A general review on emission and consumption optimization

Georgiana I. Mariș

Department of Environmental Engineering and Protection, Faculty of Agriculture, University of Agricultural Sciences and Veterinary Medicine of Cluj-Napoca, Cluj-Napoca, Romania. Corresponding author: G. I. Mariș, georgimaris25@gmail.com

Abstract. This scientific review provides a comprehensive overview of emission and consumption optimization strategies across industrial, energy, and manufacturing systems. Based exclusively on peer-reviewed scientific literature, the article examines life cycle assessment methodologies, energy efficiency measures, digital optimization tools, and policy-driven approaches. The review emphasizes that isolated technological solutions are insufficient and that integrated, system-level strategies are essential to achieve long-term emission reductions and sustainable resource use.

Key Words: emission optimization, energy consumption, energy efficiency, life cycle assessment, sustainability, system-level approaches.

Introduction. Rapid industrialization and economic growth have resulted in increasing global energy demand and greenhouse gas emissions. The industrial sector is responsible for approximately one-third of global final energy consumption and a substantial share of carbon dioxide emissions. Consequently, optimizing both emissions and resource consumption has become a critical research priority in sustainability science and industrial ecology.

Conceptual framework of emission and consumption optimization. Emission optimization focuses on reducing greenhouse gas emissions through technological, operational, and systemic interventions, while consumption optimization aims to minimize energy and material inputs per unit of output. Scientific literature emphasizes that these concepts are interdependent and must be addressed simultaneously to avoid limited or misleading sustainability outcomes.

Consumption optimization focuses on the efficient use of energy and material resources to achieve the same level of output with minimized inputs. This entails improving energy efficiency in production systems, optimizing service delivery processes, and reducing waste - concepts foundational to sustainable engineering practices (Corlu et al 2020).

Recent scholarly discourse emphasizes that these two strands (emission reduction and consumption efficiency) are deeply interconnected (York & McGee 2016; Stern 2020; Lange et al 2021; York et al 2022; Segovia-Martín et al 2023). Attempts to reduce emissions in isolation can lead to suboptimal outcomes if energy and material consumption are not co-optimized (Arrobbio & Padovan 2018; Trincado et al 2021; Fich et al 2022; York et al 2022; Segovia-Martín et al 2023); for example, efficiency gains in energy use that trigger increased demand can offset emission reductions, a phenomenon conceptually related to the rebound effect described in environmental economics (Jevons paradox) (Jevons 1865/modern interpretations - Paul et al 2019; Stern 2020; Lange et al 2021; Wang et al 2022; York et al 2022).

Life cycle assessment as an optimization tool. Life Cycle Assessment (LCA), standardized under ISO 14040 and ISO 14044, is widely applied to quantify environmental impacts across the entire life cycle of products and systems. LCA enables identification of emission hotspots and supports informed decision-making when comparing alternative technologies or process configurations (Finkbeiner et al 2006; Arvanitoyannis 2008).

LCA serves as a critical optimization tool for industries aiming to improve sustainability performance. It allows decision-makers to compare alternative technologies, materials, and process configurations based on their full environmental footprint, rather than focusing solely on operational emissions. For example, switching from conventional materials to recycled or bio-based alternatives can significantly reduce energy use and GHG emissions when evaluated over the complete life cycle (Guinée et al 2004).

Beyond environmental assessment, LCA can be integrated with multi-objective optimization models to balance trade-offs between emissions, energy consumption, cost, and other performance criteria. Such integration enables companies to identify solutions that achieve the best overall sustainability outcomes rather than suboptimal improvements in a single dimension (Finkbeiner et al 2006).

Energy consumption optimization in industrial systems. Industrial energy consumption is dominated by process heating, electricity use, and mechanical operations (Trianni et al 2019; Maghrabi et al 2023; Veronezi et al 2024). Studies demonstrate that energy efficiency measures such as process integration, heat recovery, and advanced motor systems can reduce industrial energy demand by 20-30%, providing both environmental and economic benefits (Trianni et al 2019; Errigo et al 2022; Lee & Chen 2023; Maghrabi et al 2023).

Energy efficiency improvements often target the reduction of waste energy streams and the enhancement of system performance through energy integration techniques like heat exchanger networks. By capturing and reusing heat that would otherwise be lost, industries can lower the need for external utility inputs and improve overall energy utilization. For example, mathematical optimization of heat recovery networks has demonstrated steam savings and reduced utility consumption in chemical production processes, underscoring the potential for practical application of these methods in real industrial settings (Lee & Chen 2023).

Emission reduction strategies in manufacturing. Manufacturing-related emissions originate primarily from fossil fuel combustion and material processing. Research identifies electrification, fuel switching, and material efficiency improvements as key mitigation strategies, with effectiveness strongly dependent on the carbon intensity of the electricity supply (Allwood et al 2010).

Fuel switching is another critical approach, involving the replacement of high-carbon fuels such as coal and oil with lower-carbon alternatives like natural gas, biomass, or hydrogen (Wilson & Staffell 2018; Rehfeldt et al 2020; Megía et al 2021; Osman et al 2021; Brás et al 2025). This strategy not only reduces direct CO_2 emissions but also provides opportunities for improved energy efficiency when coupled with modern combustion technologies (Wilson & Staffell 2018; Rehfeldt et al 2020; Roman-White et al 2021; Molina et al 2023; Taghavifar & Perera 2023; Brás et al 2025). LCA indicates that fuel switching can reduce process-related emissions by 20-50%, depending on the technology and fuel mix used (Pérez-Camacho et al 2019; Babaee et al 2020; Roman-White et al 2021; Alengebawy et al 2022; Taghavifar & Perera 2023; Brás et al 2025).

Role of digitalization and process optimization. Digital technologies, including artificial intelligence, digital twins, and real-time monitoring systems, enable precise optimization of industrial processes. These tools reduce energy losses, improve operational efficiency, and support predictive maintenance, resulting in measurable reductions in emissions and resource consumption.

Digitalization supports process integration and multi-objective optimization by combining operational data with life cycle and sustainability metrics. By integrating energy, material, and emissions data, industries can identify the most effective strategies to reduce environmental impacts while maintaining productivity. These approaches also enable benchmarking, scenario analysis, and continuous monitoring, ensuring that optimization measures are both scalable and sustainable.

Renewable energy integration. The integration of renewable energy sources such as solar and wind power into industrial systems represents a critical pathway for emission reduction. When combined with electrification strategies, renewable energy can significantly reduce dependence on fossil fuels, although variability requires flexible system design and energy storage solutions (Creutzig et al 2018).

System flexibility and energy storage are critical components of renewable integration. Variability in solar and wind generation requires the implementation of battery storage, demand-side management, or hybrid energy systems to maintain reliable and continuous industrial operations. Advanced control systems and digital optimization tools can coordinate energy generation, storage, and consumption in real time, maximizing renewable energy utilization while minimizing operational disruptions.

Policy instruments and regulatory frameworks. Policy instruments including carbon pricing, energy efficiency standards, and emission trading schemes play a central role in driving emission and consumption optimization. Coordinated regulatory frameworks are essential to ensure long-term investment certainty and prevent burden shifting between sectors.

Carbon pricing mechanisms, including carbon taxes and cap-and-trade systems, place a direct economic cost on greenhouse gas emissions, encouraging industries to reduce emissions where it is most cost-effective. By internalizing the environmental externalities associated with fossil fuel use, carbon pricing not only motivates technological upgrades but also incentivizes operational efficiency and fuel switching.

System-level optimization approaches. System-level optimization considers interactions between energy systems, material flows, and economic structures. Integrated strategies combining energy efficiency, renewable energy, recycling, and digital optimization consistently outperform single-technology solutions in reducing emissions and resource consumption (Creutzig et al 2018).

Material flow optimization is another critical component. By analyzing the life cycle of materials from extraction to end-of-life, industries can implement strategies such as recycling, reuse, and substitution with lower-impact materials. This reduces the environmental burden of resource extraction and processing while complementing energy optimization measures, achieving a dual benefit in both emission and consumption reduction (Allwood et al 2010).

Digital and computational tools play a key role in system-level approaches. Advanced modeling, simulation, and artificial intelligence allow decision-makers to identify optimal configurations of industrial processes, energy networks, and material loops. Multi-objective optimization frameworks can balance conflicting goals such as cost, energy efficiency, emissions reduction, and resource utilization, producing Pareto-optimal solutions that would be impossible to identify through conventional methods.

Challenges and limitations. Despite technological progress, emission and consumption optimization faces challenges related to data uncertainty, infrastructure constraints, and rebound effects. Scientific literature highlights the importance of transparent assessment methodologies and interdisciplinary collaboration to overcome these limitations.

Infrastructure constraints also pose a significant limitation. Many industrial systems and urban energy networks were designed for conventional fossil fuel-based operations, making it difficult to implement advanced efficiency measures or integrate renewable energy sources. Retrofitting existing infrastructure requires substantial capital investment, planning, and coordination, which can delay or limit the adoption of optimized technologies.

Interdisciplinary collaboration is necessary to overcome these limitations. Emission and consumption optimization often require expertise in engineering, environmental science, economics, and policy. Collaboration across these disciplines helps integrate technical solutions with regulatory frameworks, economic incentives, and societal behavior considerations, ensuring that optimization strategies are both feasible and sustainable.

Conclusions. This review shows that effective emission and consumption optimization requires holistic, system-level thinking. Life cycle assessment provides a robust analytical foundation, while integrated technological and policy strategies enable substantial and sustainable emission reductions across industrial systems.

Conflict of interest. The author declares that there is no conflict of interest.

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Author:
Georgiana-Iulia Mariș, Department of Environmental Engineering and Protection, Faculty of Agriculture, University of Agricultural Sciences and Veterinary Medicine of Cluj-Napoca, 3-5 Calea Mănăştur Street, 400372 Cluj-Napoca, Romania, e-mail: georgimaris25@gmail.com

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