REPORT

Green Transition Denmark

Technological breakthrough for direct electrification

A new climate pathway for the cement and steel industries?

So far, efforts to decarbonize energy-intensive industrial processes such as steel and cement production have primarily focused on CCS and the development of green hydrogen and electrolysis technologies. However, technological advancements in the direct electrification of heavy industrial processes are challenging this narrative.

Technological breakthroughs in direct electrification of heavy industries challenge the CCS-strategy

We are on the brink of a series of entirely new technological breakthroughs in the electrification of energy-intensive industrial processes. This is particularly true for steel and cement production, as both are well known for being hard-to-abate sectors.

In recent years, there have been significant breakthroughs in indirect electrification with the development of hydrogen-based production technologies (PtX), which opens the doors to a production based on renewable energy, rather than fossil sources such as coal, oil and gas.

Furthermore, we are also witnessing significant breakthroughs in technologies that enable the direct electrification of energy-intensive industrial processes. Today, several companies have promising technologies demonstrating that even high-temperature processes (1500-2000 degrees Celsius), which are currently essential in the production of steel and cement, can indeed be electrified. Within just a few years, direct electrification has gone from being perceived as impossible for energy-intensive production to becoming a viable option for steel and cement manufacturing. There is now widespread anticipation that production based on direct electrification could reach commercial scale within a timeframe that allows these technologies to contribute to emission reductions by 2030. See *figure 1*.

This is, in many ways, good news for the climate. If we succeed in developing and scaling solutions that enable electricity-based production processes, we can use fossil-free electricity directly from renewable energy sources such as solar, hydro, and wind. Thus, the direct electrification of these heavy industrial processes paves the way for a comprehensive, efficient, and potentially cheaper green transition. It represents a significant advancement over the solutions we have relied on so far for decarbonizing energy-intensive industries, as these solutions have not yet proven to be mature, effective, or economically viable. This applies to hydrogen-based solutions, which involve very high energy consumption[1], as well as CCS (carbon capture and storage), which many still consider a key technology for the green transition but has yet to demonstrate its effectiveness in reducing emissions[2].

Figure 1: **Direct electrification technologies are advancing rapidly**

TRL-list (Technology Readiness Level) of selected projects focused on the direct electrification of steel and cement production.

Cases	TRL-level	Employees	Expected date of first commercial production
FLSmidth	?	10,000+	End of 2025
Boston Metal	TRL 6	175	2026
Salzgitter	?	10,000+	2026
Electra	TRL 5-6	46	2026
Coolbrook	TRL 5-6	+30	Start 2025
Sublime Systems	TRL 5-6	60	2028

Overview of TRL-levels – from 1 to 9

Technology Readiness Level (TRL) is a measure of a technology's development, from research to commercialization, placed on a scale from 1 to 9. TRL 1 is basic research, while levels 2 to 4 describe different activities within technological research. 5 to 8 are the product development phases, and level 9 is final production and market introduction of the technology. Currently, most direct electrification technologies are at TRL 6 to 7, reflecting advanced pilot stages and early product development. In contrast, CCS technologies are positioned at TRL 8 to 9, indicating near-commercial readiness or full-scale implementation.

Source: Overview prepared by GTD, based on information from companies and classification into TRL levels[3].

[1] https://rgo.dk/wp-content/uploads/RGO-PtX.pdf
[2] https://rgo.dk/wp-content/uploads/CCS-RGO.notat_-1.pdf
[3] https://iti.uiowa.edu/technology-readiness-level-trl

Most pilot projects and facilities involving direct electrification are not yet in function at a commercial scale with a technology readiness level (TRL) of 6 to 7 on a scale of 1 to 10. However, the growing number of companies, the rapid pace of their advancements, and the very short timelines now being proposed for scaling up suggest potential technological breakthroughs. These could represent a massive game-changer in addressing the key climate challenges of energy-intensive industries.

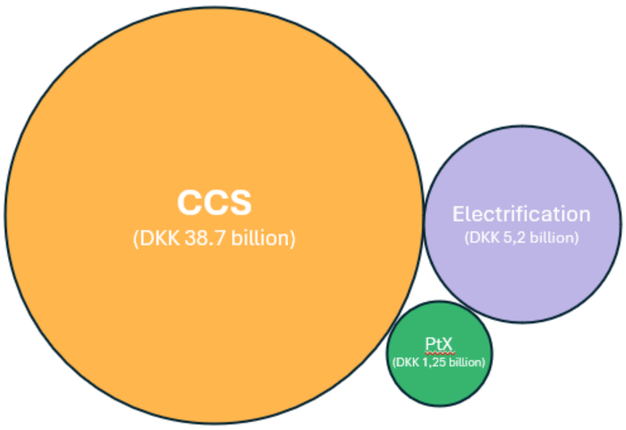
Policy recommendations: Direct electrification should be the top priority

In recent years, there has been increased political focus in Denmark, within the EU and globally to accelerate the decarbonization of steel and cement production. For example, the EU has introduced the "Net-Zero Industry Act," which aims to create better conditions for market development of low-emission technologies while supporting the EU's efforts to become independent of imported energy, including from Russia.

In Denmark, several initiatives have also been launched targeting CO_2 reductions in energy-intensive industries – with massive investments and funding for CCS, and on a smaller scale for PtX. See *figure 2*.

Figure 2: **Politically, CCS has been the chosen path**

Politically allocated funds for green technologies in the industry, billion DKK, 2020 – 2040.



Note: *The 'Direct electrification' category also includes investments related to energy efficiency, conversion, and electrification.
Note: *In addition to the above investments, a green fiscal space has been allocated in the Finance Act, with DKK 1.5 billion reserved for 2024 and DKK 3.25 billion annually from 2025-2040 for, among other things, electrification and PtX. The funds from this fiscal space will be allocated through individual finance acts.
Source: Overview created by GTD, based on information from political agreements on climate and energy.

Both in Denmark and at the political EU level, there is still a long way when it comes to incorporating the technological advancements of recent years, particularly in relation to direct electrification. This is reflected both in policy development and in the funding allocated for innovation and development within climate technologies. For example, in 2022, the Danish Energy Agency[4] estimated that only 5 percent of brick and cement production is expected to be directly electrified by 2050. In contrast, several research papers[5] and specific projects point to a much larger reduction potential for direct electrification.

As long as the new technologies and advancements are not taken into account, we will not have the right incentives, taxes and subsidy schemes in place to truly support and accelerate the direct electrification of energy-intensive industries. The perception that direct electrification is not a viable option must therefore be abandoned. Electrification should be viewed politically as a crucial part of the solution for energy-intensive industries – and as a must-win in the fight to decarbonize high-energy-intensive industrial processes, such as those in steel and cement production.

Green Transition Denmark believes that it is necessary to rethink the climate policy regarding energy-intensive industries and the reliance on CCS to solve global warming.

Therefore, it is crucial that, from a political perspective, one should:

- **Reevaluate the CCS focus – and the current political consensus that CCS is the best solution for decarbonizing energy-intensive industries.** Despite many years of development and large investments, CCS remains an inefficient and pre-commercial technology, which is difficult to scale up. And in many use cases it has uncertain climate effects and a long timeline for technological maturity[6]. Green Transition Denmark recommends temporarily pausing the roll-out of CCS in Denmark, to conduct an independent and critical analysis of whether the current expectations are realistically met. Before the Danish Government opens more bids and directly support carbon capture technology, an independent body, such as the Danish Climate Council, should be given the time and the resources to conduct a more thorough investigation of the current assumptions.

- **Designate public funds for research, development, and scaling of electricity-based production technologies and energy storage technologies.**

[4] https://ens.dk/sites/ens.dk/files/Analyser/kortlaegning_af_energiforbrug_i_produktionserhvervene_2022.pdf

[5] The CO2 reduction potential for the European industry via direct electrification of heat supply (power-to-heat)

[6] https://rgo.dk/wp-content/uploads/CCS-RGO.notat_-1.pdf

There is a need to allocate public funds to research and development in direct electrification – this will benefit Danish manufacturing companies, including the cement industry, in terms of climate reductions, but it will also serve as a leverage to strengthen the competitiveness of Danish companies in a global market where electrification technologies are rapidly gaining traction.

- **Introduce a CO_2 tax on cement production.** There is a need for the Danish government to revisit the agreement on the Green Tax reform, including the decision to introduce a CO_2 tax. It is important that the CO_2 tax is gradually phased in and increases more rapidly than currently planned. The so-called mineralogical processes – including cement production – should be included so that they are also required to pay for the CO_2 they emit (in addition to the quotas they pay/are required to pay through the EU's emissions trading system). This would provide the cement industry with a clearer incentive to reduce CO_2 emissions, and it would also make good economic sense for society. Economic experts have calculated that "the agreement on the Danish Green Tax reform for industry, among others, will result in additional societal costs of approximately DKK 1.7 billion annually in 2030 compared to a uniform CO_2 tax that achieves the same reductions[7]."

- **Ensure a sufficient supply of renewable energy for production in energy-intensive industries based on electricity.** Production based on renewable energy sources – including electrification solutions and potentially hydrogen – will require much faster deployment of renewable energy, both on land and at sea, to meet the growing demand for green electricity. In the EU, progress is too slow, and this is also the case in Denmark, where the rollout of renewable energy in recent years has virtually stalled, and the path to a fourfold increase in electricity from solar and wind on land by 2030 seems unclear[8]. In the past five years, only an additional 1.4 GW of solar and wind energy has been installed on land.
The Danish Government's new renewable energy proposal does not indicate how the fourfold increase in renewable energy until 2030 will be realized, which is why there is a need for a new and clear plan with defined priorities and deadlines for solar power and wind energy. There seems to be a particular lack of significant economic incentives for municipalities to take on projects that often face local opposition. Currently, local politicians face challenges with such projects, without being able to argue positively for their influence on municipal finances. Part of this also involves securing investments in the expansion of energy infrastructure to support the transformation of the energy grid.

- **Use public procurement as a driver.** As it stands today, the public sector is not required to meet green criteria in its purchasing decisions[9] – this also applies to construction and infrastructure projects, where large quantities of steel and cement are procured. By introducing green requirements as part of public tenders, the climate footprint of the public sector can be reduced. At the same time, it is much more attractive for businesses to invest in and develop green solutions, if the public sector pro-actively uses its huge economic power to create a stronger demand for low carbon solutions.

- **Positions oneself in the ambitious field of EU climate and industrial policy.** It is important for Denmark to exert more pressure on the EU to adopt ambitious legislation that can further promote electrification. This applies both to the deployment of renewable energy, as well as to investments and regulations that can create better incentives for companies to invest in the development of technologies that enable direct electrification.

> ”For every ton of steel made, the production process emits up to two tons of CO_2”

The energy-intensive industry: A large and growing climate footprint

Today, steel and cement are among the biggest climate challenges posed in Denmark, the EU, and globally.

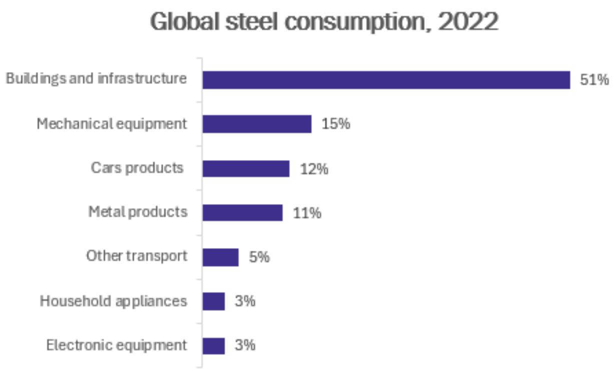
[7] https://www.altinget.dk/artikel/vismaend-co2-rabat-til-cementindustrien-koster-samfundet-17-milliarder-om-aaret
[8] Regeringens klimahandlinger udebliver fortsat – også i VE-udspillet - Rådet for Grøn Omstilling
[9] https://rgo.dk/wp-content/uploads/Groenne-offentlige-indkoeb-–-en-uudnyttet-katalysator-for-klimareduktioner-i-byggeri-og-anlaeg_Notat_RGO.pdf

Cement is one of the most widely used materials in the world, accounting for about 8 percent of global CO_2 emissions and 4 percent of CO_2 emissions in the EU. The steel industry today is responsible for about 5 percent of the EU's CO_2 emissions. Globally, steel consumption is estimated to account for between 7-11 percent of the global climate footprint. Both steel and cement are materials that are widely used in construction, infrastructure projects and in products such as cars and wind turbines, for which there are currently no obvious and fully viable alternatives. These materials are critical for our society, both in terms of mobility and infrastructure. See *figure 3*.

There is little indication that our dependency on and consumption of steel and cement will decrease in the coming years. On the contrary, forecasts show that the demand for both materials is expected to increase towards 2050. Global cement production is projected to rise by nearly 50 percent, from the current level of 4.2 billion tons per year to 6.2 billion tons annually by 2050[10]. Similarly, demand for steel is expected to grow 30 percent towards 2050 compared to 2022[11].

This could potentially have significant and negative consequences for global CO2 emissions if new technologies and methods are not developed and implemented to produce both steel and cement with a much smaller climate footprint. Without innovation in production processes, the growing demand for these materials will contribute substantially to the increase in global greenhouse gas emissions, making it much more challenging to meet climate targets and limit global warming.

Figure 3: **Steel is a big challenge**



Source: ING, 2023.[12]

Energy-intensive production

A significant reason for the high climate impact of both cement and steel lies in their highly energy-intensive production processes. These processes take place in so-called high-temperature kilns, which are heated by consuming large amounts of fossil energy. For instance, Aalborg Portland's rotary kiln 87 is heated up to 1,500 °C to produce cement clinker[13].

Another major climate challenge in cement production lies in the use of limestone (chalk), which is currently the primary raw material for cement manufacturing. The chemical formula for limestone is $CaCO_3$. When heated, limestone releases CO_2, contributing approximately 50-55 percent[14] of the CO_2 emissions from cement production during its conversion into cement clinker.

Steel production involves a process where iron ore is converted into pig iron in coal-fired blast furnaces that operate at temperatures up to 1,100 °Celsius[15]. Additionally, the process of refining pig iron into steel requires another high-temperature stage, where oxygen is introduced to reduce the carbon content, achieving the desired steel alloy. This chemical process also emits a smaller amount of CO_2 as a byproduct.

In Denmark, within the EU, and globally, high-temperature processes in cement and steel production remain heavily reliant on fossil fuels such as coal, oil, and natural gas, with a smaller share of biomass. For example, Aalborg Portland's rotary kiln is primarily fueled by petroleum coke and coal, with some use of natural gas and biogas. *See figure 4.*

Globally, more than 70 percent[16] of steel is produced using coal as the energy source. The remaining steel is produced by recycling scrap metal in an electric melting process. For every ton of steel made from virgin materials, the production process emits up to two tons of CO_2.

When looking at CO_2 emissions per ton of cement, an average of 600 kg of CO_2 is emitted (including energy consumption and the calcination process), according to the International Energy Agency (IEA) [17]. A research article from the scientific journal *Joule*, which examined the climate footprint of cement production by producers such as Cemex, Heidelberg Cement, and LafargeHolcim, also indicates emissions of 561-622 kg of CO_2 per ton of cement produced. These variations are related to the materials used in cement production, the type of kiln, and the use of different fossil fuels[18].

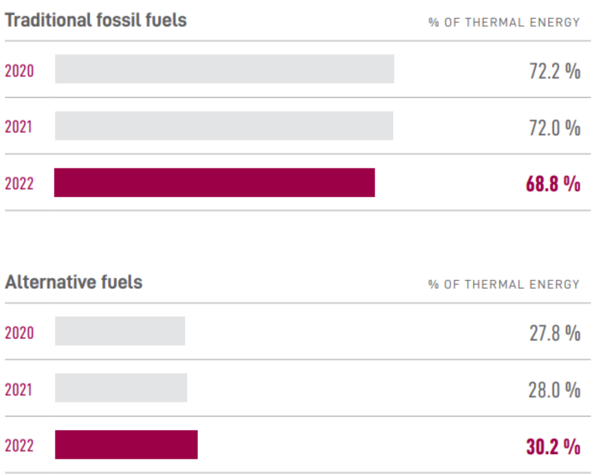
[10] https://energypost.eu/concrete-8-of-global-emissions-and-rising-which-innovations-can-achieve-net-zero-by-2050/
[11] https://www.weforum.org/publications/the-net-zero-industry-tracker/in-full/steel-industry/
[12] https://think.ing.com/articles/hydrogen-sparks-change-for-the-future-of-green-steel-production
[13] https://www.aalborgportland.dk/om-aalborg-portland/dansk-cementproduktion/
[14] https://www.dti.dk/_/media/21046_769418_Task 4_ Guidelines_final report_DTI_ 31-01-2006.pdf og https://www.cemex.com/w/cemex-and-coolbrook-electrify-cement-production-process
[15] https://leard.frontlineaction.org/coking-coal-steel-production-alternatives/
[16] https://www.euractiv.com/section/energy-environment/opinion/towards-a-european-coking-coal-and-steel-community/
[17] https://www.iea.org/energy-system/industry/cement
[18] https://www.sciencedirect.com/science/article/pii/S2542435121001975?dgcid=author

"Steel and cement are responsible for 52 percent of direct CO_2 emissions from the global industrial sector"

An assessment by the IEA[19] shows that steel and cement, together with chemicals, account for more than half of the total global industrial energy consumption. According to an analysis by the United Nations Economic Commission for Europe (UNECE) and the Economic Commission for Western Asia (ECWA), steel and cement are also responsible for 52 percent[20] of the direct CO_2 emissions from the global industrial sector.

Figure 4: **Overview of Aalborg Portland's energy consumption for cement production.**

Traditional fossil fuels account for coal and petroleum coke. Alternative fuels are natural gas and biogas



Source: Aalborg Portland, 2022.[21]

The transition is too slow

Both in Denmark, within the EU, and globally, the pace of climate reductions in the cement and steel industries is far too slow. According to the International Energy Agency (IEA), both sectors are classified as "Not on Track" in their assessments of progress toward climate transition goals.

According to the IEA[22], total CO_2 emissions from the iron and steel sector have not decreased in recent years. On the contrary, global emissions from the steel industry have risen. The primary reason for this increase is the growing steel demand over the past few years. However, when looking at the energy intensity of steel production, only minor reductions have been achieved during this period.

Furthermore, the IEA[23] assesses that emissions from cement production have remained stable over the past five years, with a slight 1% increase in 2022. The IEA points out that, like the steel industry, the cement industry is far from achieving the necessary annual reduction rates. To align with the net-zero scenario for 2050, an annual reduction rate of 4 percent is required through 2030.

The same is true in Denmark

Looking at Aalborg Portland[24], there is still a long way to go to achieve the necessary reductions in its climate footprint. The Aalborg-based cement producer needs to align with the reduction targets outlined in the Danish Climate Act and reduce emissions at a pace required to meet the net-zero target by 2045.

Aalborg Portland has reduced their Scope 1 CO_2 emissions from 2,341,966 tons in 2020 to 1,981,746 tons in 2022. During the same period, energy intensity improved from 958 to 868 kg per ton of coal equivalent (TCE), partly due to integrating more biogas as an energy source in the production process. The company has also reduced the amount of white cement produced, which emits significantly more CO_2 than traditional grey cement. However, Scope 3 emissions (which include indirect emissions across the value chain) have increased in the same period, increasing by 240,000 tons of CO_2 from 2021 to 2022 (data for Scope 3 emissions in 2020 is unavailable).

Looking ahead to 2030, Aalborg Portland's climate plan indicates that most of its climate reductions will come from Carbon Capture and Storage (CCS). Specifically, the cement producer aims to reduce its annual CO_2 emissions to a maximum of 600,000 tons by 2030. Of these reductions, 1 million tons are expected to come from CCS. *See the case on Aalborg Portland on page 7.*

[19] https://www.iea.org/reports/energy-technology-perspectives-2020/technology-needs-for-heavy-industries
[20] https://unece.org/sites/default/files/2022-11/Industry%20brief_EN_2.pdf
[21] https://www.aalborgportland.dk/wp-content/uploads/2023/04/ESG_Rapport-2022.pdf
[22] https://www.iea.org/energy-system/industry/steel#tracking
[23] https://www.iea.org/energy-system/industry/steel#tracking
[24] https://www.aalborgportland.dk/baeredygtighed/baeredygtighedsrapportering/

Case: Aalborg Portland – Can biogas and CCS climate-proof the production?

Aalborg Portland is Denmark's largest and only cement producer – and the biggest emitter of CO2 in Denmark, as it is responsible for 4.5 percent of Denmark's total emissions. Therefore, considering the increasing climate requirements both in Denmark and in the EU, there is pressure on the Aalborg-based company to find ways to achieve significant climate reductions in the coming years.

Currently, 50 percent of Aalborg Portland's emissions in Scope 1 originate from the consumption of fossil fuels, and the other 50 percent from limestone production.

Aalborg Portland presented a roadmap last year which set a net-zero target by 2050. Their goal is to reduce CO2-emissions by 1.6 million tons, capping annual emissions at 600,000 tons by 2030. This corresponds to a 73 percent reduction compared to emissions in 2021.

For their 2030 ambition, some of the reductions are expected to come from new, more climate-friendly types of cement and transitioning to production processes that are increasingly based on alternative fuels. In terms of new products, the cement producer has launched Aalborg Solid and Futurecem, which emit 20 and 30 percent less CO2, respectively, compared to traditional grey cement[25].

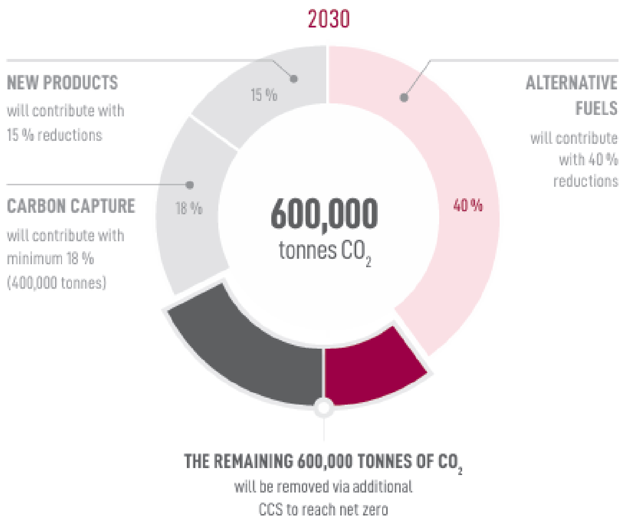
Regarding alternative fuels, Aalborg Portland is focusing on replacing conventional fossil fuels such as petroleum coke and coal for heating their rotary kilns. The transition to alternative fuels will occur in stages, first from petroleum coke and coal to natural gas, then to biomass, and finally to biogas. Currently, there are no plans for Aalborg Portland to directly electrify their production.

They are far from the only cement or steel factory to bet on bioenergy. Among others, the steel producers, German Stahl-Holding-Saar and Spanish Rio Tinto have clear plans to switch from coal to bio-based energy in an effort to decarbonize. Although this strategy does offer CO_2-emission reductions, this path brings big limitations. Bioenergy is a very limited resource, and according to the European Energy Agency (EEA) [26], we need to start planning and prioritizing who gets access to it. In the EU[27] there will not be enough bioenergy available to supply a biobased production of steel within the boundaries of the Union. Therefore, other scalable solutions are necessary to transition the production of steel and cement.

The largest portion of Aalborg Portland's reductions will come from CO_2-capture, which, according to their current reduction plan, is expected to deliver a CO_2-reduction of 1 million tons per year by 2030. *See figure 5*. Aalborg Portland has so far launched two CCUS (Carbon Capture, Utilization, and Storage) pilot projects and completed their first pilot project in 2022 in collaboration with, among others, DTU and the Innovation Fund. In 2023, they launched the so-called ConsenCUS project, which is a "collaboration with several research institutions and companies from various parts of Europe to develop a pilot plant for CO_2 capture. The goal of the project is to test a new electricity-based capture technology within CCUS, which can potentially halve the energy consumption of CO_2 capture and ensure better utilization of the captured CO2.

The ConsenCUS plant is set to replace Aalborg Portland's first pilot plant for CO2 capture. The plant, which is expected to capture up to 2.4 tons of CO2 per day, is planned to be put into operation by the end of 2023 and will be tested at Aalborg Portland until March 2024.

Figure 5: **CO_2-capture is a vital piece in Aalborg Portland's 2030-strategy**



Source: Aalborg Portland, 2022.[28]

However, there are also a number of reservations to consider regarding the realism of this goal. So far, CCS (Carbon Capture and Storage) in cement production is still only at the pilot scale. In the tests and pilot plants conducted to date, there have been several challenges related to efficiency, energy consumption, and costs. The chemical processes in the calcination process also mean that the CO2 in the flue gases is highly impure, making it difficult to capture. *See text box 1.*

[25] https://www.aalborgportland.dk/aalborg-portland-vil-reducere-co2-udledning-med-16-mio-tons-i-2030/
[26] https://www.eea.europa.eu/publications/the-european-biomass-puzzle/
[27] https://www.europarl.europa.eu/RegData/etudes/STUD/2021/695484/IPOL_STU(2021)695484_EN.pdf
[28] https://www.aalborgportland.dk/baeredygtighed/

Breakthroughs on the horizon

In recent years, large international companies in cement and steel production as well as several smaller startups have put decarbonization on the agenda and initiated multiple innovation initiatives and demonstration projects. Many are focusing on CCUS (Carbon Capture, Utilization, and Storage) projects, but there is also growing attention and an increasing number of projects concentrating on electrification—both direct and indirect (using hydrogen). *See Text Box 2*.

In the EU and the U.S., several companies are actively developing and testing new production methods that enable the direct electrification of cement and steel production. This includes addressing production processes currently reliant on high temperatures, as well as exploring new types of raw materials that allow for less energy-intensive production processes (production at lower temperatures is less energy-demanding) and thus contribute to reducing emissions. This effort includes the development of alternatives to limestone in the production of cement clinkers. *See casestudies on pages 14–18.*

The Finnish-Dutch startup Coolbrook has developed a technology for electrified kilns for cement production that can reach temperatures above 1700 degrees Celsius. These electrified kilns are powered directly by renewable energy sources, thereby eliminating the use of coal and gas. They have partnered with the Mexican cement producer Cemex to scale their technology. They expect the technology to be ready for industrial-scale commercialization by 2024. Regarding its reduction potential, it is estimated that the electric kilns can reduce CO_2 emissions from cement production by 45 percent.

Another completely new concept comes from the American company Sublime Systems, which has developed a method for producing cement via an electrolysis process

Text box 1: CCS is not yet to scale

Today, there are numerous CCS (Carbon Capture and Storage) pilot and demonstration projects in development worldwide. However, there are still no fully functional and economically sustainable projects for large-scale CO_2 capture within energy-intensive industries like cement and steel.

In the cement industry, several plants are under development, but we are still waiting for a large-scale and scalable project that is also economically viable.

For example, a small plant at a cement factory in San Antonio, Texas, captures between 30,000–50,000 tons of CO_2 annually. ArcelorMittal has opened a CO_2 capture plant at a steel mill in Belgium (Steelanol), which aims to capture 125,000 tons of CO_2 per year, though it is not yet fully operational.

Norwegian Heidelberg Cement has spent several years trying to establish a capture plant at their Norcem cement factory in Porsgrunn. However, there have been significant delays and cost overruns for what has been launched as the world's first large-scale CO_2 capture plant in the cement industry.

The Norcem Brevik plant, which has cost over 4 billion Norwegian kroner (approximately 3.2 billion Danish kroner), is expected to capture 0.4 million tons of CO_2 annually. Danish company FLSmidth is also involved in the project, which is planned to be fully operational by 2025. However, it remains uncertain whether the project will succeed.

Text box 2: Hydrogen – indirect electrification, but not without challenges

In recent years, several major steel and cement producers have invested substantial sums in developing hydrogen-based production as an alternative to coal and other fossil fuels.

Swedish steel producer SSAB aims to produce what they call "fossil-free steel." They have established a so-called "Hybrit" pilot storage facility to store hydrogen produced via electrolysis powered by renewable energy. This hydrogen is used for the direct reduction of iron ore, replacing carbon-intensive coke to remove oxygen from the ore. SSAB plans to launch its first commercial "fossil-free" steel in 2026.

ArcelorMittal, the world's largest steel producer, currently produces 88 million tons of steel annually using coal and natural gas. The company has partnered with German electricity supplier RWE to develop offshore wind and hydrogen facilities as the primary energy input for its German steel production. A 70 MW pilot plant is planned for 2026.In 2021, ArcelorMittal also signed an agreement with the Spanish government, securing €1 million in public funding, to transition to hydrogen-based steel production at their plant in Gijón, Spain. According to ArcelorMittal, this could reduce CO2 emissions by 4.8 million tons by 2025.

powered by electricity instead of fossil fuels or other energy sources. This method also allows the use of raw materials with lower CO_2 content than limestone.

Sublime Systems' technology could potentially eliminate both the use of fossil energy for heating and the CO_2 emissions from the traditional calcination process of limestone. If calcium is sourced from alternative materials instead of limestone, the process can avoid CO_2 emissions entirely. Furthermore, when using limestone, the process can capture CO_2 at 10-bar pressure and room temperature, making it easy to transfer for CO_2 storage. This technology has a potential CO_2 reduction of 100 percent.

Similarly, we see examples in steel production, such as the American startup Electra, which aims to produce steel at just 60 °C through a chemical process. This method enables the extraction of iron from iron ore entirely without the use of fossil energy, addressing 90 per cent of emissions associated with traditional steel production.

The American startup Boston Metal has developed a technology that replaces the use of fossil fuels with energy from renewable sources through an electrolysis process for steel production. Their technology further enables a direct transition from extracting iron from ore to casting steel, eliminating the need for additional chemical treatments or refinement to transform iron into steel. Boston Metal anticipates launching a commercial product by 2026. In addition, for many years, a more CO2-friendly production of new steel products has been utilized, based on recycled steel.

In this process, electricity is used as the primary energy source instead of coal. This process emits 70 percent less[29] CO2 than the production of virgin steel, and the potential for reduction is even greater if the electricity comes from solar and wind power in the future.

The transition from fossil fuels to indirect electrification through hydrogen can be an important step in the right direction to reduce CO2 emissions in the energy-intensive industries, including cement and steel production.

However, it is not always as good a climate solution as direct electrification. The production of hydrogen is, first and foremost, very energy-intensive. This is because the electrolysis process, where renewable energy is converted into green hydrogen, is an inefficient process with significant energy losses along the way. One-third[30] of the energy used is lost, making the process economically burdensome.

With direct electrification of production, there is no such energy loss, as the energy can be used more efficiently. Therefore, the same amount of energy is better utilized in direct electrification.

Furthermore, it is not certain that hydrogen is truly climate friendly. Currently, 99 percent of the world's hydrogen production is made using fossil fuels. Therefore, there is a risk that hydrogen production will not contribute to decarbonizing energy-intensive industries unless enough renewable energy is developed to produce green hydrogen. In other words, indirect electrification is not very energy- or climate-efficient compared to direct electrification.

Additionally, there is a risk of hydrogen leakage[31], as its release has a warming greenhouse gas effect, and it also requires increased safety measures since hydrogen is flammable and explosive. A study[32] published in *Nature* estimates that hydrogen warming is over 11 times more harmful to the climate than CO_2 over 100 years. Other studies[33] have shown that, over 20 years, hydrogen can be between 19 to 38 times more harmful than CO_2.

A commonly cited argument for choosing hydrogen over direct electrification is that it is not possible to achieve high-temperature heat without combustion. However, changes in processes and technological advancements in the field suggest that many processes can likely take place at significantly lower temperatures. Even for temperatures above 1,500 degrees, it may be possible to electrify directly, as long as there is a stable electricity supply. *See cases on pages 14-18.*

With the current developments and progress in direct electrification of heavy industries – including cement and steel production – caution should be exercised when introducing hydrogen. Investments in infrastructure and production equipment could lock the industry into indirect electrification, potentially delaying more effective direct electrification. Over the coming years, most, if not almost all, industrial companies will likely have good opportunities to electrify directly, thereby reducing the need for hydrogen.

Great potential for direct electrification

For many years, direct electrification has not been considered a viable path for cement and steel production. There are numerous analyses and reports that explore the potential for electrifying energy-intensive industrial processes. However, most of these reports primarily focus on the potential for electrification of heating and indirect electrification using hydrogen.

The emphasis on indirect rather than direct electrification should be seen in light of the fact that many of the technologies enabling direct electrification are new and still at the pilot project stage. But direct electrification of energy-

[29] https://steelnet.org/steelmaking-emissions-report-2022/
[30] https://baeredygtighed.dtu.dk/teknologi/power-to-x
[31] https://rgo.dk/wp-content/uploads/RGO-PtX.pdf
[32] https://www.nature.com/articles/s43247-023-00857-8
[33] https://acp.copernicus.org/articles/22/9349/2022/

Text box 3: Breakthroughs in the electrification of high-energy industrial processes beyond cement and steel

Outside of the steel and cement industries, but within other types of energy-intensive industries, the electrification is also rapidly advancing. One example is the chemical industry, where there is a growing focus on electrifying production processes that can replace fossil fuels with renewable energy sources. This is an area of focus for companies such as Danish Haldor Topsøe.
Another example is the production of mineral wool, where Danish company Rockwool has successfully electrified the stone melting process, which occurs at a very high temperature of over 1,000°C. At Rockwool's factory in Norway, traditional "cupolas" heated by fossil or biogenic fuels have been replaced with an electric heating process.

Progress is also being made in aluminum production, which has already been based on electricity as an energy source for many years through the Hall-Héroult electrolysis process. However, a large part of the electricity used in aluminum production today comes from fossil energy sources, as the industry has been unable to find cheap hydroelectric resources. There are places, including in the Nordic countries, where hydroelectric energy is used instead of coal in production. Furthermore, the process still primarily uses carbon anodes, which release CO_2 as part of the electrolysis process in the production of virgin aluminum (the electrical energy passing through an anode enables aluminum melting). Several companies are now working on switching to inert anodes. The IEA estimates that these are used in about 7 percent of total aluminum production and points out that it is a significant step in the climate transformation of aluminum production. Companies with ongoing projects for implementing inert anodes are also expecting large reductions with their use. For instance, Eurometaux highlights a reduction potential of 50 percent in relation to the overall climate footprint of aluminum production.

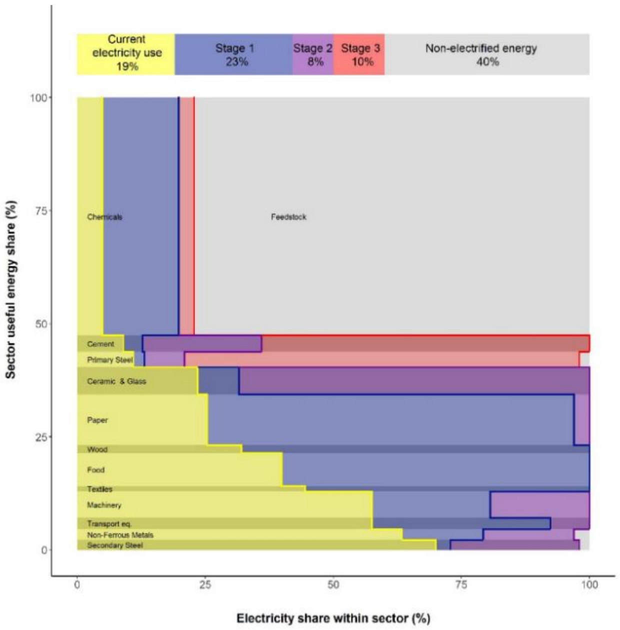
intensive industries may now be on the verge of a breakthrough. *See text box 3 on page 10.*

The potential is significant. This is highlighted in the research paper *"The CO2 reduction potential for the European industry via direct electrification of heat supply (Power-to-heat),"*[34] which underscores the possibility of direct electrification for heavy industry in the EU. The paper includes both known and emerging technologies, and based on these, it assesses how far we can go with direct electrification - particularly focusing on cement, steel, and chemicals, which are considered "the most challenging to electrify." *See figure 6 on page 10.*

The calculations do not account for indirect electrification through hydrogen. Their estimates suggest that, based on both known and new (immature and uncertain) technologies, it might be possible to electrify up to 60% of energy consumption in the production processes of chemicals, steel, and cement.

This contrasts sharply with the Danish Energy Agency's 2022 assessment[35], where only 5% of brick and cement production is expected to be directly electrified by 2050.

Figure 6: **Great electrification potential with new technologies**

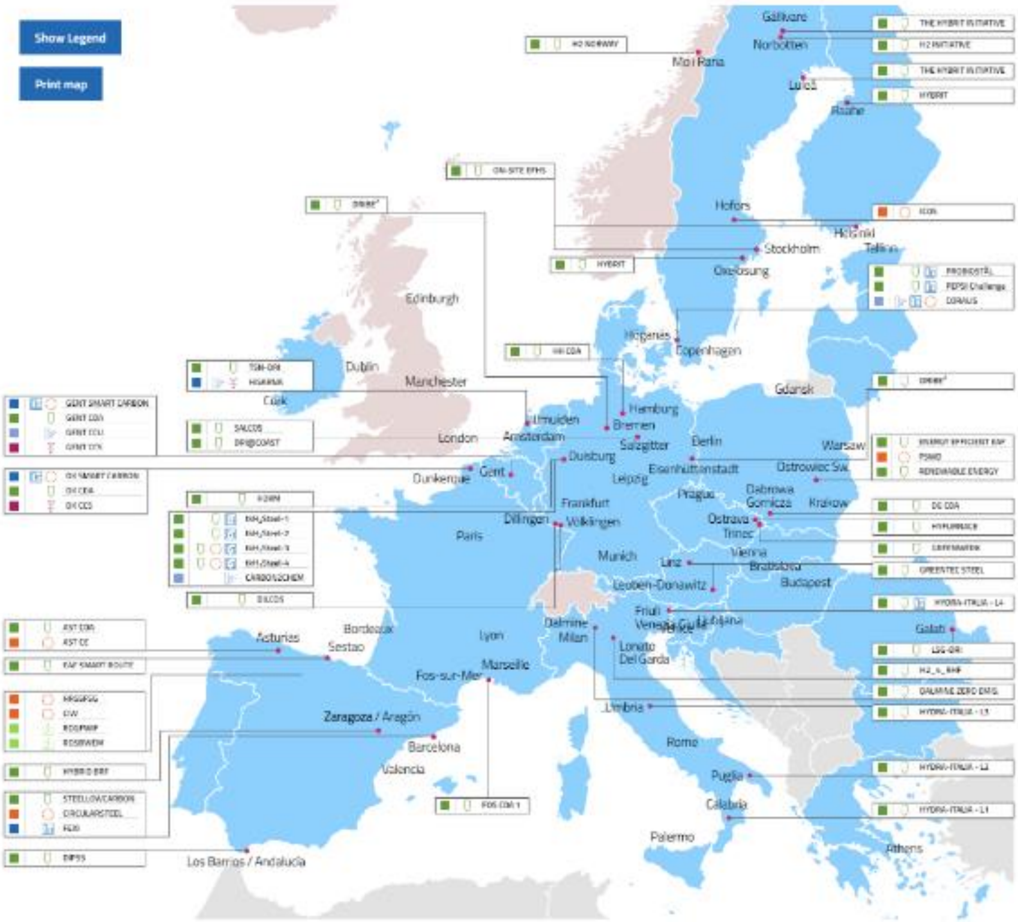


Source: IOP science, 2020.[36]

[34] https://iopscience.iop.org/article/10.1088/1748-9326/abbd02
[35] https://ens.dk/sites/ens.dk/files/Analyser/kortlaegning_af_energiforbrug_i_produktionserhvervene_2022.pdf

[36] https://iopscience.iop.org/article/10.1088/1748-9326/abbd02

Figure 7: **Several electrification projects underway in the EU steel industry**



Source: Eurofor, 2023.[37]

Specifically for cement, the CO2 reduction potential for the total climate footprint of production through direct electrification is estimated to be 31%. A significant portion of the emissions comes from the process of converting limestone to cement clinker, which, according to researchers, will require either CCS (carbon capture and storage) or alternative raw materials to limestone.

The report may underestimate other ways to reduce emissions from cement production – including the use of calcined clay and fly ash as substitutes for limestone. These have shown potential in reducing CO2 emissions in cement production, and several companies, including Heidelberg and FLSmidth, are testing them in various innovation projects.

Heidelberg estimates that there is a reduction potential of 40 percent[38] of the total CO2 emissions from cement production by replacing cement clinker with calcined clay. In addition, a material like limestone-fired clay can be produced at only 800 °C, a temperature that can be achieved with electric rotary kilns or flash calciner technologies, which can be powered by renewable energy.

For steel, the research paper points out that a scenario where production is based on metal scrap rather than virgin materials (iron ore), which can be produced with electricity, could reduce energy consumption in this sector by 70% and CO2 emissions by 74%.

However, the question remains how far the use of metal scrap can go, particularly in a scenario where demand for steel is rising. According to the European Steel Association (ESA)[39], there are currently over 60 projects underway within the EU with a technological readiness level of at least 7 out of 9 expected to be capable of producing steel at a commercial scale with significantly lower CO_2 emissions by 2030, based on both indirect and direct electrification. *See figure 7 on page 11.*

ESA's estimates suggest that these projects have a combined reduction potential of 81.5 million tons per year by 2030. This would correspond to a reduction of one-third of the total CO_2 footprint from steel production in the EU.

[37] https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Electricity_production,_consumption_and_market_overview

[38] https://www.heidelbergmaterials.com/en/pr-2023-05-15

[39] https://www.eurofer.eu/issues/climate-and-energy/maps-of-key-low-carbon-steel-projects

Barriers: CCS, economy, deployment of renewable energy, and scale

Several of the new technologies and innovations in electrification of cement and steel production are promising, and have a significant climate potential, but there are still several barriers that stand in the way of a scaling up and further commercialization.

One of the biggest barriers to the electrification of both steel and cement is the strong focus on CCS. This applies both from a political perspective and among stakeholders in the steel and cement industries.

For many years, it has been the perception that carbon capture and storage is a crucial tool for the climate transition of both industries. Back in 2021, the IEA[40] estimated that CCUS facilities/technologies must be established for more than 53% of global steel production by 2050 if we are to meet net-zero targets. As a result, large investments have been made in CCS in many countries in recent years. In Denmark alone, more than DKK 38 billion has been allocated to CCS over the next 15 years. In comparison, DKK 1.25 billion has been allocated to PtX, which is also considered a key building block in the decarbonized energy system of the future. *See text box 4.*

With the large sums that are expected to flow into CCS projects over the coming years, there will naturally be fewer funds available for other types of climate solutions.

Another significant barrier is the economy, and the costs associated with transitioning to electrified production. The development and transition to new production technologies that enable electrification is an expensive affair requiring both capital for risk-laden pilot plants, upfront investments to build new facilities, new production chains, and, as it stands today, will also come with higher operational costs.

A study from 2020, commissioned by ITRA - Energy-intensive industries – challenges and opportunities in energy transition[41], estimates that transitioning to a CO2-neutral economy will "result in price increases of 2-11 percent in the most energy-intensive sectors such as refineries, cement, fertilizers, and iron and steel."

Text box 4: Political preference for CCS

In recent years, both domestically, in Denmark, and within the EU, significant funds have been earmarked for the development of technologies and initiatives aimed at reducing the climate footprint of energy-intensive industries.

So far, a majority in the Danish Parliament, through several broad political agreements since 2020, has allocated DKK 38.7 billion for carbon capture, storage and utilization, with the aim of capturing 3.2 million tons of CO_2 by 2030. In the spring 2024, Ørsted received just over DKK 8 billion for a large CO2 capture facility, and the 20th of September 2023, a broad agreement was reached in Parliament to hold two auctions in 2024 and 2025, allocating DKK 26.8 billion to capture 34 million tons of CO2 over fifteen years. This is expected to achieve a total reduction of 3.2 million tons of CO2 by 2030.

In comparison, regarding hydrogen, another politically popular area of focus, DKK 1.25 billion has been allocated under the "agreement on development and promotion of hydrogen and green fuels (the PtX Agreement)" from 2022. The ambition here is for Denmark to aim for building 4-6 GW of electrolyzer capacity by 2030.

The government frequently mentions that the focus on CCS is due to the lack of alternative methods to reduce emissions from "hard-to-abate" sectors such as heavy industry, agriculture, and shipping and aviation.

Many international analyses, including those by the IPCC and IEA, have adopted the same approach. While it is commendable that the government and Parliament are addressing the climate challenges of these "difficult" sectors, as described in this note, the assumption that CCS is the only or best solution is hardly true for cement and steel production.

[40] https://www.iea.org/reports/net-zero-by-2050

[41] https://www.europarl.europa.eu/RegData/etudes/STUD/2020/652717/IPOL_STU(2020)652717_EN.pdf

Text box 5: CBAM

The Risk of Leakage Has Been a Key Topic on the Climate Agenda for Many Years

The issue of leakage has been central to discussions about CO_2 taxes, quotas, and ensuring fair international competition.

The EU's response to this is the so-called Climate Border Adjustment Mechanism (CBAM), which aims to prevent competitive distortions between European producers, who increasingly must pay for their CO_2 emissions, and producers in non-EU countries who are not subject to similar requirements and can therefore sell equivalent goods at a lower price.

This is particularly critical for EU industries that are highly sensitive to international competition, especially:

- Cement
- Iron and steel
- Aluminium
- Fertilizers
- Electricity

With CBAM, which is currently being tested and is expected to be implemented from 2026, goods from outside the EU in these carbon-intensive industries will be subject to a cost equivalent to the EU's quotas when sold in the European market.

An analysis of the extra costs for green steel in Sweden[42] estimates that shifting from coal to hydrogen "under current conditions and Swedish electricity prices would add about 10% to the price of a ton of unfinished steel"—and that's without the additional capital costs associated with retrofitting and redesigning production facilities. It may be more cost-effective to pursue direct electrification, as the energy efficiency of hydrogen is still a cost challenge. Coolbrook estimates that their technology with a direct electrification of the steel production will be 30-60 percent cheaper than hydrogen-based steel production.

As it stands today, the financial framework is not ambitious enough to ensure the necessary economic incentives that can pave the way for investments in the transition to electrified production. The ITRA study estimates that the investment needs in the EU remain far greater than what is currently available, pointing out that EU's carbon permit prices are not high enough to promote decarbonization, particularly in sectors such as steel and cement, at the necessary scale and pace. This is also a significant barrier in Denmark, where it has been politically decided that the cement industry and other mineral-based processes will have a lower CO_2 tax than other sectors.

For steel, a large portion of Denmark's consumption is imported from countries outside the EU, which do not have carbon pricing or climate taxes. As a result, the climate footprint is not reflected in the price, and there are no economic incentives to adopt greener solutions. *See text box 5*.

However, with the introduction of CBAM (Carbon Border Adjustment Mechanism), the EU is tightening the carbon regulation for steel and cement, making it more expensive to import these materials from countries without climate regulations. This may make investments in green solutions, including electrification, more attractive.

Another challenge is that the rollout of renewable energy is not progressing quickly enough to ensure sufficient terawatt capacity to support the green production of energy-intensive materials. For example, the research paper *"The CO2 Reduction Potential for the European Industry via Direct Electrification of Heat Supply (Power-to-Heat)"* [43] highlights that the electrification of the steel industry in Europe will require 2-3 times more electricity than the industry currently uses (1786-2313 TWh). By comparison, the total electricity production in the EU in 2021 was 2785 TWh, of which only 32% came from renewable energy sources. *See Figure 8.*

As it stands today, both domestically and in the EU, political efforts are still far from ensuring the rollout of renewable energy (RE) at the scale needed to electrify energy-intensive industries, such as steel and cement production. This is why we are seeing several large cement and steel producers entering into Power Purchase Agreements (PPAs) with renewable energy providers as a step to secure green electricity for their production. One example is steel manufacturer ArcelorMittal, which has an ambition

[42] https://www.carboncommentary.com/blog/2020/1/14/the-extra-costs-of-decarbonised-steel

[43] https://iopscience.iop.org/article/10.1088/1748-9326/abbd02

to replace coal with green hydrogen at its German production facility. As part of this, they have signed a "memorandum of understanding" with RWE, one of Germany's largest electricity producers, to collaborate on the development, construction, and operation of offshore wind farms and hydrogen plants that will supply the renewable energy and green hydrogen required to produce low-emission steel in Germany.

Another example[44] is the Swiss cement producer Holcim and the German steel producer Salzgitter, both of which have entered into PPAs with the Spanish energy company Iberdrola to purchase electricity from their 476 MW Baltic Eagle offshore wind farm, currently under construction off the island of Rügen in northern Germany.

These types of initiatives by companies themselves are important steps toward securing greater RE supply. However, they do not change the fact that there is a need for massive scaling both in terms of volume and pace regarding the expansion of renewable energy and the infrastructure needed to ensure sufficient electricity for energy-intensive production processes like steel and cement.

In addition, despite positive results in both steel and cement, there are still technologies and innovations that have yet to prove their effectiveness at a large scale.

There are some products on the market, but they are not yet at a commercial scale. For example, if we look at Sublime in the USA, they currently have only a very small-scale production and expect their first full-scale factory to be ready in 2028.

The Danish cement and steel industries

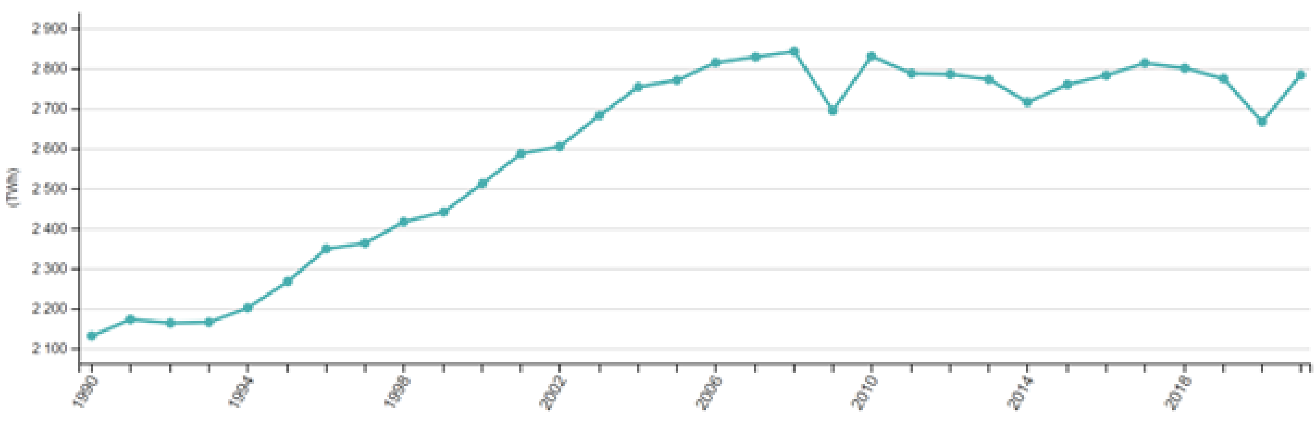
Denmark has one major cement producer, Aalborg Portland, which produces 2,363,000 tons of cement annually. In other words, Aalborg Portland alone accounts for Denmark's cement production. However, there is a large concrete supply chain with several large and smaller players to whom Aalborg Portland delivers cement.

FLSmidth is also involved in cement projects, providing technology for production but does not have its own cement production today. Additionally, there are startups, such as CemGreen, that are working on reducing the CO2 footprint of cement production.

Denmark does not currently have a steel production industry but imports large quantities of steel, mainly from Sweden, Germany, and previously also in large amounts from Russia. Denmark only has one major steel rolling mill, NLMK DanSteel, which is owned by the Belgian investment fund Sogepa and the Russian oligarch Vladimir Lisin. NLMK DanSteel is located in the city of Frederiksværk and produces hot-rolled construction steel plates for building and construction, bridge construction, the wind industry (both onshore and offshore), offshore oil and gas, shipbuilding, boilers, pressure vessels, and transport. There are also smaller companies, such as Give Steel and Grædstrup Stål, which produce steel products.

Figure 8: **The expansion of renewable energy needs to accelerate**

Electricity production, European Union, 1990-2021, TWh



Source: Eurostat.[45]

[44] https://www.windpowermonthly.com/article/1823963/iberdrola-inks-offshore-wind-ppa-cement-giant-holcim

[45] https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Electricity_production,_consumption_and_market_overview

Cases: Innovations show new paths to decarbonization

Across the EU and in the USA, there are a number of examples of new technologies and innovation projects that demonstrate new opportunities for decarbonizing energy-intensive production of both cement and steel. These solutions offer alternatives to CCS for both cement and steel production – and have the potential to be scaled up by 2030.

EcoClay™ – an electrified alternative to the CO_2-intensive calcination process

The cement company FLSmidth has teamed up with the Technological Institute, the Technical University of Denmark (DTU), energy storage company Rondo Energy, and cement producers French VICAT and Colombian Cementos Argos in the EcoClay™ project. The project, running from 2022 to 2026 and partially funded by the Danish Energy Agency's Energy Technology Development and Demonstration Program (EUDP), aims to reduce CO_2 emissions from cement production by up to 50 percent.

Specifically, the EcoClay™ project is testing and developing the possibility of replacing limestone with clay in cement production and electrifying the calcination process of the clay.

Replacing limestone with clay reduces the calcination of limestone, which emits large amounts of CO_2. Electrification replaces the use of fossil fuels like coal and natural gas, allowing for the use of electricity from CO_2-free sources like solar and wind power. By replacing limestone with clay and electrifying the process, a reduction of 35-50% in CO_2 emissions per ton of cement is expected.

In recent years, there has been increasing focus from several producers and researchers on using calcined clay as a partial substitute for cement in concrete. In trials conducted by FLSmidth, with a new clay calcination system that can produce highly reactive clay, it has been shown that up to 30 percent of the limestone content in cement production can be replaced with clay.

Clay can be integrated into cement production using existing cement plant equipment by modifying rotary kilns (traditional equipment for producing Portland cement) to use a slower and longer heating process. Additionally, as part of the project, the Technological Institute aims to develop a scalable method for firing the clay particles using electricity instead of fossil fuels like coal and natural gas.

Calcined clay can potentially also be produced using flash calcination, a new technology that activates materials more quickly and efficiently. Burnt clay can be combined with crushed limestone to offer an effective alternative to clinker with a lower CO2 footprint. Since limestone-burnt clay cement can be produced at a much lower temperature, it can be electrified, significantly reducing emissions.

The EcoClay™ partnership expects to have the first commercial full-scale production of electric clay calcination ready by the end of 2025.

Boston Metal – New electrolysis process

Boston Metals, an American startup, has been testing steel production via direct electrification based on an electrolysis process since 2013. Traditionally, most steel production starts in a blast furnace, where coke (a coal-derived material) reacts at high temperatures with iron ore, a mixture of iron oxides and other minerals. The reaction extracts oxygen and leaves liquid iron, while emitting both oxygen and carbon dioxide.

The Boston Molten Oxide Electrolysis (MOE) technology, which originated at MIT (Massachusetts Institute of Technology) and was developed in collaboration with NASA, replaces coke with an electrochemical process. This process uses electricity to heat iron ore and then creates chemical compounds that separate the iron oxides from other minerals in the ore. The result is pure liquid metal, which requires no further refining or cleaning, making it ready for direct casting into steel and iron products.

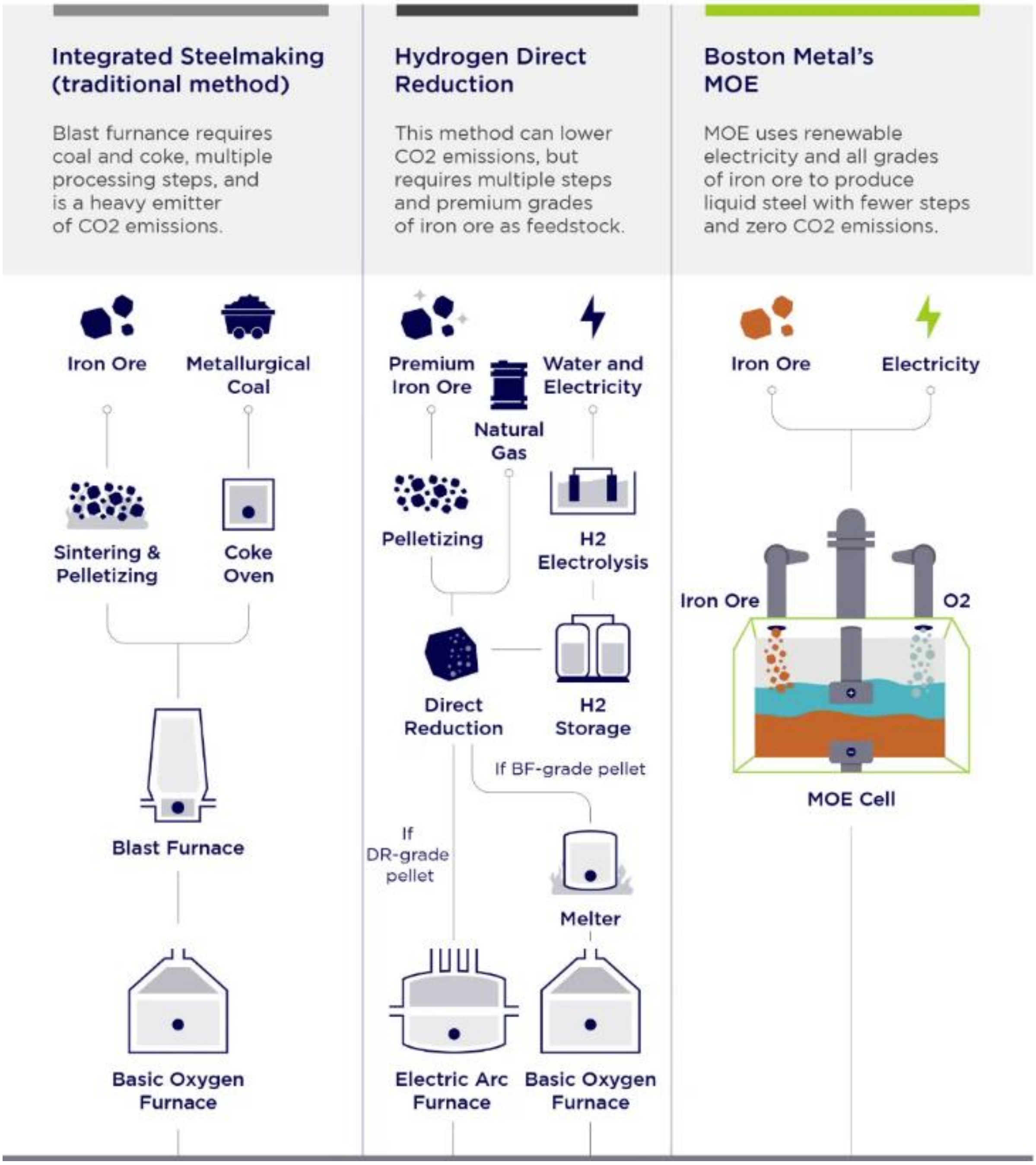
This method enables more efficient steel production with lower costs than traditional methods, and it can be CO2-free, provided the electricity used for electrolysis comes from renewable sources. In addition to steel, the technology can also be applied to a variety of other metals, including titanium, beryllium, and rare earth metals.

One of the key advantages of the MOE technology is its modularity and scalability. The model is based on how a significant portion of aluminum production has been electrified, where production capacity can be added when needed. This results in much lower upfront startup costs compared to traditional steel plants, which often require full-scale new facilities.

Boston Metal has demonstration projects in the United States, focusing on steel production, and in Brazil, where the focus is on the extraction of rare metals. The company plans to introduce high-value metals produced with its MOE technology in 2024 and expects to reach

Figure 9: **New electricity-based process for steel production**

Production of electricity, EU, 1990-2021, TWh



Source: www.bostonmetal.com/green-steel-solution/

commercial-scale steel production by 2026.

A commercial-scale demonstration project is planned for 2026. With their current pilot system and the ongoing construction of another demonstration system in Brazil, Boston Metals' technology is placed at level 6 on the TRL (Technology Readiness Level) scale.

Salzgitter – Investing in hydrogen

The German steel producer Salzgitter has set an ambitious goal to produce green steel by 2033, with a 95% reduction in CO2 emissions from steel production. In concrete terms, this means that by 2033, Salzgitter aims to produce 1.9 million tons of green steel annually, potentially reducing Germany's national CO2 emissions by about 1 percent.

Salzgitter plans to achieve this target by transitioning their steel production from being primarily based on coal to using green hydrogen via an electrolysis process. This hydrogen, generated from renewable energy, will replace the carbon previously required for smelting iron ore. According to the company's own plan, they will begin retrofitting and converting parts of their steel production plants in 2025, which they anticipate will lead to a 30% reduction in CO2 emissions by 2026.

Back in 2015, Salzgitter launched its "Salco" program, which includes a range of initiatives, research efforts, pilot projects, and partnerships.

They have, among other initiatives, installed 7 wind tubines that collectively provide 30 megawatts at their

headquarters in Salzgitter. Their specific focus is on developing and improving electrolysis technology, with a goal to enhance the energy efficiency of high-temperature electrolyser (HTE) systems, which is a challenge for making green hydrogen a commercially viable alternative to fossil energy sources.

Salzgitter has invested in an electrolysis plant that uses steam from industrial waste heat from steel production. Additionally, they have launched a project focused on resource and energy improvements across the entire value

chain. This project explores whether bio-based materials can be used to replace coal and natural gas, in order to adjust the necessary carbon content in steel. They are also looking at more efficient water use, as large amounts of water are required in the production of green steel, particularly for electrolysis. Therefore, there are significant gains to be made by increasing water recycling.

The total cost for retrofitting Salzgitter's production facilities, as well as setting up the wind turbines and electrolysis plants, is estimated to be 50 million euros. The steel producer has received nearly 1 billion euros in government subsidies from the German government.

The first large-scale phase of electrolysis-based production is planned to be operational at Salzgitter's production facility from 2026 and is expected to result in a 30% reduction in CO2 emissions. By 2033, Salzgitter expects that their entire steel production will be based on hydrogen instead of fossil fuels.

Electra: Steel production at 60 °C

The American startup Electra has developed an electrochemical refining process that can convert iron ore into iron and then into steel, using only renewable electricity. Most steel production today relies on large blast furnaces, where coke (coal) is used as an energy source to convert iron ore into pure iron at temperatures of 1400-1500 °C. Electra’s chemical process, which involves submerging iron ore in acid via an electrolysis process in water, allows for a manufacturing process that melts the ore into iron at only 60 °C, thereby avoiding the high-temperature process in blast furnaces. After this chemical process, the iron can be converted into steel using electric arc furnaces, which are already widely used in the steel industry for melting recycled steel into new products.

According to Electra’s own estimates, their technology enables the production of iron without fossil energy in the process of extracting iron from ore, which accounts for 90% of emissions in steel production. Electra’s process, due to its low temperature of 60 °C, is far less energy-intensive than traditional steel production.

In addition, the process is highly flexible, as it can be turned on and off based on the availability of energy. This gives Electra's technology the potential to act as a stabilizer for the energy grid in a future where solar and wind power are the primary energy sources.

Furthermore, their chemical process allows for the use of lower-quality iron ore (with 30-35% iron content) without additional refining processes. According to Electra, this will help ensuring that their technology will not increase steel production costs, particularly in a future where high-quality iron ore (+60% iron content) is expected to become scarce.

In 2022, Electra raised 85 million USD in investments from Breakthrough Energy Ventures (Bill Gates' climate investment fund), Nucore, the largest steel producer in the USA, and Amazon to build a larger testing facility, which is scheduled for completion in 2023 in Boulder, USA. However, they plan to fully commercialize their technology from 2026 and onward, aiming for large-scale adoption by 2030.

Electra's current ambition is full-scale commercialization from 2026 onward, aiming for large-scale adoption by 2030. They do not expect increased costs compared to traditional fossil-based production. Electra plans to scale their technology from laboratory production and expects to have a pilot system ready by the end of 2023. With this new pilot system, the technology will progress to level 5-6 on the TRL scale.

Coolbrook

The Finnish-Dutch company, CoolBrook, has developed a technology that can potentially heat industrial furnaces to over 1700°C using electricity from renewable energy sources. CoolBrook's technology – the so-called RotoDynamic Heater – opens the possibility of replacing coal and gas, which have long been the primary energy sources in high-temperature processes such as steel and cement production. According to CoolBrook, there is no CO_2 emission associated with their technological process, and they estimate that it has the potential to reduce global CO_2 emissions by over 2 billion tons per year – equivalent to 30 percent of total global industrial CO_2 emissions and 7 percent of global CO_2 emissions.

CoolBrook's technology, developed in collaboration with Oxford, Cambridge, and Ghent universities, as well as companies like Neste Engineering and Mitsubishi Heavy Industries, is based on turbine technology. This technology uses electricity and rotational kinetic energy to produce the extreme heat required for many heavy industrial processes. It enables the electrification of industrial processes, where it has previously been difficult to reach temperatures over 500-600°C in production processes.

CoolBrook’s technology has shown positive results in testing and demonstration projects in recent years but has not yet been tested on a fully commercial scale. According to CoolBrook, their technology can be installed directly at existing industrial facilities, which significantly reduces the timeline and costs associated with transitioning from

fossil-based to renewable energy. The next step is to implement the technology on commercial production sites. CoolBrook has announced partnerships

with both cement and steel producers, including UltraTech Cement Limited, CEMEX, and ArcelorMittal, to implement and test the technology at specific large-scale industrial facilities. These demonstration projects are expected to be operational in 2024, with full commercial deployment of the technology expected to begin in 2025.

The first large-scale demonstration projects are expected to be operational in 2024. From 2025, CoolBrook expects its technology to be ready for commercial rollout. According to CoolBrook[46] the costs of their technology will be 30-60% lower than the operational costs if production were based on green hydrogen. Based on the above, CoolBrook is positioned at level 7 on the TRL scale.

Sublime Systems – USA

The American company Sublime Systems has developed a new method for cement production using an electric-based electrolysis process. This process can use electricity from solar and wind, instead of fossil energy, and it can also use alternative calcium sources to the CO2-heavy limestone that is currently the primary raw material in cement production.

Traditional cement production is linked to processes that emit large amounts of CO2—primarily from the heating of limestone using fossil fuels and from the chemical process when limestone (CaCO3) is heated to high temperatures, breaking down into CaO and CO2. The CO2 from traditional cement production is mixed with other pollutants and diluted, making it difficult to capture.

[46] https://coolbrook.com/technology/

Sublime Systems' new production technology potentially eliminates both sources of emissions. The company uses electrochemical processes to extract calcium, a key component of cement. This technology can be powered by electricity from solar and wind, and it allows for the use of various calcium-rich raw materials that are not bound to carbonate (CO3), thus avoiding the CO2 emissions from the raw material.

Additionally, Sublime's platform can also use abundant and inexpensive limestone for cement. All the CO2 produced during the conversion process of limestone can be captured at 10 bar and room temperature, making it easy and cost-effective to transport to a CO2 storage facility. This means there is no need for expensive and energy-intensive CCS (carbon capture and storage) plants. The production takes place at room temperature.

According to the company, the energy consumption of the new process, at its current development stage, is on par with traditional cement production without CCS. The most common CCS technology, using amine scrubbing of flue gases, increases energy consumption by up to 50%. Unlike traditional cement production, the new process has no emissions of dust, NOx, or heavy metals.

Sublime's process can be fully powered by renewable electricity from solar and wind. The electrolysis process can also be ramped up or down to take advantage of periods of cheap electricity. This means it can act as a flexible electricity consumer—similar to how hydrogen production is expected to operate in a future electricity system based on fluctuating solar and wind power.

Sublime's cement has just been ASTM-certified, which means its quality and performance are at least equivalent to traditional Portland cement. There is strong interest in Sublime's technology, and last year the company raised $40 million from investors, including a large sum from Siam, the largest cement producer in Southeast Asia.

About the report

This report was published in January 2024 and was compiled by Anna Fenger Schefte, Senior Analyst at the Council for Green Transition, Jens Dahlstrøm Iversen, Senior Advisor on Energy and Climate, and Erik Tang, Senior Consultant.

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Green Transition Denmark

Green Transition Denmark is an independent environmental organization that works to promote a green and sustainable transformation of society. We do this by creating and disseminating knowledge about green solutions and by influencing politicians, companies and citizens to make green choices.