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Review

Role of energy value chain in carbon neutrality: A review

Zheng Luo[1,2], Xiaojie Lin[1,2,*], Yanling Wu[1,2,*], Wei Zhong[1,2]

[1] College of Energy Engineering, Zhejiang University, Hangzhou 310058, Zhejiang Province, China
[2] Shanghai Institute for Advanced Study, Zhejiang University, Shanghai 201203, China
*** Corresponding author:** Xiaojie Lin, xiaojie.lin@zju.edu.cn; Yanling Wu, shelleywu@zju.edu.cn

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Abstract: Value chain analysis is an important tool for optimizing operations and decision-making in enterprises. As the concept of sustainable development gains recognition worldwide, research on value chains is increasingly focused on sustainability. Traditionally, energy management and value management have operated in parallel with limited intersections. However, after the 2015 Paris Agreement set the goal of achieving net-zero emissions, carbon management has become integral to national strategies, necessitating a re-evaluation of traditional value chains. In this paper, the "energy value chain" is introduced, a novel concept that integrates energy consumption with value creation and carbon emissions, emphasizing the coupling relationships among "energy flow", "value flow", and "carbon flow." From a review of current value chains in the power, steel, petroleum, and transportation industries, the specific energy value chain for each industry is defined and its rationale and effectiveness are discussed. This integrated analytical method provides a strategic tool for industries or enterprises to optimize energy consumption, reduce carbon emissions, and enhance competitive advantage.

Keywords: energy value chain; energy consumption; value creation; carbon emissions

1. Introduction

The history of human development can be simply described as a history of energy utilization. However, as natural resources become increasingly depleted, the management of energy consumption is becoming more and more refined. Governments and relevant organizations worldwide have implemented policies to limit energy consumption. In 2017, The European Union introduced the "Energy Efficiency Directive", which aims to prompt member states to set efficiency targets to promote efficient energy consumption [1]. In 2015, China proposed evaluating national energy consumption based on the total amount and intensity of energy consumption [2]. In this wave, enterprises, as both policy implementers and innovation leaders, are also making their efforts. For example, Siemens developed the SIMATIC energy management software, which integrates all functions from data recording to energy analysis, effectively helping customers reduce energy costs and improve energy efficiency [3]. Schneider Electric's EcoStruxure platform integrates the Internet of Things, sensors, and cloud computing technologies to achieve intelligent energy management and optimization [4]. Global efforts are being made to enhance the efficient and clean use of energy.

The value chain was introduced by Porter in 1985 [5]. The value chain points out that the competitive advantage of enterprises is not only from the external market environment but also from the organization and management of internal activities. These activities, which include every activity from raw material procurement to production, and from sales to after-sales service, constitute a value-creating process known as the value chain. Through value chain analysis, enterprises can identify activities advantageous or to be improved to achieve long-term competitive advantage. As competition among enterprises intensified and market demands became more complex, value chain analysis has expanded from individual enterprises to entire industries. Enterprises began to recognize that optimization across the entire industry value chain, not just internally, could yield greater competitive advantages. For example, the collaboration between automakers and parts suppliers in the automotive industry exemplifies the application of this broader value chain perspective [6,7]. With the advent of economic globalization, production activities have increasingly globalized, and value chain analysis has extended from local industries to a global scale. The concept of the global value chain (GVC) has gradually gained widespread acceptance [8]. GVC focuses on the production, distribution, and consumption of products and services on a global scale. GVC analysis emphasizes the division of labor and cooperation among different countries and regions within the global production network. Researchers and policymakers are now focusing on how to enhance national or regional economic competitiveness through the GVC and how to achieve higher added value within the GVC.

The global energy and climate crises have underscored the need for industries to prioritize clean, efficient, and sustainable development. As a response, the field of value chain research has introduced various concepts, such as the sustainable value chain, which emphasizes not only value creation but also the conservation and efficient use of resources to ensure long-term sustainability. Energy management, an essential component of sustainable development, is increasingly recognized as critical in supporting these efforts. However, most corporate energy management strategies remain focused on energy costs, lacking the strategic depth needed to examine how energy consumption actively contributes to value creation. While some studies have attempted to merge value chain analysis with energy sector applications [9–11], these research works often remain superficial, focusing on basic applications rather than delving into the complex role of energy consumption in value creation. Specifically, they fail to adequately explore the relationship between "energy flow" and "value flow". The lack of a comprehensive analytical framework to integrate these two critical flows represents a significant gap in current research.

With the advent of global warming and the establishment of the United Nations' Social Development Goals, carbon has become a crucial factor in industrial and enterprise development. Various countries have implemented policies to protect the environment. Against this background, carbon emission management has also gradually been incorporated into value chain management [12–14]. For instance, the European Union's "Eco-design for Sustainable Products Regulation" imposes restrictions on the carbon footprint of all products placed on the market or put into use [15]. Under the management pressures of energy, carbon, and value, an integrated approach that combines carbon flow, energy flow, and value flow is required. However, effective joint analytical methods to support multi-objective management have not yet emerged. In this study, through a review of relevant research, the "energy value chain", a new framework that unifies these flows, has been defined, serving as a strategic tool to optimize operations in a carbon-constrained economy.

The structure of this paper is as follows. Section 1 outlines the background for the concept of the energy value chain, and the current state of energy management and carbon management within the value chain is briefly introduced. The feasibility of energy flow–value flow–carbon flow multi-perspective analysis is also analyzed.

In Section 2, drawing from existing research, the specific definition of the energy value chain is presented, based on the perspective that energy consumption supports value creation. The significance of the energy value chain from the viewpoints of different stakeholders is analyzed.

In Section 3, more specific energy value chains for different industries due to the unique energy consumption processes, production workflows, and supply chain structures are proposed. The role played by the energy value chain within these industries is also examined.

In Section 4, the analysis of the energy value chain concept is examined and more specific methodologies for energy value chain management are presented.

2. Definition and significance of energy value chain

2.1. Definition of energy value chain

The structure of both the traditional value chain and energy value chain is fundamentally similar, as both describe the process of raw material purchase-production-sales. However, compared with the traditional value chain, which focuses solely on the value flow, the energy value chain emphasizes the supporting role of energy consumption in value-creating activities. It places greater emphasis on the interaction between energy flow, value flow, and carbon flow [16–18]. Compared with energy flow and value flow, the definition of carbon flow is vaguer. In this study, the definition of carbon flow specifically refers to the movement of carbon emissions within the energy network. This carbon flow is represented as a virtual network that mirrors the topology of the energy network. Unlike the tangible parameters in an energy network—where nodes and branches correspond to energy consumers/producers and transport parameters, such as voltage, hydraulic pressure, or temperature—in this virtual carbon network, nodes represent carbon emissions associated with energy consumption and production, while branches represent emissions linked to energy transport.

Drawing from the development patterns of the traditional value chain from enterprises to industries and considering the differing interests of stakeholders at various levels, the research objects of the energy value chain in this research were divided into industry and enterprise. Based on these objects, the energy value chain was defined in two ways: general and special. The specific definitions are as follows:

1) **General energy value chain:** Consider an industry as a whole, its energy value chain encompasses all value-creating and transferring activities supported by energy consumption, from the extraction of basic raw materials to the formation of the final consumer products. In the general energy value chain, enterprises or even clusters of enterprises are viewed as the conversion hubs for energy flow, value flow, and carbon flow, which create and transfer value, as shown in **Figure 1**.

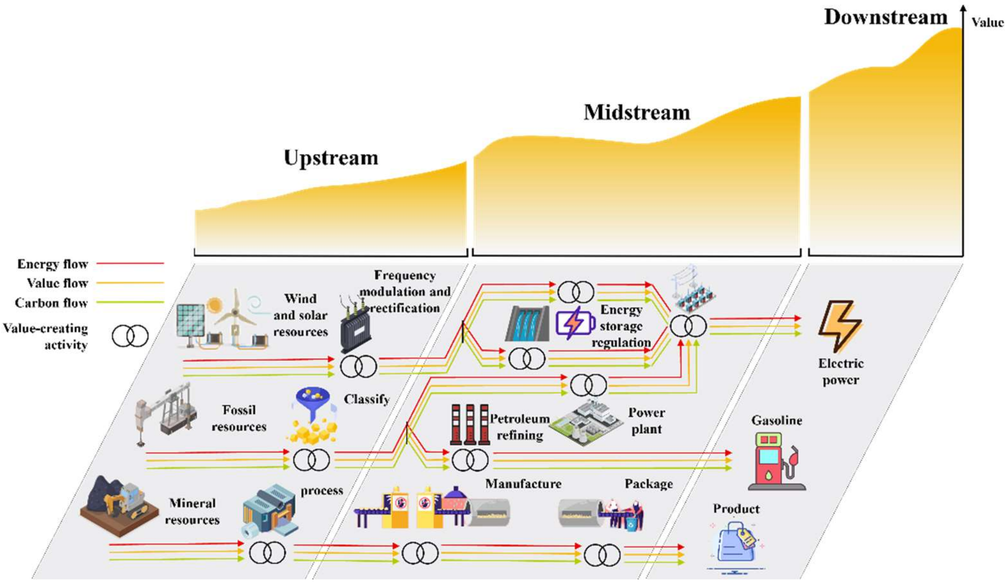

Figure 1. General diagram of energy value chain.

2) **Special energy value chain:** This energy value chain focuses on midstream enterprises with high energy consumption and intensive value-creating activities. It considers the enterprise as a whole, encompassing all activities that create and transfer value supported by energy consumption, from the purchase of raw materials to the formation of the final product. In the special energy value chain, the different activities of the production process are viewed as the conversion hubs for energy flow, value flow, and carbon flow—activities that create and transfer value. Compared with the traditional value chain, there are some differences in the "upstream-midstream-downstream" segments for the energy value chain, as outlined below [17,19]:

- **Upstream:** In traditional value chains, upstream activities usually focus on the extraction and supply of raw materials. However, the energy value chain expands this by integrating the production processes of energy-related products and services. Besides conventional raw materials, this also includes renewable energy sources, such as wind and solar power. The acquisition of these materials involves specific extraction processes, which are fundamental to the subsequent stages of energy production. In this study, to simplify the presentation and focus on the core components of the energy value chain, interactions between industries, specifically power, petroleum, and manufacturing industries, were streamlined to emphasize the distinct processes within each industry.
- **Midstream:** The midstream stage in the energy value chain primarily concerns the generation and conversion of energy, which introduces a high degree of technical complexity. This stage relies on specialized infrastructure, such as power plants, and is governed by physical principles, such as the second law of thermodynamics, which sets limits on efficiency. Such technical constraints mark a significant divergence from midstream operations in traditional value chains, which are generally less constrained by physical laws and focus more on the transformation of raw materials.

- **Downstream:** While traditional value chains focus on the distribution of physical goods, the downstream stage of the energy value chain deals with energy commodities, such as electricity and natural gas, which present unique challenges due to their storage limitations. This stage requires a delicate balance between supply and demand and involves sophisticated management systems to ensure stability, contrasting with the traditional focus on warehousing and logistics.

2.2. Significance of energy value chain

An analysis of the energy value chain targets different stakeholders, and the roles and significance of the energy value chain for each stakeholder are not yet fully clear. In this section, the roles and significance of the energy value chain from the perspectives of enterprises, industries, governments, and the global carbon neutrality goal are discussed in detail.

1) **Enterprises:** Historically, enterprises have often considered energy flow, value flow, and carbon flow in isolation, neglecting the influence of the enterprise as a link in the industry on the coupling of these flows. A general analysis of the energy value chain can precisely locate an enterprise's interaction within its industry's energy flow, value flow, and "carbon flow, thereby fully uncovering the enterprise's advantages and fostering differential competitive strength [17,20,21]. The special energy value chain provides a tool to analyze value-creation and energy-consumption processes of various activities, such as conversion, manufacturing, transportation, storage, and sales of raw materials. By analyzing these processes, enterprises can accurately identify key value-creation activities, low energy-efficiency activities, and high carbon emission activities. This analysis supports strategic decision-making, optimizes value chain configuration, and enhances competitiveness [17,20,21].
2) **Industries:** Under the threat of a global energy crisis, countries around the world are actively seeking cleaner, more sustainable energy (e.g., hydrogen and nuclear energy). The acceleration of this process necessitates continuous updates and iterations of energy consumption structures across various industries. In this context, the energy value chain can guide the energy consumption structure transformation of different industries from the perspective of energy flow, carbon flow, and value flow [19,20,22].
3) **Governments:** Firstly, energy value chain analysis can guide governments in identifying potential fields for resource conservation or pollution reduction, which is increasingly important in the context of environmental sustainability and climate change [16,17,22,23]. Secondly, from an economic perspective, the energy value chain can help developing countries identify opportunities to capture a larger share of added value. This is particularly crucial for countries currently engaged in low-value, labor-intensive manufacturing, as it can help them avoid being trapped in low-value segments of the value chain [16,17,22,23]. Finally, understanding the energy value chain can assist governments in formulating policies, including environmental regulations and taxation, that influence the scale, shape, and form of industry value chains [16,17,22,23].

4) **Global carbon neutrality goals:** The development of the energy value chain can contribute in several ways. Firstly, optimizing the energy value chain can support enhanced energy efficiency, significantly reducing carbon emissions. As proposed by Liu et al. [24], improving energy and environmental efficiency in a positive feedback loop can provide insights from a global value chain perspective. Secondly, the clean energy driven by the energy value chain also aids in achieving carbon neutrality. For instance, the structural decline in China's CO_2 emissions is attributed to transformations in industrial and energy systems [25]. Thirdly, as suggested by Cai et al. [26], the development of the energy value chain can involve implementing stricter environmental regulations, optimizing energy structures, and improving energy efficiency. This helps reduce the net emissions embedded in trade, particularly for economies with high carbon emissions. Finally, the role of global value chains in the CO_2 emission growth of both developed and emerging economies is also significant. Therefore, understanding and developing these carbon-emission-reduction-focused value chains can help achieve global carbon neutrality goals.

3. Energy value chain in various industries

Compared with the special energy value chain, the general energy value chain supports a comprehensive analysis at the industry level, making conclusions more applicable across different industries. The general energy value chain includes multiple stakeholders, such as governments, industries, and enterprises. A key issue addressed in this research is how the energy value chain benefits every industry. Therefore, in the following text, the energy value chain refers to the general energy value chain.

Additionally, due to differences in energy consumption structures across various industries, using a single, generic energy value chain for analysis is impractical. Developing specific energy value chains applicable to various industries holds deeper significance for the following reasons [22,27,28]:

1) **Diverse production processes:** Different industries involve various types of energy consumption and production. A single energy value chain is insufficient for the detailed management of energy flow and value flow required by each industry.
2) **Energy transition:** The global energy crisis has accelerated the shift from fossil fuels to renewable energy. This transition often introduces volatility in energy supply. Developing a specific energy value chain for each industry allows for a thorough analysis of energy consumption and the importance of each segment, enabling the selection of more stable fossil fuels or cleaner renewable energy sources to structure the energy value chain.
3) **Energy security and efficiency:** Specific energy value chains in different industries can help address the impossible trinity of ensuring energy security, economic growth, and efficiency. This is particularly crucial in the context of the rapid expansion of the digital economy, which requires exploring digital governance in the energy industry, supply chains, and value chains.

In this study, the power industry, steel industry, petroleum industry, and transportation industry—four industries that contribute the most to global carbon emissions and have the highest energy consumption and carbon emission density—were selected as research objects [29]. The significance and role of the energy value chain in these industries is discussed.

3.1. Power industry

For the power industry, a complete value chain encompassing the four segments of source-network-load-storage has been developed. Based on this, an exclusive and detailed energy value chain for the power industry was further developed [30–32], as shown in **Figure 2**.

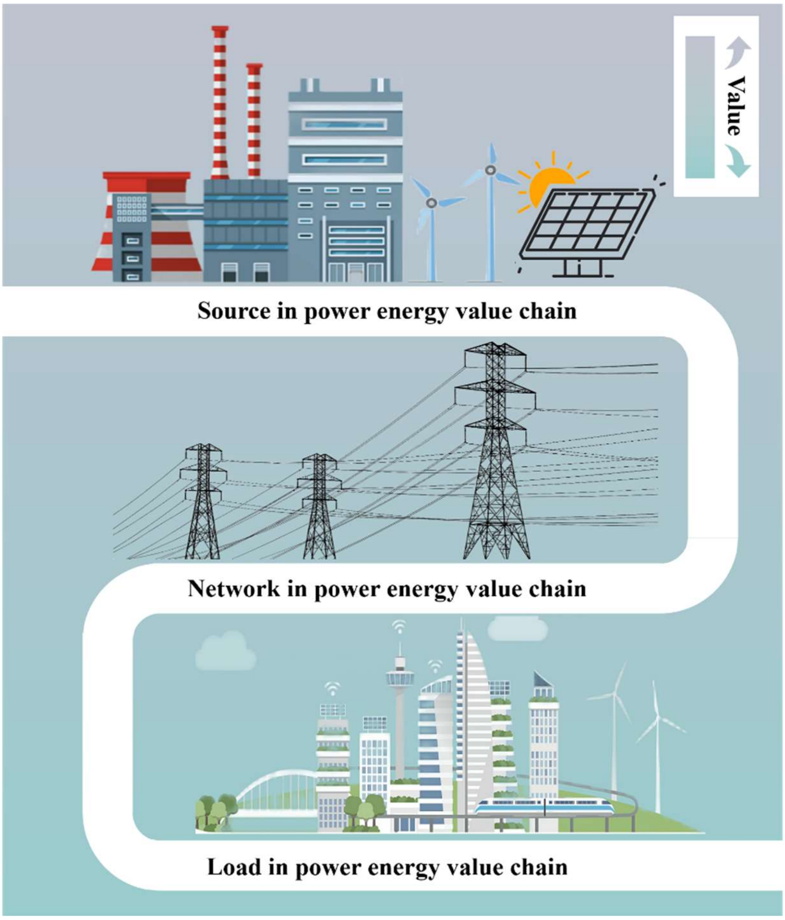

Figure 2. Power industry's energy value chain.

1) **Source:** This is the initial segment of the power industry's energy value chain, primarily responsible for energy production. Activities in this segment include the extraction of raw materials (such as coal, natural gas, or oil), the utilization of renewable energy sources (such as solar and wind power), and electricity generation (such as coal-fired power plants, nuclear power plants, and hydroelectric plants). Enterprises in this segment mainly include owners or managers of coal mines, oil fields, and power plants.
2) **Network:** This segment is mainly responsible for the transmission and distribution of electricity. The structure of the power grid can vary by country and is generally divided into centralized and decentralized models. Enterprises in

this segment primarily include the owners or managers of these power grids.

3) **Load:** This segment primarily consumes energy. It involves the use of energy by end-users in industries, transportation, buildings, etc. This segment comprises a complex array of enterprises, virtually encompassing all businesses.
4) **Storage:** This segment involves energy storage. Energy storage is not confined to a specific segment and can exist across all source-network-load segments. Each entity may deploy different types of energy storage for various purposes.

One of the primary objectives of the energy value chain is to identify activities that create the most value across the chain. Traditionally, in the power industry, the source segment has been the central value-creating node. However, with the rise of innovations in distributed energy generation and storage technologies, the power industry's energy value chain is undergoing a fundamental transformation. Technologies, such as distributed generation, energy storage systems, and electric vehicles (EVs), are playing increasingly vital roles in value creation and resource management. This shift in focus from the source segment to the load segment signifies a redistribution of value across the chain, altering the conventional understanding of where value is created [30].

This transformation is driven by several forces, including the growing need for carbon neutrality and global energy transition to cleaner sources. As the power industry is responsible for a significant share of global carbon emissions, the energy value chain presents a strategic framework to align decarbonization goals with economic efficiency. Notably, the integration of innovative technologies, such as smart metering, distributed generators, and virtual power plants, alongside the deep incorporation of energy storage and EVs, offers new pathways to decarbonization and efficiency improvements [33]. These innovations not only optimize energy distribution and reduce wastage but also help in aligning the energy sector with net-zero carbon targets. Furthermore, the digitalization of the energy industry is facilitating new business models that leverage the exponentially increasing data within power networks, further enabling consumer participation in energy optimization efforts [34].

The urgency for net-zero transformation in the power sector is compounded by its significant carbon intensity. A comprehensive energy value chain analysis focused on the interactions between energy flow, value flow, and carbon flow can provide unique insights into how different segments of the chain contribute to carbon emissions. One critical mechanism enabled by the value chain is the concept of counter-flow, where consumers, particularly those with renewable energy sources, feed excess energy back into the grid. This process, made possible by the proliferation of distributed energy resources, not only decreases reliance on fossil fuels but also leads to net carbon reductions when the energy fed into the grid exceeds consumption [34].

Additionally, the energy value chain can serve as a blueprint for the replacement of high-carbon processes with low-carbon alternatives. For example, integrating smart grid technology enhances energy efficiency by optimizing electricity distribution, reducing energy losses, and consequently lowering carbon emissions [31]. Beyond technology, the energy value chain can identify high-carbon segments within the power industry, allowing policymakers and industry leaders to target and gradually phase out or simplify carbon-intensive processes, contributing directly to carbon neutrality goals.

While value creation has historically centered on maximizing efficiency and economic gains, the energy value chain provides a holistic framework to balance these objectives with sustainability and carbon reduction. For instance, energy value chain analysis highlights the critical role of information and communications technology in improving operational efficiency and asset management. As an example, Tokyo Electric Power Company has integrated blockchain technology to manage electricity flows more effectively, improving the efficiency of energy distribution and significantly reducing costs [35].

Moreover, the energy value chain's emphasis on resource integration and allocation is crucial for minimizing operational costs, while contributing to carbon reduction. The inclusion of distributed generators in virtual power plants, the development of smart meters, and the integration of EVs not only streamline production processes but also enhance the power sector's ability to achieve carbon neutrality [36]. Through such initiatives, the entire energy value chain undergoes a shift, as the digitalization of processes and the advancement of clean technologies reshape the landscape of value creation, aligning it with global decarbonization goals.

3.2. Steel industry

From a thorough examination of the value chain and smelting process of the steel industry, the steel industry's energy value chain was proposed to be divided into several key segments, defined as follows [37–39], as shown in **Figure 3**:

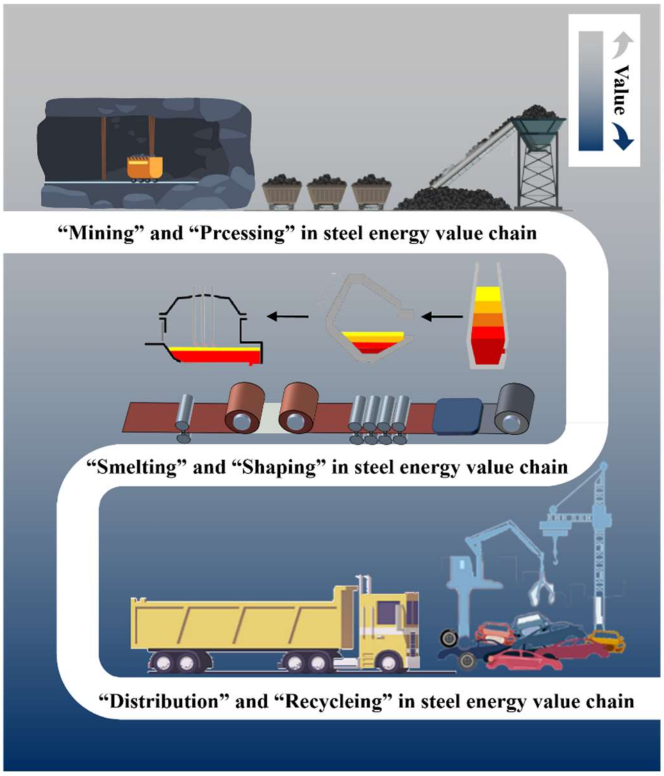

Figure 3. Steel industry's energy value chain.

1) **Mining:** The first step in the steel industry's energy value chain involves the extraction of raw materials, primarily iron ore and coal. This process is energy-intensive and requires the use of heavy machinery for mining and transportation, with the main energy consumption being electricity.
2) **Processing:** The raw materials are then processed into forms suitable for steel production. This includes crushing and washing iron ore and coking coal to produce coke. Both processes require significant amounts of energy, primarily in the form of heat.
3) **Smelting:** The processed materials are used to produce steel. This is usually done in a blast furnace, where iron ore is reduced to iron by burning coke in the presence of limestone. The iron is then converted into steel in a basic oxygen furnace. Both processes are energy-intensive, requiring substantial amounts of heat (from coal combustion) and electricity.
4) **Shaping:** The steel is then shaped into various forms, such as sheets, rods, or beams. This is done through various processes, such as rolling, forging, or extrusion, all of which primarily use electricity.
5) **Distribution:** The final products are distributed for use in various industries. Although this segment is less energy-intensive than the previous segments, it includes interaction with the transport industry.
6) **Recycling:** Finally, steel can be recycled at the end of its lifecycle, reducing the demand for new raw materials and the energy needed to extract and process them. This includes collecting and sorting scrap steel and then melting and reshaping it.

The steel industry presents substantial opportunities for energy savings across every segment of its energy value chain, making it a critical area for achieving carbon neutrality. Through an in-depth review of research on the energy value chain, it becomes evident that each segment holds untapped potential for both energy optimization and carbon reduction.

The first segment of the steel industry's energy value chain involves the extraction and processing of raw materials, such as iron ore and coal, which are particularly energy-intensive. This phase offers significant potential for reducing energy consumption and minimizing carbon emissions. Material flow analysis, as discussed by Panasiyk et al. [40] and Michaelis and Jackson [41,42], demonstrates that energy value chain analysis can identify inefficiencies in both material and energy use. These inefficiencies represent not only opportunities for cost reduction but also essential leverage points for reducing the carbon footprint of the industry. By focusing on this segment, energy value chain analysis contributes directly to the broader goal of carbon neutrality by highlighting areas where energy inputs can be reduced, thus lowering associated emissions.

The second major segment is smelting, where energy waste is pervasive, particularly in the form of waste heat. Smelting is one of the most carbon-intensive processes in steel production due to the high energy demands for melting iron and removing impurities. Energy value chain analysis allows for systematic quantification of energy waste in each production activity, thereby providing actionable insights for deploying energy recovery technologies. These technologies, such as waste heat recovery, not only cut down energy usage but also contribute to substantial reductions in carbon emissions by enhancing overall energy efficiency [38].

The final segment of the steel industry's energy value chain covers the distribution and use of finished steel products. In this stage, energy costs and emissions can be further minimized through the optimization of logistics and transportation, as well as by encouraging the recycling and reuse of steel. Recycling, in particular, plays a pivotal role in reducing the demand for energy-intensive primary steel production, thus cutting emissions across the value chain. By promoting a circular economy within the steel industry, energy value chain analysis helps to reduce both energy consumption and carbon emissions over its products' lifecycle.

Compared with the power industry, which tends to have strong regional characteristics, the steel industry is more vulnerable to international energy market conditions and policies. Energy value chain analysis becomes essential for managing these global risks and uncertainties. First, it enables the steel industry to better understand international trade dynamics, particularly regarding the energy inputs essential for production. By mapping out key factors affecting energy costs and availability, the energy value chain equips the industry with the tools to anticipate and respond to changes in international trade policies that may disrupt energy supply. In this regard, energy value chain analysis serves as a foundation for creating more resilient and adaptive strategies, ultimately contributing to the industry's long-term carbon reduction goals.

Furthermore, energy value chain analysis helps the steel industry navigate the complexities of global energy distribution, especially in terms of geopolitical risks. For example, if energy supplies originate from regions with unstable political or economic conditions, the analysis can help steel companies diversify their energy sources or enhance energy efficiency as a risk mitigation strategy. Such strategies not only secure energy supplies but also reduce reliance on carbon-heavy energy sources, thus advancing carbon neutrality efforts.

Finally, the energy value chain is instrumental in guiding the steel industry through global policy trends, particularly those related to energy and climate change. As governments worldwide adopt stricter carbon regulations, industries must adapt to increasingly stringent environmental standards. By understanding the flow of energy and carbon within the value chain, steel manufacturers can develop proactive strategies, such as investing in carbon-reducing technologies, to align with regulatory trends and mitigate rising costs associated with carbon emissions [38,43]. This anticipatory approach ensures that the industry not only complies with global decarbonization policies but also plays an active role in advancing carbon neutrality.

3.3. Petroleum industry

Through a comprehensive review of the petroleum industry, the petroleum industry's energy value chain was defined as follows [44,45], as shown in **Figure 4**:

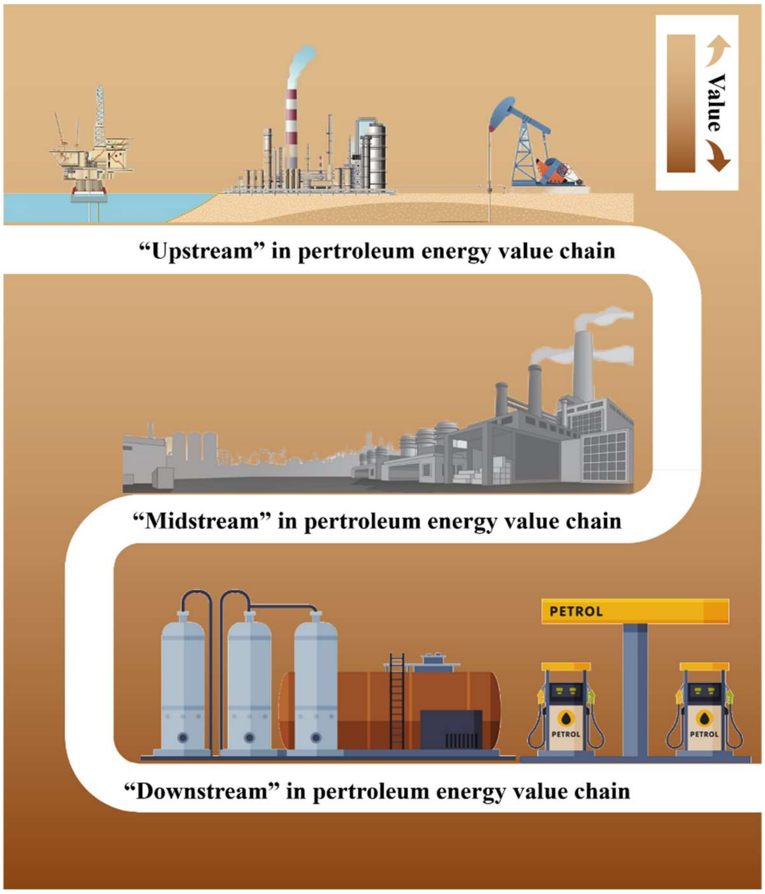

Figure 4. Petroleum industry's energy value chain.

1) **Upstream:** This is the first segment of the petroleum industry's energy value chain, involving the exploration, development, and production of crude oil or natural gas. Exploration includes identifying rock layers associated with oil or gas deposits and conducting geological surveys and seismic tests at potential sites. Development is the construction phase, during which wells are drilled and natural gas reservoirs are prepared for extraction. Production is the extraction segment, where crude oil or natural gas is extracted from underground.
2) **Midstream:** This segment involves the transportation, storage, and wholesale marketing of crude oil or refined petroleum products. Pipelines, trucks, ships, and railways are often used to transport oil and gas to various locations. Storage facilities are used to hold large quantities of oil and gas, and wholesale marketing includes selling petroleum products to distributors.
3) **Downstream:** This is the final segment of the petroleum industry's energy value chain, involving the refining of crude oil and the processing and purification of raw natural gas. It also includes the marketing and distribution of products derived from petroleum. The downstream sector reaches consumers through various products, such as gasoline, kerosene, jet fuel, diesel, heating oil, fuel oil, lubricants, waxes, asphalt, natural gas, and liquefied petroleum gas.

The petroleum industry, as a critical global resource, faces heightened risks from international conditions, more so than industries such as the steel industry, due to its direct exposure to geopolitical and market fluctuations. The energy value chain framework offers a strategic lens through which the industry can navigate these complexities, particularly in addressing the dual challenge of market adaptation and carbon neutrality. Firstly, the energy value chain facilitates the alignment of innovation resources with evolving market demands, such as the growing emphasis on renewable energy and sustainability. This alignment might involve improving refining efficiency or developing new products that are consistent with the global shift toward clean energy. By leveraging the energy value chain, the petroleum industry can diversify its portfolio, incorporating renewable energy sources to reduce its dependence on oil and gas, thus mitigating risks associated with political and economic instability.

In addition to diversification, the energy value chain can guide the industry in restructuring its business models to manage inherent risks more effectively. This restructuring could include investing in infrastructure resilience, securing supply chains, and developing contingency plans to address potential disruptions. For instance, by identifying bottlenecks within the energy flow, the industry can implement proactive risk management strategies that buffer it against global volatility. Furthermore, the global push towards climate mitigation presents opportunities for the industry to innovate by adopting renewable energy technologies, such as wind, solar PV, and bioenergy, which are becoming increasingly mainstream [28,46].

The ongoing development of EVs further amplifies the decoupling of the petroleum and transportation industries, compelling the petroleum sector to undergo significant transformation. The petroleum industry's energy value chain provides a robust strategic framework to facilitate this transition, enabling the industry to adapt to and capitalize on the growing dominance of EVs. One critical aspect of this adaptation involves using carbon flow analysis within the energy value chain to assess the feasibility of integrating biofuels, hydrogen, and electricity into various segments. By promoting diversified energy alternatives, the energy value chain can guide the petroleum industry toward a low-carbon, sustainable future [46].

Moreover, the energy value chain helps to redirect value flows toward the EVs' energy ecosystem. For example, petroleum companies can leverage their extensive infrastructure to support the development of clean energy for EV charging stations. This not only creates new revenue streams but also positions the industry as a key player in the transition to a low-carbon economy. By repurposing existing assets and expertise, the industry can retain relevance in a rapidly transforming energy landscape, playing an active role in the transformation [45,46].

The petroleum industry, a major global contributor to carbon emissions, faces intense pressure to achieve net-zero targets. The energy value chain offers a comprehensive framework for identifying strategic points where emissions can be reduced, thus aligning the industry with broader carbon neutrality goals. Firstly, investing in carbon capture and storage (CCS) technology is crucial. By focusing on key emission points, such as extraction sites and refineries, the industry can significantly curtail its carbon footprint. This approach not only ensures compliance with stringent regulatory requirements but also reinforces the sector's commitment to addressing climate change [47].

Beyond CCS, integrating renewable energy into the operational mix is essential to reducing reliance on fossil fuels and minimizing carbon emissions. This strategy supports the industry's transition toward sustainability, while reinforcing the energy value chain's role in driving systemic change. Improving energy efficiency through the adoption of energy-saving technologies and practices across the exploration, production, refining, and transportation stages also plays a pivotal role in lowering emissions. Analysis of the energy value chain can identify inefficiencies and guide interventions, making these practices some of the most cost-effective solutions for reducing the sector's carbon footprint.

Finally, the industry's investment in low-carbon technologies must be sustained and expanded. Research and development in this area are vital for maintaining leadership in sustainable practices, while also opening pathways for new methods of energy production and utilization. By strategically utilizing the energy value chain, the petroleum industry can innovate in a manner that contributes to both its economic competitiveness and the global carbon neutrality agenda [46].

3.4. Transportation industry

Through a comprehensive review of the entire industrial chain process in the transportation industry, the transportation industry's energy value chain was proposed to be defined as follows [48], as shown in **Figure 5**:

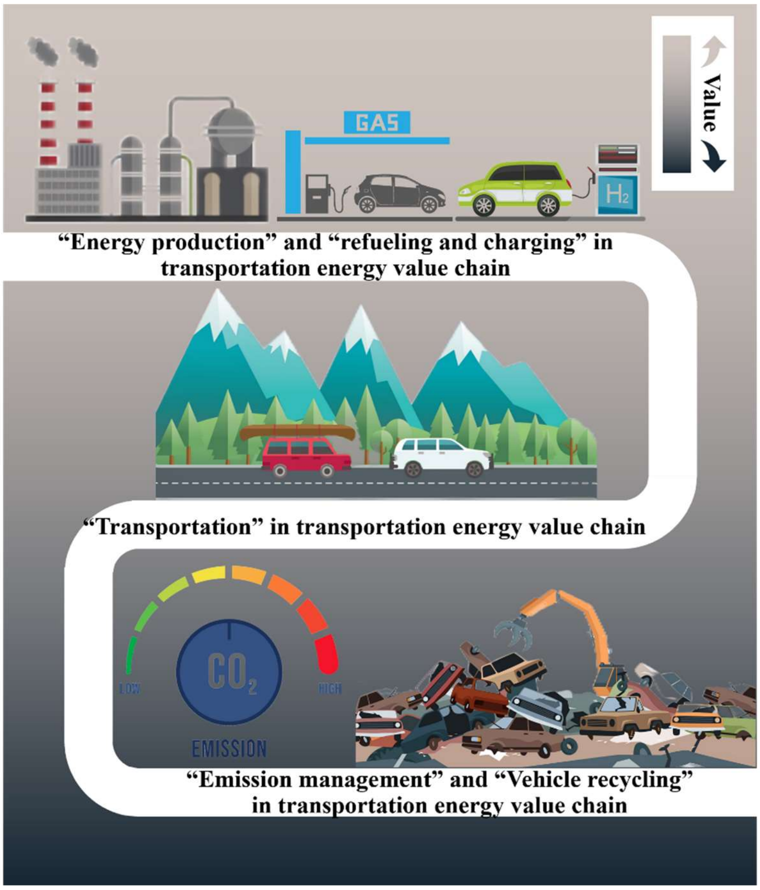

Figure 5. Transportation industry's energy value chain.

1) **Energy production:** This segment involves producing various types of energy needed for transportation. It includes refining crude oil into gasoline and diesel, storing electricity in batteries, and converting renewable energy into hydrogen

usable by vehicles to ensure compatibility with different modes of transportation.

2) **Refueling and charging:** This segment involves the infrastructure necessary for directly providing fuel to vehicles, including gas stations and EV charging stations. The development of this infrastructure is key to supporting diverse vehicle types and the broader adoption of clean transportation technologies.
3) **Transportation:** In this segment, the focus is on the actual use of energy by vehicles to achieve mobility. Here, improving energy efficiency involves technological advancements in vehicle design and operation, such as engine improvements and the use of lightweight materials.
4) **Emission management:** Given the environmental challenges associated with transportation, this segment focuses on reducing emissions through advanced technology and managing the overall environmental footprint of transportation activities.
5) **Vehicle recycling:** The final segment involves environmentally responsible vehicle disposal and recycling, aiming to recover valuable materials and mitigate the environmental impact of vehicle decommissioning.

By deconstructing the energy value chain into its essential components—production, storage, distribution, and end-use—stakeholders can identify critical points for innovation that directly contribute to carbon neutrality. This structured approach not only enables the integration of diverse energy sources but also ensures that technologies and infrastructure are optimized for present and future energy demands in ways that reduce carbon emissions. In the production phase, for example, innovations that increase efficiency, such as the use of renewable energy sources, such as wind, solar, and hydrogen, directly support decarbonization efforts. Enhanced fossil fuel extraction and processing methods also contribute by reducing energy intensity and emissions during the transitional phase towards a cleaner energy mix. In terms of storage and distribution, advances in battery technology, hydrogen storage solutions, and smart grid systems play essential roles. These innovations not only help reduce energy waste during distribution but also enable the stable flow of clean energy from renewable sources, thereby lowering reliance on carbon-intensive energy forms [48,49].

At the end-use stage, especially in the transportation industry, integrating multi-fuel systems and improving fuel cell technology enhances vehicle efficiency, allowing greater flexibility in energy sources, while supporting the decarbonization of transportation. A comprehensive energy value chain analysis is instrumental in shaping policies that encourage the adoption of clean energy technologies, improve energy security through diversified energy sources, and ultimately drive down emissions in line with global climate goals.

As the transportation industry experiences an influx of new technologies, the rational allocation of innovation resources becomes critical. For instance, EVs present an opportunity to significantly reduce carbon emissions, yet a deeper analysis of their energy value chain reveals several challenges that must be addressed to realize their full potential. Key areas, such as battery technology improvements, expansion of charging infrastructure, and changes in consumer behavior, emerge as essential. This analysis also brings attention to the dependence on critical raw materials, such as lithium and cobalt, which pose significant supply risks. Similarly, hydrogen fuel technologies face distinct challenges in production, storage, and distribution, as well as the need for integration with existing natural gas infrastructure. The analysis of these challenges helps identify where technological and resource investments can yield the most substantial impact [48].

Moreover, the energy value chain serves as a strategic tool for governments and industries to meet carbon neutrality targets. By mapping the flow of energy across different stages, stakeholders can prioritize actions that maximize emission reductions. For instance, policymakers can focus on incentivizing research into energy storage technologies or subsidizing the transition from fossil-fuel-based transportation to electric-powered and hydrogen-powered systems. Furthermore, understanding the energy value chain enables firms to adjust their production and supply strategies in response to governmental regulations aimed at carbon reduction, thus ensuring compliance, while maintaining competitiveness.

This structured approach also facilitates a critical re-examination of the value chain as heavy vehicle manufacturers transition to electrified power systems. The shift requires industries to reconfigure assembly lines, invest in battery production technologies, and address the limitations of current infrastructure. Such a reassessment, guided by energy value chain analysis, ensures that firms can streamline operations and reduce costs, while simultaneously advancing their carbon neutrality goals [48]. Through energy value chain insights, transportation companies can also uncover new opportunities in emerging clean energy sectors. Collaborations with energy suppliers and tech companies for biogas integration in heavy transportation and shipping, for instance, offer new avenues for innovation, diversification, and profit generation [48,50]. These shifts align the transportation industry with broader efforts to slow climate change and accelerate the path to a decarbonized future.

3.5. Role of energy value chains in facilitating cross-industry synergies

With the complex background of economic globalization, net-zero emission targets, and changes in international circumstances (such as the Russia-Ukraine conflict), traditional modes of collaboration between industries have been altered, and new modes of collaboration are gradually emerging. Based on this context, a comprehensive review of the changes and trends in the collaborative relationships among the four selected industries is provided in this section, and the role of the energy value chain is also discussed.

Under the pressure of carbon emissions, various industries are pursuing cleaner and lower-carbon energy forms. For the steel industry, traditional smelting processes primarily consume thermal energy from the combustion of fossil fuels. However, smelting is now increasingly utilizing electric arc furnaces. Compared with traditional blast furnaces, electric arc furnaces can save 60% to 70% of energy [51]. In the petroleum industry, broader electrification is recommended by government agencies. A report mentioned that a large-scale substitution of electricity in the pilot project at the Daya Bay Petrochemical Park in Huizhou could reduce emissions of particulate matter, SO_2, NO_x, and CO by 40%, while emissions of volatile organic compounds could be reduced by 6% [52]. In the transportation sector, this shift is reflected in the widespread adoption of EVs. The market penetration rate of EVs increased from 4.2% in 2020 [53] to 17.1% in 2023 [54]. In their pursuit of cleaner and lower-carbon energy forms, all these industries have not ignored the key concept of electrification, which in turn places greater responsibility on the power industry. The power industry has long been making efforts to provide low-carbon, green electricity to various sectors, with 30% [55] of global electricity coming from renewable energy sources as of 2023.

This electrification transformation implies more frequent interactions between the power industry and various sectors, with increased energy, value, and carbon exchanges and transfers. The energy value chain, as a method of joint modeling and analysis of energy, value, and carbon, can help enterprises more clearly discern industry development trends, thereby enabling better decision-making.

4. Summary and prospect

In this paper, an energy value chain is defined as one that integrates energy flow, value flow, and carbon flow based on the traditional value chain concept. Through a comprehensive review of related studies, the significance of the energy value chain for different stakeholders, its specific definitions, and its roles across various industries have been discussed, confirming the validity and rationality of the energy value chain. The discussion indicates that the energy value chain can effectively identify low energy efficiency, high carbon emissions, and low value-creating activities within industries and enterprises, guiding strategic decision-making and value chain adjustments. However, there are some limitations in the research on the energy value chain, as follows:

- With the future development of electricity and carbon trading markets, industries and enterprises will be more affected by market fluctuations. The role of the energy value chain as a unified analysis method of energy flow, value flow, and carbon flow in this context has not been validated.
- The energy value chains of various industries do not exist independently; their interactions and influences have not been considered and discussed.

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References

1. European Commission. Energy efficiency directive. Available online: https://energy.ec.europa.eu/topics/energy-efficiency/energy-efficiency-targets-directive-and-rules/energy-efficiency-directive_en (accessed on 10 October 2024).
2. National Development and Reform Commission People's Republic of China. Report on the Implementation of the 2014 National Economic and Social Development Plan and the Draft Plan for 2015 (Chinese). Available online: https://www.gov.cn/xinwen/2015-03/17/content_2835413.htm (accessed on 10 October 2024).
3. Simens. Simatic Industrial Automation Systems. Available online: https://mall.industry.siemens.com/mall/en/WW/Catalog/Products/5009999 (accessed on 10 October 2024).

4. Schneider Electric. EcoStruxure Platform. Available online: https://www.se.com/ww/en/work/campaign/innovation/platform.jsp (accessed on 10 October 2024).
5. Porter ME. Competitive Advantage: Creating and Sustaining Superior Performance. Free Press; 1985.
6. Masiero G, Ogasavara MH, Jussani AC, et al. The global value chain of electric vehicles: A review of the Japanese, South Korean and Brazilian cases. Renewable and Sustainable Energy Reviews. 2017; 80: 290-296. doi: 10.1016/j.rser.2017.05.148
7. Nauhria Y, Kulkarni MS, Pandey S. Development of Strategic Value Chain Framework for Indian Car Manufacturing Industry. Global Journal of Flexible Systems Management. 2017; 19(S1): 21-40. doi: 10.1007/s40171-017-0179-z
8. European Union. Industrial Development Report 2002/2003: Competing Through Innovation and Learning. European Union; 2004.
9. Wang L, Yue Y, Xie R, et al. How global value chain participation affects China's energy intensity. Journal of Environmental Management. 2020; 260: 110041. doi: 10.1016/j.jenvman.2019.110041
10. Yao X, Shah WUH, Yasmeen R, et al. The impact of trade on energy efficiency in the global value chain: A simultaneous equation approach. Science of The Total Environment. 2021; 765: 142759. doi: 10.1016/j.scitotenv.2020.142759
11. Yang B, Liu B, Peng J, et al. The impact of the embedded global value chain position on energy-biased technology progress: Evidence from chinas manufacturing. Technology in Society. 2022; 71: 102065. doi: 10.1016/j.techsoc.2022.102065
12. Zhang Z, Li J, Guan D. Value chain carbon footprints of Chinese listed companies. Nature Communications. 2023; 14(1). doi: 10.1038/s41467-023-38479-5
13. Liu C, Zhao G. Can global value chain participation affect embodied carbon emission intensity? Journal of Cleaner Production. 2021; 287: 125069. doi: 10.1016/j.jclepro.2020.125069
14. Zhao G, Liu C. Carbon emission intensity embodied in trade and its driving factors from the perspective of global value chain. Environmental Science and Pollution Research. 2020; 27(25): 32062-32075. doi: 10.1007/s11356-020-09130-3
15. European Union. Ecodesign for sustainable products regulation. Available online: https://commission.europa.eu/energy-climate-change-environment/standards-tools-and-labels/products-labelling-rules-and-requirements/ecodesign-sustainable-products-regulation_en (accessed on 10 October 2024).
16. Dahlström K, Ekins P. Combining economic and environmental dimensions: Value chain analysis of UK iron and steel flows. Ecological Economics. 2006; 58(3): 507-519. doi: 10.1016/j.ecolecon.2005.07.024
17. Mokadmia Z, Rahmounib B. Electric energy value chain in Morocco. Available online: https://www.semanticscholar.org/paper/Electric-Energy-Value-Chain-In-Morocco-MOKADMIa-RAHMOUNIb/41dc6de5411b462c0b3890f660961ffe61046d52 (accessed on 10 October 2024).
18. Breyer C, Tsupari E, Tikka V, et al. Power-to-Gas as an Emerging Profitable Business Through Creating an Integrated Value Chain. Energy Procedia. 2015; 73: 182-189. doi: 10.1016/j.egypro.2015.07.668
19. Hörbe Emanuelsson A, Johnsson F. The Cost to Consumers of Carbon Capture and Storage—A Product Value Chain Analysis. Energies. 2023; 16(20): 7113. doi: 10.3390/en16207113
20. Attias D (editor). The Automobile Revolution: Towards A New Electro-Mobility Paradigm. Springer; 2016.
21. Jarvis SM, Samsatli S. Technologies and infrastructures underpinning future CO_2 value chains: A comprehensive review and comparative analysis. Renewable and Sustainable Energy Reviews. 2018; 85: 46-68. doi: 10.1016/j.rser.2018.01.007
22. Wu G, Pu Y, Shu T. Features and evolution of global energy trade network based on domestic value-added decomposition of export. Energy. 2021; 228: 120486. doi: 10.1016/j.energy.2021.120486
23. Munasinghe M, Jayasinghe P, Ralapanawe V, et al. Supply/value chain analysis of carbon and energy footprint of garment manufacturing in Sri Lanka. Sustainable Production and Consumption. 2016; 5: 51-64. doi: 10.1016/j.spc.2015.12.001
24. Liu H, Li J, Long H, et al. Promoting energy and environmental efficiency within a positive feedback loop: Insights from global value chain. Energy Policy. 2018; 121: 175-184. doi: 10.1016/j.enpol.2018.06.024
25. Guan D, Meng J, Reiner DM, et al. Structural decline in China's CO_2 emissions through transitions in industry and energy systems. Nature Geoscience. 2018; 11(8): 551-555. doi: 10.1038/s41561-018-0161-1
26. Cai Y, Qian X, Nadeem M, et al. Tracing carbon emissions convergence along the way to participate in global value chains: A spatial econometric approach for emerging market countries. Frontiers in Environmental Science. 2022; 10. doi: 10.3389/fenvs.2022.1039620

27. Gamarra AR, Lechón Y, Escribano G, et al. Assessing dependence and governance as value chain risks: Natural gas versus concentrated solar power plants in Mexico. Environmental Impact Assessment Review. 2022; 93: 106708. doi: 10.1016/j.eiar.2021.106708
28. Pan L, Liu P, Li Z. A system dynamic analysis of China's oil supply chain: Over-capacity and energy security issues. Applied Energy. 2017; 188: 508-520. doi: 10.1016/j.apenergy.2016.12.036
29. Fennell P, Driver J, Bataille C, et al. Cement and steel—Nine steps to net zero. Nature. 2022; 603(7902): 574-577. doi: 10.1038/d41586-022-00758-4
30. Smith R, MacGill I. The great rebalancing: Rattling the electricity value chain from behind the meter. In: Sioshansi FP (editor). Innovation and Disruption at the Grid's Edge: How Distributed Energy Resources are Disrupting the Utility Business Model. Elsevier; 2017. pp. 41-64. doi: 10.1016/b978-0-12-811758-3.00003-6
31. Peng J, Wen L, Xiao J, et al. Industrial Chain, Supply Chain and Value Chain in the Energy Industry: Opportunities and Challenges. MDPI; 2024. doi: 10.3390/books978-3-7258-1200-4
32. Gert B, Marius B, Anna P. Regulatory and institutional aspects of smart grids. In: Van Dinther C, Flath CM, Madlener R (editors). Smart Grid Economics and Management. Springer; 2022. pp. 107-135.
33. van Dinther C, Flath CM, Madlener R, et al. Smart Grid Economics and Management. Springer International Publishing; 2022. doi: 10.1007/978-3-030-84286-4
34. Park C, Heo W. Review of the changing electricity industry value chain in the ICT convergence era. Journal of Cleaner Production. 2020; 258: 120743. doi: 10.1016/j.jclepro.2020.120743
35. Stapczynski S. Blockchain, drones are strategies for survival at Japan's Tepco. Available online: https://www.bloomberg.com/news/articles/2018-01-09/blockchain-drones-are-strategies-for-survival-at-japan-s-tepco (accessed on 10 October 2024).
36. Appelrath HJ, Kagermann H, Mayer C, et al. Future Energy Grid. Springer Berlin Heidelberg; 2012. doi: 10.1007/978-3-642-27864-8
37. Wang RQ, Jiang L, Wang YD, et al. Energy saving technologies and mass-thermal network optimization for decarbonized iron and steel industry: A review. Journal of Cleaner Production. 2020; 274: 122997. doi: 10.1016/j.jclepro.2020.122997
38. Ghazinoory S, Fatemi M, Adab A. Iranian steel value chain: Advantageous but unsustainable. Clean Technologies and Environmental Policy. 2022; 24(7): 2099-2115. doi: 10.1007/s10098-022-02300-6
39. Conejo AN, Birat JP, Dutta A. A review of the current environmental challenges of the steel industry and its value chain. Journal of Environmental Management. 2020; 259: 109782. doi: 10.1016/j.jenvman.2019.109782
40. Panasiyk D, Laratte B, Remy S. Steel Stock Analysis in Europe from 1945 to 2013. Procedia CIRP. 2016; 48: 348-351. doi: 10.1016/j.procir.2016.04.084
41. Michaelis P, Jackson T. Material and energy flow through the UK iron and steel sector. Part 1: 1954-1994. Resources, Conservation and Recycling. 2000; 29(1-2): 131-156. doi: 10.1016/S0921-3449(00)00048-3
42. Michaelis P, Jackson T. Material and energy flow through the UK iron and steel sector: Part 2: 1994-2019. Resources, Conservation and Recycling. 2000; 29(3): 209-230. doi: 10.1016/S0921-3449(00)00041-0
43. Peng J, Xie R, Lai M. Energy-related CO_2 emissions in the China's iron and steel industry: A global supply chain analysis. Resources, Conservation and Recycling. 2018; 129: 392-401. doi: 10.1016/j.resconrec.2016.09.019
44. Ahmad NKW, de Brito MP, Rezaei J, et al. An integrative framework for sustainable supply chain management practices in the oil and gas industry. Journal of Environmental Planning and Management. 2016; 60(4): 577-601. doi: 10.1080/09640568.2016.1178105
45. Hunt JD, Nascimento A, Nascimento N, et al. Possible pathways for oil and gas companies in a sustainable future: From the perspective of a hydrogen economy. Renewable and Sustainable Energy Reviews. 2022; 160: 112291. doi: 10.1016/j.rser.2022.112291
46. Nurdiawati A, Urban F. Decarbonising the refinery sector: A socio-technical analysis of advanced biofuels, green hydrogen and carbon capture and storage developments in Sweden. Energy Research & Social Science. 2022; 84: 102358. doi: 10.1016/j.erss.2021.102358
47. Ramos G. Decarbonization for Oil and Gas Value Chain: An Update Review. Angolan Industry and Chemical Engineering Journal. 2021; 1(1). doi: 10.47444/aincej.v1i1.5

48. Nabati H, Fard MB. Production as a source of competitive advantage in the value chain of electrified heavy vehicles manufacturing companies. Available online: https://www.diva-portal.org/smash/get/diva2:1601129/FULLTEXT01.pdf (accessed on 10 October 2024).
49. Salimi M, Hosseinpour M, Borhani TN. The role of clean hydrogen value chain in a successful energy transition of Japan. Energies. 2022; 15(16): 6064. doi: 10.3390/en15166064
50. Arfan M, Wang Z, Soam S, et al. Biogas as a Transport Fuel—A System Analysis of Value Chain Development in a Swedish Context. Sustainability. 2021; 13(8): 4560. doi: 10.3390/su13084560
51. Worldsteel Association. Energy use in the steel industry. Available online: https://worldsteel.org/wp-content/uploads/Fact-sheet-Energy-use-in-the-steel-industry.pdf (accessed on 10 October 2024).
52. Wei J. The inevitable choice for low-carbon development in the oil and gas industry: Electrification of energy use in production (Chinese). Available online: http://www.sinopecnews.com.cn/xnews/content/2023-08/07/content_7072863.html (accessed on 10 October 2024).
53. Ritchie H. Tracking global data on electric vehicles. Available online: https://ourworldindata.org/electric-car-sales (accessed on 10 October 2024).
54. Low J. Global EV market forecasted to reach 17.5 million units with solid growth of 27% in 2024. Available online: https://www.canalys.com/newsroom/global-ev-market-2024 (accessed on 10 October 2024).
55. Ritchie H, Rosado P. 30% of the world's electricity came from renewable sources in 2023. Available online: https://ourworldindata.org/data-insights/renewable-electricity-2023 (accessed on 10 October 2024).