Commercial with very low adoption rate stage: The technology is proven and is being commercialized but has a very small market share.

The purpose of this paper is solely informational. Many emerging technologies are proprietary and/or the manufacturers who are developing a new technology are the primary sources of information about it. Thus, in some cases, we identify a company that is the source of a technology so that readers can obtain more information about the company and product. Because the nature of emerging technologies is continual and often rapidly change, the information presented in this paper is also subject to change.

Alternative Emerging Ironmaking Technologies

Originally, we reviewed the following 12 alternative emerging ironmaking technologies that reduce energy use and carbon emissions: the COREX process, the FINEX process, Tecnored, ITmk3, the paired straight hearth furnace, the coal-based HYL process, the coal-based MIDREX process[1], molten oxide electrolysis, suspension hydrogen reduction, fine ore reduction in a circulating fluidized bed, charging carbon composite agglomerates, use of biomass and waste oxides, and the cyclone converter furnace. However, because of the space constraint, the subsections below describe only three of these technologies which are commercial but with very low adoption rate. The detail information on all the 12 technologies can be found in Hasanbeigi et al. (2013).

Table 1. A Comparison of Ironmaking Technologies

Iron making technologies	Reducing agent and energy source				Form of iron ore that can be used				Oxygen is needed	Coal gasification is needed	Commercial-ization status
	Non-coking Coal	Coke	NG [a]	Other	Sinter	Pellet	Lump ore	Fine ore			
Blast Furnace		X			X	X					Commercial
COREX® Process	X				X	X	X		X		Commercial with very low adoption rate
FINEX® Process	X							X	X		Commercial with very low adoption rate
Tecnored	X					X [b]		X [b]			Pilot
ITmk3 Ironmaking Process	X					X [c]		X [c]			Demonstration
Paired Straight Hearth Furnace	X					X [d]		X [d]			Development
Coal-Based HYL Process- A Syngas based DRI Plant	X					X	X			X	Commercial with very low adoption rate
Coal-Based MIDREX Process	X					X	X		X	X	Demonstration
Fine Ore Reduction in the Circulating Fluidized Bed (Circored® and Circofer®)	X [e]		X [e]					X			Demonstration/ Pilot
Cyclone Converter Furnace	X					X	X		X		Pilot
Producing Iron by Electrolysis of Iron Ore (Molten Oxide Electrolysis)				X [f]		X	X				Research/ Development
Suspension Hydrogen Reduction of Iron Oxide Concentrate			X [g]	X [g]			X	X		X [g]	Research/ Development
Ironmaking using Biomass and Waste Oxides				X [h]		X [h]					Research

[a] NG: Natural gas
[b] Pellets or briquettes used in Tecnored process are made from low-grade iron ore fines; low-cost reductants such as non-coking coals; pet-coke; biomass and briquettes of coal fines; fluxes; binders; and returned fines which are mixed and agglomerated into pellets or briquettes.
[c] Low grade ores are beneficiated, and the resulting fines (with >62% Fe content) are pelletized and used.
[d] Cold-bonded self-reducing pellets composed of iron oxide and coal. The sources of the iron oxide can be iron ore fines, recycled steel plant wastes, or a combination of the two. The reductant is high-volatility coal.
[e] Circored is gas-based (hydrogen as reductant), and Circofer is coal-based.
[f] Only electricity is used.
[g] Three reductants are suitable for this process: H_2, natural gas, or synthetic gas produced from partial combustion of coal and/or waste plastics.
[h] This process uses wood charcoal in ore waste pellets (composite pellets) in a RHF.

[1] Natural gas-based HYL and MIDREX processes are commercialized; thus, they are not included in this section as emerging technologies.

COREX Process

COREX is an industrially and commercially proven SR process that allows for production of hot metal directly from iron ore and non-coking coal. COREX differs from BF production in using non-coking coal as reducing agent and energy source. In addition, iron ore can be directly charged to the process in form of lump ore, pellets, and sinter (Siemens VAI. 2007).

The COREX process is a two-stage direct smelting process, consisting of: 1) a melter-gasifier, which melts the DRI and gasifies the coal; and 2) a DRI shaft furnace mounted above melter-gasifier, which reduces lump ore or pellets to DRI by reducing gas from the melter-gasifier. The shaft furnace is a modified MIDREX DRI counter-current reactor without a cooling zone in which lump ore or/and pellets are reduced to approximately 85-percent metallization. The hot DRI at a temperature of approximately 800^0C is discharged from the shaft furnace by means of horizontal screw conveyors, to the charging pipes of the melter-gasifier. The reducing gas enters the bottom of metallization zone. The fresh reducing gas from the melter-gasifier enters the shaft furnace at approximately 800°C and then exits from the furnace top at ~450 °C. The melter-gasifier, which completes the reduction and melting of the DRI, consists of a fluidized bed chamber resting on liquid slag and a hot metal bath. Coarse coal is charged to the top of melter-gasifier and charred in the fluidized bed. Oxygen is injected via tuyeres around the circumference of the melter-gasifier. This forms a raceway in which the oxygen reacts with charred coal to form CO. For optimum energy efficiency and economics, the process requires the following auxiliaries: 1) CO_2 stripping of the shaft top gas, which enables better utilization of the process gas (after CO_2 stripping, the rich reducing gas could be recirculated to the shaft furnace); and 2) In most cases, co-generation of the export gas, required because of the high calorific value of the gas. An additional DRI shaft furnace could be also installed to utilize the off gas and to produce an amount of DRI equivalent to the hot metal from the melter-gasifier (APP 2010).

Some of the limitations of the COREX process are (Agrawal and Mathur 2011):

- It can't use ore fines directly
- There are restrictions on non-coking coal (volatile matter of carbonaceous material to be maintained at around 25%
- Net export gas should be utilize very economically, otherwise the process becomes un-viable.

There are five commercial COREX units in operation in China, Korea, India, and South Africa (Siemens VAI 2007). The following benefits are reported for COREX compared to a conventional BF (APP 2010; Siemens VAI. 2007):

- No need for coking coal and coke
- Fuel savings of 18 percent and oxygen consumption reduction of 13 percent (reported for a low-export gas system demonstration in India)
- Approximately 20-percent lower CO_2 emissions per tonne of product
- Approximately 30-percent lower NOx emissions per tonne of product
- No VOC emissions; significantly lower SOx emissions
- Fuel rate significantly reduced by circulation of the shaft furnace top gas back to the shaft furnace

- Reduced investment and operation costs
- Lower slag production (18-percent slag production reduction reported in a low-export gas system demonstration in India)

FINEX Process

The FINEX smelting-reduction process is based on the direct use of non-coking coal and fine ore. The major difference between the COREX and FINEX processes is that the FINEX process can directly use sinter feed iron ore (up to 12 mm) (Siemens VAI. 2007), without agglomeration.

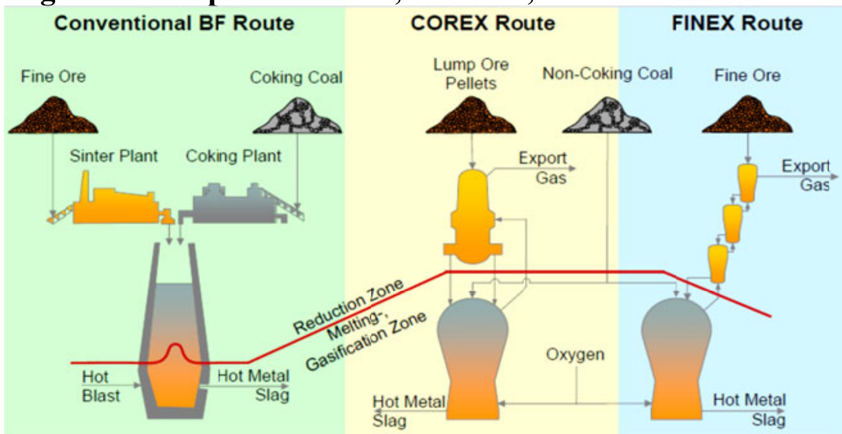
The FINEX core plant consists of a melter-gasifier and a series of successive fluidized bed reactors that form a counter-flow system in which ore fines are reduced in three or four stages to DRI. The upper reactor stage serves primarily as a preheating stage. In the succeeding stages, the iron ore is progressively reduced to fine DRI. The fine DRI is then compacted and charged in the form of hot compacted iron (HCI) into the melter-gasifier. The charged HCI is subsequently reduced to metallic iron and melted. The heat needed for the metallurgical reduction and melting is supplied by coal gasification with oxygen. The reduction gas, also produced by the coal gasification, is passed through the fluidized bed reactors. The FINEX export gas is a highly valuable product and can be further used for DRI/HBI production, electric energy generation, or heating. The hot metal and slag produced in the melter-gasifier is frequently tapped from the hearth, as is also done in BF or COREX® operation (Siemens VAI. 2007).

Currently there is a FINEX demonstration plant in Korea with an annual hot metal capacity of 900,000 t/year. Based on good results at the FINEX demonstration plant, the host steel company planned to construct a 1.5-million-t/year industrial FINEX plant in Korea which was commissioned in 2007 (Siemens VAI. 2007).

Figure 1 compares the BF, COREX, and FINEX processes. The following benefits are reported for COREX compared to BF production (APP 2010; Siemens VAI. 2007):

- No need for pelletizing, sintering, or agglomeration of iron-bearing materials
- Allows use of fine concentrates
- Capital cost claimed to be 20 percent lower than for BF, and production cost 15 percent lower
- Lower emissions because of lower energy consumption and no need for coke making
- Direct utilization of non-coking coal
- High valuable export gas for a wide range of applications in metallurgical processes and energy production
- Production of hot metal with quality similar to that produced in a BF

Figure 1. Comparison of BF, COREX, and FINEX Processes



Source: Grill 2009

Note: This figure is primarily for illustration of major differences between three process. For the case of BF, however, in addition to sinter than is shown, the lump iron ore or sinter (or combinations) can be charged in BF.

Coal-Based HYL Process: A Syngas-based DRI Plant

The HYL process is designed to directly reduce iron ores using reducing gases in a solid-gas moving bed reactor. Oxygen is removed from the iron ores by chemical reactions based on H_2 and CO to produce highly metallized DRI (Danieli and Tenova 2011).

The original HYL technology used natural gas, but Tenova HYL has built a new coal-based HYL technology (also known as Energiron HYL technology) by adding a coal gasification technology to HYL. The reactor and its peripheral systems and the principles of operation for the coal-based HYL process are same as for the gas-based HYL process in which oxide material is fed from the top and is reduced by a counter-current flow of H_2 and CO containing gas. Because this process does not use natural gas, a lower-carbon-content product (around 0.4 percent) is expected. Similar to the gas-based HYL process, in the coal-based process, the furnace top gas is cooled and cleaned, and its CO_2 is removed and then recycled into a reducing gas circuit. Reducing gas is produced in a coal gasifier that can process practically any kind of carbon-bearing material. Coal and oxygen are injected into the gasifier, and almost all carbon in the coal is gasified. The gas is dust laden and includes CO_2 and H_2O as well as other impurities. It is cleaned and cooled in a series of cyclones and H_2O, CO_2, and sulfur are removed. Because the HYL reactor is designed to work with high-H_2-content reducing gas, and the gas from the gasifier contains considerable amounts of CO, a gas shift reactor is required to convert CO into H_2 by the reaction $CO + H_2O \rightarrow CO_2 + H_2$. The shift reactor is installed before the CO_2 removal system. The temperature and pressure of the gas are then regulated before injection into the reactor (APP 2010).

Four units, each 2.75 million-t/year coal-based HYL plant will be built by the technology providers in India. (Tenova HYL 2011). The technology provider claims the following benefits for coal-based HYL compared to BF production (APP 2010; Tenova HYL 2008):

- No need for coking coal and coke
- No need for natural gas
- Allows usage of low-quality coals
- Production of hot DRI that could be charged to EAF with significant energy savings

Emerging Energy-efficiency Technologies for the Pulp and Paper Industry

Table 2 presents an overview of some of the emerging technologies that reduce energy use and carbon emissions for the pulp and paper industry with their commercialization status. The subsections below describe only three of these technologies due to space constraint. The detail information on all the 15 technologies and more emerging technologies can be found in Kong et al. (2012).

LignoBoost® Process

LignoBoost is a new technology that extracts lignin from black liquor with the potential to create new revenues for pulp mills. Figure 2 shows a flow diagram of LignoBoost in chemical pulping. As it shows, the technology uses CO_2 to lower the pH of the black liquor which causes precipitation of lignin. The precipitate is then dewatered using a filter press. LignoBoost then overcomes conventional filtering and sodium separation problems by re-dissolving the lignin in spent wash water and acid. The resulting slurry is once again dewatered and washed with acidified wash water to produce virtually pure lignin cakes (Metso 2012).

Lignin is an outstanding biofuel with high heat value. It can be used in a power plant boiler, recovery boiler, or lime kiln to replace fossil fuel. Potential savings from using lignin in a lime kiln are as much as 50 liters of fuel oil per tonne of pulp. Lignin can also be used as the raw material for making chemicals instead of petroleum-based products, which makes it a very interesting substance for the chemical industry where many companies are looking for renewable raw materials for manufacturing food, dyes, plastics, pharmaceuticals, and other products. Activated carbon is another product with potential to be made from lignin (Innventia 2012). There are successful trials using lignin to make carbon fibers. Pulp mills can derive additional income from using lignin as fuel and selling it for further refining.

Table 2. An Overview of Emerging Pulping and Papermaking Technologies

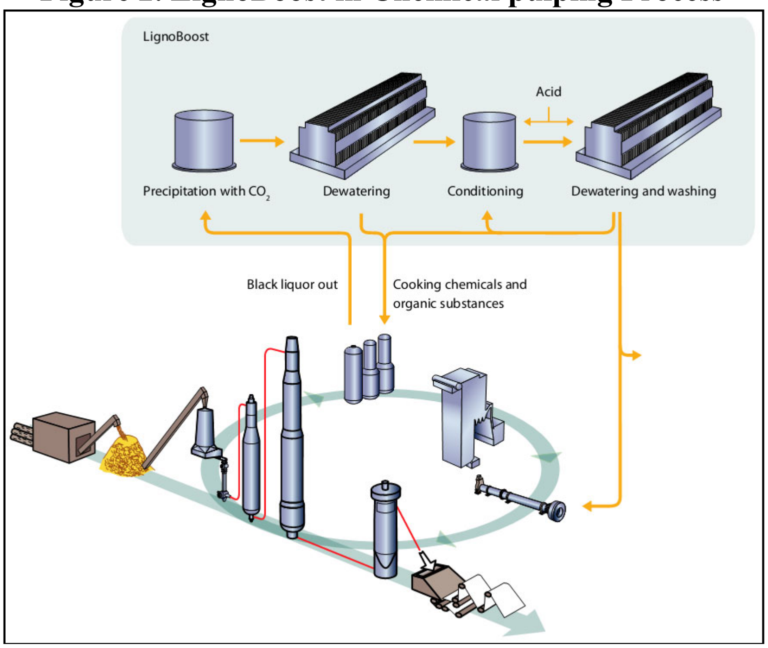
No.	Category/Technology name	Commercial Status			
		Development	**Pilot**	**Demo**	**Commercial with very low adoption rate**
Emerging pulping technologies					
1	LignoBoost Process		X		
2	Directed green liquor utilization pulping			X	
3	Membrane concentration of black liquor	X			
4	Dual-pressure reheat recovery boiler		X		
5	Borate auto-causticizing [a]	X			X
6	Black liquor gasification [b]	X	X		
Emerging papermaking technologies					
7	Aq-vane technology	X			
8	High consistency papermaking		X		
9	Dry sheet forming [c]				

No.	Category/Technology name	Commercial Status			
		Development	Pilot	Demo	Commercial with very low adoption rate
Emerging papermaking technologies					
10	Displacement pressing	X			
11	Impulse drying in wet pressing process			X	
12	Gas-fired dryer		X		
13	Boost dryer		X		
14	Condebelt drying				X
15	Microwave drying	X			

[a] Full Auto-causticizing: Development stage; Partial Auto-causticizing: Commercial with very low adoption rate.
[b] Atmospheric low-temperature BLG: Demonstration stage; Pressurized high-temperature BLG: Pilot stage.
[c] Specialty paper products: Commercial with very low adoption rate; producing standard paper grades: Development stage

LignoBoost technology was first developed by researchers at Innventia and Chalmers University of Technology. A demonstration plant with a capacity of 6,000 to 10,000 t lignin/year is integrated into the pulping process in Sweden in 2007 (Innventia 2012). In 2011, the technology provider announced the sale of the first commercial LignoBoost technology to a pulp mill in North Carolina. This LignoBoost plant will be in commercial operation in 2013 (Metso 2012). IEA estimates that if the surplus lignin (i.e., the lignin that is not used by the mill itself but is sold to the market) sells for more than US$ 5.5/GJ, this process would generate additional profits for the mill (IEA 2009).

Figure 2. LignoBoost in Chemical pulping Process



Source: Metso 2012

Black Liquor Gasification

Black liquor gasification (BLG) entails pyrolyzing concentrated black liquor into an inorganic phase and a gas phase through reactions with oxygen or air at high temperatures. It is an alternative to using a recovery boiler to produce electricity, chemicals, or fuels such as dimethyl ether (DME), synthetic gas (syngas), methanol, hydrogen, or synthetic diesel (Naqvi et al. 2010). BLG can also be integrated with combined-cycle (CC) technology (BLGCC), which has potential to produce significantly more electricity than current boiler/steam turbine systems and could even make the mill an electricity exporter (Martin et al. 2000b). Alternatively, the syngas can be used as a feedstock to produce chemicals, thereby using the pulp mill as a biorefinery (Worrell et al. 2004).

BLG can increase energy recovery efficiency by 10 percent compared with conventional recovery technology (Cheremisinoff and Rosenfeld 2010). In addition, it can increase the amount of electricity generated at the pulp mill by two to three times (Gebart 2006). Aside from saving energy, BLG also can improve pulp yield and pulp quality and lower the requirement for make-up salt cake compared to the conditions with a conventional recovery boiler. However, the investment for a full-scale pressurized BLG process unit is larger than for a new conventional recovery boiler. The capital costs for BLG were estimated at \$200-500 million, compared to \$100-150 million for conventional recovery system, and the annual non-fuel O&M costs were estimated at \$10-20 million (Larson et al. 2009). The greater investment will limit the commercialization of BLG in the pulp and paper industry. The causticizing and lime kiln load increases 20 percent which can adversely impact the mill’s capacity for pulp production. However, this problem can be eliminated by including direct causticization technology which is under development (ITP 2011). Another major disadvantage for BLG is that a new method for recovering sulfur and sodium must be installed since kraft pulping economics require nearly complete recovery of inorganic chemicals (Brown 2012).

To date, only small, commercial, atmospheric low-temperature BLG units have been built, while similar-size pressurized demonstration BLG units do not yet exist (Bajpai 2010; Naqvi et al. 2010).

High Consistency Papermaking

High consistency papermaking process would require that the approach and short circulation systems, fluidization and dewatering processes take place at high consistency (EIPPCB 2001). The processed pulp enters at the forming section, and has more than double the consistency (3 percent) compared to that of normal slurry. High consistency papermaking could increase forming speed and lead to energy savings in the pressing section, due to reduced dewatering and vacuum power requirements (Martin et al. 2000b). Increasing the forming consistency from 0.7 to 7 percent would reduce the flows around the wet end by 10 fold. Since 25 percent of a paper machine’s energy consumption is used for pumping water and stock alone, significant energy savings could be realized (Cichoracki et al. 2001).

Efforts aimed at increasing the forming consistency have been going on since 1980s, but with little success (EIPPCB 2001). This development has been limited to a consistency of around 3 percent because of the deterioration in sheet properties. Recently, it has been suggested that up to 6 percent may be possible while still achieving good formation (Cichoracki et al. 2001). A high consistency device was built by Cichoracki et al. (2001) for forming webs at the consistency of 5-15 percent. To date, webs have been formed at 5-12 percent consistency, with grammages ranging from 275 to 1000 g/m^2. The web width is 300 mm and speeds up to 700 m/min are currently possible. However, a current drawback, which still needs to be overcome, is the defiberability of the sheet as compared to that of conventional market pulp sheets. Also, the modern paper machines have winder web width and higher machine speed than can be achieved with the current technology mentioned above.

Due to improved fibers retention, the consumption of chemicals and the environmental load of the process will also be reduced. Results from early high consistency research indicate that in addition to economic and environmental benefits other advantages may be gained in terms of sheet properties and process variables. Stock storage and pump size could be reduced, and initial dewatering elements in the forming section could be eliminated, all resulting in simplified wet end section of papermaking and a shorter less expensive paper machine (Cichoracki et al. 2001; EIPPCB 2001). It was reported that 10-15 percent savings in capital costs can be realized for the paper machine wet-end since it allows for reductions of the size of both the forming and drainage area (Martin et al. 2000b). Progress is still needed for high consistency papermaking in the mixing of fibers and chemicals and in screening, air removal, fluidization, dewatering of furnish, and in process control (EIPPCB 2001).

Conclusions

This paper describes 3 alternative emerging iron making technologies for the steel industry and 3 emerging technologies for the pulp and paper industry for energy-efficiency and CO_2 emissions reduction. The information presented for each technology was collected from various sources, including manufacturers. All the emerging technologies presented in this paper are alternatives to conventional production of iron and paper. It is likely that no single technology will be the best or only solution but instead that a portfolio of technologies should be developed and deployed to address the increasing energy use and CO_2 emissions of the steel and paper industry.

Table 1 shows a comparison of some of the aspects for different ironmaking technologies explained in this paper with the conventional iron making in blast furnace. COREX® Process, FINEX® Process, and Coal-Based HYL Process are very promising alternative emerging iron making technologies because they are already commercially proven and are commercialized but they have very low adoption rate in the steel industry worldwide. As can be seen from Table 1, all the alternative emerging ironmaking technologies eliminate energy-intensive coke production.

Table 2 presents an overview of the emerging energy-efficiency technologies in the pulp and paper sector. For space limitation, we only give the three most promising technology here, i.e. LignoBoost® Process, Black Liquor Gasification, and High Consistency Papermaking, in terms of their huge energy efficiency improvement and CO_2 emissions reduction potentials in the future pulp and paper industry.

As can be seen from the information presented in this paper, most of the technologies have not been commercialized yet. Therefore, further research is needed to improve and optimized these technologies in order to make them commercial. In addition, for some technologies, there was not much information available except from the technology developer. Conducting independent studies and validation on the fundamentals, development, and operation of these emerging technologies can be helpful to private and public sectors as well as academia.

Acknowledgments

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