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STRATEGIC VISION FOR DECARBONIZING GLOBAL INDUSTRY THROUGH EVIDENCE-BASED DIGITALIZATION

Modern industry significantly shapes both environmental outcomes and the advancement of global economies and societies. According to the Global Carbon Budget, approximately 70% of worldwide carbon dioxide emissions arise from four key industrial sectors: steel, cement, chemicals, and pulp and paper production [1]. Notably, the steel, cement, and chemicals sectors are now regulated under the EU's Carbon Border Adjustment Mechanism (CBAM), which places a carbon fee on imports. This policy targets the carbon intensity of imported goods, aiming to balance competitiveness while incentivizing emissions reductions. The pivotal role these sectors play in emissions highlights the urgent need for systemic changes and innovations in industrial processes to drive sustainable global development.

Russia's military aggression against Ukraine threatens energy-intensive industries, as they mostly rely on fossil fuels as an important raw material for energy generation. As Stoker shows, in the face of acute gas shortages, EU governments can take emergency measures to decide on its priority distribution, which are not always effective and lead to downtime [2]. Implementing low-carbon practices in industry, though crucial, presents formidable challenges, particularly due to the scale and intensity of industrial production processes. One promising avenue is hydrogen technology, which, while historically less economically viable than traditional energy sources, is gaining renewed interest. The tripling of natural gas prices from March 2021 to 2022 has spurred a reassessment of hydrogen production, positioning it as a potentially competitive alternative. This shift highlights how changing economic factors can accelerate the adoption of innovative solutions that were once considered too costly, opening new pathways toward sustainable industrial transformation.

Conversely, over the past decade, the industry has undergone a notable transition from conventional production to the provision of comprehensive product and service packages. This has resulted in the gradual dissolution of the distinction between the secondary and tertiary sectors, accompanied by an increase in technological intensity [3]. In this context, the growing scarcity of resources is perceived as a trend that may exert pressure on energy-intensive industries due to their substantial dependence on energy, which is still predominantly sourced from fossil fuels. This deficit is partially offset by the advent of digital technologies that offer efficacious alternative solutions, such as 3D printing. According to Hedberg, this trend is driving the transition of modern industry players from a focus on product acquisition to a focus on service acquisition [4].

It is beyond doubt that the decarbonisation of industry is of the utmost importance for ensuring the climate neutrality of the global economy. However, the European Commission's analysis [5] reveals that a significant proportion of the reduction in greenhouse gas emissions (by 15–30%) in energy-intensive industries over the past 30 years has been achieved through energy efficiency improvements rather than the transformation of production models. Concurrently, it is observed that further efficiency improvements necessitate the development of breakthrough technologies.

The role of digitalisation is becoming increasingly significant and promising [6]. This is evidenced by the global rise of smart manufacturing, where digital technologies are increasingly integrated into production processes to enhance efficiency, reduce waste, and lower emissions (Figure 1).

As can be observed, the global smart manufacturing market was valued at USD 254.24 billion in 2023 and is anticipated to expand at a compound annual growth rate (CAGR) of 14.9% between 2023 and 2030. The development of powerful trends such as Industry 4.0, cyber-physical systems and artificial intelligence has effectively led to the implementation of policies that drive the integration of manufacturing, information technology and innovation in the EU and globally. As Lu asserts, digital twins of industrial facilities play an important role in the double transition, assisting in the identification of the optimal environmental option for the development of production systems through modelling and forecasting [8].

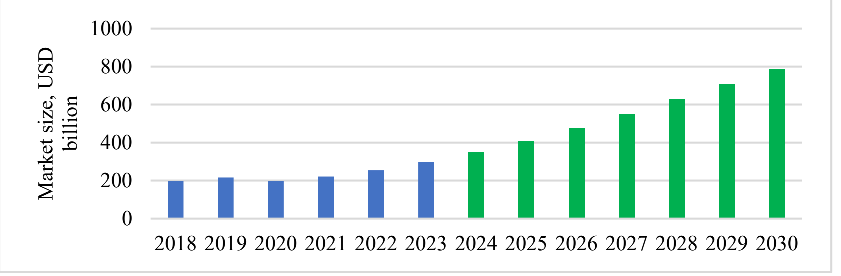

Figure 1. Forecast of smart manufacturing dynamics in the world

Source: based on statistics [7]

As the prospect of climate neutrality draws near, data-driven material optimisation represents a promising avenue for the green-digital transition of industry. This approach is based on the integration of artificial intelligence for big data analytics, machine learning, and the development of digital twins, which facilitate improvements to existing materials and processes, as well as the development of new generations of materials. As indicated in a report published by the European Commission, the demand for carbon-intensive materials is projected to increase by 10–30% by 2050, predominantly for the manufacture of cement, steel, fertilisers and aluminium [5]. The pursuit of climate-neutral industrial development necessitates the identification of environmentally benign alternatives and the prolongation of the lifespan of materials throughout the product life cycle. A study conducted by the team of American scientists [9] demonstrated that the development of new materials through traditional methods can span a period of up to 20–30 years. This considerably impedes the pace of technological innovation and its integration within industrial contexts. This delay could prove critical, given the urgency of adopting new green manufacturing practices to achieve climate neutrality by 2050. Digitalisation can help reduce the time required to develop new materials and assist in the management of the complexity of optimisation processes by incorporating environmental criteria into the calculation.

Another important area of the double transition in industry is the real-time digital tracking of materials. The EU is currently developing solutions for such tracking based on blockchain technology and the Internet of Things. In addition, digital product data sheets provide information on the full value chain of a product and thus increase transparency, which helps consumers make greener choices and facilitates recycling. Digital product data sheets can also be used by authorities to verify compliance with green standards.

Digital material traceability has great potential in achieving climate neutrality in industrial production. However, ensuring the competitiveness of recycled materials remains a debatable issue, as their environmentally friendly processing may have a higher 'green mark-up' compared to the cost of primary raw materials. Another problem is ensuring data security and confidentiality.

The twin transition of industry toward climate neutrality represents a multifaceted challenge, demanding robust support for research and innovation, the adoption of circular economy practices, and the establishment of comprehensive regulatory frameworks. Essential to this shift are also advanced information security protocols for tracking material flows, deeper insights into consumption patterns, and clear, measurable goal setting. Furthermore, fostering effective public-private partnerships is crucial to aligning resources, expertise, and commitment, ensuring that this transformative journey is both collaborative and impactful.

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