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**Research Article**

# The Green Burden: Why the Steel Industry Cannot Rely on Hydrogen and Green Energy as a True Alternative

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**ABSTRACT**

This article critically examines the economic and operational burdens placed on the European steel industry by current decarbonization policies and the EU's climate neutrality transition targets. While European Union climate regulations increasingly prioritize low-emission technologies, their practical implications for energy-intensive sectors such as steelmaking remain underexplored. Through a comparative analysis of cost structures, production routes, feedstock availability, and regulatory frameworks, the study highlights the impact of emissions reduction mandates, carbon pricing mechanisms, and policy uncertainty on industrial competitiveness, investment stability, and supply chain dynamics. Emphasis is placed on the role of Europe's energy mix, the reliability of renewable electricity sources, and a realistic evaluation of hydrogen as a proposed energy carrier. The findings suggest that the accelerated push toward green transformation risks undermining Europe's industrial foundation without delivering commensurate environmental or economic gains. The article calls for a reassessment of prevailing climate strategies, emphasizing the need for realism - anchored in improved energy efficiency, support for research into more feasible technologies, and policies that promote both social and economic sustainability.

**Keywords:** Steel, EAF and BF-BOF, energy transition, iron ore, scrap, direct reduced iron (DRI), electricity, green energy, inertia, hydrogen, nuclear power, fossil-fuel energy, carbon tax, social and economic sustainability.

## INTRODUCTION

Steel is an indispensable material for modern society. From skyscrapers and public transportation systems to automobiles, household appliances, and industrial machinery, steel underpins global infrastructure and development. As urbanization and industrialization continue to expand, particularly in emerging markets, demand for steel remains robust.

However, the steel industry is under increasing pressure to decarbonize as part of global climate commitments. Such energy-intensive industries, like steel, are caught at the crossroads of economic realism and climate policy ambition. The European Union and other advanced economies have set ambitious targets to achieve net-zero greenhouse gas emissions by 2050. These climate goals place the steel industry under significant pressure, given its status as one of the most energy-intensive and carbon-emitting sectors globally. While the push toward "green" energy and hydrogen-based steel production is well-intentioned, this study argues that such a transition is economically burdensome, technologically uncertain, and potentially unrealistic in the current context, particularly for the steel sector. The energy transition requires an unprecedented realignment of capital, regulatory frameworks, industrial infrastructure, and societal behavior toward renewable energy sources. This raises legitimate concerns about the economic rationality and

social feasibility of such a profound shift. This research critically examines the foundations of this transformation by addressing the origin and nature of energy, evaluating the technical and economic characteristics of steelmaking, and analyzing how these two spheres intersect within the broader framework of the "green" transition.
This analysis will provide a comprehensive, evidence-based evaluation of the energy inputs in steelmaking, current production routes, and their role in the broader debate on decarbonization. The findings will offer valuable insights into whether the steel industry's green transition is truly feasible and what implications this has for the future of energy, industry, and society.

## GLOBAL ECONOMIC OUTLOOK – APRIL 2025 UPDATE

Global growth is projected to remain steady at 3.2% in 2024 and 3.3% in 2025, in line with the April 2024 World Economic Outlook. However, varied economic momentum has slightly narrowed output divergences across countries as cyclical drivers fade and activity better aligns with long-term potential. Despite improved trade-particularly through strong Asian tech exports-persistent inflation in services is complicating the normalization of monetary policy. Upside inflation risks have increased due to continued geopolitical tensions and growing policy uncertainty, thereby raising the likelihood of prolonged high interest rates. Carefully sequenced fiscal and monetary policies will be necessary to manage inflation and preserve growth.
While global trade and industrial activity picked up early in 2024, performance varied by region. Europe showed a modest recovery driven by services, while China's rebound was led by a surge in domestic consumption. In contrast, the U.S. and Japan underperformed due to weaker consumption and supply disruptions, respectively. Meanwhile, the disinflation momentum has slowed globally, driven by stubbornly high services inflation despite easing goods prices.

## EU STEEL MARKET OVERVIEW

The EU steel market has remained under sustained pressure since mid-2022, with Q2 2024 marking yet another contraction in apparent steel consumption. Volumes fell by 1.3%, following a 3% decline in Q1, bringing total consumption down to 34.8 million tonnes. This persistent weakness reflects a combination of high energy costs, geopolitical uncertainty, and tightening financial conditions across the EU.
After a steep 8.3% contraction in 2022, the market experienced a revised -6% decline in 2023 (from an earlier -9% estimate), marking the fourth recession in five years. For 2024, apparent steel consumption is now expected to fall by another 1.8% (a downward revision from the previous +1.4% growth forecast) due to a weakened industrial outlook and sluggish demand in key consuming sectors such as construction and automotive. While a modest recovery is anticipated in 2025, overall consumption levels are expected to remain below pre-pandemic norms.
Domestic steel deliveries continued their decline in Q2 2024, falling by 1.7%, consistent with ongoing weak local demand. This follows sharp annual drops of -9.1% in 2022 and -4.6% in 2023. Steel imports, including semi-finished products, also declined by 1.5% in Q2, after a brief uptick in Q1. Nevertheless, the import share of total steel consumption rose to 28%, up from 27% in the previous quarter, indicating persistent competitive pressure from non-EU suppliers.
The Steel Weighted Industrial Production (SWIP) index - an indicator of activity in key steel-consuming sectors - fell by 2.1% in Q2 2024, following a 2.4% drop in Q1. Although these sectors showed mild resilience in 2023 (+0.9% growth), their output began to deteriorate sharply in 2024 amid inflationary headwinds, tight monetary conditions, and softening global demand.
The downturn is broad-based, affecting:

- The construction sector has been in recession since Q3 2022, recording only a 0.4% growth in Q2 following a -2.6% contraction in the previous quarter.
- Automotive: Despite seven quarters of sequential growth, output remains below 2019 levels.
- Mechanical engineering, metalware, and domestic appliances: All experienced contractions in Q2.

The SWIP index is projected to shrink by 2.7% in 2024 (revised from -1.6%) before a modest recovery of +1.6% in 2025 (down from +2.3%). However, a return to full normalization is not expected in the near term

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## THE STEEL INDUSTRY TODAY AND ITS FUTURE DEVELOPMENTS

Steel is deeply embedded in every aspect of our modern lives — from buildings and infrastructure to transportation, appliances, and food preservation. As the world's most important engineering material, steel's strength, durability, and recyclability make it indispensable. It is also one of the most energy-intensive materials to produce. However, once made, steel can be recycled indefinitely. With a global recovery rate exceeding 70%, it is the most recycled material on Earth. Moreover, 97% of the by-products from steel production, such as slag, are also reused — commonly in concrete manufacturing.

Historically, steel has been a critical driver of economic development, from ancient tools and weapons to the Industrial Revolution. Today, steel remains a key component in future progress. Urbanization is accelerating, with half the world's population living in cities in 2010; by 2050, it is expected to double to nearly 70%. Megacities will require immense quantities of materials — particularly steel, which already accounts for 50% of global demand in construction. As urban density increases, steel will be crucial for constructing vertical infrastructure and transportation systems.
Additionally, as global energy demand rises, steel remains vital in the development of both fossil fuel and renewable energy systems — from pipelines and rigs to wind turbines and solar structures.
Given the strategic importance of steel, this analysis examines the changes transforming the industry, primarily driven by the urgent need for climate action and decarbonization. The goal is to understand the full steelmaking process, its energy requirements, and the feasibility of transitioning to "green steel" by 2050. It raises a fundamental question: *Can energy truly be non-fossil and green — and even if it can, is it realistic to transform the entire global energy system to achieve net-zero emissions?* The study will further investigate how the energy transition affects the **European steel sector,** focusing on regulatory pressures, cost implications, and industrial competitiveness.

This research delves into key questions:

- Can the steel industry realistically transition to net-zero emissions?
- Is it technically and economically viable to shift entirely to green, non-fossil energy sources in steelmaking?
- Why is such massive capital investment being directed into this transition, and do the outcomes justify it?
- What are the risks of centering our entire energy and industrial systems around decarbonization?

The European steel sector offers a critical case study in industrial decarbonization. In response to stringent climate mandates, producers are being increasingly pushed to decommission coke ovens and blast furnaces, transitioning toward Electric Arc Furnaces (EAFs) powered by low-carbon electricity—ideally from renewable sources—and exploring alternative smelter technologies, which are currently being studied for commercial scalability. This transition reflects broader regulatory and environmental pressures requiring the phase-out of carbon-intensive assets and the adoption of so-called cleaner, more energy-efficient steelmaking technologies.
This shift is not only capital-intensive but also affects competitiveness, energy sourcing, and industrial jobs.
In 2023, global crude steel production reached 1,892 million metric tons (Mt), of which 72% was made using the conventional Blast Furnace–Basic Oxygen Furnace (BF/BOF) method and 28% via the Electric Arc Furnace (EAF) route. The potential for decarbonization here is enormous yet challenging.

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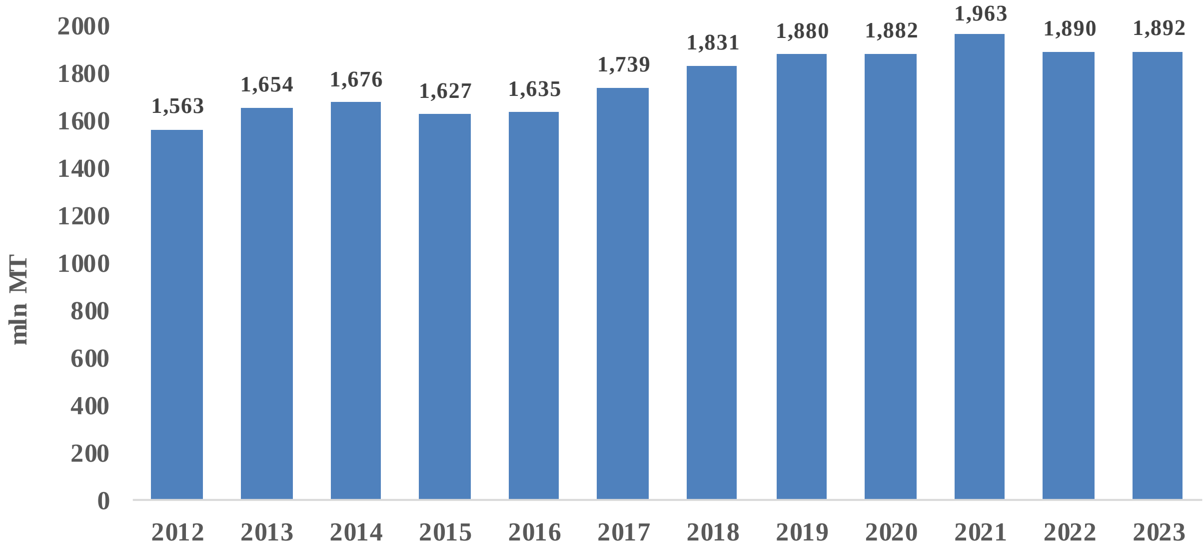


**Figure 1.** World Crude Steel Production from 2012 to 2023 (source: Statista, 2025).

From the chart, we can see that steel production rose from 1,563 million metric tons (MT) in 2012 to a peak of 1,963 million MT in 2021. This represents a growth of ~26% over 9 years, indicating robust global demand—primarily driven by Asia, especially China and India. In 2022, production fell to 1,890 million metric tons (MT) and marginally increased to 1,892 million MT in 2023. This slowdown is likely due to post-COVID market adjustments, energy transition policies in Europe, rising input costs, and geopolitical disruptions.
Despite the pandemic, 2020 shows no major drop in production, suggesting strong resilience in steel demand, especially due to infrastructure-driven recoveries in major economies.

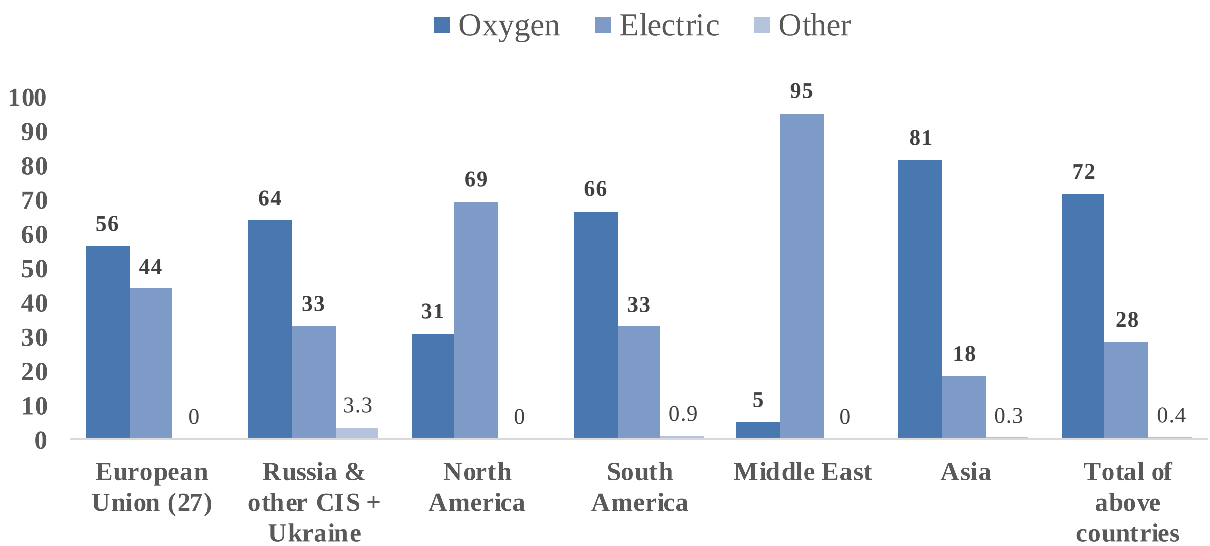


**Figure 2.** Crude Steel Production by Process 2022 (Source: World Steel Association 2023).

While Europe is under policy pressure to shift from BOF to EAF (and eventually to hydrogen-based DRI-EAF), much of the world's steel is still made via BOF. Meaning the global "decarbonization" pathway will be uneven and costly. Out of the total crude steel production of 136 million metric tons (Mt) in the European Union, approximately 56.3% is produced via the blast furnace–basic oxygen furnace (BF-BOF) route, while the remaining 43.7% is produced using the electric arc furnace (EAF) route.

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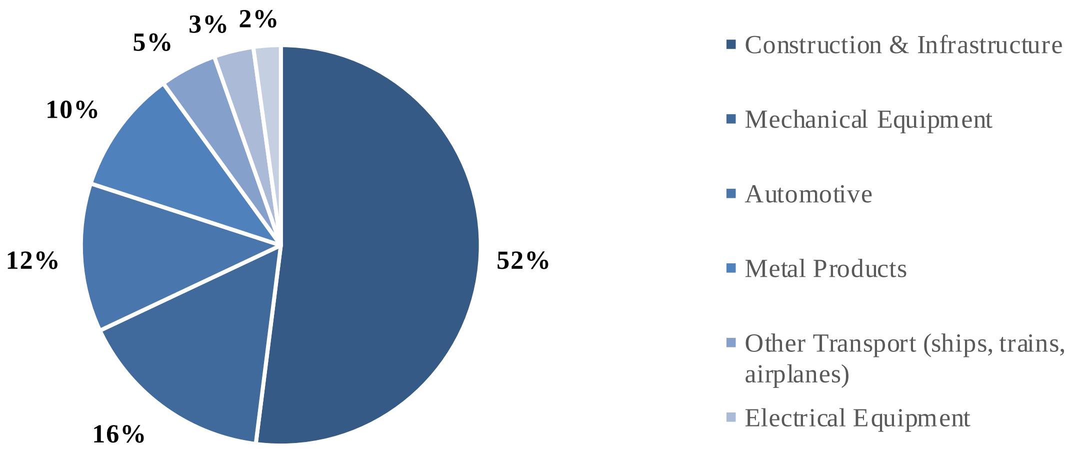


**Figure 3.** Steel use by sector (source: (source: World Steel Association 2023).

As mentioned earlier, due to ongoing urbanization and global development, the demand for steel is expected to continue rising, with 52% of total consumption driven by the construction and infrastructure sectors.

## ENERGY CONSUMPTION IN STEELMAKING: SOURCE AND INTENSITY

To fully assess the feasibility of decarbonizing the steel industry, it is essential to examine the energy sources, consumption intensity, and the technological viability of clean alternatives like hydrogen.
Steel production is among the most energy-intensive industrial processes globally. The two primary routes - BF/BOF and EAF - have very different energy intensities.
In both cases, energy consumption is a core cost driver. According to the IEA, the steel industry accounts for about 7–9% of global $CO_2$ emissions, making it a key sector in any net-zero pathway. Therefore, understanding how energy is generated and delivered becomes crucial in determining whether "green steel" is realistically achievable or merely an idealistic notion.

## ELECTRICITY AND ENERGY CONSUMPTION: EAF VS. BF-BOF

The electricity consumption of Electric Arc Furnaces (EAF) and Blast Furnaces (BF-BOF) differs substantially, reflecting their distinct technological principles and fuel requirements. Below is a comparative analysis of the two:

**Electric Arc Furnaces (EAF)**

- Primary Energy Source: Electricity
- Average Capacity of EAF commonly produces 30,000 to 80,000 tons of steel per month.
- Typical Energy Consumption:
    - EAFs consume approximately 350-750 kWh of electricity per ton of steel produced, depending on the feedstock (scrap vs. DRI) and furnace efficiency.
    - The lower end applies to high-quality scrap-based operations, while the higher end reflects DRI-fed or hybrid systems.
- Process Overview:
    - EAFs generate extreme temperatures (up to 1,800°C) by arcing electricity through graphite electrodes, melting recycled steel, or DRI.
    - The electrical load is intense and fluctuating, requiring robust grid infrastructure or dedicated power sources.

- EAF operations are batch-based and can be paused or restarted more easily than BF, offering more flexibility but also causing voltage instability if not managed properly.
- Indirect Emissions Concern:
  - The carbon intensity of EAF steelmaking is heavily dependent on the grid electricity mix. If the electricity comes from coal or gas, the emissions are still considerable. For example, Electric Arc Furnaces (EAFs) supplied with electricity generated from fossil-fuel-dominant grids can emit up to 1.1–1.2 tones of $CO_2$ per tonne of steel produced, whereas EAFs using electricity from fully renewable energy sources can reduce emissions to below 0.1 tones of $CO_2$ per tonne.

**Blast Furnaces (BF- BOF)**

- Primary Energy Source: Coke (derived from metallurgical coal).
- Average Capacity: A large BF can produce 150,000 to 400,000 tons of hot metal per month, which is then converted into steel in a Basic Oxygen Furnace (BOF).
- Electricity Consumption:
  - While the electrical energy demand is lower than EAFs - around 50-100 kWh/ton of hot metal - blast furnaces require chemical energy from coke.
  - The total energy demand (thermal and electrical combined) in traditional blast furnace–basic oxygen furnace (BF–BOF) routes is substantially higher - typically ranging from 20 to 30 GJ per ton of hot metal - compared to just 3 to 6 GJ per ton for electric arc furnaces (EAFs).
- Process Overview:
  - The blast furnace reduces iron ore using coke as both fuel and reducing agent in a continuous process.
  - The resulting hot metal is then refined in a Basic Oxygen Furnace (BOF) using oxygen to lower carbon content and remove impurities.
- Emissions Profile:
  - BF-BOF systems are the most carbon-intensive steelmaking route, emitting 1.8–2.2 t $CO_2$ per ton of steel, depending on fuel mix and process efficiency.
  - Unlike EAF, BF emissions are process-intrinsic, as $CO_2$ is released directly from the chemical reduction of iron ore using carbon (coke).

**Table 1.** Comparison between EAF and BF-BOF

| PARAMETER | ELECTRIC ARC FURNACE (EAF) | BLAST FURNACE (BF-BOF) |
|---|---|---|
| **Average capacity** | 30 000-80 000 t/month | 150 000-300 000 t/month |
| **Main energy source** | Electricity | Coke (coal) |
| **Electricity usage** | 350–750 kWh/t | 50–100 kWh/t |
| **Total energy input** | 3–6 GJ/ton | 20–30 GJ/ton |
| **Carbon emissions** | 0.1–1.2 t $CO_2$/t (grid-dependent) | 1.8–2.2 t $CO_2$/t |
| **Flexibility** | High (batch process, start-stop friendly) | Low (continuous operation required) |
| **Main feedstock** | Scrap, DRI, pig iron | Iron ore, coke |
| **Grid impact** | High voltage, fluctuating load | Low impact on grid |

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At first glance, energy intensity in EAF looks quite attractive unless it is taken into account that it depends on the feedstock (scrap vs. DRI). While EAF uses electricity, the actual carbon intensity depends on the electricity mix, i.e., whether it comes from coal, natural gas, or renewable sources.
Another significant point to mention is that the energy input required to produce Direct Reduced Iron (DRI) depends on the reduction method and feedstock used (e.g., natural gas, coal, or hydrogen).

Here's a breakdown of the approximate energy requirements for producing one metric ton of DRI, expressed in GJ:

**1. Natural Gas-Based DRI (Midrex or HYL processes)**

- Energy input: 10-14.8 GJ/tonne DRI
- Most commonly used route, especially in MENA.
- Efficiency depends on gas quality and plant design.

**2. Coal-Based DRI (Rotary Kilns, common in India)**

- Energy input: 15-21.5 GJ/tonne DRI.
- Higher energy consumption due to lower reduction efficiency.
- Also produces more $CO_2$ per ton.

**3. Hydrogen-Based DRI (Green DRI)**

- Energy input: ~43-49 GJ/tonne DRI (including electrolysis energy for $H_2$ production), which includes consumption of an extra ~4,000-4,500 kWh/t of electricity for auxiliary purposes. This pushes the total electricity demand to ~12,000-13,500 kWh per t of DRI.
- Green hydrogen production requires ~50-55 kWh per kg of $H_2$
- Technology status: Still in the early deployment phase, with projects like Hybrit (Sweden) leading pilot-scale efforts.

**Table 2.** Comparison of Steel Production Routes in Terms of Energy Use, Emissions, and Decarbonization Potential.

| CRITERIA | BF-BOF | EAF (Scrap) | NG-DRI + EAF | COAL-DRI + EAF | $H_2$-DRI + EAF |
|---|---|---|---|---|---|
| Energy intensity | High | Low | Moderate | High | Very High |
| Energy cost | Volatile | Medium to High (depends on region, but rising electricity prices in Europe) | Medium | Low (in coal-rich regions) | Very High |
| Process efficiency | Low | High | Medium | Low | Low |
| $CO_2$ emissions | High | Very Low | Medium | High | Very Low |
| Decarbonization fit | Limited | Scrap-limited | Good | Poor | Excellent, but technically complex |
| Feedstock | Iron ore + coal (abundant, high carbon) | Scrap (recycling-based; limited availability, slower supply chain) | NG+High-grade iron ore (limited availability) | Coal + High-grade iron ore (limited availability) | High-grade iron ore + green $H_2$ (limited availability) |

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As shown in Table 2, scrap-based EAF remains the most energy and cost-efficient route. However, its potential is limited by the availability and quality of scrap. The NG-DRI + EAF route presents a viable transitional solution. It offers lower emissions than the traditional BF-BOF process and is more scalable than scrap-only production. However, it relies on access to both natural gas and high-grade iron ore, the availability of which is limited, making it unsuitable as a mass-scale solution. Looking ahead, hydrogen-based DRI + EAF is the "most promising" route for achieving full decarbonization. Despite its potential, it faces several challenges:

- The process has low energy efficiency.
- It depends on abundant and affordable green electricity.
- For hydrogen-based steel to be cost-competitive, green $H_2$ prices must drop below $2/kg.

It is important to emphasize that the lack of carbon in hydrogen-based DRI ($H_2$-DRI) presents a serious technical challenge, especially for steelmaking via Electric Arc Furnaces (EAF), including higher energy demand, limited slag foaming, and the need for external carburization. These challenges must be addressed through technological innovations, process control, or the use of supplementary carbon sources, which may impact both cost and emissions. Essential point to note that the global availability of high-grade iron ore, which is typically defined as ore with Fe content above 65%, is extremely limited, representing only about 3% to 4% of total global iron ore resources. This scarcity poses a significant constraint on the growth potential of Direct Reduced Iron (DRI) production. The same scenario applies to scrap availability - while, in theory, all new steel could be produced from recycled scrap, this is currently unfeasible due to limited scrap availability. The primary reason is the long service life of steel products, which can range from a few weeks (e.g., packaging) to over 100 years (e.g., buildings and infrastructure), with an average lifespan of approximately 40 years. As a result, there is a significant time lag between steel production and when it becomes available for recycling. Steel demand continues to grow faster than scrap is released from the stock of 'steel in use'. According to estimates from the World Steel Association, global end-of-life ferrous scrap availability is projected to increase from approximately 400 million tonnes in 2019 to about 600 million tonnes by 2030 and 900 million tonnes by 2050, marking a growth of over 500 million tonnes over the next 30 years.
Focusing on Europe, studies estimate that the potentially available domestic post-consumer scrap (PADPS) will rise from around 93 million tonnes in 2030 to approximately 137 million tonnes by 2050, reflecting an average annual growth rate of about 1.6%.

All currently available scrap is already being recycled, leaving minimal scope for increased supply in the near term. Future scrap availability will depend primarily on the gradual rise in post-consumer scrap, meaning a full transition to scrap-based steel production is unlikely within this century.

### Hydrogen: A Savior or a Mirage?

Hydrogen is widely promoted as the most promising pathway for green steelmaking, especially when used as a reducing agent in hydrogen-based DRI (H-DRI) processes.
Theoretically, replacing carbon-based reductants like coke or natural gas with hydrogen can eliminate nearly all direct $CO_2$ emissions from the reduction process. However, hydrogen itself is not an energy source - it is an energy carrier, and its sustainability entirely depends on how it is produced. In steelmaking, it is proposed as a potential replacement for carbon-heavy coke in the DRI process.
There are multiple types of hydrogen, classified by color based on their production methods:

- **Grey Hydrogen**: Produced from natural gas via steam methane reforming, emitting $CO_2$.
- **Blue Hydrogen**: Similar to grey, but with carbon capture and storage (CCS).
- **Green Hydrogen**: Produced from water electrolysis using renewable electricity.
- **Turquoise Hydrogen**: Produced via methane pyrolysis, resulting in solid carbon and hydrogen.

Consider turquoise hydrogen via plasma pyrolysis: to produce 1 kg of hydrogen, 4 kg of methane is needed. The lower heating value of the hydrogen is 120 MJ (33.3 kWh), while 4 kg of methane provides 200 MJ (55.6 kWh). Thus, only 60% of the original methane's energy is retained in the hydrogen, without even accounting for the 15 kWh of electricity required for the pyrolysis. The net result is an energy return of just 47%, making hydrogen a fundamentally inefficient energy carrier.

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Electrolysis fares no better. Electrolyzers require vast amounts of high-quality electricity, which is most effectively sourced from renewable energy like wind or solar. However, green hydrogen accounts for less than 5% of global production due to its exorbitant cost. Even if the cost of electrolysis falls in the future, the conversion inefficiencies, storage complications, and transportation challenges make hydrogen unviable as a large-scale energy solution. Scaling this to global levels would require unprecedented expansion in renewable energy infrastructure - raising major concerns about grid capacity, storage, and intermittency.

Hydrogen fuel cells, often touted for their use in mobility and stationary power, are only 40-60% efficient. Moreover, hydrogen is highly flammable and requires specialized infrastructure, which further raises costs and complicates safety and logistics. These issues make hydrogen better suited for niche applications or as an energy storage medium for surplus renewable energy rather than as a universal energy solution.

Currently, more than 95% of global hydrogen is produced using fossil fuels (grey and blue). Green hydrogen accounts for less than 1%, primarily due to its high cost and limited infrastructure.

Despite the potential of hydrogen-based steelmaking, several challenges remain. The success of electric arc furnaces (EAF) and hydrogen-based DRI processes depends on electricity prices, with high tariffs making EAF less competitive. Even if powered by clean electricity, the carbon footprint of production remains linked to the grid mix; if coal or gas dominates, emissions are just relocated rather than eliminated. Additionally, scaling green hydrogen requires significant investments in electrolyzers, renewable power plants, storage infrastructure, and DRI retrofits, making the transition both costly and complex. These factors create significant barriers to large-scale decarbonization in the steel industry.

**The Global Energy Landscape: Demand, Mix, and Transition Challenges**

As nations grow wealthier and populations expand, global energy demand is rising rapidly. This trend is particularly pronounced in emerging economies, where industrialization, urbanization, and access to modern amenities drive increasing consumption. Without significant improvements in energy efficiency, this rising demand will continue to push total global energy use upward year after year.

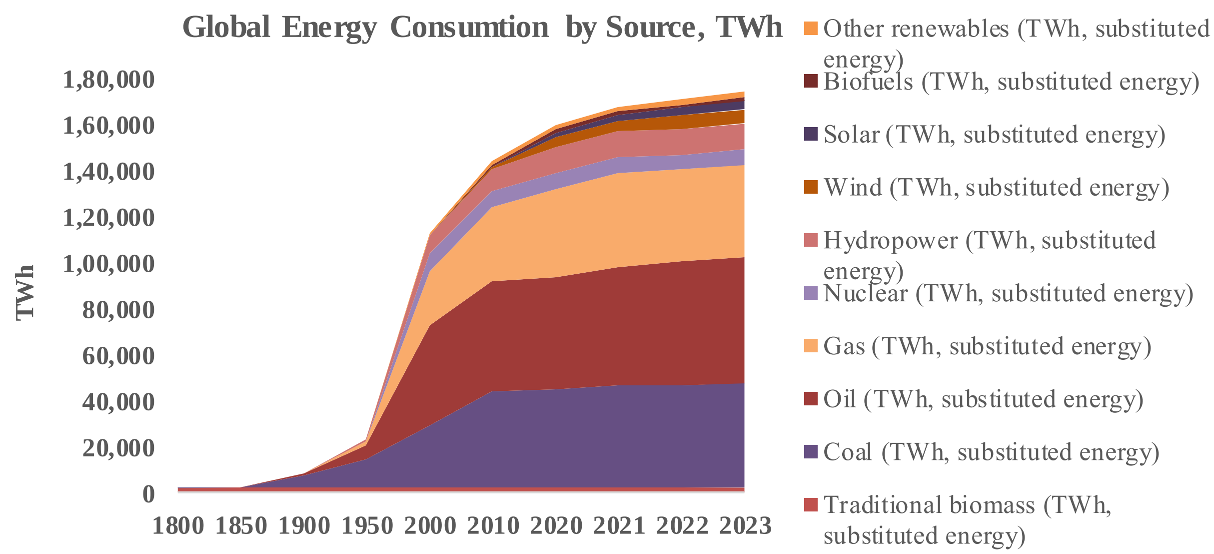


**Figure 4.** Global Energy Consumption by Source (source: Energy Institute - Statistical Review of World Energy 2024)

An interactive view of global energy use shows that energy consumption has increased almost every year for more than five decades, with only occasional dips during major global crises (e.g., the 2008 financial crisis or the 2020 COVID-19 pandemic). This consistent growth underscores the magnitude of the challenge: despite policy commitments and technological advancements, the world continues to increase its total energy consumption, with much of it still being met by fossil fuels. The implication of this rising demand is profound: not only must we develop enough new energy to satisfy this growth, but to achieve "decarbonization goals," that new energy must be low carbon. In other words, the

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transition challenge is two-fold:

1. Meet the expanding global demand, and
2. Simultaneously, replace existing fossil fuel-based infrastructure.

This makes the path to "net-zero emissions" far more complex than simply "swapping out" fossil fuels. It involves rebuilding the energy backbone of global industry, transportation, and urban development from the ground up.

**Electricity Generation: The Global Mix**

Understanding the current electricity mix is essential for analyzing where energy for steel production (especially Electric Arc Furnaces) might come from.

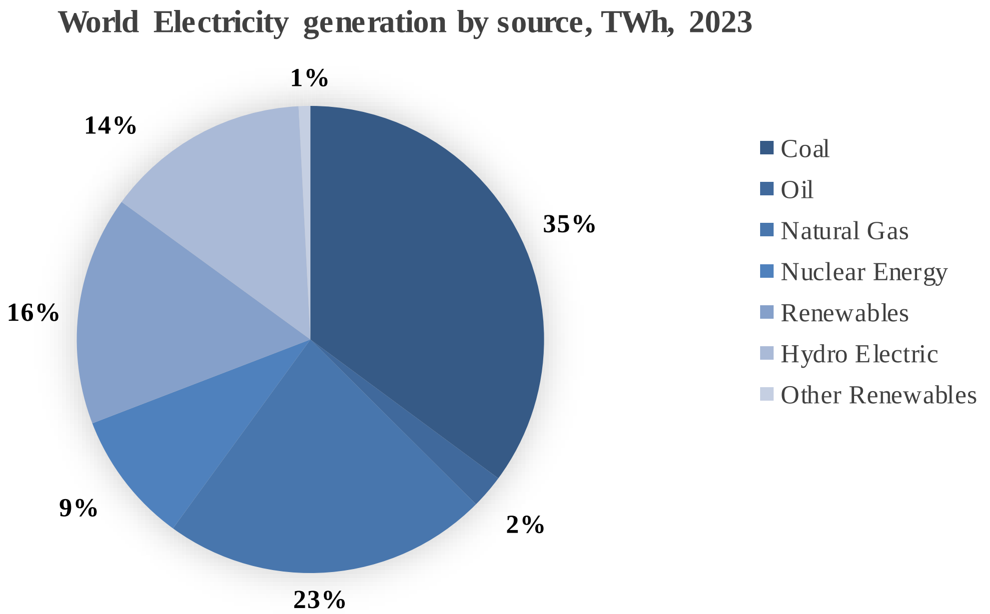


**Figure 4.** World Electricity generation by source (source: IEA statistics 2023).

According to Our World in Data and IEA statistics, the global electricity mix in recent years has consisted of the following approximate shares:

- **Coal**: ~35-36%
- **Natural Gas**: ~23%
- **Hydropower**: ~16%
- **Nuclear**: ~10%
- **Wind**: ~7–8%
- **Solar**: ~40-5%
- **Oil and other**: ~6%

Despite the rapid growth in wind and solar energy, fossil fuels still account for around 60–65% of global electricity production. This presents a major issue for "green" steel: even if an EAF uses electricity rather than coal, the carbon intensity of that electricity determines whether it is genuinely low-emission or not.

- **Coal remains dominant** in many regions, especially in Asia, where countries such as China and India heavily rely on coal-fired power plants.
- **Natural gas**, often promoted as a "transition fuel," still emits $CO_2$ and contributes significantly to total emissions.
- **Wind and solar** are the fastest-growing segments, but their intermittency and relatively low-capacity factors limit their reliability for heavy industry unless paired with large-scale storage or grid upgrades.

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- **Hydropower and nuclear**, while stable and low carbon, face geographic, political, and other acceptance constraints.

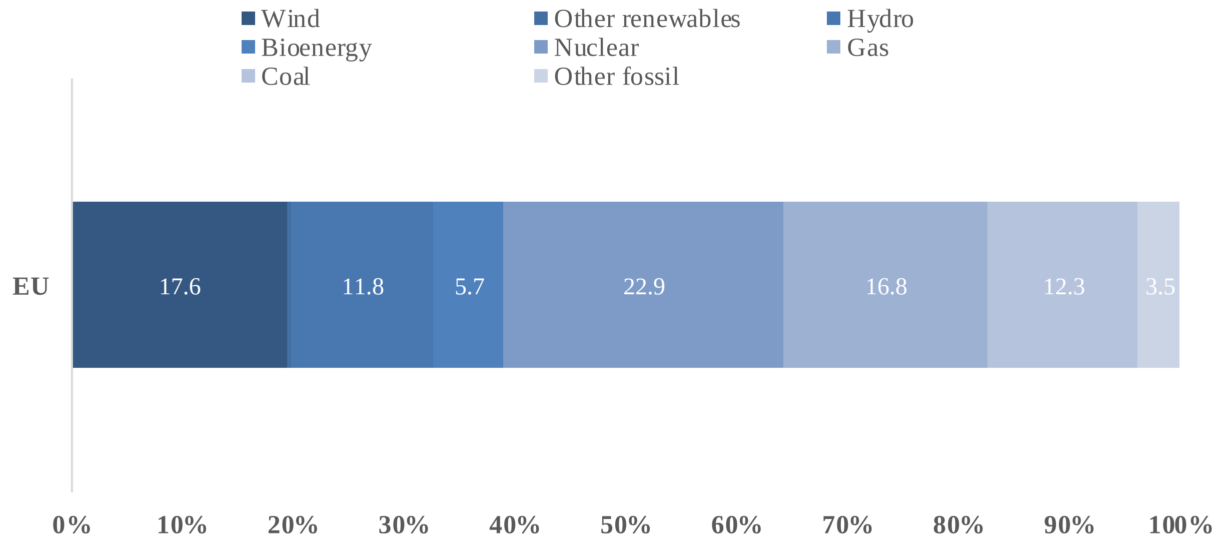


**Figure 5.** The EU Electricity generation by source (source: Annual Electricity data, Ember 2023).

At 22.8%, nuclear energy continues to play a stabilizing role due to its baseload capabilities and its status as a clean energy source. Fossil fuel-based generation (gas, coal, oil) share is 32.5%. Wind energy became the largest single renewable source (18.5%), outpacing hydro and solar.
The share of clean energy (renewables + nuclear) is now at 67.5%, showing positive momentum.
However, the variability of renewables requires grid modernization, storage, and flexibility measures to maintain stability. Hydropower is a clean, renewable energy source that generates electricity without direct $CO_2$ emissions. Once built, it offers one of the lowest-cost electricity options, making it both environmentally and economically efficient in regions with suitable water resources.
Considering the "urgent need to decarbonize" the global energy system, nuclear energy stands out as a clean, stable, and reliable source that merits greater attention and investment.
Nuclear power offers several strategic advantages:

- **Stable and long-term electricity supply**: A single reactor can operate continuously for 30 to 60 years, providing baseload power with minimal interruption.
- **High power density and low operating costs**: Once constructed, nuclear plants offer low marginal **costs** and can deliver high output from a relatively small land and ecological impact.
- **Proven safety and reliability**: Decades of technological advancement and regulatory oversight have made modern nuclear reactors among the safest and most reliable energy sources available.
- **Energy independence:** Nuclear is insulated from the volatility of fossil fuel and renewable energy markets, contributing to energy security and price stability**.**

As the world transitions to low-emission energy, nuclear power must play a pivotal role in the energy mix, particularly for industries and regions that require continuous, clean electricity.

**Why Green Energy is not a panacea**?

The central critique of the green energy discourse is its detachment from the physical and economic realities of industrial energy use. Renewable energy sources, such as wind and solar, are variable and geographically constrained,

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requiring massive land use and storage solutions. Steel plants, which operate full-time with high thermal demands, cannot rely on unstable electricity flows or speculative hydrogen supplies.

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Moreover, the idea of converting all energy production to non-fossil sources involves astronomical costs, infrastructure overhauls, and global coordination on an unprecedented scale. For steel producers, especially in Europe, this means shutting down cost-effective BF/BOF plants and replacing them with EAFs and DRI units powered by expensive hydrogen or renewable electricity, which is also limited in availability. Moreover, the global potential for scaling DRI is restricted due to the limited supply of high-grade iron ore, as discussed earlier. The cost burden of this transition threatens to reduce the competitiveness of European steel, increase prices for end-users, and potentially outsource emissions to countries with looser environmental controls.
It is essential to understand concepts such as inertia in electricity systems, which is fundamental to the stability of the power grid, especially in conventional (synchronous) power systems.
**Inertia** in the context of electricity refers to the stored kinetic energy in the rotating masses of large generators, such as those in coal, gas, hydro, and nuclear power plants. These generators are connected directly to the grid via synchronous machines**.** When the grid frequency (e.g., 50 or 60 Hz) fluctuates due to a sudden loss of generation or increase in demand, the spinning masses resist this change due to their physical **inertia,** helping to:

- Slow down the rate of frequency change**.**
- Buy time (seconds) for other control systems to respond (like automatic generation control or battery systems).

Wind turbines and solar PV systems **don't have inertia**. Inertia is an essential element of a stable power grid**.** In traditional power systems, it is provided by the physics of rotating machines. In modern "green" systems, it must be reproduced artificially using technology.

## CONCLUSION: A CALL FOR REALISM

Steel remains central to human development and will be critical for the construction of future megacities, renewable energy infrastructure, and global transportation systems. Yet the narrative of green hydrogen and renewable-only energy as silver bullets for decarbonizing the steel industry is fundamentally flawed. Hydrogen is not a primary energy source, and green energy is neither universally available nor economically and by nature viable for round-the-clock industrial use. As already mentioned, hydrogen is not a true energy source - it is a secondary energy carrier that must be produced using other energy inputs, often at significant cost and energy loss. Renewables (especially when combined with storage) introduce inefficiencies - adding conversion cycles (e.g., electricity → hydrogen → storage → electricity again) that erode overall system efficiency.
Overall, the world's average monthly steel production is 170-180 mln t, out of which 13-14 mln t in Europe monthly production in 2022 (worldsteel.org), out of which 57% was produced in BF-BOF, and 43% in EAF (ref. Figure 2). This means that to meet the current production level, we need to transfer an additional 57% of European crude steelmaking capacity to the Electric Arc Furnace (EAF) process, which would require a substantial amount of capital. The main question is where to allocate it and whether it is worth it. What about the sufficiency of feedstock, such as high-grade iron ore for DRI and scrap?
Despite efficient operations, European steel producers have structurally higher costs compared to major steel-producing regions globally, such as the Commonwealth of Independent States (CIS), India, top-quartile players in the North American Free Trade Agreement (NAFTA), and top- and second-quartile players from developed countries in Asia. This is primarily because Europe faces higher costs for landed raw materials, energy, labor, and other cost factors.[1]
I may link the shutdown and bankruptcy of some steelmaking plants in Europe as one of the reasons the policy compels them to convert to EAF, injecting huge capital expenditures, whether businesses are already struggling with material and energy supply, with soaring prices, which brings to the point where making the cost of semi-finished steel products come to be higher than market prices, due to downwards in economic trends, particularly in Europe. This leads to the point that thousands of employees remained unemployed. While the quality of steel produced in EAFs, especially when based on scrap, has improved, concerns remain regarding impurities and consistency. As a result, industries such as automotive are still cautious and typically limit EAF-based steel to non-critical components. At the same time, sectors such as aerospace and defense generally do not use it at all due to stringent performance and quality requirements.

[1] **McKinsey&Company "The future of the European steel industry," March 2021.**

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EAFs are complex systems that require specialized equipment, including the furnace itself, electrodes, transformers, off-gas treatment facilities, and charging systems. The cost of procuring and installing these components can be substantial. Building and setting up the physical infrastructure for the EAFs operation, including the furnace building, foundation cooling system, and power distribution networks, add to the initial investment. This financial barrier can impact a company's decision to enter the market, expand operations, or upgrade existing facilities.

Another burden for these producers is the newly imposed carbon taxes (European Union Emissions Trading System (EU ETS) allowances), which significantly increase their production costs. Example: At €90/tonne $CO_2$ (as seen in the EU ETS), BF-BOF operators face up to €180/tonne of steel in added costs, reducing profit margins or requiring higher steel prices. Buyers may choose cheaper foreign steel unless protected by the EU's Carbon Border Adjustment Mechanism (CBAM). Existing integrated steel plants (BF-BOF) may become stranded assets (an investment that loses its value or becomes unusable before the end of its expected life) - it brings to bankruptcy and shut down of plants if they can't afford the added carbon costs. This puts thousands of jobs, billions in capital, and EU steel self-sufficiency at stake.

As per World Bank Group, "Carbon pricing is an instrument that captures the external costs of greenhouse gas (GHG) emissions - the costs of emissions that the public pays for, such as damage to crops, health care costs from heat waves and droughts, and loss of property from flooding and sea level rise - and ties them to their sources through a price, usually in the form of a price on the carbon dioxide ($CO_2$) emitted. A price on carbon helps shift the burden for the damage from GHG emissions back to those who are responsible for it and who can avoid it".

Efforts to decrease emissions, which is a more accurate statement than "decarbonization," must be tempered by technological realism, economic viability, and geopolitical pragmatism. The steel industry cannot shoulder the full burden of energy transition policies that ignore industrial energy demands. Instead of imposing costly transitions, policymakers should prioritize incremental improvements in energy efficiency, support research into more feasible technologies, encourage social and economic sustainability, and ensure global competitiveness is preserved. A sustainable future requires balance—not blind adherence to ideology. The steel industry, like the broader energy landscape, must be allowed to evolve based on scientific, economic, and engineering realities - not on vague aspirations detached from industrial practicality.

And mainly, why do we need to set aside entire economies and inject billions of investments just to add another cycle (or cycles) in electricity production under the name of being "green"? Are we sacrificing economic rationality and energy realism for "idealism"? Entire industries currently put all their efforts into capturing carbon, when carbon is an essential part of our ecosystem; it is not a pollutant.

The most viable and technologically sound pathway for the future of steel production lies in the continued development and modernization of the existing Blast Furnace–Basic Oxygen Furnace (BF–BOF) infrastructure. BF–BOF remains the backbone of global primary steelmaking, and its efficiency can be significantly improved through process innovation and emissions mitigation technologies, etc.

Alongside this, nuclear power should be prioritized as the primary energy source, including for heavy industrial sectors like steel, that run continuously and require stable baseload power to avoid disruptions and economic losses. With the current level of technological advancement, I am confident that the safety concerns traditionally associated with nuclear power plant development can be further addressed and mitigated. Ongoing innovations in reactor design, monitoring systems, and emergency protocols continue to enhance safety standards, making nuclear energy a viable and secure component of the global energy mix as a clean, cost-effective source of power, contributing to the global shift toward sustainability.

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