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Making Circular Business Models Beneficial for Steel Production, for the Environment, and for Market Protection

Vytváření cirkulárních obchodních modelů přínosných pro výrobu oceli, životní prostředí a ochranu trhu

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Abstract

From an economic burden to a competitive profitable differentiator. Reconciling the requirements for industrial production of steel with the reduction of waste (energy, materials, emissions, etc.) is a constant balance exercise of steel mills. Steel operators must define environmental and circular milestones that enhancing a viable manufacturing base that can compete in international markets. The authors elaborate on the mayor lean efficiency development of the steel industry and conceptually explore the critical strategic considerations of a fully circular steel market.

The authors explore the different learning mechanisms accompanying the transition and the consequences for the value & supply chains in both developed and emerging economies. The delicate phase of the energy and circularity transition requires adaptation to new competitive forces and legislative framework that will shape the steel market and will define new business model paradigms for a material that will continue to be an strategic component of the human society: steel.

Keywords: *Circularity, competition, value-streams, steel business models, energy efficiency, waste reduction, circular market and profitability creation*

Abstrakt

Od ekonomické zátěže ke konkurenční výhodě a ziskovému odlišení. Slaďování požadavků na průmyslovou výrobu oceli se snižováním množství odpadu (energie, materiálů, emisí apod.) představuje pro ocelárny trvalé hledání rovnováhy. Výrobci oceli musí stanovovat environmentální cíle a principy cirkulární ekonomiky tak, aby podporovaly životaschopnou výrobní základnu schopnou obstát v mezinárodní konkurenci.

Autoři se zaměřují na hlavní směry rozvoje štíhlé výroby (lean manufacturing) a zvyšování efektivity v ocelářském průmyslu a současně koncepčně analyzují klíčové strategické aspekty plně cirkulárního trhu s ocelí. Dále se věnují mechanismům učení a osvojování nových přístupů, které provázejí tento přechod, i jejich dopadům na hodnotové a dodavatelské řetězce ve vyspělých i rozvíjejících se ekonomikách.

Citlivé období energetické transformace a přechodu k cirkulární ekonomice vyžaduje přizpůsobení novým konkurenčním podmínkám i legislativnímu rámci, které budou formovat budoucí podobu trhu s ocelí a určovat nové obchodní modely pro materiál, jenž zůstane i nadále strategickou součástí lidské společnosti – ocel.

Klíčová slova*: cirkularita, konkurence, hodnotové toky, obchodní modely v ocelářství, energetická účinnost, snižování množství odpadu*

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1. Circularity and steel

Steel is a significant contributor to economic potential of a given country either by its own contribution to GDP or by the ability to indirectly feed a market (construction, machinery, mining, infrastructure). Steel industry, especially in Europe, is confronted with serious competitive challenges both in its domestic and international markets [1]. The World Steel Association in its 2025 sustainability report [2] declares a dynamic industry focusing on the development of sustainable practices and adherence to several indicators that keep updating themselves in time. The figure **fig. 1** below shows in bold new milestones and criteria that have been added during 2025 [2]. They cover environmental, social, economic and governance criteria with healthy trends of modest (but positive) trends in the economics results while continuous trends diminishing the level of emissions. This reflects a dynamic industry wiling to improve operations, being more efficient and environmentally conscious. At the same time the same source [3] reports that still the industry produces more tons of CO_2 than tons of steel and that the dominant route for producing steel (+60%) is based on the integrated Blast Furnace (BF) + Basic Oxygen Furnace (BOF). Significant differences exist between the main geographic areas (the Americas, Europe, Asia and India). The only geographic area losing capacity to produce steel is Europe. Overcapacity means that the mild growth from all other areas tends to be funneled to the export market. Only significant exception to this rule seems to be India that increased its production of steel but reduced its export (an indication of an internal healthy market consuming the additional production). Different levels of trade barriers and tariffs exist in all geographies to protect the ability to sovereignly produce steel locally. There is a renewed interest in reinvigorating the defense industry in Europe and therefore increasing steel production to meet the new demands [4].

The competitive position of European steel producers in the international markets is challenging as their higher manufacturing costs and the abundance of dirtier but cheaper steel in the market from multiple sources leads to an unbalanced offering situation.

Fig. 1 Sustainability indicators by the World Steel Association in its 2025 report [2]

Obr. 1 Ukazatele udržitelnosti uvedené WSA ve zprávě z roku 2025 [2]

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The industry has naturally been evolving into more efficient production means by leaner and more environmentally friendly processing routes. The authors can appreciate firsthand the transition from a cost burden of some off-gas treatment plants that have given place to new preheating means to reduce the energy consumption of steel making and become a significant competitive advantage (particularly when energy prices are high and volatile) [5]. Embedding sustainability in the steel business strategy entails cultural, technical and operational paradigm changes within the organization. New processes and tools that will enable sustainable steel processes require to be truly integrated throughout the entire company´s value chain.

In present times, the concept of Circular Economy (CE) is at the core of the steel industry, as part of its production is obtained by recycling and re-melting/ transforming steel from end-of-life goods. Circularity also entails the design of steel products aiming at longer longevity in service and with proper recycling and wast management practices [6-8]. It encompasses both the direct metallic products as well as the byproducts (slag, dust, consumed refractories, etc.)

According to IRENA (International Renewable Energy Agency) [9] there are 4 circular economy pillars that have a direct impact on 10 domains evenly spread between the environmental impact and the economic aspects of the steel products in service (**fig. 2**).

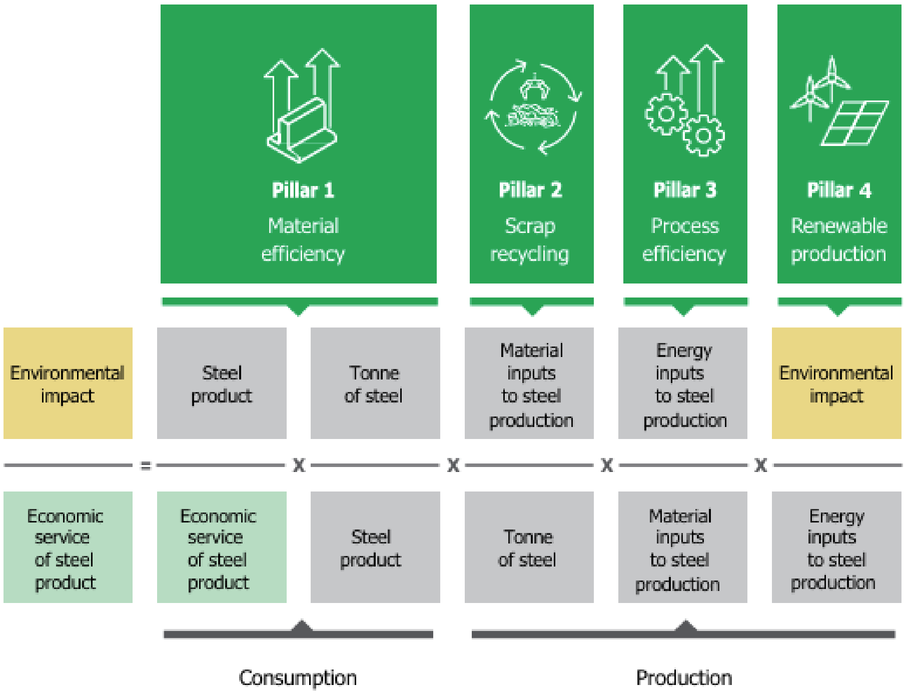

Fig. 2 Sustainability indicators by the World Steel Association in its 2025 report [9]

Obr. 2 Ukazatele udržitelnosti uvedené WSA ve zprávě z roku 2025 [9]

The impact of steel operations in the economic life of communities, industries and countries mean that economic growth and wealth cannot be decoupled from the value chain supporting them. **Fig. 3** represents how literature has treated these interactions to achieve harmonious development. The way authorities and communities are informed and take decisions with a better understanding is becoming an important pole of attraction This type of relationship often implies working relationships and the environmental impact for those communities near the steel plants.

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It involves elements of technological feasibility, combined with regulations and incentives for the successful and ecologically friend operation of the mill facility. This The public-technology interaction lies in the "Public Space" in **fig. 3**. These interactions deploy policies and rules setting the boundary conditions within which the steel plant operation could take place. It aims at deploying policies for setting the boundary limits of the operation to coexist with its surrounding communities.

It is crucial to recognize that there is no universal solution for integrating sustainable steel operations into the social and economic tissue of a given society. Even cultural differences, historical and economic differences can define and significantly shape unique solutions.

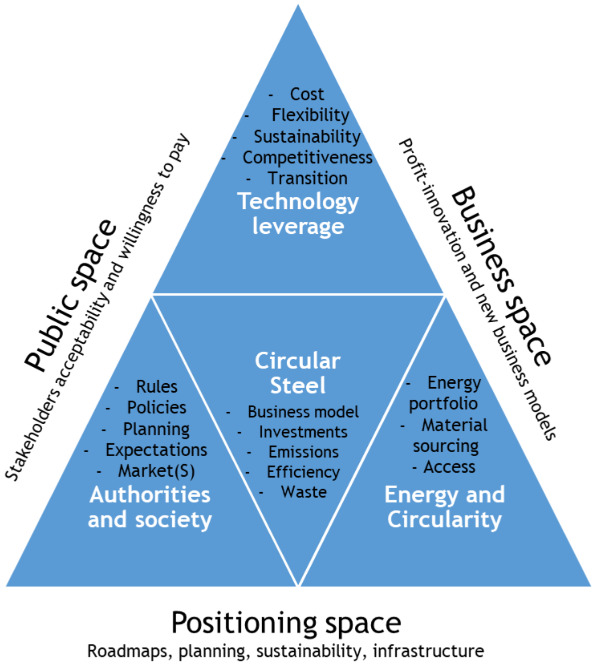

Fig. 3 Different decision spaces framing the sustainable possitioning of circular steel
Obr. 3 Různé rozhodovací mechanism vymezující udržitelné postavení oceli v oběhovém hospodářství

The ¨business space¨ in **fig. 3** is driven by the technology-enabled paradigm shift offered by renewable energies, new reducing agents (like hydrogen) and the strategic decisions related to the direction the steel company wants to pursue (partially to also align with the requested tradeoff from the public space. The technology paradigm shift offered, among other things, by new energy sources, storage capacity, AI, automation, sensing, etc. holds immense potential and it mobilizes both national and international resources pushing the boundaries of technical and deployment feasibility. It is a gradual and negotiated process.

The ¨positioning space¨ defines the strategic aim of both the country/community and the company. It looks forward to preparing the platforms to build the future and the competitive advantages. This is country specific and depends on the ability to build infrastructure for change (human and physical) and have a plan for the deployment with lower degree of uncertainty. Looking at the specific tools and criteria that might be relevant in defining the circular profile of a steel meltshop and its ecosystem, it is worth focusing on the interfaces along the different spaces as shown in **fig. 4**.

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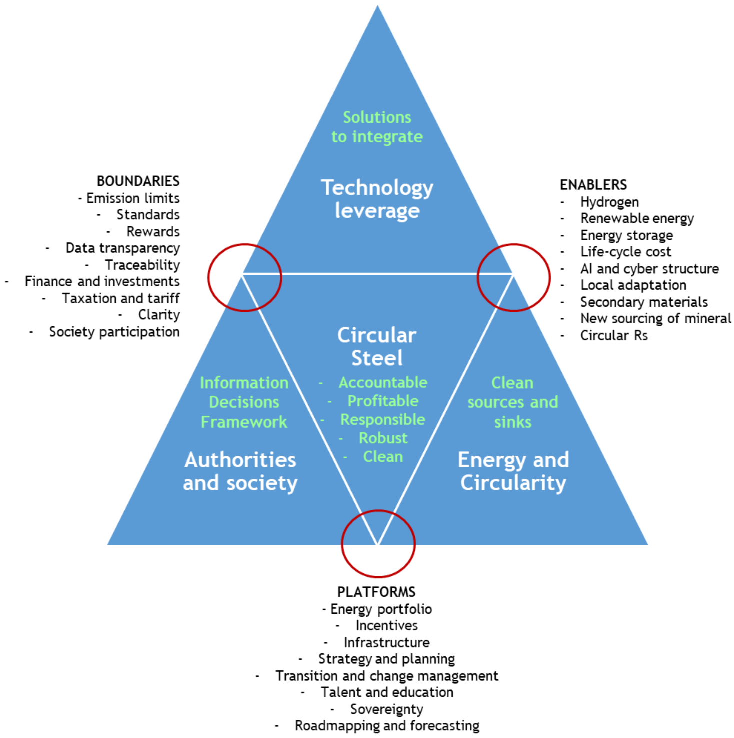

Fig. 4 Tools and criteria for the interfaces with the circular steel space
Obr. 4 Nástroje a kritéria pro propojení s odvětvím cirkulární oceli

The interfaces between technology and authorities/society have a focus on two main aspects: Creating the boundary conditions within which the steel company operate and producing the communication channels so that the society, the decision makers are properly and transparently informed and can take faster and well-informed decisions that are understandable for the whole community. The creation of such traceable and transparent information systems allows more direct information and participation of all the stakeholders.

The interface along the ¨business space¨ is mainly focused with the technological choices that are both mature enough and suitable for the specific boundary conditions and goals determined in the other two sides of the triangle. As such, there are no absolute best practices but only the best practices for specific set of conditions and with positioning goal.

The last, and not least, dimension is the long-term positioning of society vis a vis of their environment. It includes transformation and changes for energy and waste management. It looks after the preparation of the human capital and the physical infrastructure. It aims to ensure the permanence of a sustainable and profitable steel operation within the parameters set.

It should be clear that none of the three sides of the analysis is independent of each other. The approach is not deterministic and cannot avoid a degree of uncertainty that is normal for every strategic endeavor. This is the equilibrium under which the steel industry has evolved, with differences in different geographies and markets.

A different, and maybe complementary, analysis could be brought forward for a more distant time horizon. Playing on hypothetical fully circular scenario where not only the steel producers but also the steel users will be fully circular some interesting implications could be derived.

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They help to understand the different implications for the structuring of the supply and value chains of the steel of the future. Pinto and Deamer [10] have approach this situation to prepare some scenarios about a future where not only the production will be circular but also the final destination of the steel (e.g. automobile) will be fully in accordance with circular economy (**fig. 5**). Their analysis takes a long period of time (up to year 2196) and their modelling looks at different strategies, hedging vs integration vertically and horizontally, for both sides of the supply chain. What is interesting to mention from the circularity point of view is more related to the consequences that this bilateral fully circular approach entails for volumes and value chains.

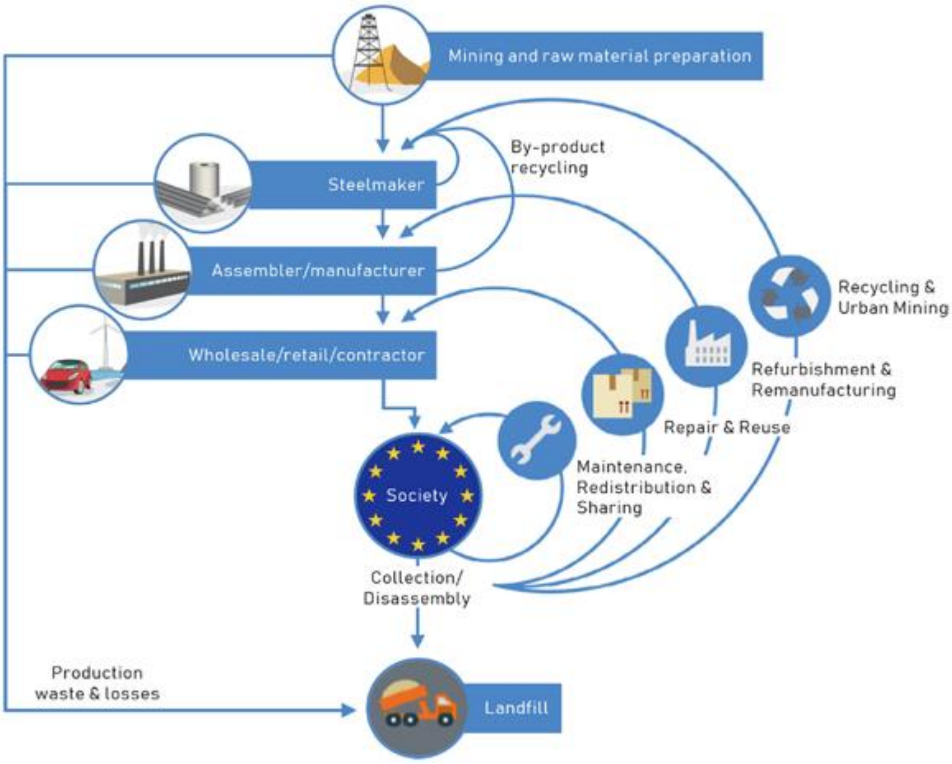

Fig. 5 Circular economy framework applied to the EU steel industry by [10]

Obr. 5 Rámec cirkulární ekonomiky aplikovaný na ocelářský průmysl EU podle [10]

The general observation of the outcome of their long-term models is that there is a reduction of the amount of new steel from BF+BOF needed and a minimal reduction on the amount of steel produced from scrap. Regarding the Blast Furnace + Basic Oxygen Furnace their models show a reduction bigger than two thirds (but not a total dispersion). Similar profiles can be observed for the amount and type of slags produced and recycled. The author's conclusion is that the steel making facilities should either integrated or hedge vertically (recycling) while for the demand side they should integrate or hedge horizontally (collect, sort, repair, reuse and refurbish).

One aspect that was not addressed by the authors is that the overall decoupling between production and consumption will significantly narrow and that scrap becomes and strategic commodity that needs transparent markets for a proper management. The moment consumption (and therefore the availability of scrap) becomes geographically close to consumption, the overall global balances and competition will change.

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2. Industrial ecosystem, learning loops and arbitrage decisions

It is obvious that the steel industry has not undergo such level of circularity, sustainability and integration. It is equally important to note that the steel producers have significantly shifted their production, reducing their energy and waste footprints. It seems to the authors that the current challenges for the European steel industry are derived from the transition nature of the business and its implications for both the value chain and the competitivity.

It is important to understand that the steel market is global, interconnected and smart. While some protective measures to fence off unfair competition from suppliers outside Europe may sound logical, their implications in the global arena might seem a bit more surprising. Some new mechanisms are becoming enforceable in the European Union in 2026, namely:

a) The State Aid Guidelines for Emission Trading System (ETS)
b) indirect cost compensation. Carbon Border Adjustment Mechanism (CBAM)
c) The Circular Economy Act (announced for quarter 4 of 2026).

While the idea of a tax on steel produced under less clean methods the moment it enters Europe may sound logical and common sense, there is risk of circumvention that could harm European exports:

a) When goods produced in low-carbon production facilities in third countries are redirected to European customers while carbon-intensive production continues for other markets (so-called ‘shuffling’).
b) Similarly, greenwashing can occur through carbon accounting practices, such as energy-intensive metals production benefiting from market-based instruments to appear low-carbon while still relying on high-emission energy sources or misleading scrap content accounting practices.

As overcapacity is here to stay, the need for exporting steel is not an accessory but a vital lifeline for the industry that should be supported either by the right balancing of tariff and incentives and by a more assumed political view of supporting green steel European producers.

On the positive side the Circular Economy Act should improve the functioning of secondary raw material markets and create a single market for waste. It is still not clear whether scrap will be covered by the Act but there certainly is a need for a single open European market for scrap. Metal scrap should circulate freely, to ensure that it can be recycled in the most performant facilities and to make use of economies of scale.

The steel industry has gone through some learning loops but has not reached a fully circular functioning. Each learning loop incorporates the precedent and adds new challenges, goals, and guiding principles (**fig. 6**).

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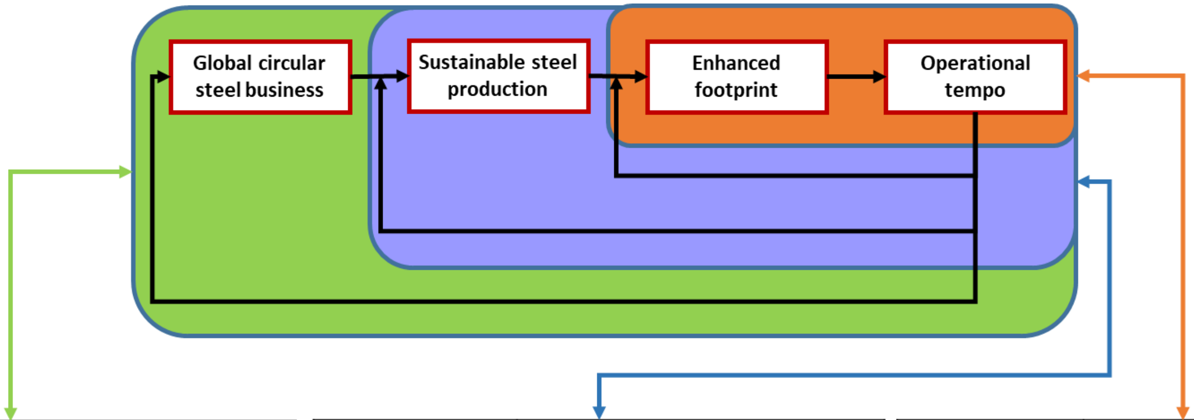

3rd learning loop	Global circular steel business
Guiding principle	- Scrap as strategic resource and market - General electrification & decarbonation
Functional goals	- Supply chains reassessment - Circularity as business enabler and market protection tool
Constrains	- Transition and infrastructure cost - Transparency and traceability tools - Harmonization of standards
Key elements	- Continuous diagnosis (telematics and cybernetics) - Cloud and AI monitoring - New secondary material market
Brand new concepts	- No hydrogen steel making - Thermal Energy Storage (TES) - Material sourcing locations moving closer to consumption locations - Energy islands

2nd learning loop	Sustainable steel production
Guiding principle	- Increased percentage of recycled steels vs new steel - For the latter, DRI gaining global traction
Functional goals	- Optimize electricity supply chain. - Minimize any form of waste
Constrains	- Access and price of scrap - Overcapacity thrown to international market competition
Key elements	- Increased market protectionism - Energy sourcing shift and insecurity - Unbalanced export market - Social, political, and defense pressure
Brand new concepts	- Hydrogenation (gradual). Steam reforming shift to electrolyzers. - Digital twins and optimized maintenance.

1st learning loop	Lean practice to energy and emissions
Guiding principle	- Maximize asset utilization , - Compete within boundaries - Minimize energy bill - Steel quality
Functional goals	- Minimize: idle time, cost, penalties. - Maximize consistency and tonnage
Constrains	- Wild competition environment - High energy prices - No premiums for green practice
Key elements	- Progressive (reactive) decarbonation - Slow transitioning to electrification - Cautious investments - Minimum profitability for survival
Brand new concepts	- Micro and mini mills - Gasification (NG, NG+H2) - PPA - CBAM, ETS, carbon tax

Fig. 6 Circular Steel Learning Cycles
Obr. 6 Cyklické procesy učení pro cirkuární ocelářství

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3. The digital dimension

There is a digital and data dimension that is essential in the quest from steel industry to meet its compliance with International Sustainability Standards Board (ISSB) norms ensuring that steel manufacturers adopt Environmental, Social, and Governance (ESG) frameworks to minimize carbon emissions, enhance resource efficiency, and maintain a competitive edge. The use of AI, ML, digital twins and other mathematical tools is generalized in the leading steel producing companies around the world.

As per UNEFED (United Nations Economic Commission for Europe), a circular economy is an economy were

a) The value of materials in the economy is maximized and maintained for as long as possible.
b) The input of materials and their consumption is minimized; and
c) The generation of waste is prevented as well as negative environmental impacts reduced throughout the life cycle of materials

All the above requires an ever-richer data infrastructure and advanced simulations tools to ensure transparency, enforceability of the standards and an agile adaptation to ever increasing challenges from the legitimate society quest of clean production.

4. Scenario analysis and conclusions

Efforts to green the steel industry follow at least two parallel approaches: enhancing the circularity of the operations and decarbonizing. For the latter, the steel sector requires at least a 50 % and up to a 90 % reduction in emissions by 2050 to align with global net-zero targets from the Paris Agreement. For the former there is a plethora of research ideas and piloting plants.

Fig. 7 presents some of the potential options for the liquid metal processes under fully orthogonal (completely linear independent bi-dimensional quadrants). Each of the technologies has pros and cons, but some of them are facing some of the last years in service. There is a generalized idea, that the authors do not counter, that the future of steelmaking is electrified and hydrogenated.

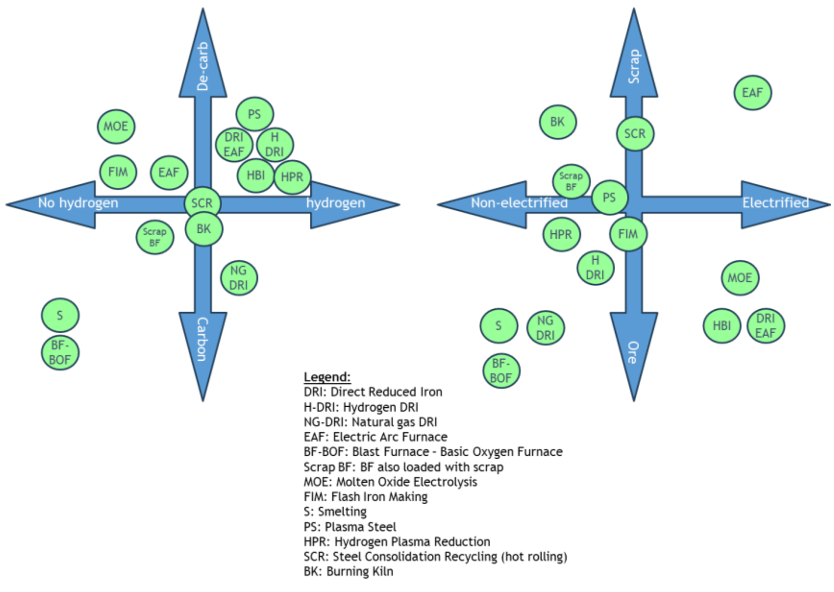

Fig. 7 Orthogonal scenario views of production alternatives for steel making
Obr. 7 Ortogonální pohledy na scénáře alternativ výroby oceli

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As water is the most common source material for green (or clean) hydrogen, there is the assumption that hydrogen is unlimited and its extraction is equally unrestrained. Already in 2024 [13] the IEER (Institute for Energy and Environment Research) stated that ¨*The high water intensity of hydrogen production raises important issues for siting hydrogen production facilities, competition among water uses….¨.* The authors, therefore have included a technology that claims its main advantage resides in producing steel or pig iron without a Blast Furnace and completely hydrogen free. The name of the technology is Molten Oxide Electrolysis (MOE) [14].

Circularity in steel making and the associated lean positions in energy and waste are clear differentiators in the market if the users themselves are willing to grant a premium for clean circular steel or if the authorities decide (as they did with renewable energy at is beginning). The steel industry will continue to face turbulence until new competing paradigms are established and the consumption and production delocalization might end.

During its recent history, sustainability and circularity have been two key allies of the steel industry allowing it to fence off competition, enjoy some incentive in key large markets. There is no rational for it to change.

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REFERENCES

[1] OECD (2025), OECD Steel Outlook (2025), OECD Publishing, Paris, https://doi.org/10.1787/28b61a5e-en.
[2] World Steel Association. Sustainability performance of the steel industry. Sustainability indicators report (2025). Brussels Belgium. steel@worldsteel.org
[3] World Steel Association. World Steel in figures 2025. Brussels Belgium. steel@worldsteel.org
[4] How much will rising defense spending boost Europe’s economy? | Goldman Sachs
[5] SANZ, A. Danieli Environmental Solutions for Steel Meltshops. *La Metallurgia Italiana*, 2/99, pp. 27-45.
[6] HARPPRECHT, C., SACCHI, R. , NAEGLER, T., van SLUISVELD, M., DAIOGLOU, V., TUKKER, A., AND STEUBING, B. Future Environmental Impacts of global Iron and Steel Production. Royal Society of Chemistry. *Energy Environ. Sci*., (2025), 18, pp. 8009
[7] EUROPEAN COMMISSION. Joint Research Center (JRC). Capturing the Potential of the Circular Economy Transition in the EU Steel Industry. (2025). ISBN 978-92-68-31754-9 doi:10.2760/3418709 KJ-01-25-477-EN-N
[8] SIMONI, M.; REITER, W.; SUER, J.; DI SANTE, L.; CIRILLI, F.; PRAOLINI, F.; MOSCONI, M.; GUZZON, M.; MALFA, E.; ALGERMISSEN, D.. Towards the Circularity of the EU Steel Industry: Modern Technologies for the Recycling of the Dusts and Recovery of Resources. *Metals* (2024), 14, 233.
[9] IRENA International Renewable Energy Agency. Towards a Circular Steel Industry. 2023. Towards a circular steel industry
[10] PINTO, J.T.M. and DEAMER, A. Supply Chain Integration Strategies and Circularity in the European Steel Industry. Resources, Conservation and Recycling, Vol. 153, (2020), pp 104517
[11] HEDSTROM, P., LAMELAS CUBERO, V., SIDGURSSON, J., OSTERBER, V., KOLLI, S., ODQVIST, J., HOU, Z, and ARIGELA, V. G. Physics-Informed Machine Learning for Steel Development: A Computational Framework and CCT Diagram Modelling . Hedström et al. 2025 (preprint)
[12] Sarfarazi, S.; Mascolo, I.; Modano, M.; Guarracino, F. Application of Artificial Intelligence to Support Design and Analysis of Steel. Structures. *Metals* (2025), 15, 408.
[13] IEER. Water Requirements For Various Approaches To Hydrogen Production. Water-requirements-for-hydrogen-production-January-2024.pdf
[14] LAMBOTTE, G. Carbon-free Iron for a Sustainable future | IEDO 2023 AMMTO & IEDO JOINT PEER REVIEW May 16th-18th,(2023) Washington, D.C.