WHITE PAPER

The Winds of Change in Green Steel

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To achieve its climate goals, the European Union is set to significantly expand offshore wind capacity. Steel is an essential ingredient in the manufacture of wind turbines. However, traditional grey steel is highly carbon-intensive. Production routes exist today that can deliver green steel. But, because green steel is still more expensive than grey steel, its adoption will only happen through regulatory mandates or incentives. For 0.05ct/kWh, the EU could avoid millions of tons of CO_2e emissions by 2030.

Introduction

The European Union has ambitious plans to ramp up offshore wind capacity to help drastically reduce its carbon footprint. The EU itself is targeting at least 60 gigawatts (GW) of installed capacity by 2030, a four-fold increase from its 15 GW of installed capacity in 2021. But at a national level, the EU's 27 member countries have set targets that aim for about 110 GW of capacity by then.

While these goals will have a major impact on the decarbonization of the European energy sector in the long run, the carbon-intensive processes involved in manufacturing wind turbines, especially steel production, are set to have a negative effect on the EU's carbon footprint in the near term.

Indeed, producing the steel needed to achieve these targets would generate a significant amount of greenhouse gas emissions at a time when it's imperative that emissions are kept to a minimum. This predicament demonstrates the urgent need to invest in less carbon-intensive steel production methods.

This paper will examine the impact of using green steel in the manufacture of offshore wind turbines, focusing on the EU as an example for other regions. Firstly, we will look at the range of current steel production routes. Secondly, we will consider the benefits of green steel compared to traditional grey steel. Finally, we will look in detail at key decision makers and how they can drive the adoption of green steel in offshore wind through their actions at different stages in the offshore wind project lifecycle.

Steel production routes and green steel

Flat steel production has historically been a very carbon-intensive process. Blast furnaces and basic oxygen furnaces (BF-BOFs), used to produce traditional grey steel, require large amounts of heat to remove oxygen from virgin iron ore using coking coal as both a fuel and a reducing agent. This creates a lot of emissions. Moreover, European steel producers import the coking coal from outside the region, generating additional transportation-related emissions.

Direct-reduced iron with electric arc furnaces (DRI–EAFs), using natural gas as both fuel and reductant, is a mature technology with fewer emissions than BF-BOFs. These emissions can be lowered even further when the DRI process is fueled with green hydrogen, which will replace natural gas in the long run. Eventually, the entire DRI-EAF production process will be powered using renewable energy. The result of this technology is green steel, which offers significantly reduced carbon dioxide equivalent (CO_2e) emissions per ton of steel produced than grey steel.

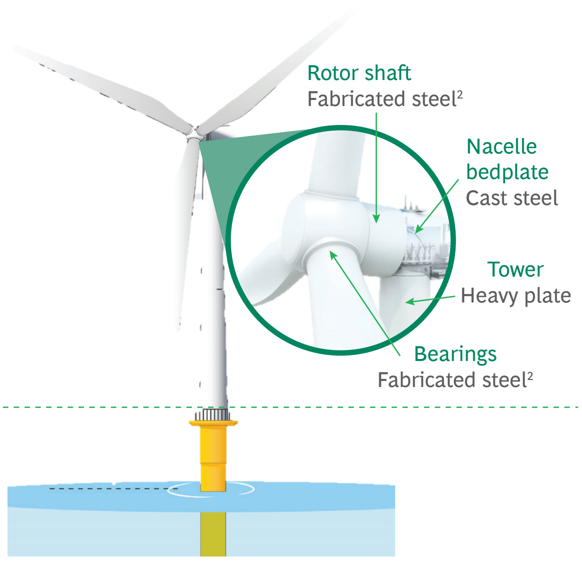
Steel requirements in offshore wind turbines

Wind turbines represent a significant customer sector for flat steel producers because of the large steel volumes needed to manufacture turbines and the ambitious growth plans for wind energy (particularly in the EU). Offshore wind turbines, including their steel-heavy foundations, are a key segment as they are generally larger than onshore turbines and typically require either jacket or monopile foundations, with a state-of-the-art monopile foundation's steel content usually weighing between 2,000 and 2,500 tons and the total steel used per turbine weighing around 3,000 to 3,500 tons. By comparison, onshore wind turbines are usually made up of around 340 tons of steel in total. (See Exhibit 1).

Within the EU, offshore wind power generation is gaining importance. While offshore wind currently only makes up 8% of the EU's total installed wind capacity of 204 GW, reaching the EU's goal of 60 GW by 2030 would involve ramping up installations to more than 6 GW per year for the remainder of this decade, tripling recent installation rates. And despite individual wind turbines getting bigger, the number of turbines installed each year would need to increase from around 250 in recent years to 400 per year going forward. Such an expansion would mainly require national governments to simplify permitting procedures.

Exhibit 1 - Because of Steel Requirements, Wind Turbine Manufacturing Provides a Route to cut Carbon Emissions

Illustrative Perspective (2030)		Onshore *5MW capacity*	Offshore *15MW capacity*
Wind turbine	Tower	~270t	~800t
	Nacelle bedplate	~70t	~200t
	Rotor shaft	*Not relevant, as fabricated steel is made from specialized steel rods and hollow-structural-section (e.g., 440C)*	
	Bearings		
Foundation		*Onshore foundations only use minimal steel in rods for rock anchors and as reinforcement in concrete foundation*	~2,250t
Total		~340t ca. 70t/MW	+~3,000t → ~3,250t ca. 220t/MW



2,000 – 2,500t assuming fixed-bottom monopile foundation[1] and water depth based on reference projects in 2027–2030

1. Foundation of wind farms predominantly fixed-bottom with monopile, rarely jacket or floating foundation.

2. Fabricated steel is used to increase strength and durability of wind turbine components.

Sources: Wood Mackenzie, NREL, S&P Commodities, BCG analysis.

The benefits of using green steel in offshore wind turbines

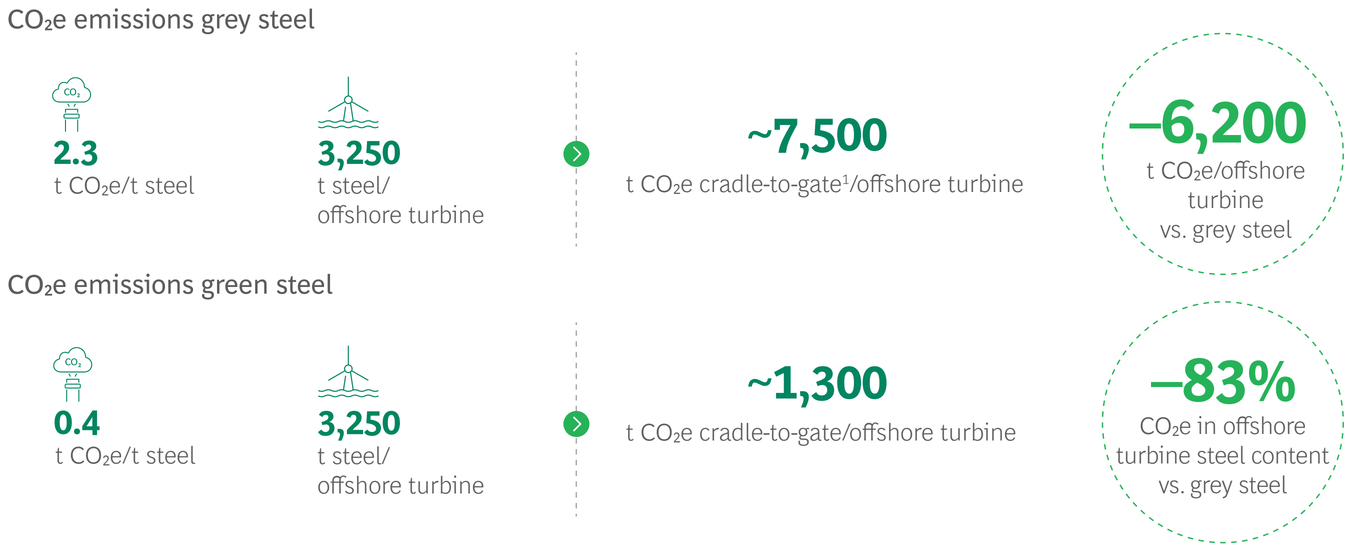
Using green steel in the manufacture of offshore wind turbines will have a significant, positive impact on the EU's carbon emissions. The use of grey steel with the BF-BOF route generates around 2.3 tons of CO_2e emissions per ton of steel produced. Based on the amount of steel used in an offshore wind turbine, this results in the following emissions:

- *Per wind turbine:* Producing the approx. 3,250 tons of grey steel required for a single 15 megawatt (MW) offshore wind turbine generates around 7 to 8 kilotons (kt) of CO2e emissions.
- *Per MW installed:* Assuming a typical capacity of 15 MW for each offshore wind turbine, this equates to around 500 tons of CO_2e emissions per MW installed.
- *Per offshore wind park:* An average offshore wind park with a capacity of 900 MW emits around 450 kt of CO_2e (from steel production) before it even starts to generate electricity. This is equivalent to per-passenger emissions from approximately 5 million economy flights between Berlin and Brussels.

By comparison, DRI-EAF green steel production (using green hydrogen made from renewable energy) only emits around 0.4 tons of CO_2e per ton of steel produced. This production route results in the following emissions when applied to offshore wind turbines:

- *Per wind turbine:* Using the DRI-EAF route would reduce CO_2e emissions from producing steel for a 15MW offshore wind turbine by more than 6 kt to around 1.3 kt. (See Exhibit 2).
- *Per MW installed:* The same 15 MW wind turbine would therefore emit 90 tons of CO_2e less per MW installed.
- *Per offshore wind park:* A 900 MW wind park would only emit around 80 kt of CO_2e (from steel production) as the use of green steel in turbine manufacture would reduce emissions by as much as 370 kt. This saving is equivalent to per-passenger emissions from approximately 4.1 million economy flights between Berlin and Brussels.

Exhibit 2 - Using Green Steel Reduces the CO_2e Emissions From Manufacturing a 15MW Offshore Turbine by Up to 83%



Note: Cradle-to-gate includes all greenhouse gas emissions up to the point when a steel product leaves the factory gate i.e. from activities like raw material supply, transport and manufacturing of products. Emission Scope 1, 2 and 3U calculated up to hot rolled coil stage, expressed in per ton of crude steel.

Sources: Wood Mackenzie, BCG analysis.

While green steel is more expensive than traditional grey steel, the additional expense of using green steel in the manufacture of offshore wind turbines results in only a marginal increase in capital expenditure (CAPEX) and levelized cost of energy (LCOE) over the lifetime of a turbine. Why is this?

Assuming additional CAPEX of €900,000 (based on a premium for green steel of €250 to €300 per ton), the extra cost may seem significant at first glance. However, this equates to €60,000 per MW of installed capacity for a representative 15MW offshore wind turbine. Compared to a CAPEX baseline of €3,000,000 per MW capacity installed with grey steel, using green steel would represent an increase in CAPEX of less than 2%.

Taking into account a turbine's LCOE over the course of its lifetime, the impact on LCOE is even less:

- Offshore wind turbines are projected to have 4,000 full load hours a year (assuming a wind park efficiency of 95% and a capacity factor of 48%) for representative projects in the North Sea and Baltic Sea this decade.

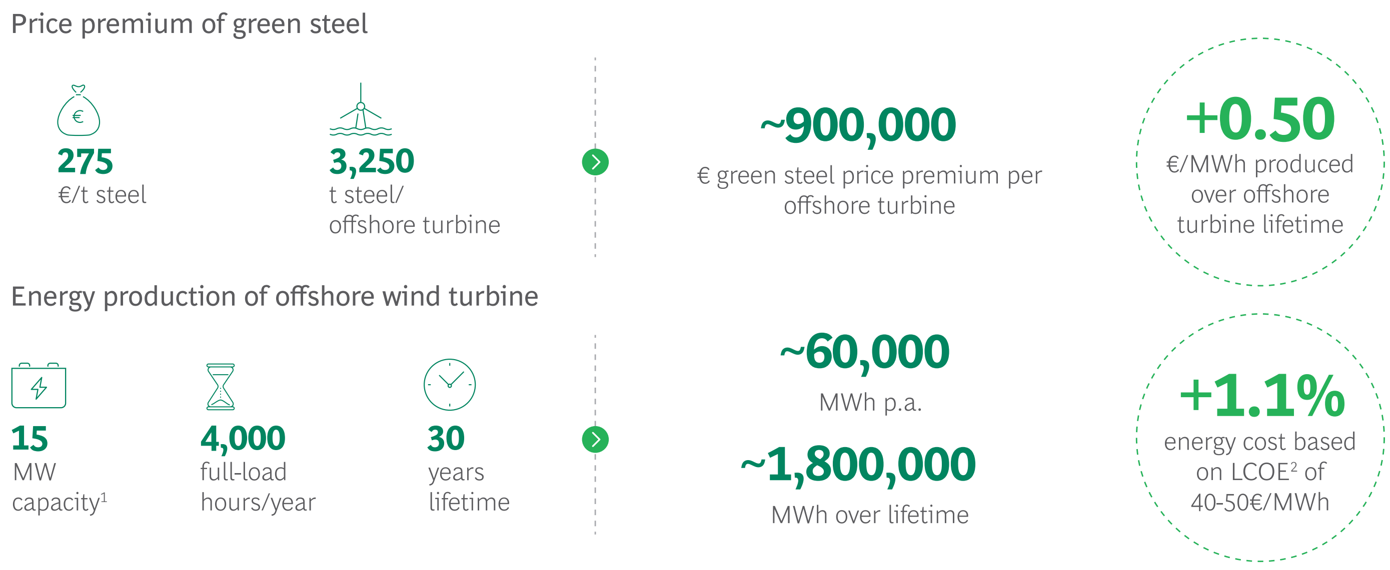
- Based on a generating capacity of 15 MW and a lifetime of 30 years, this results in energy production of 1,800,000 megawatt-hours (MWh) over the life of the turbine.

- Converting additional CAPEX of €900,000 per wind turbine into a price premium on top of the LCOE per megawatt-hour (MWh) of energy produced would thus result in only an extra €0.50 per MWh.

While the EU is targeting a LCOE for offshore wind of €30 to €40 per MWh by 2030, experience from recent projects suggests that a LCOE of €40 to €50 per MWh is more realistic. An additional €0.50 would mean an increase in the LCOE of just 1%. (See Exhibit 3).

From a consumer's perspective, predicting the future trajectory of energy prices is difficult. Prices tend to be highly volatile and price growth forecasts are rather debatable. Consequently, a pass-through of the LCOE increase could well have an even smaller impact on industrial or private consumers.

Exhibit 3 - The Green Steel Price Premium Increases an Offshore Wind Turbine's LCOE by About 1% Over Its Lifetime



1. Expected capacity for 1 wind turbine built 2027-2030.

2. Levelized cost of electricity.

Sources: European Commission, 4C Offshore, Wood Mackenzie, BCG analysis.

From an energy efficiency standpoint, the benefits of using green steel to manufacture offshore wind turbines rather than grey steel become clear when one examines the comparatively short amount of time it would take an offshore wind turbine to generate the energy required to produce the green steel required for an equivalent turbine. Consider the following:

- The energy necessary to produce a ton of green steel (using the DRI-EAF route with green hydrogen) is approximately 3 MWh. Most of this energy is required for the production of the green hydrogen (around 2,300 kWh (kilowatt-hours) per ton), with the remainder used in the DRI-EAF process.
- Thus, producing the 3,250 tons of steel needed to build a standard offshore turbine would require a total of 9,800 MWh of energy if green steel was used.
- Given that a standard turbine generates 60,000 MWh of energy each year, it would take the turbine just two months – or 0.5% of its lifetime - to generate this amount of energy. (See Exhibit 4).

In other words, during the vast majority of its lifetime (99.5%), the turbine would produce additional renewable energy.

Exhibit 4 - Two Months of Generation Would Deliver Sufficient Power to Produce the Green Steel for a Single Offshore Wind Turbine

Green steel energy requirements

~3
MWh/ton
green steel

3,250
t steel/turbine

~9,800
MWh to produce green steel per turbine

~2
months ops to produce green steel equivalent production energy

Energy production of one offshore wind turbine

15
MW
capacity[1]

4,000
full-load
hours/year

30
years
lifetime

~60,000
MWh p.a.

~1,800,000
MWh over lifetime

~0.5%
of wind turbine's lifetime energy production

Note: Assumed DRI-EAF with green H2 production route. ~725 kWh/t energy required in DRI-EAF, ~2,300 kWh/t energy required in green H2 production.

1. Expected capacity for 1 wind turbine built 2027-2030.

Sources: 4C Offshore Wood Mackenzie, BCG analysis, BCG emissions model.

In summary, using green steel instead of grey steel to manufacture offshore wind turbines drastically reduces emissions from steel production and does so at marginal extra cost – from both a financial and energy efficiency perspective.

Finally, one further potential benefit from using green steel in turbine construction is the mutual reinforcement of their respective growth trajectories via a virtuous cycle. The rapid expansion of wind energy capacity is one of the biggest development initiatives in the EU and will require significant amounts of steel. A commitment by Brussels to use green rather than grey steel would create a clear demand signal and so encourage large steel manufacturers to increase investments in green steel. The green energy produced by wind turbines made from green steel could also be used to produce even more green steel.

We have examined the advantages of using green steel in the manufacture of offshore wind turbines. Next, we need to consider how the decision-making process behind the creation of offshore wind projects can drive the adoption of green steel.

"Using green steel in offshore wind turbines drastically reduces emissions at marginal extra cost – from both a financial and energy efficiency perspective.

Key stages in the offshore wind project life cycle

While the lifecycle of offshore wind projects is broadly the same, individual elements can vary significantly from one project to the next. Nevertheless, a knowledge of the offshore wind value chain, life cycle, and typical processes is essential for steel players to understand how decisions by key actors can affect the use of green steel.

Offshore wind projects usually involve a preparatory stage that can take up to seven years. Here, the groundwork is carried out to identify the lease area, obtain relevant permits, and define auction rules. The official process is then split into five main phases:

- Auction preparation phase (2-4 years)
- Site auction (around 3-12 months)
- Development (around 2-5 years)
- Construction (around 2-4 years)
- Operations and maintenance (up to 30 years)
- Decommissioning and materials recycling

During the auction phase, the regulator issues a project tender inviting bids from interested parties. This tender includes the licensing criteria. Developers then prepare their bids by creating financial models (incorporating assumptions about key cost and revenue considerations) so they can determine the value of the development rights. After all the bids have been submitted, the regulator evaluates each one and awards the project to the developer with the strongest bid.

The successful developer then starts the development phase with the aim of achieving a positive final investment decision (FID) and commencing construction. During this phase, the developer conducts geological surveys, applies for permits, and identifies preferred suppliers. Some of the information it collects at this stage is also used to create a more detailed financial forecast. Additionally, the developer negotiates supplier contracts, arranges debt financing with commercial banks, and may discuss terms with potential equity investors. Having completed this phase, the developer then makes the FID.

During the construction phase, original equipment manufacturers (OEMs) procure the necessary components and materials from suppliers so that they can produce the wind turbines and foundations. These suppliers purchase raw materials, including steel, from subsuppliers – usually directly but sometimes through framework agreements with OEMs. Once they are built, the turbines are delivered and installed at the wind park.

Once construction and installation are complete, the wind park can start to operate. For European offshore wind parks built between 2027 and 2030, the expected lifespan is more than 30 years. During the park's operating life, the project developer, an independent power producer, or an OEM maintains the turbines.

At the end of its lifespan, the wind park is decommissioned. Responsible decommissioning is important for mitigating environmental risks and ensuring proper recycling of materials, including steel. But because offshore wind technology is fairly new and turbines have a relatively long useful life, the industry has up to now lacked knowledge and experience with decommissioning. This situation is set to change, however, as many turbines will reach the end of their useful life over the next few years.

Different approaches for promoting green steel in offshore wind

Our analysis suggests that efforts to increase the use of green steel in offshore wind projects need to be driven at either the auction phase or the development phase. The following section outlines how key actors at each phase could achieve this goal.

The auction phase:

Regulators are key stakeholders in the auction phase. Because they set the auction rules and licensing criteria, they can drive the use of green and low-carbon materials, including steel. A range of options exist for them to encourage or even enforce the use of green steel. Broadly speaking, these can be divided into mandates and financial incentives.

With mandates, an environmentally responsible regulator could take the most direct approach and prescribe the use of green steel in the auction rules. Alternatively, they could make emissions from the wind park construction part of the criteria for awarding the project. Either way, including green steel-specific criteria in the tender process ensures that developers factor into their initial bids the additional costs arising from the use of green steel.

As well as creating mandates for using green steel in wind turbines, the regulator has another effective route at its disposal for promoting the use of green steel via offshore substations. Substations collect the electricity generated by wind turbines and export it to the grid via undersea cables. Compared to a wind park, the steel involved in building a substation is relatively small (at around 20,000 tons per gigawatt of capacity, which is less than 10% of the steel required for an entire wind park).

Nevertheless, offshore substations are normally built by Transmission Systems Operators (TSOs), which are typically either fully or partly state-owned. This means that regulators can explicitly include the use of green steel in the public procurement rules that such entities must follow. In this way, the regulator can ensure that green material requirements are applied consistently across all components of an offshore wind park.

However, explicit mandates for using green steel could make offshore wind investments less attractive because they involve additional costs for developers. Even though a level playing field exists among bidders for European projects, Europe is still competing internationally to attract investment and interest to achieve its ambitious offshore wind targets. An alternative to mandates would be incentives that make the use of green steel more financially attractive for developers.

These incentives could be in the form of contracts for difference (CFDs), which are already being used in the UK. CFDs guarantee developers price security over the lifetime of the contract provided the amount of low-carbon materials used in a project’s construction meets the level set by the regulator. A pre-agreed price for the electricity generated by the project (the “strike price”) is established during a competitive process.

By raising the strike price (thereby increasing project revenues) for developers that were prepared to use green steel during construction, regulators could make their projects more financially attractive. Using this approach, European regulators could attract investors by making the business case for developing sustainable offshore wind parks more appealing – instead of imposing an additional regulatory burden on developers that diminishes the attractiveness of wind park investments.

A key challenge in promoting the use of green steel, either through mandates or incentives, is that the auction phase lacks standardization. Both the auction landscape and regulatory responsibilities are complex and fragmented, with processes and requirements differing significantly between regions. While the overall sequence of events (with the regulator issuing a project tender that includes licensing criteria, followed by bids from project developers, followed by the regulator selecting the winning bid) remains the same, auction rules differ by auction scope and type.

For example, when it comes to auction scope, the land lease and energy offtake components can be auctioned together or separately. This is because energy and land are managed by different regulatory authorities. The auction itself can be determined by bid price only or it can be decided through a bid book. A price-only approach selects the winner purely on the basis of price, making it significantly faster. By comparison, bid book auctions involve both price and non-price criteria, including local material sourcing, job creation, and community engagement.

Another complexity involves the fragmentation of regulatory responsibilities. Within the EU, auctions are managed by a single national regulatory body. Examples include Germany's Bundesministerium für Wirtschaft und Klimaschutz, the Danish Energy Agency, and the Dutch Rijsdienst voor Ondernemend Nederland. However, in the US and some other countries, regulatory organizations with different offshore wind responsibilities exist at both a federal and a state level. This adds further complexity, particularly in the case of processes that split site and offtake auctioning.

This more distributed organizational setup requires concerted action and greater collaboration between stakeholders when mandating or incentivizing green steel at the auction phase to achieve impact at scale. When assessing different ways to incorporate green steel requirements, the fact that project developers base their business case and bids on cost estimates and data obtained during the auction phase has two implications for regulators.

Firstly, developers prefer a joint lease and offtake agreement auction as revenues (a consequence of the offtake price) and costs are determined jointly. This provides developers with planning security when factoring in the extra expense associated with green steel.

Secondly, should the auction process need to be split into two, regulators should consider including mandated green steel requirements in the lease auction. Financial incentives can be included later, in the energy offtake agreement auction. This would allow project developers to formulate a more accurate business case early on.

The development phase:

Once the auction is finished, the developer with the winning bid prepares to commence construction. First, a positive FID is needed. Making the FID requires the developer to conduct more thorough planning. This is the primary purpose of the development phase. During this phase, the developer deepens efforts started when preparing their original bid. This involves obtaining approvals, getting offers from OEMs and component suppliers, conducting soil tests, and negotiating with commercial fisheries, as well as other operational planning tasks. The developer also finalizes financing for the project.

Financing is a particularly powerful lever for increasing the use of green steel in offshore wind projects. Both debt and equity providers can link their financing conditions to a project's emission intensity or they can explicitly require the use of green steel in construction. Such conditions can provide developers with a financial incentive to use green steel, offsetting the additional upfront cost they will incur when procuring green steel.

This way, even if regulators have not mandated or incentivized project developers to use green steel during the auction phase (meaning that developers have not factored it into their initial business case), developers can maintain planned profit margins, while still choosing green steel.

Green steel in the construction phase:

The choice of green steel suppliers is made during the construction phase either by the turbine and foundation manufacturers or by their suppliers (i.e., component manufacturers). Because these players prioritize their own profitability, which depends to a large extent on the cost of raw materials and components, over other considerations, they base their decision to use a steel supplier on price. Therefore, it is crucial that using a supplier of green steel is made an explicit requirement early in the project as these companies will not choose green over grey steel purely on cost grounds.

The EU could avoid millions of tons of emissions using green steel in offshore wind

The expansion of offshore wind in the EU is already well underway. Capacity grew by a compound annual growth rate (CAGR) of 17% between 2016 and 2021 - although growth will need to triple between now and 2030 for the EU to achieve its 60 GW goal. Consequently, switching to green steel quickly is of crucial importance.

Around 20 million tons (Mt) of CO_2e emissions could be avoided by 2030 if all the wind turbines needed to meet the EU target used green steel instead of grey steel. This saving is equivalent to per-passenger emissions from approximately 210 million economy flights between Berlin and Brussels, or approximately 2.5% of Germany's 2022 greenhouse gas emissions. Based on the national ambitions of the EU's 27 member countries (which imply a target of around 110 GW of offshore wind capacity by 2030), switching to green steel could avoid up to 40 Mt of CO_2e emissions. And given the official EU target for 2050 (300 GW), avoided emissions could rise to 120 Mt of CO_2e by mid-century.

Currently, developers compete to supply electricity to the grid based on the cost of the energy they produce. They are not incentivized to reduce emissions. Wind park revenues are determined by fixed compensation arrangements. This means that developers build wind parks at the lowest possible cost in order to protect their margins. Paying a premium for green steel directly impacts their profitability.

This predicament highlights the urgent need to promote the use of green steel, ideally at the auction phase, in order to achieve the significant CO_2e savings highlighted above. This can be done by adjusting tender requirements and introducing mandates or financial incentives. Making green steel a prerequisite for further offshore wind developments would also be a logical step, enabling the EU to meet its sustainability goals.

The bottom line: the expansion of green energy in the EU, in the form of offshore wind, should not at the same time produce CO_2e emissions that are – to a large extent – avoidable.

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