Present needs, recent progress and future trends of energy-efficient Ultra-Low Carbon Dioxide (CO₂) Steelmaking (ULCOS) program

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ABSTRACT

The iron and steel industry is the largest energy consuming manufacturing sector, consuming 5% of the world’s total energy consumption and producing 6% of the total world anthropogenic CO₂ emission. Under the European Ultra Low CO₂ Steelmaking (ULCOS) program, several breakthrough technologies for the drastic reduction of CO₂ emissions from iron and steelmaking industry have been investigated, including (1) blast furnace with top-gas recycling (TGR-BF), (2) a new smelting reduction process (Hisarna), (3) advanced direct reduction (ULCORED) and (4) electrolysis of iron ore (ULCOWIN and ULCOLYSIS). Besides, hydrogen-based steel making and the use of biomass as reducing agent have been evaluated as supporting technology to decrease CO₂ emissions. The aim of the present article is to analyze the technological developments in iron and steel industry and the progress of present experimental works developed inside the ULCOS I and II projects by collating updated information from a wide range of sources. In addition, the breakthrough technologies expected to develop or are currently being demonstrated at pilot/industrial scale for significant reduction of CO₂ emissions in Europe have been identified in this paper. Economic and environmental performance of the ULCOS cutting edge technologies shows that the implementation of CCS technology in coal-based integrated steel plants might reduce 80% of CO₂ emissions. However, hydrogen and biomass-based steelmaking also offers very attractive perspectives, while raising lots of major challenges. Finally, comparative assessment of the ULCOS program with others CO₂ breakthrough programs around the world has also been done.

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1. Introduction

Global warming is one of the crucial challenges of humanity. In order to combat climate change, several ambitious objectives have been set in Europe such as 20–20–20 target and the 2050 Energy Roadmap [1]. The 20–20–20 target aims to reduce 20% CO\textsubscript{2} emissions compared to 1990 levels, produce 20% renewable energy and reduce 20% primary energy consumption by 2020. The 2050 Energy Roadmap illustrates a European pathway for the reduction of 80–95% greenhouse gas emissions (GHG) by 2050 compared to the 1990 levels [2,3].

In 2008, EU Emission Trading System (EU ETS) launched a series of targets through EU Strategic Energy Technology Plan (SET-Plan) for the development of clean, efficient and low-emission technology in energy-intensive industries [4,5]. Iron and steel production is one of the biggest energy-intensive and CO\textsubscript{2} emission industries worldwide. Due to the dominating iron and steelmaking processes are still mainly coal-based and highly dependent on fossil fuels such as oil, diesel, and substantial amounts of fossil CO\textsubscript{2} emissions are released [6]. Globally, iron and steel production accounts for about 6% of anthropogenic CO\textsubscript{2} emissions each year [7]. In the EU, the sector is accountable for 4.7% of the total CO\textsubscript{2} emission (182 million tonnes of CO\textsubscript{2}) and approximately 27% of CO\textsubscript{2} emission from the global manufacturing sector [8,9]. One ton of steel manufacturing emits about 1.8 t of CO\textsubscript{2} [10] and collective energy demand of steel production is 210–35.4 GJ/t steel [11].

There are two main methods for producing steel: (1) extracting iron from iron ore through a reduction process, (2) recycling steel scrap through a melting process. Steel production from crude iron ore is preceded by iron production. The main refining process for iron production is through the blast furnace and basic oxygen furnace method (BF+BOF), accounting for 95% of global iron production and about 70% of global steel production [12]. On the other hand, about 5% of global iron is produced via direct reduced iron (DRI) method. Electric arc furnace (EAF) uses scrap steel and steel recycling, where the steel or solid iron from a direct reduced iron process is melted by electric power [13]. About 30% of global steel is produced via this method [14]. In the ironmaking process, the blast furnace process extracts iron from crude iron ore (Fe\textsubscript{2}O\textsubscript{3}) by heating the ore and melting the metal fractions to liquid pig iron. An efficient reduction reaction is required, in order to extract the O\textsubscript{2} from the iron ore. This is achieved by adding a reducing agent, usually coke, to the blast furnace. The carbon reacts with the iron oxide and produces carbon monoxide, which again reduces the iron oxides to pure iron during a combustion process. Finally, iron oxides are chemically converted into molten iron (Fe), which produces massive amounts of CO\textsubscript{2} and carbon monoxide (CO) as a by-product gas or blast furnace gas (BFG). The basic chemistry of the iron-making processes is listed as the following equations [15]:

\[
\begin{align*}
C + \frac{1}{2}O_2 &\rightarrow CO \\
C + O_2 &\rightarrow CO_2 \\
Fe_2O_3 + 3CO &\rightarrow 2Fe + 3CO_2 \\
Fe + O_2 &\rightarrow FeO \\
Si + O_2 &\rightarrow SiO_2
\end{align*}
\]

Thus, large amounts of CO\textsubscript{2} are produced by the reduction reaction in the blast furnace and the combustion reaction of carbonaceous materials (coke breeze, etc.) and carbon-containing gases, such as blast furnace gas (B gas) and coke oven gas (C gas) in the sintering machine, coke ovens, and hot stoves. Therefore, controlling and reducing CO\textsubscript{2} emissions from this industry is now a pressing issue [16]. Over the last decade, a number of researches and development initiatives around the world under the ‘CO\textsubscript{2} breakthrough Programs’ (ULCOS\textsuperscript{1}, AISI\textsuperscript{2}, POSCO\textsuperscript{3}, COURSE50\textsuperscript{4}, etc.) have been investigated [17] for carbon-free green and sustainable iron and steel production. The target is to develop CO\textsubscript{2} breakthrough technologies in combination with top gas recycling for the blast furnace (TGR-BF), direct reduction (DR) with electric arc furnace (EAF), iron ore electrolysis also called electrowinning (EW), carbon capture and sequestration (CCS) by using fossil fuels, biomass, hydrogen and electricity as innovative reducing agents for the reduction process [4,18]. Among all of these research programs, the Ultra-low CO\textsubscript{2} Steelmaking (ULCOS) is the most extensive research program with big budget. It is a consortium of 48 European companies and organizations from 15 European countries and is supported by European Commission. ULCOS consists of all major European Union steel plants, engineering partners, research institutes and universities [19]. It is divided into two phases: ULCOS I in 2004 and ULCOS II in 2010. It is proactively looking for solutions to the threat of global warming. The main aim of this massive project is to reduce CO\textsubscript{2} emission by at least 50%, i.e., to reduce CO\textsubscript{2} emission from 2 t CO\textsubscript{2} per ton steel to 1 t CO\textsubscript{2} per ton steel production [20]. In addition, for large scale industrial production it will develop potential and feasible ultra-low CO\textsubscript{2} steel production technologies that must be sustainable, i.e., environmentally-friendly, economically viable and socially acceptable [21,22].

From the beginning of the second phase of the ULCOS proposed CO\textsubscript{2} emission projections for the year of 2010–2050. According to the ULCOS research, prediction, worldwide average CO\textsubscript{2} emissions are 1.8 t for every ton of steel produced in the year of 2010 [16]. In 2050, a trend scenario assumes that CO\textsubscript{2} emissions will be cut by only 15% (1.1 t\textsubscript{CO2/crude steel}), mainly dependent on the extensive deployment of advanced technologies like Best Available Technologies (BATs) [23]. On the other hand, low carbon (LC) scenario assumes that global emissions can be dropped around 0.2 t CO\textsubscript{2}/t crude steel in such a way, if CO\textsubscript{2} breakthrough technologies are available and policies have been designed to be applied (Fig. 1) [24–27].

There are a few numbers of studies have been done on worldwide CO\textsubscript{2} breakthrough programs focusing on their current research status and environmental assessment. To the best of our knowledge, there is no study focusing on comprehensive study on ULCOS and comparative assessment of the ULCOS program with

\[
2Mn + O_2 \rightarrow 2MnO \\
2P + 5FeO \rightarrow P_2O_5 + 5Fe
\]

1 ULCOS—Ultra-Low CO\textsubscript{2} Steelmaking (EU).
2 AISI—American Iron and Steel Institute with technology roadmap programme.
3 POSCO—CO\textsubscript{2} Breakthrough Framework (Korea).
4 COURSE50—CO\textsubscript{2} Ultimate Reduction in Steelmaking process by innovative technology for cool Earth 2050.
others CO₂ breakthrough programs. This paper therefore proposes to close this gap by providing a holistic, long-term analysis of the potential role of ULCOS CO₂ breakthrough technologies in Europe. In addition, in this paper, we try to understand the role of technological change and the diffusion of energy efficient low-carbon technologies to explain the trends in emissions reduction improvement. Following research questions could be answered in this paper:

What is the present status of ULCOS CO₂ breakthrough technologies in the steel sector as a tool for CO₂ emissions mitigation? How mature is CCS (Carbon capture and storage) technologies as a solution against other approaches? Are there gaps in the technologies and barriers to its implementation in the iron and steel sector? What are the future prospects of others ‘CO₂ breakthrough program’?

The presented paper begins with the description of ULCOS concept (Section 2). ULCOS project outlooks and future targets are presented in Section 3. The following section briefly discussed regarding new ULCOS breakthrough technologies and their experimental results are given in Section 4. Section 5 provides economic and environmental performance of ULCOS technologies and Section 6 illustrates a comparative analysis of the ULCOS with others CO₂ breakthrough programs. Finally, Sections 7 and 8 provide future research and a summary of the paper with conclusions. This paper, hopefully, will be useful for engineers, researchers, steel companies, policy makers, investors and other interested parties to build sustainable green iron and steel industry.

2. ULCOS concept

The EU CO₂ breakthrough program, ULCOS proposed a concept in terms of CO₂ breakthrough technologies as shown in Fig. 2. This triangle matrix explains how reducing agents and fuels can be selected from three possibilities such as carbon, hydrogen, and electrons. The mock ternary diagram represents all existing energy sources where coal is near to carbon on the carbon–hydrogen line, natural gas is near to hydrogen and hydrogen from electrolysis of water is on the hydrogen–electricity line, etc. [27].

The exiting steel technologies are based on fossil fuels, i.e. mostly on carbon, natural gas, mix of carbon and hydrogen and electric arc furnaces are shown in blue boxes in the Fig. 2. On the other hand, for CO₂-lean process routes, ULCOS has identified three major way of solutions: (1) decarbonizing whereby coal would be replaced by hydrogen or electricity in hydrogen reduction or electrolysis of iron ore processes (2) CCS technology introduction (3) use of sustainable biomass are presented in green boxes in the diagram [28].

3. ULCOS project outlooks and future target

Initial phase of ULCOS research program has investigated 80 different concept routes using mathematical modeling and laboratory tests to evaluate their feasibility in terms of energy consumption and CO₂ emissions, operating cost of steelmaking and sustainability [29]. Among all of these, six processes routes have been selected for further investigation and commercial implementation. In Table 1 their present progress and future target including timelines has been illustrated.

In its last meeting of European Steel Technology Platform (ESTEP) has decided to further move forward the ULCOS I. It would be completed in 2010 and to launch ULCOS II. The ULCOS II would be run from 2010 to 2015 and the results of ULCOS II can be potentially moved into commercial deployment within 15–20 years from now (Table 1 and Fig. 3).

The development and implementation of ULCOS breakthrough technologies into mature steel industries includes a level of risk

Fig. 1. Simplified projections of CO₂ emission from iron and steel industry [27].

Fig. 2. Pathways of ULCOS breakthrough technology [27].
and at least one additional scale up step. In ULCOS II all kinds of demonstration stages would start as well as ULCOS II will explore some technological investigation of ULCOS I to assess their potential feasibility under large scale, industrial production [30]. In that case, a considerable R&D investment by the ULCOS consortium, the European Commission and other financing partners will be needed.

Both ULCOS I and ULCOS II programs are funded by privately and publicly. In ULCOS I 60% cost was supported by ULCOS consortium and 40% was contributed by European commission through its 6th Framework and the RFCS programmes. Conversely, the level of public and private funding of ULCOS II has not been unveiled yet, but the structure of the funding makes it clear that it would be more than 50% [31]. (Table 2)

### Table 1

<table>
<thead>
<tr>
<th>Technology</th>
<th>Programs</th>
<th>Main advantages compared to reference</th>
<th>Potential drawbacks compared to reference</th>
<th>Technological Maturity prediction</th>
</tr>
</thead>
<tbody>
<tr>
<td>ULCOS-BF (Top gas recycling) With CCS</td>
<td>FP6 ULCOS</td>
<td>50% CO₂ reduction compared to average blast furnace</td>
<td>Higher operational costs</td>
<td>2010: Pilot phase demonstrator 2020: Commercial deployment</td>
</tr>
<tr>
<td></td>
<td>RFCS ULCOS</td>
<td>Expected to be the standard for newly built plants (retrofit option)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>RFCS IDEOGAS</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>RFCS TGR-BF</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Green BF</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>HIsarna (Coke free steelmaking) with CCS</td>
<td>FP6 ULCOS</td>
<td>80% CO₂ reduction compared to average blast furnace with CCS, 20% without CCS</td>
<td>Needs replacement of existing blast furnaces</td>
<td>2020: Pilot phase demonstrator 2030: Commercial deployment</td>
</tr>
<tr>
<td></td>
<td>HIsarna RFCS</td>
<td>Lower investments and operational costs due to broader range of available inputs</td>
<td></td>
<td></td>
</tr>
<tr>
<td>ULCORED (Fastmelt process of direct reduction) with CCS</td>
<td>FP6 ULCOS</td>
<td>55% CO₂ reduction compared to average blast furnace with CCS, 5% without CCS</td>
<td>Essentials replacement of existing blast furnaces Higher investment costs</td>
<td>2015: Pilot phase demonstrator 2020: Commercial deployment</td>
</tr>
<tr>
<td></td>
<td>ULCORED RFCS</td>
<td>Lower operational costs due to broader range of available inputs</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Electrolysis (ULCOWIN &amp; ULCOLYSIS)</td>
<td>FP6 ULCOS</td>
<td>Probably no carbon is needed in the production process</td>
<td></td>
<td>2010: not developed</td>
</tr>
<tr>
<td></td>
<td>RFCS IERO</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>ANR ASCOPE</td>
<td></td>
<td></td>
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<tr>
<td></td>
<td>Auto thermal cell</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>H₂ Reduction</td>
<td>FP6 ULCOS</td>
<td>Further work…</td>
<td></td>
<td>2010: not developed</td>
</tr>
<tr>
<td>Use of sustainable biomass</td>
<td>FP6 ULCOS</td>
<td>Further work…</td>
<td></td>
<td>Not developed</td>
</tr>
</tbody>
</table>

Table 2

<table>
<thead>
<tr>
<th>ULCOS project details.</th>
<th>ULCOS I</th>
<th>ULCOS II</th>
</tr>
</thead>
<tbody>
<tr>
<td>Start date</td>
<td>2004-09-01</td>
<td>2010</td>
</tr>
<tr>
<td>Project cost</td>
<td>35280915 euro</td>
<td>N/B</td>
</tr>
<tr>
<td>Contract type</td>
<td>Integrated project</td>
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</tr>
<tr>
<td>End date</td>
<td>2010-08-31</td>
<td>2050</td>
</tr>
<tr>
<td>Project status</td>
<td>Completed</td>
<td>N/B</td>
</tr>
<tr>
<td>Project funding</td>
<td>19996966 euro</td>
<td>N/B</td>
</tr>
</tbody>
</table>

N/B: not available.

4. Current status and future research of ULCOS program

From the beginning of quite a few breakthrough technologies for the reduction of CO₂ emissions from iron and steelmaking industry have been investigated in the context of Ultra Low CO₂ Steelmaking (ULCOS) program. Finally, ULCOS has selected four process concepts that could lead to a drastic reduction of CO₂ emissions by more than 50% compared to the present best practices. This four cutting edge technologies are: (1) Top Gas Recycling Blast Furnace with CO₂ Capture and Storage (CCS), (2) HIsarna with CCS, (3) ULCORED with CCS, (4) Electrolysis. Additionally, hydrogen-based steel making and the use of biomass as reducing agent have been evaluated as supporting technology to decrease CO₂ emissions [32, 33]. The ULCOS experiment and program structure has been illustrated in Fig. 4. The key strategies of ULCOS have been included in this program as described below [17].
4.1. **ULCOS blast furnace process (SP1 & SP2)**

Blast Furnace (BF) is the most energy consuming process in integrated steel plants. So it is essential to reduce fossil CO\textsubscript{2} emissions from this process [35]. ULCOS has invented top gas recycling blast furnace (TGR-BF) is a blast furnace gas separation technology for clean steel production. Top gas used to absorb CO\textsubscript{2} inside blast furnace acts as a reducing agent. It effectively reduces carbon emission around 50%. The integrated use of TGR-BF and CO\textsubscript{2} capture and storage (CCS) technologies is helpful to remove nitrogen from the TGR-BF and oxygen injection into BF can also effectively recover CO\textsubscript{2}. After extraction of CO\textsubscript{2} from recycled gas by using VPSA CCS technology, the cryogenic techniques is applied to store [36]. The following three different versions were tested [37]:

- **Version 4**, the treated is a recycled gas in the main tuyeres and additional tuyeres located in lower stack at 1250 °C and 900 °C respectively. The expected carbon saving is 26%.
- **Version 3**, the treated gas is recycled through the main tuyeres only and expected carbon saving is 24%.
- **Version 1** has the same flow sheet like version 4 but the recycled gas is cold and expected carbon saving is 22%.

In 2007 the first experiment was successfully done at LKAB’s Experimental Blas Furnace (EBF) in Lulea, Sweden and it ran efficiently with high thermal stability, including up to 24% CO\textsubscript{2} reduction. After this for the second phase ULCOS 2, EU invested hundreds of million euros for the promotion and planning of TRG-BF. It was successful, this technology will hopefully, mitigate CO\textsubscript{2} emission of almost 1.5 Mt per year, i.e. about 1/3 for a BF [39]. (Fig. 5)

**Status** [40–42]:

- Demonstration project in Florange as a part of EU ETS (NER 300)
- Top gas recycling has been experimentally tested at the LKAB’s Experimental Blast Furnace (EBF) in Luleå, Sweden, two RFCS projects: ULCOS-NBF (2004 to 2009) and ULCOS TGR-BF RFCS (started in 2009).
- ULCOS BF, version 1, 3, 4 were tested, finally V4 was preferred for the follow-up ULCOS BF demonstration project on industrial scale under ULCOS II at ArcelorMittal, Florange (France) and ArcelorMittal Eisenhüttenstadt (Germany).
- ULCOS BF mode without CO\textsubscript{2} storage is expected at Eisenhüttenstadt plant in 2014
- ULCOS BF mode with CO\textsubscript{2} storage is expected at Florange plant in 2016
- First full scale (industrial) CCS project
- Operational within 2014–2015
- Test phase of +/– 10 years
- Industrial implementation after 2020
4.1.1. ULCOS-EBF result

Within the research teams, lots of works have been done to study ULCOS BF process such as theoretical studies (e.g. heat and mass balance models; tuyere and raceway model; model of the BF internal state) using mathematical models and laboratory investigations (e.g. reduction; hot degradation; softening-melting). The results of the ULCOS EBF campaigns are very promising in view of carbon saving. In all versions (1, 3, 4) of ULCOS-EBF connected with Vacuum Pressure Swing Adsorption (VPSA), a new CCS technology for the removal of the CO2 of the top gas was built by Air Liquide and worked very well during the campaigns [38].

4.1.1.1. Blast furnace operation.

More importantly, during the three testing coal and coke input dropped from around 530 kg to 400 kg and carbon input was reduced from 470 kg to about 350 kg/thm, resulting in a carbon saving 120 Kg C/thm, which represents a considerable carbon saving (Fig. 6) [43].

ULCOS-BF version 3 could be reduced up to 15% of carbon consumption with a top gas recycling ratio of 72%. In contrast, version four found 24% carbon saving with 90% top gas recycling ratio. Besides, approximately 123 kg/thm coal and coke consumption were saved in this new process compared to the reference operation period. From these results a good correlation between injected CO\textsuperscript{+}H\textsubscript{2} and reductant rate where coal and coke could be reduced by 17 kg per 100 N m\textsuperscript{3} (CO\textsuperscript{+}H\textsubscript{2}) injected (Fig. 7) [37].

4.1.1.2. Results of the VPSA plant.

The operation of VPSA process was smooth and proven to be without failure. It processed up to 97% of blast furnace top gas and average CO2 content in injected gas was 2.67%, while the required value was 3%. The CO recovery was 88%. It always delivered the essential gas amount and quality [38].

4.1.1.3. Reduction of CO2 emission.

Top gas recycling blast furnace combined with VPSA CCS technology reduced CO2 emissions up to 1270 kg/thm, which shows 76% of CO2 emitted during the reference period. Result is 24% mitigation by gas recycling and 52% reduction by VPSA with considering the underground storage of the extracted CO2 (Fig. 8) [38].

Fig. 9 illustrates how CO2 emission reduction depends on the volume of treated gas injected at the blast furnace. The results of ULCOS-EBF campaigns proved that it is promising to run a blast furnace in an integrated steelmaking plant at a much lower fossil carbon consumption level as today’s blast furnaces do by applying top gas recycling and CCS technology.

4.2. HIsarna smelter

The HIsarna process is based on a modified version of the Hismelt smelter technology. It is a concept using a combination of
three new ironmaking technologies: (a) coal preheating and partial pyrolysis in a reactor, (b) melting cyclone for ore melting and, (c) melter vessel for final ore reduction and iron production [44].

HiSarna is a bath-smelting technology that combines coal preheating and partial pyrolysis in a reactor. It uses a smelter vessel for final ore reduction and a melting cyclone for ore smelting. By removing sintering and coking processes it reduces CO2 emission. Moreover, by using biomass or natural gas instead of coal, processing combustion gases, storing CO2 and recycling heat energy HiSarna technology reduces almost 70% CO2 emission [45]. Benefits of the HiSarna process are:

- Reduction of the CO2 emissions per ton with 20%.
- Reduction of the CO2 emissions per ton with 80% if the process is combined with CCS.
- Elimination of coke and sinter/pellet plant emissions.
- Use of non-coking coal qualities.
- Use of low cost iron ores, outside the blast furnace quality range.
- Economically attractive even at small unit size (0.8–1.2 M thm/y).

A pilot plant of this technology was set up by TATA Iron and Steel Group of European Companies in Holland Ijmuiden in September 2010 with 65 kt annual outputs under ULCOS II project Design output of TATA Steel HiSarna pilot plant is 8 t/h of hot metal. Ore and coal injection capacity are 8 t/h and 15 t/h respectively. However, if it is going to be successful, the technology will be used at a commercial level before 10–20 years [46]. (Fig. 10)

**Status [40]:**

- Demonstration plant built in Ijmuiden, Germany(TATA Steel) in 2011 without CCS
- Piloting continued until 2012
- Industrial scale demonstration would be launched within 2014–2018
- Industrial implementation would be done in 2020 and beyond

4.3. Direct-reduced iron with natural gas (ULCORED) (SP3)

The project ULCORED is built up for iron ore pretreatment especially for sintering and preheating. To produce direct-reduced iron (DRI) for sending to electric arc furnace (EAF) the reducing agent such as natural gas or biomass gas is used in a reactive level for the iron ore sintering process. In gas purification process traditional reducing agent is replaced by natural gas. Top gas recycling and preheating processes, reduce natural gas consumption (Fig. 11) [47].

By this technology, we can reduce 60% CO2 emission and also it is an economical and efficient process since natural gas is expensive.

**Status [40]:**

- Reduction likely up to 70% CO2 including CCS compared to average EU BF
- Direct Reduction with natural gas mainly through Midrex technologies
- Still need to move to pilot phase

4.4. Direct electrolysis of iron ore (ULCOwin & ULCOlysis) (SP5)

The principle of the direct electrolysis of iron ore has been applied in ULCOWIN project, which products are iron and oxygen with zero carbon emission. The ULCOWIN technology is different from others conventional smelting process where employs a new method for steel production. Its reaction temperature is around
110 °C where iron ore and iron are used as an anode and cathode precipitation respectively. Electrolysis of iron ore does not emit CO₂ (Fig. 12).

Although, its initial production rate is very low production efficiency, only 5 kg iron per day, but its cost is reasonable. Hence, the ULCOS team developed a process named ULCOLYSIS for melting iron ore at 1600 °C by using electric direct reduction [50]. This is the least developed technology in contrast with other three alternatives [49].

**Status [40]:**
- Still in Laboratory phase but proof of concept is achieved
- Shows diverge when market-ready post 2030 (EU) or post 2050 (US)
- MOE is becoming a “hot” field in metallurgic research, especially as potential (cheap) storage technology for intermittent renewable energy (MIT)

### 4.5. Hydrogen-based steel making (SP4)

By hydrogen-based steel making route, CO₂ emissions would be reduced by more than 80%. Hydrogen steelmaking will depend profoundly on the availability of green hydrogen. It can be generated from natural gas by steam reforming (SMR) or from water by electrolysis. Today hydrogen based steel making is a potential low carbon and economically attractive route in a few countries where natural gas is cheap [34,51].

A few number of studies have been done focusing on utilization of hydrogen in industrial furnace [52]. H₂ production from BFG (Blast Furnace Gas) and COG (Coke oven gas) [53,54], nuclear hydrogen steelmaking system [55–57] in different countries out of ULCOS. In 2013 Ranzani da Costa et al. [57] proposed pure H₂ based steel making process by developing mathematical modeling where pure hydrogen (H₂) used as reducing agent in the direct reduction (DR) process. It might be the core process of a new and cleaner way to produce steel with lower CO₂ emissions. ULCOS studied a hydrogen-based steelmaking breakthrough route where H₂ would be generated by water electrolysis using hydraulic or nuclear electricity. In a shaft furnace, by using H₂ iron ore would be reduced to direct reduced iron (DRI) and carbon-free DRI would be processed in an electric arc furnace (EAF) to produce steel (Fig. 13) [57]. This route would be a promising breakthrough technology regarding CO₂ emissions up to 300 kg CO₂/ton steel, as well as the CO₂-cost of electricity, and emissions from the DR furnace almost zero. It shows an 84% cut in CO₂ emissions compared to the current 1850 kg CO₂/ton steel of the best blast furnace route [58].

This new route would be a more sustainable way for iron and steel production. Nevertheless, its future development and deployment is largely dependent on the emergence of a so-called H₂ economy, when this gas would become available in large quantities, at competitive cost, and with low CO₂ emissions for its production. In addition, the uncertainties lay with the competition of other sectors for hydrogen consumption, for example, transportation sector would be ready to pay much higher prices for it than the steel industry.

### 4.6. Biomass-based steel production (SP7)

Using biomass as a bioreducer in the blast furnace could be one of the processes to reduce the fossil CO₂ emissions of steelmaking. Biomass constitutes mainly carbon (C), hydrogen (H), oxygen (O), nitrogen (N), and sulfur (S) and 50 wt% (dry matter, dm) shear of carbon in the wood. The carbon content in the wood biomass is low compared to fossil fuels for example coal, coke or oil used in iron and steelmaking [59]. Besides, the sulfur content is also low approximately 0.01–0.1 wt% (dm) which is advantageous for blast furnace ironmaking [59]. Besides, the sulfur content is also low approximately 0.01–0.1 wt% (dm) which is advantageous for blast furnace ironmaking [59]. The key challenges in using biomass, whether it might be considered sustainable are: (1) the cultivation of biomass does not damage the environment in terms of deforestation, air and water pollution and reduction of biodiversity (2) the use of biomass will not be occurring undesirable social and economic impact such as food price increment and removal of the original people from their land [60].

The most prospective solution for biomass production for the steel industry is charcoal by planting eucalyptus trees in tropical countries (e.g. Brazil or Angola). In Brazil eucalyptus plantation technology is mature and has advanced conversion process. A small size BF with 100% charcoal is being run in Brazil (e.g. Acesita) and bringing a version of this technology to Europe is the challenge for ULCOS. However, it is difficult to sustain high hot strength of coke required in blast furnace when charcoal is added in the coal blend [61].

In 2013, Srivastava et al. [62] produced a self-reducing iron oxide and biomass composite pellet to develop a sustainable iron making process. It would utilize an environmental friendly
reducing agent which was renewable and not derived from fossil fuels. He proposed a process where biomass utilizes atmospheric CO$_2$ for plant growth and converts into carbohydrate that can further be used as reducing agent for iron oxide reduction. In contrast removal of coal from ground adds CO$_2$ to the atmosphere further be used as reducing agent for iron oxide reduction. In contrast removal of coal from ground adds CO$_2$ to the atmosphere.

Carbon capture and storage (CCS) presents one of the most promising options for large scale CO$_2$ emission reduction for the future. Iron and steel plants are suitable for CCS because emissions generated from single fixed and easily accessible points. In order to capture CO$_2$ from emissions needed to separate from gases composition of TGR-EBF shows in Table 3. The use of biomass as a reducing agent for ironmaking process [62].

4.7. ULCOS CCS project (SP6)

ULCOS incorporated different CCS technologies in its ongoing experimental projects in Europe. A new CCS technology named VPSA (Vacuum Pressure Swing Adsorption) built by Air Liquide has been deployed in Lulea TGR-BF experimental project. For a larger scale experiment, a commercial blast furnace will be set up under ULCOS II. In this plant the flue gases will be stored in deep saline aquifer where higher level of purity in CO$_2$ is required. By using cryogenics further purification of the steam would be done in the BF. Here, the optimized system consists of a combination of a PSA and of a cryogenics (Fig. 15).

ULCOS TGR-BF experiments show that chemisorption technologies such as amine scrubbing, physisorption, the VPSA or PSA and cryogenics have different fields of optimality. The level of CO$_2$ concentration of the gas stream to be treated in the TGR-BF for physisorption systems are the best in terms of technical performance and economical operation. It has also been efficient if CCS is applied in ULCORED. For Hlsarne only a cryogenics unit is enough because it directly delivers a very-high concentration of CO$_2$. In contrast, if CCS is deployed in others stack of the steel mill, and then an amine scrubbing unit would be the best solution. Input gases composition of TGR-EBF shows in Table 3.

Besides, ULCOS program considered commercial MDEA amines for restoring the sorbent of 3.2 GJ/tco2. R&D is trying to improve this performance up to 1.8 GJ/tco2 by reducing temperature and wasted heat. Table 4 shows the comparison of various CO$_2$ capture technologies that are available nowadays for the iron and steel industry. ULCOS decided to storage CO$_2$ in geological reservoirs (geo-storage) in the deep ocean or by the mineralization of some other compounds, chemical reactants or rocks. For CO$_2$ storage ULCOS has been examined mineral sequestration seriously [68,69].

5. Economic and environmental performance of ULCOS technologies

Table 5 summarizes indicative figures for the environmental and economic performance of the ULCOS breakthrough technologies compared with the current average blast furnace in Europe. These figures illustrate the basic configuration for the processes. If we compare with formerly proposed benchmark level for the EU ETS allocation in phase 3, which is 1460 kg CO$_2$ eq./tonne HM, it shows that all selected technologies are score better. It finds out that Hlsarne process of coke-free ironmaking and steelmaking would offer the better environmental and economic benefits compared to the existing blast furnace with and without top gas recycling. It is significantly more energy efficient than the current technology such as pelleting/sintering and comparable to other innovative processes. By combining with CCS technology it might reduce 80% of CO$_2$ emissions. On the other hand, energy consumption for TGR-BF is not given as coke consumption is replaced by electric power necessity for CO$_2$ separation [70].

In the long term ULCORED might be available as breakthrough technology by complete coverage of electricity energy consumption from renewable energy. It might be able to reduce CO emissions up to 80–95%. Currently this technology is not under development and not all aspects would be evaluated yet [73].

The ULCOS program updates are shown in Table 6 for carbon reduction technology, where ULCOS program has invested huge amount of money. The ULCOS program has been facing a series of challenges like achieving sufficient efficiency for real-world applications, cost effectiveness and mainly how to transform these revolutionary technologies in the conventional BF process.

6. Comparison between ULCOS and other CO$_2$ breakthrough programs

There are a number of sustainable irons and steelmaking programs have been developed around the world under CO$_2$ breakthrough program. The international Iron & Steel Association are working together to exchange knowledge and information for sustainable green iron and steel manufacturing. Extensive researches and investment are taking place in [74]:

- The EU (ultra-low CO$_2$ steelmaking, or ULCOS I and ULCOS II)
- The US (American Iron and Steel Institute)
- Canada (Canadian Steel Producers Association)
- Australia (BlueScope Steel/One Steel CSIRO coordination)
- South America (ArcelorMittal Brazil)
- Japan (Japanese Iron and Steel Federation)
- Korea (POSCO)
- China (Baosteel) and Taiwan (China Steel) and

COURSE 50 is a national CO$_2$ breakthrough program in Japan led by the Japan Iron and Steel Federation [66]. It aims to decrease CO$_2$ emissions by around 30% through suppression of CO$_2$ emissions from blast furnaces besides capture-separation and...

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$^a$ The size of EBF is 1.1 m that produces 1.5 t/h of hot metal. A production BF produces between 50 and 500 t/h depending on its size.

$^b$ The pilot planned for the Eisenhüttenstadt is 0.6 Mt/year and the Florange Demonstrator is 1.4 Mt/year.
recovery of CO\textsubscript{2} from blast furnace gas (BFG) by launching a new amine scrubbing technology. The ready-to-use technology concepts would be available by 2030 and the final goal of industrializing and transferring the developed technologies by 2050 [75,76]. Moreover, POSCO (Pohang Iron and Steel Company) has also been developing an ammonia-based scrubbing CCS technology for the adaption to the FINEX and to the COREX processes [77].

The United State of America started AISI (American Iron and Steel Institute) CO\textsubscript{2} breakthrough program organized by some top universities in USA to promote carbon reduction in steel industry. It includes the use of several kind of clean energy and development of CO\textsubscript{2} capture and separation technology. For example, high temperature electrolysis was examined at Massachusetts Institute of Technology (MIT), hydrogen reduction of iron ore in the laboratory, preparatory to transposing to a flash furnace reactor at Utah University, mineral sequestration at Columbia University and CO\textsubscript{2} collection from EAF fumes using lime at Missouri Rolla University [78,79]. According to the AISI CO\textsubscript{2} Breakthrough Program, there are two innovative technologies have been identified to cut CO\textsubscript{2} emissions [80]: (1) Molten Oxide Electrolysis (MOE) – Reduction of iron ore through electrolysis. (2) Hydrogen Flash Smelting – Reduction of iron ore in a suspension, with hydrogen as a reducing agent.

However, Canadian program, run by Canadian Steel Producers Association (CSPA) and Arcelor Brazil separately have been developing biomass-based steel production [81]. There are also on-going program in Australia (such as Bluestripe+OneSteel consortium) and Taiwan (China Steel) which either ambitious in terms of mitigation level or still at a conceptual level in academic work carried out in universities. Timeline of these programs are not published except ULCOS and COURSE-50. Besides, what is happening in China about CO\textsubscript{2} breakthrough program is not described clearly and India has decided to participate with the program, but not yet physically contributed [13]. (Table 7)

All of these programs are similar to ULCOS program but they are less advanced in terms of developing breakthrough technologies and their progresses are not yet widely reported. A brief comparison among worldwide major CO\textsubscript{2} breakthrough programs is given in Table 8.

### 7. Future research

After analyzing feasibility of different breakthrough technologies options, the implementation of CCS technology in coal-based integrated steel plant would be an effective way for sustainable green iron and steel manufacturing. It is, therefore, recommended that future research involving the environmental performance and potentials of CCS technology deployment to all stacks in steelworks. For example, advanced Blast Furnace with oxygen injection and carbon capture and storage (CCS), Smelting Reduction Process with CCS and advanced Direct Reduction process with CCS might be the possible best way of steelmaking. Further research and development programmes should be conducted in order to assess the CO\textsubscript{2} breakthrough technologies of steel production. It should be considered from the perspective of environmental impact analysis and life cycle assessment, which allows the eco-efficiency analysis. In addition, techno-economic analysis of the ULCOS technologies is recommended as future studies.

Finally, it is likely that no single option, or technology will be the best or only solution, but a combination of breakthrough technologies should be developed and deployed to address the increasing energy use and CO\textsubscript{2} emissions of the iron and steel industry. More importantly, shifting away from traditional processes will require extensive research and development to address the issues and barriers confronting CO\textsubscript{2} breakthrough technologies, both government and private support and funding for development and deployment of alternative low-carbon technologies.

### 8. Concluding remarks

The paper highlights the current status, future trends and significance of incorporation of CO\textsubscript{2} breakthrough iron and steelmaking technologies to reduce the GHGs emissions. Reduction of CO\textsubscript{2} emissions and dust pollution is a very important aspect in the iron and steel industry. New solutions are constantly being searched for to reduce CO\textsubscript{2} emissions under worldwide CO\textsubscript{2} breakthrough program. As a part of worldwide CO\textsubscript{2} breakthrough
The European ULCOS program has been running according to a plan: it has moved from phase 1 to phase 2 during its second phase and produced a substantial amount of knowledge and scientific and technological results. For the Top Gas Recycling Blast Furnace, Hisarna and ULCORED, the aim of a 50% mitigation of carbon dioxide (CO2) emissions could be accomplished if each of these technologies is combined with CCS technologies.

Although CCS is considered a promising solution for emission reduction, it contributes to reducing the overall efficiency of a steel plant due to the high energy consumption for solvent regeneration during capture processes. Therefore, combination of CO2 capture and utilization (CCU) technologies with waste heat recovery from flue gas and molten steelmaking slag could be critical in the near-term to support longer-term objectives for deployment of CCS in steel industry from the year 2035 onwards. The utilization of CO2 includes: CO2 to fuels, enhanced commodity production, enhanced hydrocarbon production, CO2 mineralisation and chemicals production will produce a lot of profits, while CCS is an only waste mitigation technology. With CCU the CO2 is converted to value added products. However, hydrogen and biomass-based steel-making also offer very attractive perspectives, while raising lots of major challenges. They will also require much research and development before they can be proven and implemented commercially.

Finally, it is clear that CO2 breakthrough technology has not fairly reached the level of being technology for the deployment in

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**Table 4**

Comparison of the mature CO2 capture technologies for the steel industry.

<table>
<thead>
<tr>
<th>Units</th>
<th>PSA</th>
<th>VPSA</th>
<th>VPSA + compression and cryogenic flash</th>
<th>Amines + compression</th>
<th>PSA + cryogenic distillation compression</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Recycled gas (process gas)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CO yield (%)</td>
<td>88.0</td>
<td>904</td>
<td>973</td>
<td>999</td>
<td>100</td>
<td></td>
</tr>
<tr>
<td>CO % vol</td>
<td>71.4</td>
<td>682</td>
<td>689</td>
<td>678</td>
<td>695</td>
<td></td>
</tr>
<tr>
<td>CO2 % vol</td>
<td>27</td>
<td>30</td>
<td>30</td>
<td>29</td>
<td>27</td>
<td></td>
</tr>
<tr>
<td>N2 % vol</td>
<td>135</td>
<td>157</td>
<td>156</td>
<td>151</td>
<td>154</td>
<td></td>
</tr>
<tr>
<td>H2 % vol</td>
<td>124</td>
<td>130</td>
<td>126</td>
<td>121</td>
<td>124</td>
<td></td>
</tr>
<tr>
<td>H2O % vol</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>21</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td><strong>CO2 rich gas captured</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CO % vol (dry)</td>
<td>121</td>
<td>107</td>
<td>33</td>
<td>0</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>CO2 % vol (dry)</td>
<td>797</td>
<td>872</td>
<td>963</td>
<td>100</td>
<td>100</td>
<td></td>
</tr>
<tr>
<td>N2 % vol (dry)</td>
<td>56</td>
<td>16</td>
<td>3</td>
<td>0</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>H2 % vol (dry)</td>
<td>25</td>
<td>6</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td></td>
</tr>
</tbody>
</table>

**Suitable for transport and storage?**

- Yes
- No

**Energy requirements for CCS process**

- Capture process kWh/t CO2
- Compression for storage kWh/t CO2
- Electricity consumption (CP + CS) kWh/t CO2
- LP steam consumption GJ/t CO2
- Total energy consumption GJ/t CO2

---

**Table 5**

Environmental and economic performance of TGR-BF compared with current EU average technology for pig-iron production [70–72].

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>Current EU average BF</th>
<th>TGR-BF configuration</th>
<th>Hisarna</th>
<th>ULCORED</th>
</tr>
</thead>
<tbody>
<tr>
<td>Production capacity (Mt HM/yr)</td>
<td>0.5–5.0</td>
<td>0.5–5.0</td>
<td>0.5–1.0</td>
<td>0.5–1.0</td>
</tr>
<tr>
<td>Environmental aspects</td>
<td>100% (±17 GJ/tonne HM)</td>
<td>80%</td>
<td>95–85%</td>
<td></td>
</tr>
</tbody>
</table>
| Energy consumption CO2 emission (tonne/tonne HM) | 1650 | 790 (–52%) | 730 (–40%) | 760 (?)
| -with CCS: | 1650 | Not relevant | 1320 (–20%) | 1590–1420 (–5%)
| -without CCS: | 1650 | Not relevant | 1320 (–20%) | 1590–1420 (–5%)
| Economic aspects | 100% | 105% | 75% | 200%–no CCS |
| -Greenfield | 100% | 105% | 75% | 200%–no CCS |
| -Brownfield | – | 25% | 65% | 80–90% |
| OPEX (incl. energy, excl. depreciation costs) | 100% | 120% | 90% | 80–90% |

Notes: The proportions should be interpreted as relative scores, as the performance of the reference average blast furnace is set at 100%. The other data are absolute figures.

*HM=hot metal (or pig-iron).

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**Table 6**

Brief keys of ULCOS program updates [48].

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>ULCOS</th>
<th>TGR-BF</th>
<th>Hisarna</th>
<th>ULCORED</th>
<th>ULCOWIN</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fuel</td>
<td>Coal and sustainable biomass</td>
<td>Coal and sustainable biomass</td>
<td>Natural gas</td>
<td>Electricity</td>
<td></td>
</tr>
<tr>
<td>Phase</td>
<td>1.5 t/h pilot tests demonstration under way</td>
<td>1 t/h pilot plant startup 2010</td>
<td>1 t/h pilot plant to be erected in 2013</td>
<td>Laboratory</td>
<td></td>
</tr>
</tbody>
</table>

---

**Table 7**

Comparison among the projections for steel production in 2050.

<table>
<thead>
<tr>
<th>Source of estimates</th>
<th>Annual production (Mt/yr)</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>ULCOS-LEPI</td>
<td>2450/2550</td>
<td>POLES estimates</td>
</tr>
<tr>
<td>RITE</td>
<td>2200</td>
<td>Markal model</td>
</tr>
<tr>
<td>Tokyo university</td>
<td>1800</td>
<td>MFA model</td>
</tr>
<tr>
<td>IEA Blue Maps (low/high)</td>
<td>2350/2700</td>
<td></td>
</tr>
</tbody>
</table>
Table 8: A brief comparison among CO₂ breakthrough programs [48,65,67].

<table>
<thead>
<tr>
<th>Programs</th>
<th>Involving</th>
<th>Aim &amp; target</th>
<th>Best result</th>
</tr>
</thead>
<tbody>
<tr>
<td>AISI – technology roadmap programme 1 (US)</td>
<td>AISI and the US Department of Energy's (DoE), Office of Industrial Technology</td>
<td>Program designed to (1) increase energy efficiency, (2) increase competitiveness of North American steel industry, (3) improves the environment</td>
<td>(1) Suspension Hydrogen Reduction of Iron Oxide Concentrate;</td>
</tr>
<tr>
<td>POSCO CO₂ Breakthrough Framework (Korea)</td>
<td>POSCO, RIST, POSLAB, POSTECH</td>
<td>Under framework contains six projects: (1) Pre-reduction &amp; heat recovery of hot sinter, (2) CO₂ absorption using ammonia solution, (3) Bio-slag utilization for the restoration of marine environments, (4) Hydrogen production using COG and wastes, (5) Iron ore reduction using hydrogen-enriched syngas, and (6) Carbon lean FINEX process.</td>
<td>(2) Molten Oxide Electrolysis; (3) CO₂ absorption using ammonia solution; (4) Carbon lean FINEX process</td>
</tr>
<tr>
<td>COURSE50 (Japan)</td>
<td>Japanese Iron and Steel Federation (JISF), Japan Ministry of Economy, Trade and Industry</td>
<td>Development of innovative technologies for solving global environmental problems including R&amp;D projects, public relations activities and promotes industry/institute cooperation.</td>
<td>(1) Scenario-making for global warming mitigation; (2) CO₂ separation, capture and storage; (3) CO₂ fixation by plants and its effective use</td>
</tr>
<tr>
<td>ULCCS - Ultra-Low Carbon dioxide Steelmaking-1&amp;2 (EU)</td>
<td>All major EU steel companies, energy and engineering partners, research institutes and universities, European Commission</td>
<td>Cooperative R&amp;D initiative to research rapid CO₂ emissions reduction from steel production including process science, engineering, economics and foresight studies in climate change.</td>
<td>(1) Top Gas Recycling Blow Furnace with CO₂ Capture and Storage (CCS); (2) IEARNA with CCS; (3) Direct Reduction with CCS; (4) Electrolysis</td>
</tr>
<tr>
<td>Bluescopesteel (Australia)</td>
<td>Australian steel companies, Post Kembla Steelworks</td>
<td>Committed to improvement environmental performance and the efficient use of natural resources, reduce, reuse, recycle of waste material.</td>
<td>(1) Developed energy-efficient technology</td>
</tr>
</tbody>
</table>

steel industry as it is still a concept that needs to be fleshed out and authenticated at a credible scale. The initially gap and barrier is therefore to make this technology available, which requires an enduring research and development effort through larger scale laboratory, pilot and demonstrator. In the steel sector, CCS technology could be implemented from 2020 to 2050 since all technical, financial and cost berries would be overcome.

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