

Flue Gas Cleaning to Optimize CO₂ Capture



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Four large families of CO₂ capture technologies have been developed: absorption, mostly with amines; adsorption primarily on metal organic framework; membrane separation; and cryogenic; and some combination of two technologies to achieve optimum efficiency and lower cost. Key to efficient CO₂ capture are the pollutants NO_x, SO_x, mercury, HF, dust, etc., and other main molecules, N₂, O₂, H₂O and CO. This article examines which of the components will need to be reduced, at what levels (lower than currently mandated by the regulations) and which technologies are needed.

Many carbon capture (CC) technology developers and original equipment manufacturers (OEMs) are focusing on improving their core technologies, the actual “capture” or extraction of the CO₂ from the flue gas, but little is described regarding the interface between the various processes leading to the formation of the CO₂-containing flue gas and that capture itself.

It should be noted that there also exists another way toward CO₂ removal from flue gas, one which bypasses the extraction of the CO₂ and utilizes the flue gas directly as-is, i.e., without CO₂ separation, for instance with the accelerated carbonation of calcium or magnesium oxide minerals.

With the R&D efforts toward better solvents, more efficient heat transfer, lower pressure drops, enhanced materials, etc., what comes out of the stack is assumed to be perfect for the carbon capture plant, but is not so. The main keys to an efficient (CapEx, OpEx, size of plant, byproducts generation, etc.) CO₂ capture plants are:

- The CO₂ concentration in the flue gas.
- The types and concentrations of pollutants such as NO_x, SO_x, mercury, HF, dust, etc., which impacts both the CC

system efficiency but also the CO₂ purity itself.

- The quantity of the other main molecules, N₂, O₂, H₂O, CO, etc.
- The temperature of the flue gas as it enters the CC system, which is linked to the energy intensity (GJ or kWh/ ton of CO₂ captured) of the system.
- Maximizing the use of waste heat from the process plant to reduce the external need for energy.

This article shall examine these different areas, which level of processing needs to be achieved and which technologies are needed.

Unlike the other major building materials — cement, glass, lime and aluminum — that release CO₂ from their intrinsic processes (calcination, carbon rods consumption), the CO₂ produced by the steel industry stems mostly from the combustion/oxidation of carbon-based fuels. Also, unlike those other plants, an integrated steel mill — whether with blast furnace or electric arc furnace (EAF) — has multiple stacks, including those of its own power plant, and each stack produces different flue gas characteristics.

At the same time, carbon capture doesn't stand so predominantly as the last step to be undertaken to

achieve carbon neutrality, as is the case for the cement industry, the other industry equal to steel in terms of global CO₂ release, with each accounting for around 7% of the world total. This is because of the several hydrogen pathways available to the steel industry, not to mention even more advanced options such as molten oxide electrolysis.

Discussion

This article is divided into several parts. First, a quick overview of the main carbon capture technologies will be given and how they relate to steel plants. Then the focus will be on the various streams of flue gas and their processing, waste heat recovery, flue gas cooling, air pollution control and CO₂ concentration increase. Third will be a look at the energy requirement for such carbon capture plants. Finally, the practical approaches for plants to implement such projects will be described.

Carbon Capture: A Quick Overview

One of the unknowns for the industry at large is which carbon capture technology will be prevalent in the future. As of today, there is not a single industrial plant fitted with more than small demonstration units. One should not assume there will be one solution that will fit all. The absorption technology is currently the most advanced as it is already used for the extraction of very high CO₂ concentration (e.g., natural gas sweetening or biogas upgrading) and therefore will be mentioned more often than the others. It doesn't reflect the author's view on which technology is the best, especially for the building

material industries of cement, glass, and steel, where having to add what amounts to a chemical plant to the back of their processes might not be so attractive.

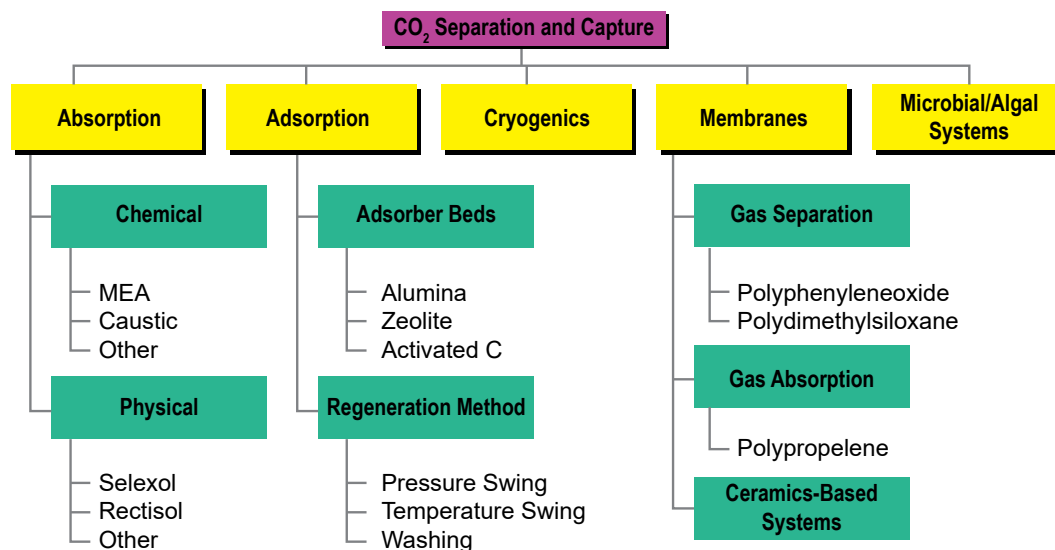
Currently, four main technologies (see Fig. 1) are vying for predominance, namely absorption (usually amines but also ammonia-based solvents and others), adsorption (metal organic framework (MOF) being the main support), cryogenic, and membranes (of various sorts and separation principles). Within each family a great number of variations exist and lately even hybrid options are being looked at, for instance membrane separation followed by (vacuum) pressure swing adsorption (V/PSA).

Absorption employing chemical solvents (which use chemical bonds to capture CO₂) or physical solvents (which use intermolecular force to capture CO₂) is the most common technology used for gas separation. At lower CO₂ partial pressure, chemical solvents have a higher absorption capacity, but at higher concentrations, physical solvents are preferred. Chemical solvents are usually regenerated by raising the temperature to release CO₂, while for physical solvents, the pressure is reduced. An illustration of that technology is given in Fig. 2, courtesy of Shell CANSOLV.

Adsorption is also chemical or physical. Chemical bonding results in a strong interaction between the gas molecule and sorbent, and is for low CO₂ concentration in the gas streams. Regeneration is accomplished using a thermal swing adsorption (TSA) process, i.e., the adsorbent is regenerated by raising its temperature to liberate the CO₂. Physical adsorption offers a weaker interaction between the gas molecule and sorbent and is applied to higher CO₂ concentration feed streams. Regeneration is

Figure 1

Some CO₂ post-combustion capture technologies. Source: National Energy Technology Laboratory.



In membrane separation, partial pressure is the driving force and is more favorable when the gas stream is at high pressure, which is not the case at an industrial plant stack. There are many different membrane materials characterized by their permeation flux, i.e., the volume flowing through the membrane per unit area per unit time and by the permeability which is the transport flux of material through the membrane per unit driving force per unit membrane thickness. Only electricity is required to operate.

The respective merits and technology readiness levels (TRLs) of these technologies is not the topic here. This work is focused on the conditions of the flue gas for the optimum use of those technologies in terms of CapEx, OpEx, and footprint and the energy/power requirements to operate them.

Since this article only looks at the mill's flue gases, only the post-combustion decarbonation technologies are being discussed, even if — especially for the steel industry — many other pathways should be implemented first. Some would say that if carbon capture, utilization and storage (CCUS) becomes mainstream with an acceptable cost, then a facility should wait until 2045 and then install such a CCUS plant. But that would be a very risky approach. A better one is first to reduce the plant CO₂ footprint to the maximum extent prior to considering CCUS, especially considering the high energy requirements — and costs — of those technologies.

Even if all technologies require some electrical consumption for operating the fans and pumps, the main distinction is between: (a) electricity driven — the membrane technology where the flue gas needs to be compressed and the cryogenic one where the very low temperatures are achieved through gas compression/expansion, and (b) the thermal energy for the absorption and adsorption technologies in the form of steam. The R&D work of the technology providers is generally twofold: (1) to increase the solvent efficiency, the adsorption medium or the membrane selectivity, etc., and (2) to improve the actual CO₂ extraction efficiency and reduce the volume and footprint of the systems.

Both the amount of electricity and the quantity and quality (temperature and pressure) of the steam are the key characteristics of the efficiency of the capture system. For instance, one original equipment manufacturer indicates that because they only need slightly superheated steam or hot water at 85°C as a heat source, the reboiler heat rate is 2.4 GJ/ton of CO₂ captured, a substantially lower energy need. Others require steam at 110–120°C. The lower the required temperature (and overall mass flow), the more the various waste heat streams from the steel plant could become available to further reduce the amount of supplementary energy needed.

These are the topics being developed below.

Note that as a very large amount of energy — thermal or electrical depending on the technology — is needed to separate the CO₂ from the other molecules in the flue gas,

to assess it one should set aside the electricity consumption needed for the CO₂ transportation. There are two ways by which large amounts of CO₂ may be transported: compression of CO₂ to dense phase (>74 bar) for pipeline transport or refrigeration of CO₂ to liquid phase for transport by ship, truck or train. As captured CO₂ usually contains water, it must be removed prior to transport to prevent CO₂ and water-forming acids. That dehydration is typically done in conjunction with compression or refrigeration.

Flue Gas Processing

The amount of flue gas processing, including cooling, cleaning, concentrating and gathering various sources gas(es) — upstream of the CO₂ capture plant itself — also has an important impact on the CapEx, OpEx and footprint of that plant.

Another impact is on the complexity in the integration of the CC plant within the existing assets, for instance the integration of the steam and condensate systems, expansion of the cooling systems, flue gas and exhaust connections, gas recycling systems, and others. This is especially true for the steel industry that has multiple stacks from which to capture CO₂, all with different characteristics between blast furnace, EAF, coke and ironmaking, converter, reheat furnace, and heat treating furnaces.

Below are some values of CO₂ concentration in the flue gas of different processes:

- COREX smelting reduction process: 32–35.
- Hot stove: 24–28.
- Lime calcining: 7.1–8.1.
- Sinter plant: 3.7–4.2.

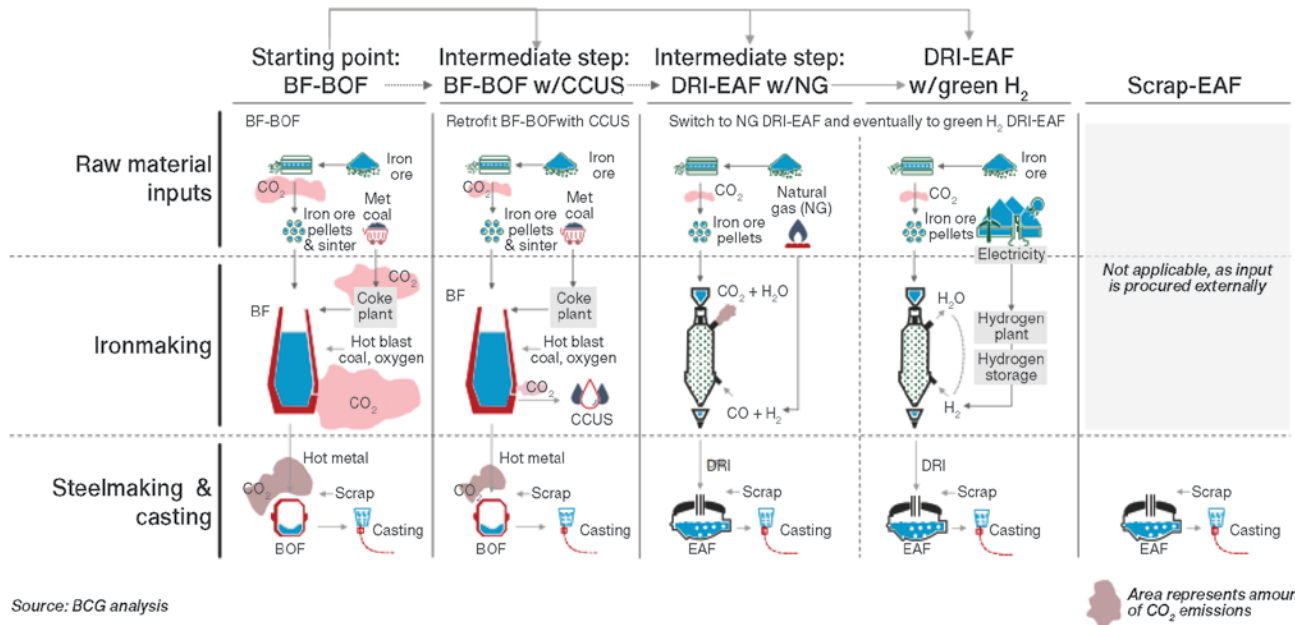
In addition, some of the flue gases have calorific value, such as blast furnace gas (BFG) and coke oven gas (COG) and are thus already used as fuel; is CO₂ capture better done before or after they have been combusted? Furthermore, with the steel industry clearer pathways toward decarbonation are currently in use, such as electrification (either (a) direct (EAF) or (b) indirect (hydrogen utilization)), and some completely new ways like iron ore electrolysis that would not emit CO₂. The focus in this article is only on the CO₂-emitting processes.

Waste Heat Recovery, Flue Gas Cooling

A common thread with the energy transition/industrial decarbonation movements for major steel players is the need for additional electricity, coupled with lower emissions. With the common pledges and commitments toward “net zero” by 2050, with intermediate goals for 2030, there is a huge increase in the amount of electricity needed. Whether for hydrogen making, methanation, oxy-combustion, mineralization, alternative fuel preparation, flue gas pressure boosting, amine regeneration, etc., this is all part of the direct and indirect electrification

Figure 4

CO₂ is present at various points of a steel mill, not to mention the power plant. Courtesy BCG Analysis.



Source: BCG analysis

Area represents amount of CO₂ emissions

trend. It could double or quadruple the peak load of a plant.

Independently of a carbon capture plant, many steel plants worldwide could self-generate a portion of their electrical need 24/7 CO₂-free by installing a waste heat recovery (WHR)/organic Rankine cycle (ORC) power plant, using the flue gas from various sources, furnaces, dry slag granulation, coke dry quenching processes, etc.

Why Waste Heat Recovery?

First, carbon capture processes require a large amount of energy and everything the plant can provide will be beneficial; second, the flue gas needs to be cooled down, better recovering some of the energy in doing so than cooling by air dilution, which reduces the CO₂ concentration in the flue gas, or water spraying in a time when water conservation is key.

An integrated steel plant will have a power plant as part of its operation with steam production for various usages besides electricity production, such as vacuum creation for degassing. Depending on the mass flow and temperature of the flue gases, a water/steam cycle that could combine with the existing one would be the natural solution. However, if the temperature and flow are lower or vary greatly, or are located far away from the power plant, then an ORC could be better suited. As shown in Fig. 5, even with the intermittencies of an EAF, energy could be stored as a thermal fluid much more efficiently than with steam storage, and thus still provide 24/7 fully decarbonated electricity to the plant, or even drive directly a large fan, pump or compressor.

The most common CO₂ capture process for post-combustion capture consists of two stages. In the first stage, CO₂ is removed from the flue gas by absorption in a scrubber or absorber column (packed bed or gas/liquid contactor). The rich solvent-containing CO₂ is then heated in a reboiler and associated stripper column to release the CO₂, which is compressed in an additional step for transport.

In the CO₂ stripping process with membrane assembly/water solutions, the flue gas needs to be treated at low pressures and cooled down to temperatures of 40–50°C because lower temperatures are favored by the exothermic absorption process and to minimize solvent loss, with regeneration at treatment temperatures of 90–130°C.

Although a heat exchanger will not lower the flue gas temperature to the required optimized temperature for carbon capture of around 40°C, it could — depending on the sulfur content in the gas — lower it down to about 130°C, thus reducing the overall energy and water requirement of the final step.

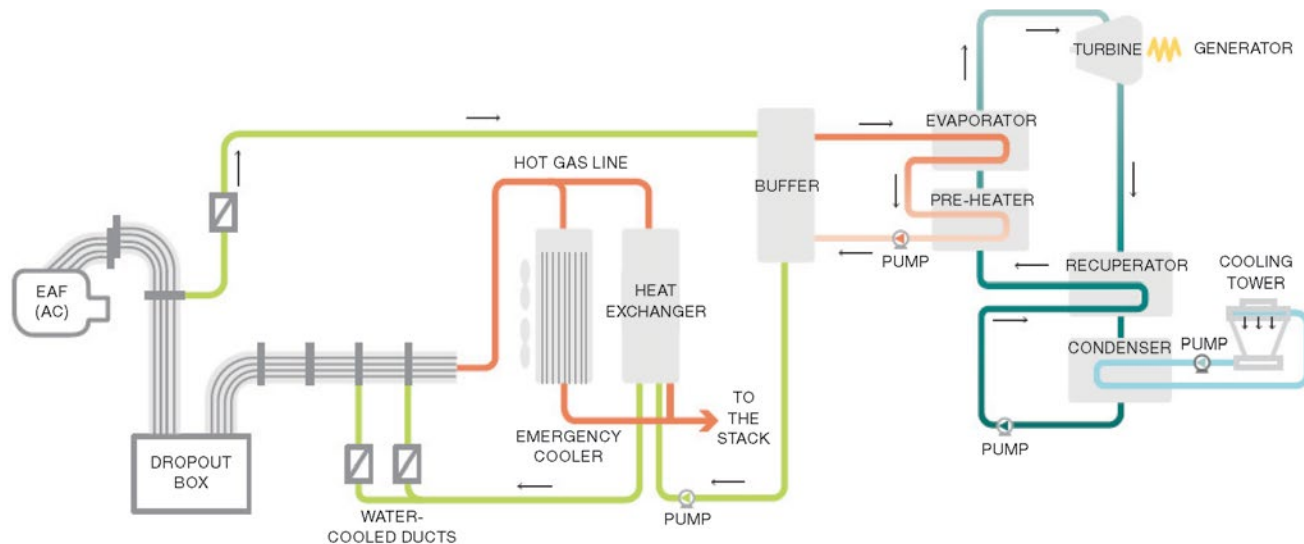
Some numbers, which are a composite from various sources: Absorption and adsorption require steam temperature between 85 and 120°C, and between 1 and 1.5 kg of steam/1 kg of CO₂ captured. Less for adsorption but it also requires some extra cooling air.

So, the energy (thermal) requirement for solvent/sorbent regeneration is about 3 ± 0.5 GJ/t of CO₂ captured 835 ± 135 kWh.

The best amines receipt on the market currently is said to require about 650 kWh/t of CO₂ captured for its desorption.

Figure 5

Waste heat recovery/organic Rankine cycle system installed at the exhaust of an EAF. Courtesy EXERGY.



Nevertheless, various publications would give numbers around 250 kWh/t of CO₂ captures.

If associated with the power plant of the integrated steel mill, the most efficient way to reheat the rich solvent in the reboiler is by steam extracted from a steam turbine cycle. However, if not, then a boiler must be added, usually firing natural gas, which will emit additional CO₂ and add to both CapEx and OpEx, especially considering the constraints associated with operating a power plant.

One of the reason these numbers are all over the place, and they are important because they translate into cost per ton of CO₂ capture, is the lack of reference conditions, as well as an absence of definition of the scope, flue gas conditioning, CO₂ delivery, accounting for the waste heat recovered or not, etc.; hence the importance of looking

deeper into the conditioning/processing of the flue gas prior to entering the carbon capture system itself.

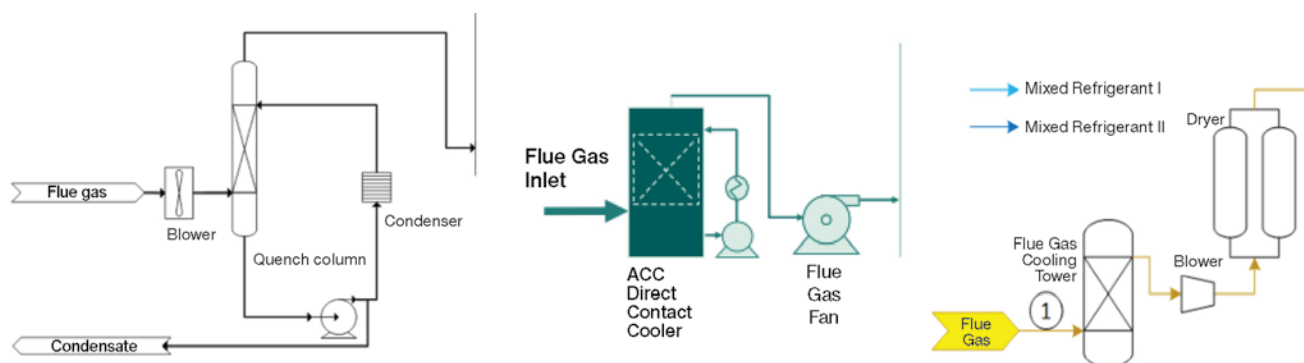
Air Pollution Control

Air pollution control (APC) falls into the gap between the process plant and the future carbon capture (CC) process. Its importance is not only for keeping within the ever more stringent regulatory limits but also to participate in the optimization of the CO₂ capture plant. Yet it has, until recently, not been looked at very closely.

Fig. 6 shows three extracts of CC schematics found in the brochures of OEMs. All simply refer to flue gas quenching, using direct contact cooler, whereby particulates and some contaminants are washed away (the contaminated water has to be treated further), and the

Figure 6

Extract of diagrams for carbon capture plants, showing the limited description of the actual flue gas preparation.



flue gas is both cooled and dried as the water vapor is condensed. This fuzzy area is where CC OEMs are keeping very vague so that to minimize the scope and intensity of their CO₂ capture plant.

Some technologies are said to be tolerant to SO_x and NO_x and that their elimination prior to entering the carbon capture system itself is not necessary; for instance, an absorption method uses enzymatic solvent and consists

Table 1

Characteristics of the Four Families of CO₂ Capture Technology

	Absorption	Adsorption	Membranes	Cryogenic
Pressure	>0.04 barg	—	>1 barg [3]	—
Temperature	<40°C	<50°C	<50°C	—
Dust	<10 mg/Nm ³	—	<30 mg/Nm ³	—
Particulate size	—	—	—	—
CO ₂	>4% <35%	>15%	>15%	—
H ₂ O	No free water	No free water	No free water	Trace
O ₂	<8% [8]	No limit	No limit [5]	Some limit
CO	<50 ppm? [9]	No limit	No limit	—
VOC	—	<1 ppm	Trace	—
HCs	—	[2]	Trace	—
SO _x - as SO ₂	<5-50 ppm	<5-50 ppm	<20 ppm [4]	<320 ppm
NO _x	<50 ppm; <5 ppm [1]	<100 ppm; <5 ppm [1]	<20 ppm [4]	<160 ppm
Mercury	?	Trace	—	[7]
Other acid gases	?	—	—	[7]
Dioxins and furans	—	—	—	[7]
Others Hf, HCl, etc.	?	<1 ppm	—	[7]

Approximate limits of the main characteristics of flue gas, to allow for efficient carbon capture by different technologies. Note: Those values are composite from various technology providers and as such are just indicative. Some suppliers take a lighter view on the question than others.

[1] NO₂.

[2] Light HCs pass through or are regenerated by the steam, heavy HCs < 1 ppm.

[3] Effectiveness of CO₂ capture will also depend on the flue gas pressure.

[4] Not because they hurt the membranes, but because they permeate with the CO₂.

[5] There is not a good selectivity between CO₂ and O₂ for membrane separation.

[6] The process does not capture NO as effectively as it does NO₂.

[7] System will remove all compounds with higher molecular weight than CO₂.

[8] Amine "recipe" can be adjusted to reflect the flue gas composition.

[9] CO shouldn't be an issue as it doesn't form heat stable salts.

of a potassium carbonate salt and an enzyme (carbonic anhydrase (CA), a metalloenzyme that contains a zinc ion, which acts as the catalytic site) in water. But what are the levels of pollutants? And what about other pollutants?

The data gathered in Table 1 is a compilation of the information that has been obtained from various technology providers. Due to the competitive nature of their work and in the absence of actual running carbon capture plants at steel plants, these values must be interpreted as indicative only and are ranging over broader limits. In fact, there is no absolute. For instance, SO₂ and CO₂ would compete to be scrubbed by amine solutions. High SO₂ concentration in the flue gas doesn't preclude CO₂ capture but would require more amine makeup, more energy for the desorption, and likely larger pieces of equipment. At the end — and for every given plant — the entire set of conditions would have to be analyzed.

Table 1, while it only provides indicative values, shows that some of the existing air pollution limits are sufficient to meet the requirement of those carbon capture technologies (dust limit can easily be achieved with bag and ceramic filters) while others would require much stronger control technologies to be implemented.

Two points also have to be made:

- Some of the aforementioned carbon capture technologies are also claiming to be able to provide air pollution control of some of the pollutant species, which could render existing equipment obsolete or be utilized as a backup only. Therefore, any project would have to be looked at in its entirety, especially greenfield ones.
- As some of the pollutants will pass through the carbon capture plant and end up in the CO₂ stream, the choice of capture technology and the level of flue gas preparation will also have to be decided in relation to the CO₂ level of purity and pressure/temperature needed for the downstream steps of either direct utilization (atmosphere control in a greenhouse or for the food industry), transformation (accelerated carbonation, methanation, photosynthesis), or sequestration (through pipeline or truck transportation, (enhanced oil recovery (EOR), etc.).

What are the technologies required to achieve these various concentration limits and conditions?

As seen in Fig. 6, the presentations of the various carbon capture companies will simply show a direct contact cooler (DCC) upstream of their system: A single square with a fan. This is, of course, misleading. Some supplementary flue gas treatment will be required even if those CC companies would likely want it located on the plant side and not in their scope of supply.

Two options emerge.

First, the “wet” solution, as illustrated in Fig. 7, the one usually mentioned by the carbon capture providers

as they need the best flue gas conditions and are not focusing on how to optimally achieve those conditions. It revolves around the DCC technology that encompasses a variety of systems such as spray cooler, water recycled gas quencher, dry bottom evaporative cooler, i.e., various sorts of wet scrubbers. These technologies are well-known and have been used across industrial applications over the years, including metal processing and incineration plants. However, the same way as lot of these industries have been moving away from wet processes whenever possible because of water usage restriction, “zero reject operation” policy, energy requirement to operate the scrubbers, and OpEx and are trending toward dry-based technologies such as dry scrubbers, catalysts, bags and ceramic filtration methods, etc.

Furthermore, in order for the DCC to operate with low maintenance (lower pressure drop), the flue gas to be cooled should be free of most dust and pollutants, otherwise this buildup inside the cooler has to be flushed through blowdown and has to be further processed as waste.

If the gas temperature must be below saturation (dew-point), since the cooler the better for the carbon capture system, then chiller technology must be used and water removal from the flue gas will also occur.

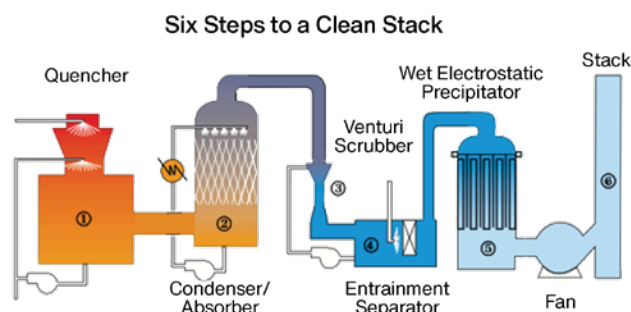
Finally, such an approach will reduce the CO₂ concentration at the entrance of the carbon capture plant, as some of the CO₂ would have already been scrubbed away, a negative effect for the efficiency of CC. These “wet” technologies require large amounts of electricity to operate.

Second, the “dry” approach considers that many installed APC systems could simply be upgraded. Dust removal with either bag filters or ceramic filters can achieve <5 mg/Nm³ and therefore appears to be already below the needed cleanliness; but that would not necessarily be the case for the few remaining plants operating an ESP.

Gas cooling is needed; 40°C or below is often mentioned. Such cooling can only be done after de-NO_x,

Figure 7

Flue gas processing before CO₂ capture, using wet technologies. Courtesy ENVITECH.



de-SO_x, mercury removal as these processes (dry sorbent injection (DSI) of hydrated lime or sodium bicarbonate and SCR catalytic reaction with ammonia or urea) require high flue gas temperature and humidity content).

For instance, a full system could comprise of:

1. Ceramic filter system (incorporating dry sorbent injection) for simultaneous PM, NO_x, SO_x, Hg furans, dioxins and long-chain volatile organic compounds (VOCs).
2. A thermal oxidizer for short-chain VOCs.
3. A heat exchanger/WHR boiler, which in absence of SO_x could cool the gases down to around 100°C.
4. A wet quencher, a relatively simple piece of equipment, which would bring the temperature down to around 70°C.

To go below the water dew-point, a sub-cooling tray type vessel/condensing scrubber could bring the flue gas to almost ambient temperature. It may have to be followed by a demister. It would recover the latent heat of the gas to be used to lower the overall energy requirement of the carbon capture system. This final step could provide an extra polishing of the flue gas.

However, there could be some pollutants — for instance, bromine — that can only practically be removed with some wet scrubbing technology. Few processes, mostly in metal recovering smelters, have to deal with bromine, and that pollutant might not interfere with the carbon capture process.

This “dry” approach should therefore be evaluated. But the important point is that any APC project should now consider the fact that a CO₂ capture plant might one day be incorporated into the overall mill operation and technical choices should be made accordingly.

Additional Flue Gas Treatment, Enhancement, CO₂ Concentration

In this section are considerations for the optimization of the flue gas composition, its mass flow, its CO₂ concentration and the pressure at which it needs to enter the CC system.

These parameters influence greatly the costs (CapEx and OpEx) of the CO₂ capture plant, and also its footprint, which any project manager will recognize to be always an issue. This is illustrated in Fig. 8.

Size can be managed with the ducting together of various streams, even considering other external but nearby processes. The charts in Fig. 8 were established on the

Figure 8

From the Global CCS Institute. Cost of CC depending on the size of the plant and the CO₂ concentration in the flue gas — from CCE CCS Technology Readiness and Costs 2022.

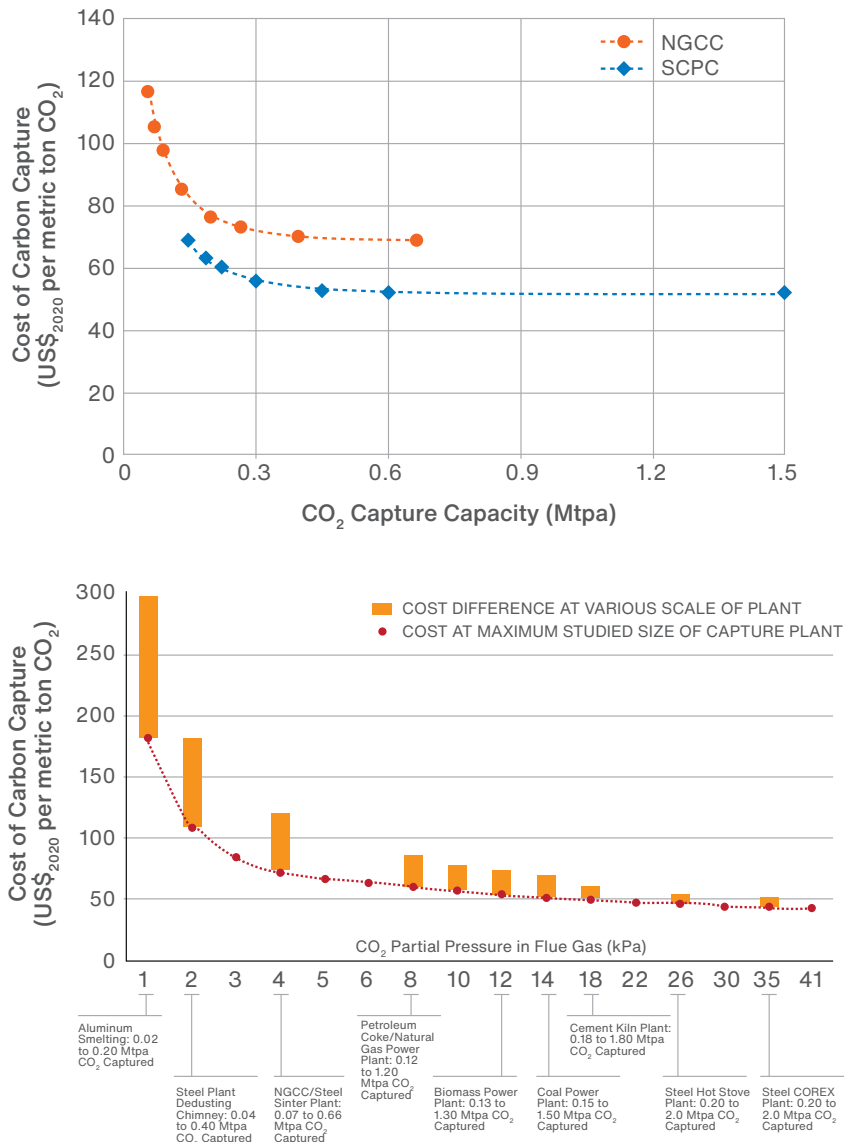
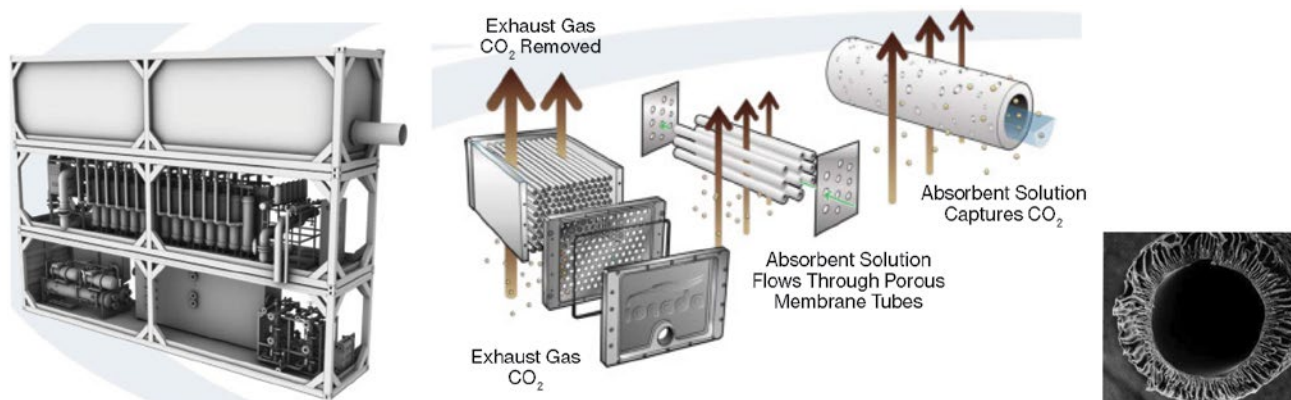


Figure 9

IONADA modularized/containerized solution for smaller carbon capture plants.



basis of the absorption technologies offered by large players. There are many companies that are developing cost-effective solutions — usually containerized — for a stream of 20–30,000 tons/year and their multipliers. Fig. 9 illustrates such a modularized/containerized approach by IONADA with an absorption system utilizing hollow membrane contactors as the exchange medium (instead of pack bed column) for a very compact system.

CO₂ concentration can be increased by using oxygen enrichment in the combustion. Displacing air by oxygen is removing nitrogen from the flue gas. It also has the side benefit of allowing production increase by reducing the amount of flue gas that must be handled (filters, ID fans). Oxygen enrichment comes at the cost of producing oxygen. Today with oxygen potentially a byproduct of hydrogen generation through electrolysis and with the cost of CO₂ on the rise, that approach has to be evaluated.

Eliminating the many false air entries into the process will also have similar benefits. This shows that even if CC will be done by third-party companies with the steel plant role being limited to deliver the flue gas, the steel mills should not keep a passive role as a lot can be done on the process side.

Finally, another consideration is concentrating CO₂ but also reducing the overall accounted CO₂ in the flue gas. One option is with alternative fuels, assuming high biogenic content, meaning that actual CO₂ is emitted but not accounted for as such and therefore a less intensive/efficient CO₂ capture might be sufficient. Gas such as syngas and biogas, including or not hydrogen, would make it possible to reach a high solid alternative fuels (biomass and waste) substitution rate.

The Use of Flue Gas “As-Is”

What if CO₂ could be used/transformed without going through the capture step? This approach has and is being seriously looked at.

For instance, using photosynthesis, the flue gas, which must be purified, is percolated through the bath where microalgae multiply under the dual effect of sunlight and CO₂. Thus, the CO₂ is transformed into biomass that can serve as a fuel for a virtuous circle.

Another example is the accelerated carbonation, whereby the flue gas is brought into contact with calcium or magnesium oxide, and under certain pressure, temperature, humidity and time, the minerals are carbonated to become aggregate that is used in the construction industry. These pathways are mostly being looked at by the cement and lime industry as it is closer to their processes. Fig. 10 is one illustration of that direct flue gas CO₂ utilization approach by the startup company CARBON RESOLVE. It is, however, only applicable for a cement plant.

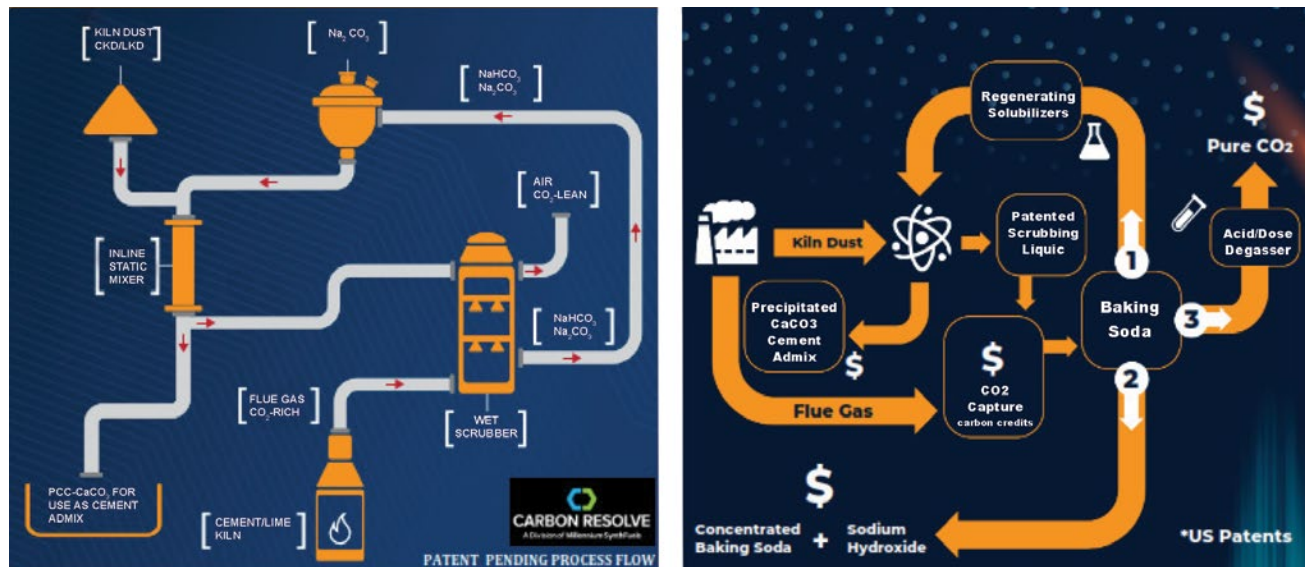
One point to be made is that these decarbonation technologies, although their application will be specific to each process, have much in common and will contribute to the industrial cluster approach whereby several industries would combine resources for higher efficiency, for instance with slag cement.

The Implementation of the Above Projects

So, the development and execution of carbon capture plants is complex, requires a variety of expertise, and needs to consider a very large number of parameters — not all technical — will need a large amount of energy. As a result, future CC plants will also likely be handled by third-party companies dealing with CO₂, even if a steel

Figure 10

CARBON RESOLVE Kiln dust to precipitated calcium carbonate.



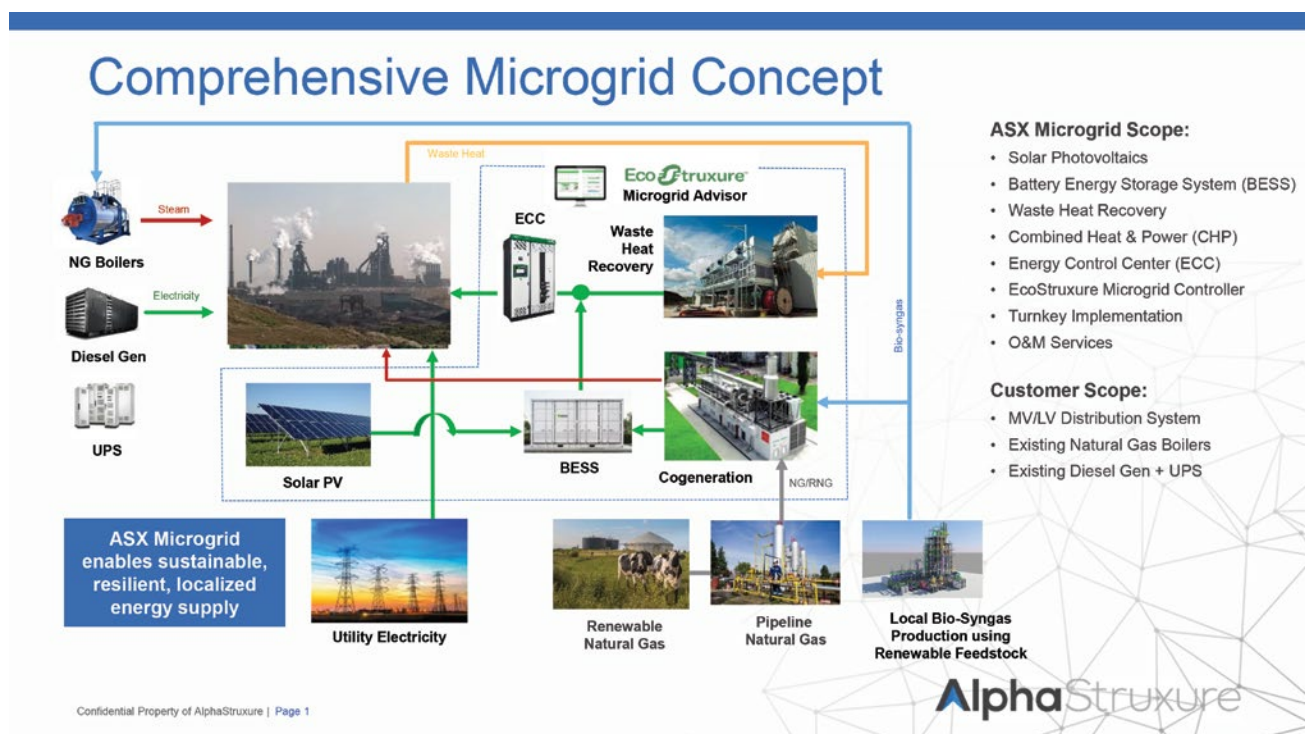
plant should still work to minimize the size of that CC plant with the approach presented above.

Enter the X as a Service (XaaS) model, where X could be energy, decarbonation, resilience or environmental

compliance; the denomination doesn't have to precisely cover the services offered. It goes beyond third-party project financing. Those "as a Service" companies are often a division of a deregulated arm of a utility, a large

Figure 11

Energy as a Service capabilities, from actual industrial project. Courtesy Alphastruxure.



investment group in a joint venture with an engineering firm, an offspring of large oil and gas companies, etc. They have in general large financial capabilities and look at servicing a plant for 10–20 years under various forms of long-term service agreements.

A typical project, as some are currently being developed, combines some renewable electricity sources (that could include a power plant run with biomass/waste), a 24/7 fully decarbonated electricity generation through a WHR/ORC unit, and some form of energy storage with a discharge duration of 2–4 hours. It incorporates existing backup gensets and will likely consider electrolyzers with both hydrogen and oxygen supply. It will be grid-connected and have highly sophisticated control system with weather prediction, grid signal and various energy costs input. More and more the system (microgrid) would have an islanding capability, i.e., capable of partially running the plant — albeit in a degraded mode — should the grid go dark.

The decarbonation/environmental compliance could be part of the overall approach, or by itself it will offer the plant the security of being environmentally compliant for 10 or more years and at the same time being prepared to deliver the flue gas in an optimum condition to the future carbon capture installation.

Even more than the financial benefits is the ability of an XaaS company to extract the maximum value for the project out of all the external and internal plant constrains, to deal with the permitting issues, to maximize any tax credit and subsidies, and to provide the proper and optimized carbon accounting. Lately the guarantee on delivered power, i.e., resilience, has become a dominant advantage. The straight payback of such projects might be well above the acceptable threshold for deciding on traditional projects, but should still deliver a high internal rate of return and for a long enough period to satisfy the XaaS investors. Fig. 11 gives a simplified example.

Three concepts are and will likely gain predominance to support the ongoing transformation of the steel industry:

- Microgrids, which can be defined as the combination of decentralized electricity production, with or without energy storage — optimized in terms of resilience, electricity cost, and CO₂

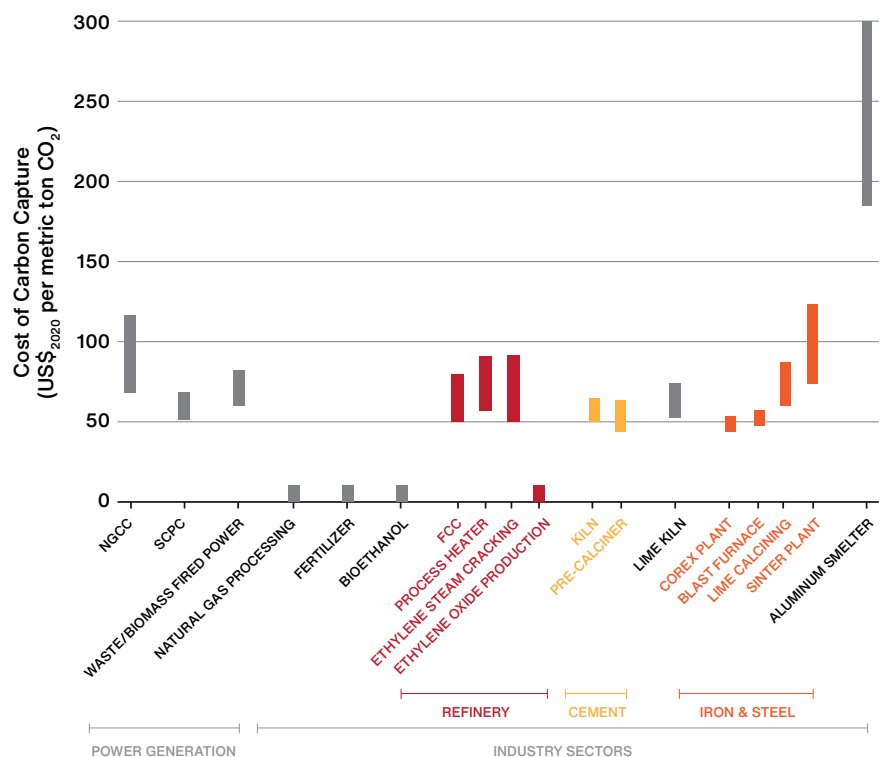
reduction — that can be under certain conditions islanded, i.e., decoupled from the grid.

- Sector coupling, out of which microgrids are part of, refers to the optimization of the integration between the electricity supply and demand; in this case between the steel plant and its microgrid and the grid network. For example, the handling of peak loads, the avoidance of curtailing, or grid frequency stabilization.
- Industrial clusters refer to the search for synergies between different industrial processes/plants such as the ones presented in Fig. 12 — usually physically close to one another — where byproducts from one can be raw materials for another, where various utilities can be pooled and thus also improve sector coupling, and finally where various stream of flue gases could also be combined into a single CO₂ carbon capture plant. For example, one such cluster is when slag is granulated and then exported to be transformed into cement.

Thus, as the steelmaking process itself becomes a smaller part of the overall plant operations, with more and more companies interested in the industry or rather in its stacks exhaust, it is natural to see the emergence of Energy-as-a-Service companies that propose an

Figure 12

Cost comparison of CO₂ capture between various industries, and within a steel integrated mill, from CCE CCS Technology Readiness and Costs 2022.



all-inclusive approach to these aspects of energy transition and industry decarbonation.

Conclusions

It seems these days that the public, governments, companies and financial institutions are now embedded in a spinning wheel, which is both accelerating and growing to the point of often leaving the realm of reality. In the middle of all these movements sit the steel plants, where one could feel that steelmaking is gradually becoming a secondary issue, even if the market demand for the product remains strong. It is as if the stack exhaust sides of a plant became more important than the slabs leaving the rehear furnace!

The electrification (direct or indirect) of the steelmaking economy is moving forward, due to or despite the fluctuation (trending upward) of the cost of energy, the ever-increasing issue of resiliency — as a combination of the increasing intermittent renewable generation and the catastrophic weather events — and with the industrial decarbonation movement having passed its point of no return with calls and incentives for its acceleration. This is happening amid a slew of contradictions — for instance, on one hand, tax credits and subsidies are boosting decarbonation projects, and on the other hand, some plants are getting penalized by their utility for self-generating a portion of their electricity — so-called departing charges — or facing impossible hurdles to get their permits.

Stakeholders — shareholders, clients and governments — are now demanding “green” steel, and companies have committed to deliver as written on the ever more impressive sustainability reports produced yearly. But keep in mind that green doesn’t mean simple; on the contrary, those carbon capture plants are complex, expensive to build and to operate, utilize a large amount of energy — and require substantial footprint. Even if for the steel industry actual carbon capture will be relegated to the end of the chain — a solution to be implemented as the final stage — plants should already prepare for that time even if faced with the additional complexity of predicting a future with new fluctuating parameters such as the cost of CO₂, and investment and production tax credits that come and go with successive governments.

If the Energy-as-a-Service approach lowers the cost of energy (electricity), while de-risking its supply (resiliency), and at the same time delivering a reduction of the carbon footprint, then that approach should be embraced by the industry. If Environmental Compliance-as-a-Service is able to achieve the required projects implementation for the flue gas “carbon capture readiness,” then that option should be considered by the industry.

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References

1. Renewable Thermal Collaborative – Iron & Steel Sector Perspectives.
2. “The Right Technology Pathways,” *Green Steel European Conference*, November 2021.
3. “Making Net-Zero Steel Possible,” *World Economic Forum*, September 2022.
4. “Iron & Steel Technology Roadmap,” International Energy Agency, 2022.
5. “Enhancing Efficiency,” *EXERGY – Energy Global Magazine*, August 2021.
6. “Can Current Air Pollution Control Technologies Provide Clean Enough Flue Gas For Optimized CO₂ Capture?” *National Carbon Capture Conference*, November 2022.
7. “Designing Simple and Efficient DSI System,” AIST Environmental Technology Committee Meeting, March 2022.
8. “Environmental Sustainability and Energy Conservation,” AIST Webinar, May 2021. ◆



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