A Discussion of Supply-side Solutions to Carbon Reduction in the Energy Sector

Qi Zhan*

London School of Economics and Political Science, London, UK

Abstract: Climate change is evolving into a very concern that has to be taken into account, and the energy sector is observed to be to blame for the excessive emissions of greenhouse gas (GHG), mainly carbon dioxide, among all kinds of human activities. While great efforts are made to cover the gap between carbon emission and absorption through energy consumption, limited attention has been drawn to the supply-side. Therefore, the study aims at exploring supply-side solutions to emission reduction in the energy sector by drawing a blueprint for low-carbon energy supply and providing suggestions for solutions based on the logic behind each strategy. The article divides the supply-side solutions into industrial solutions and auxiliary solutions in accordance with their connection with the energy industry. Further, it discusses sub-types of solutions along economic and technological feasibilities of renewable energy technologies (RETs). The research concludes that the low-carbon transition of energy supply is in urgent need for systematic supply-side solutions. Admittedly, the alignment with the climate goal of carbon reduction is the key component of supply-side solutions; nevertheless, the solutions should go beyond and give consideration to promoting the transition as a whole.

1. Introduction

With increasing concerns about climate change and other natural disasters along, the latest evidence points out, however, the acceleration of global warming and the significant risks it poses. In the Sixth Assessment Report (2023), the Intergovernmental Panel on Climate Change (IPCC) confirms that the average global surface temperature for 2011–2020 is 1.1°C above the pre-industrial baseline of 1850–1900.[1] The rise leads to a series of unpredictable consequences, such as frequent extreme weather and biodiversity loss – particularly, some of the impacts already go beyond adaptation. The report estimates that anthropogenic factors, GHG emissions in particular, are responsible for the warming. Specifically, among all kinds of human activities, the energy sector is often seen to contribute to emissions the most. In accordance to the United Nations (UN) (2023), energy generation and supply (mainly power and heat supply) brings around 35% of total emissions. [2] In addition to that, the International Energy Agency (IEA) (2024) finds that the source even accounts for 43.8% of global carbon emissions from fuel combustion and that carbon emissions from the power industry increased the most among all sectors between 1970 and 2022.[3] However, when including transport, manufacturing, buildings, and other industries related to energy consumption, the energy sector represented even as much as 73% of global emissions in 2017 in the estimate by the World Economic Forum (WEF) (2020). Therefore, reducing GHG emissions from the energy sector is a critical move in alignment with climate goals of 1.5°C and requirements for sustainable development as demonstrated by sustainable development goals[1].[4] As show in fig 1 and 2.

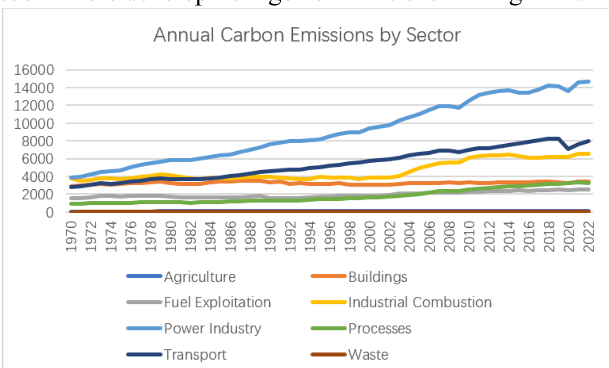

Fig. 1. Annual Carbon Emissions by Sector – IEA (2024).

[1]The climate goal, first put forward in the Paris Agreement, is an international and intergovernmental agreement to limit global temperature within 1.5°C (and well below 2°C) above the pre-industrial levels. The sustainable development goals (also SDGs) are a set of goals adopted by members of the UN, highlighting the inner-connections between different aspects of sustainable development and reflecting a general care for the peace and prosperity of all human beings.

*Zhanqi670@163.com

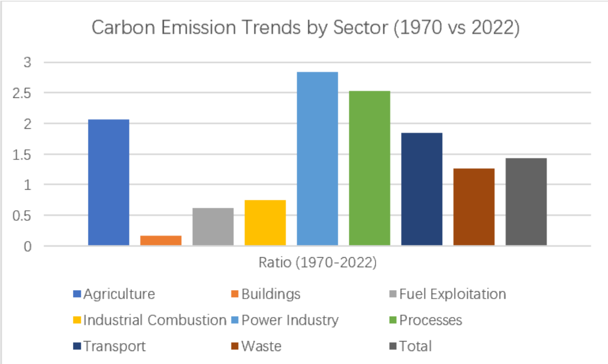

Fig. 2. Carbon emission trends by sector (1970 vs 2022) – IEA (2024).

Generally, GHG emissions from the energy sector are dominated by two forces: energy consumption and energy supply, which also spark a debate between demand-side and supply-side solutions to GHG reduction in the sector[2]. Supporters for demand-side solutions argue that "the higher the energy demand…, the slower the transition to carbon-free energy production." They contend that renewable energy supply must first meet the increasing demand driven by energy consumption growth before replacing and reducing fossil fuel production. Therefore, demand-side solutions are thought to be not merely necessary but flexible, practical, and resistant to environmental risks (Creutzig et al., 2018; Mayer et al., 2024).[5],[6] In contrast, the opposite, like Sinn (2008), refute that demand reductions are ineffective without corresponding responses from suppliers.[7] They emphasise the ineffectiveness in addressing market failures, such as the green paradox. However, it is surprising that supply-side policies have been far less widespread for a long time, and the gap between the two sets of solutions further limit the potential of supply-side solutions in practice. In response, this article aims to draw attention back to the supply-side solutions to carbon reduction in the energy sector by investigating the difficulties confronted by low-carbon energy supply and the solutions accordingly, thus providing a reference for policymaking.

To analyse the low-carbon transition in energy supply, this article is structured into five main sections. The first part is a brief introduction to the context and the structure of the research. The second part reviews previous studies on key definitions and recent theories regarding supply-side solutions for low-carbon energy supply and summarises the research gap in accordance. The third and fourth sections examine how the energy sector promotes low-carbon energy supply and how financial, fiscal, legal, and intelligent support complement the supply-side solutions. The final part includes a conclusion that finds that the industrial solutions and auxiliary solutions collectively constitute the implication of the supply-side solutions to carbon reduction in the energy sector, where both types of solutions promote the low-carbon transition of energy supply quickly and smoothly.

2. Literature review

2.1. Energy sector and supply-side solutions to carbon reduction

Before further discussion, the research needs to first qualify two definitions – "energy sector" and "supply-side solutions". Typically, the energy sector is a collective term from the production to the consumption of energy, or the totality of all the industries involved in the process. In practice, however, the categorisation of the energy sector may vary. A common approach is based on different types of energy, which often involves traditional energy, such as coal, oil, gas, and electricity of different types, like thermal power, wind power, water power, and nuclear power. Particularly, some studies tend to place renewable energy under the category of electricity with increasing practices of green electricity. Another widely adopted approach categorises the energy sector based on usage scenarios, such as electricity and heat generation, as well as sectors like buildings, agriculture, transportation, and chemicals. Though the two methods have different focuses, they both reflect the development of energy as a whole, indicating the interdependence and interaction between supply and demand. Therefore, the analysis below will take both definitions of the energy sector into consideration.

In contrast, the categorisation of supply-side solutions to carbon reduction in the academic literature is expansive and developing. Generally, the solutions refer to policies/strategies that "target a range of sectors, infrastructures, and products to achieve sustainability aims" or aim at mitigating GHG emissions by limiting the supply of carbon-intensive energy and coordinating decrease in fossil fuels consumption with demand policies (Trencher et al., 2023).[8] Early thinking concentrates on the economic dynamics of specific fossil fuels with production, pollution, and investment patterns, while recent studies explore the relationship more inclusively (Bohm, 1993).[9] For instance, some researchers divide the supply-side policies into restrictive (e.g., subsidy reduction, tax, and production quotas) and supportive ones (e.g., R&D subsidies and feed-in tariffs) (Green and Denniss, 2018).[10] Le Billion and Kristofferson (2020) make the interaction with fossil fuel consumption a primary concern.[11] Meanwhile, Lazarus et al. (2015) and Scott et al. (2022) attempt to expand the scope of research to include technology solutions, regulatory approaches, and information programs in the framework.[12],[13] In short, discussions on supply-side solutions have

[2] In a general context, the supply-side solutions to adapting and mitigating climate change refer to a range of measures to promote low-carbon/carbon-free energy supply or/and to reduce fossil energy supply, such as developing renewable energy technologies, improving energy efficiency, keeping fossil fuels underground and so on. Sometimes, the supply-side solutions may be generalized as the supply-side technology solutions centered on renewable energy technologies. In contrast, the demand-side solutions imply strategies that target consumer behavior, technology choices, lifestyle, and so on. However, there are also many measures covered by both sides, such as reducing energy waste and promoting carbon tax.

transitioned from industrial policies and fiscal and financial policies to a larger framework of technological and legal policies. In response to the evolution, the article attempts to develop a new framework to integrate the solutions based on Scott et al. and Lazarus et al. by dividing supply-side solutions into industrial solutions and auxiliary solutions, including financial, fiscal, legal, and intelligent policies, that support the implementation of industrial policies.

2.2. Criticisms on low-carbon supply-side solutions in the energy sector

Admittedly, there remains a controversy on the supply-side solution to carbon reduction in the energy sector. One group of scholars expresses concerns about the inefficiency and uncertainty of the supply-side solutions for reducing carbon emissions from the energy sector. Quiggin (2023) attributes the limitations to the need for scaling up and investment in the renewable energy sector, as some supply-side options for emission reduction are "still at the R&D phase." [14] Zhao, Li, and Zhang (2024), however, concentrate on the uncertainty of renewable energy supply due to its weather dependence.[15] Mashayekhi, Read, and Lindhult (2016) argue that neither gains in energy efficiency nor renewable supplants are efficient and effective in reducing energy demand. Some researchers express these concerns more mildly. Pellegrini and Arsel (2022), for instance, suppose supply-side policies should be "effective and complementary to existing policies" despite operational uncertainties. Wiedmann et al. (2020) think that the low-carbon energy technologies do play a positive role in controlling past emissions but contribute little to absolute emissions reductions at present. Several studies acknowledge the potential of low-carbon energy supply solutions but highlight the great barriers to implementing the policies, like Rayner (2021), who emphasises the inadequate institutional responses as an impediment to restricting international fossil fuel supply.

In contrast, another group of scholars considers supply-side solutions to be essential, especially in their relation to demand-side solutions. The demand-side solutions refer to a sum of policies and practices that aim at reducing energy demand and consumption by motivating consumers, including reducing energy waste, improving energy efficiency, and so on. In comparison, though also categorised according to the policy purpose, the supply-side solutions concentrate on improving low-carbon energy supply and energy efficiency from the supply side. On one hand, the reduction requires cooperation and coordination between demand-side and supply-side solutions. For instance, Paul and Moe (2023) agree that the coordination between supply-side and demand-side action is important not only for industrial analysis but also for achieving rapid decarbonisation "in a way that protects health and economic security." Prest (2022) start from carbon leakage and find it able to be effectively mitigated when policies from both sides are implemented "in parallel with similar vigor." On the other hand, solutions for low-carbon energy supply are thought to have distinct advantages over demand-side solutions. Sinn (2008) believes that effective mitigation measures must "succeed in flattening the carbon supply path" in global energy markets. Similarly, Dion (2019) attributes their contribution to the prevention of the "green paradox" and lock-in and stranded assets. Furthermore, Lazarus et al. (2015) identify the cost advantage of supply-side solutions, which allows for "greater emission reductions at the same (or lower) cost than demand-side policies alone." From the perspective of regulation, the cost-effectiveness is also reflected by cost-efficiency and easy enforcement of supply-side treaties compared to demand-side treaties (Stankovic et al., 2024).

In summary, most criticisms of low-carbon supply-side solutions in the energy sector focus on the technological and financial uncertainties, as well as potential inefficiencies in echoing changes in energy demand. Supporters, however, emphasise the coordination benefits of supply-side solutions and their cost-effectiveness in promoting the transition. One reason for this divergence is whether the supply-side solutions to carbon reduction in the energy sector are treated at the same level as demand-side solutions rather than, for example, a combination of technological solutions and financial solutions, which will be discussed in the following part.

2.3. A Return to supply-side solutions to carbon reduction in the energy sector?

Although the role and effectiveness of supply-side solutions to carbon reduction in the energy sector remain debated, the demand side increasingly dominates the discourse. In comparison, supply-side solutions are often seen as, according to Creutzig et al. (2018), a set of technology solutions or financial solutions. There appear to be different explanations for the mismatch between solutions of both sides. Lazarus et al. (2015) attribute the underestimation of supply-side solutions to resistance from political economies, consumption-orientated national accounting standards, and public perceptions. According to Santos et al. (2022), however, low compatibility with mainstream economics, choice of discount rate, and national heterogeneity in the rates of GHG emission and growth are to blame. In other words, the underperformance of supply-side solutions to carbon reduction in the energy sector is largely resulted from the constraints of established frameworks and outdating thinking patterns. To empower supply-side solutions, it is necessary to have systematic integration and enrichment of supply-side solutions. Newell and Daley (2024) believe supply-side climate policies are supposed to move beyond addressing specific fossil fuels and policies targeting certain stages in the fossil fuel value chain. Creutzig et al. (2017) agree on the significance of technological learning and support in promoting renewable energy deployment but emphasise the importance of effective yet various financing instruments and careful yet considerate management of system integration, like market stability reserve, public-private partnerships (PPPs), and other new forms of carbon credit like "pro set, for future success.

Additionally, Hille, Althammer, and Diederich (2020) complement how the provision of legislative and regulatory support promotes supply-side solutions.

In conclusion, the reduction in emissions from the energy sector is confronted with inevitable uncertainties generated by renewable energy substitutes and inefficiencies arising from research, development (thereof R&D), and deployment at the early stage, which underscores how technological and economic feasibility shape supply-side solutions. However, the challenges are more than that. The policy implications of supply-side solutions are largely simplified and distorted—technological and financial constraints have been overstated in previous literature. Another weakness revealed by past studies is the lack of systematic integration between different supply-side solutions. Consequently, excessive focus has been placed on isolated supply-side initiatives, like promoting energy efficiency or finding renewable energy supplants. In contrast, the interconnections among various supply-side solutions are ignored. As an equal party to demand-side solutions, supply-side solutions are not only important but necessary. Therefore, as pointed out, more efforts are required to develop supply-side solutions to carbon reduction in the energy sector.

3. Supply-side solutions to carbon reduction in the energy sector

To reduce carbon intensity from the energy supply, it is essential to phase out fossil fuels and switch to low-carbon or carbon-free energy sources. For this sake, both industrial and auxiliary solutions are needed. In detail, the low-carbon transition of energy supply involves examining how low-carbon energy supply displaces traditional fossil fuel supply and how the transition is motivated. Following the issue, this chapter will first investigate the industrial transition to low-carbon energy supply by considering technological and economic feasibility and then examine how financial, fiscal, legal, and intelligent supports and provisions align with reducing carbon intensity of energy supply.

3.1. Industrial solutions to carbon reduction in the energy sector

As mentioned above, there are mainly two factors determining the replacement of low-carbon/carbon-free energy for fossil fuels: technological feasibility and economic feasibility—the former refers to whether renewable energy can replace fossil fuels for specific uses, and the latter one indicates whether the renewable energy alternative can be scaled up. Accordingly, this section first analyses two types of industrial solutions: promoting the replacement of renewable energy and reducing carbon emissions from fossil fuels, based on technological feasibility, and then develops supply-side policy implications for each type of solution by combining economic feasibility and specific energy application scenarios.

3.1.1. Promoting the replacement of renewable energy

When RETs allow for the replacement of fossil fuels, there are mainly two sets of measures in promoting the replacement according to economic feasibility and attraction: the electrification of renewable energy (or green electricity/power) and non-electrical use of renewable energy. In detail, compared with thermal power, green power promises a low price with the help of strong grid systems and versatility of electricity. For example, since the National Development and Reform Commission promoted the development and deployment of wind power in 2005, the cost of power in China has decreased dramatically, even lower than that of thermal energy by 2021 (CICC, 2019). Meanwhile, similar practices can also be found across the world. However, green electricity may struggle to cover all the application scenarios of fossil fuels, like long-distance transportation and the chemical industry (Ficca, Marulo, and Sollo, 2023). Therefore, though less economically attractive and feasible, non-electrical use of renewable energy remains necessary.

During replacement for thermal power, the electrification of renewable energy is challenged by two issues: the instability of green electricity and the adaptability of the grid system. Firstly, green electricity is less stable than thermal power due to dependence on weather, geography, season, and so on, leading to variance in the quality of green electricity and challenges with grid connection (Zhao, Li, and Zhang, 2024). Secondly, apart from dependence on environmental issues, instability is reflected by inflexibility. Some renewable energy generation struggles to respond quickly to changes in grid load compared to thermal power, and consequently, additional costs for peak shaving also challenge green electricity (Sun et al. 2024). Thirdly, the introduction of green electricity also brings challenges to the preset grid capacity and grid-connectedness, as green electricity is taken little consideration during the design of the grid system (Mureddu et al., 2015). In response to the concerns, the electrification of renewable energy can be promoted in the following ways. On one hand, improving the stability of green electricity through energy storage is crucial—such technologies can both reduce pressures from peak shaving and effectively mitigate local grid overloads brought by green electricity access (Islam et al., 2024). For example, UK energy providers, like British Gas, promote solar panels and solar batteries for smart energy management. On the other hand, grid expansion and implementation of smart grids are expected to improve the adaptability of the grid by accommodating more intermittent renewable generation and increasing the capacity of grid-connected renewable energy (Hu et al., 2014). In addition to that, there is also evidence suggesting that the combination of multiple green powers is potentially able to compensate for the fluctuation of a single green energy, which improves stability and flexibility at the same time (Liu et al., 2020). In the case of King Island, Australia, the use of a mix of wind and solar power produces around 65% of its electricity with great stability.

Undeniably, the electrification of renewable energy offers a promising path for fossil fuels. However, due to the nature of electricity, the electrification does not suffice to meet all the replacement scenarios. Firstly, for long-distance transportation, like aviation, which is highly dependent on endurance and safety, green electricity, along with battery technologies, is challenged by low energy density, storage difficulty, and high-temperature sensitivity (Hızarcı and Arifoğlu, 2023). Secondly, for the metal smelting industry, like iron and aluminium, the redox reaction involved in the industrial process inevitably leads to the use of fossil fuels as well. Though the appearance of electric arc furnace technology has reduced coal usage to some extent, completely eliminating fossil fuels remains challenging (Reyes-Bozo et al., 2024). Thirdly, for some chemical industries, such as plastic, FF remains the ideal raw material (Levi and Cullen, 2018). Therefore, the non-electrical use of renewable energy serves as a necessary complement to electrification solutions. Hydrogen energy is one of the key alternatives to green electricity, particularly in the transportation and chemical industries. On one hand, hydrogen energy, along with hydrogen fuel cells, has high energy density and fast charging speed, which will match the need for long-distance transportation. On the other hand, hydrogen is also expected to replace fossil fuels as raw material in chemical industries, such as synthetic ammonia and methanol, or as a reductant in the smelting industry (Islam et al., 2024). Additionally, biofuel is considered a promising alternative energy source, though it remains under further investigation.

In the case of hydrogen-powered aircraft, for example, as the aircraft becomes technologically feasible, it appears to be an attractive alternative to the kerosene-powered aircraft in the long term. It is worth noting that fuel cells contribute little to reducing in-flight emissions unless they become lighter, more powerful, and more durable to ensure large, fuel cell-powered transport aircraft reliable in long-distance transportation. Therefore, lightweight liquid hydrogen tanks along with the integration into the airframe become crucial to the hydrogen-powered aircraft. With regard to the energy performance of liquid hydrogen, Gallagher, Stuart, and Spence (2024) compare liquid hydrogen aircraft with three different sustainable aviation fuel aircrafts and find liquid hydrogen aircraft yield the lowest energy consumption in almost all cases. In terms of environmental effectiveness, in the case of green hydrogen from electrolysis with wind energy, the total carbon emissions can decrease to 80% of that of fossil fuels according to Donateo et al. (2024).

3.1.2. Reducing carbon emissions from fossil fuels

However, RETs do not always guarantee the complete replacement for fossil fuels nor the provision of carbon-free energy supply. For instance, the production of natural-gas-based hydrogen (blue hydrogen) inevitably generates GHG emissions. Meanwhile, some RETs have difficulty breaking through within the short term (Ohene, 2023). As a result, the supply-side solutions to carbon reduction should not only focus on renewable energy suppliers but control carbon emissions where renewable energy is not able to be involved. In this sense, the clean use of fossil fuels could be promoted through inter-industry integration and inner-industry compensatory measures.

From the inter-industry level, industrial integration and cooperation can improve energy efficiency and help reduce systematic carbon emissions. Based on current modes of industrial collaboration, there are two ideas for industrial solutions to carbon reduction from fossil fuels. For industries with possibilities of material circulation or product circulation, it is important to establish business ecosystems and, hence, a circular economy (Marques-McEwan et al., 2023). Depending on the potential for circulation, two approaches to establishment can be considered. Specifically, when industrial symbiosis is possible, the by-product of one industry becomes the resource for another within the ecosystem, and the promotion of key technologies and the change of paradigm are necessary. When, however, the recycling of by-products does not suffice to provide resources for another industry, it is necessary to increase the proportion of recyclable products in the industrial ecosystems as much as possible, especially those involving carbon emissions. For example, the carbon emitted by chemical production can be captured and used as material for chemical production again (Budzianowski, 2017). Industries without opportunities for circulation can cluster together to enhance the energy efficiency of fossil fuels and infrastructures. Specifically, carbon emissions can be mitigated through collective investments in energy-saving equipment, resource sharing, or centralised carbon emission treatment.

Here is an instance of developing crcular economy within chemical industry: The surfactants of laundry detergent capsules, typically occupying 15–50% of the product weight, generally come from fossil carbon. In an innovative alternative practice, Unilever develops a new equipment to capture and liquify carbon emitted within the steel manufacturing plant. The liquified carbon is transformed into ethanol through a fermentation process and finally into surfactants for laundry detergent capsules. After the trial in Aisa, similar pilots are esablished in Europe and South Africa. Besides, once the detergent capsule is consumed, it will dissolve in water, and then be processed at individual water treatment plants worldwide. The following image by Marques-McEwan et al. demonstrates the industrial processes. As show in fig 3.

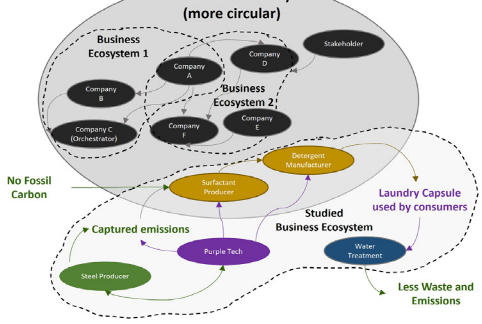

Fig. 3. Circular chemical industry system by Marques-McEwan et al.

From the inner-industry level, compensatory measures include both the introduction of carbon capture, utilisation, and storage (CCUS) technologies and the optimisation of industrial processes. Admittedly, apart from renewable energy supplants and inter-industry integration, there are still cases where neither technological nor economic feasibility is high enough to reduce the pressure from carbon emissions due to the limitations of RETs. Therefore, CCUS technologies are needed for carbon removal in industrial links involving carbon emissions, such as in the metal smelting, chemical, and cement industries but potentially do not suffice to be the main measure of carbon reduction. For example, the captured carbon emissions account for less than 0.5% of total emissions in the US, according to Mon, Tansuchat, and Yamaka (2024). Meanwhile, as mentioned above, the captured carbon can be used as a material as well, which further reduces the waste of energy. Similarly, optimising industrial processes can further reduce carbon emissions. The first approach involves introducing green equipment, such as switching to electric vehicles for material transportation, to reduce the reliance on fossil fuels. The second is to improve the efficiency of energy supply with improvements in the supply chain—for example, using the Internet of Things (IOT), big data, and blockchain to establish a smart supply chain by monitoring the input of fossil fuels or updating real-time carbon emission data. According to Arana-Landín et al. (2023), the four technology groups (AI, Big Data, IoT, and Robotics) will potentially improve energy efficiency by approximately 25% in processes where they are integrated globally. The third approach is to clean fossil fuels, such as replacing coal with natural gas and washing coal to improve combustion efficiency. As show in fig 4.

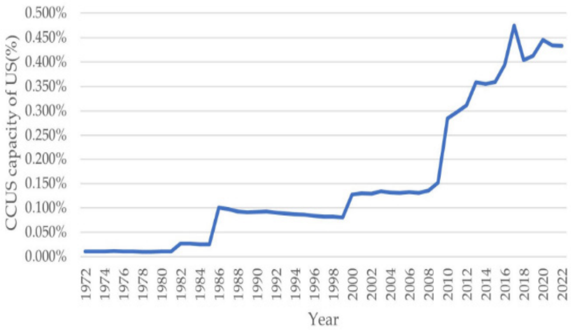

Fig. 4. Percentage of abated CO2 by CCUS from total CO2 emissions of US by Mon, Tansuchat, and Yamaka.

To sum up, according to the difference in technological and economic feasibility of renewable energy, there are two paths for the energy industry to achieve carbon reduction from the supply side. One approach is to promote the displacement for fossil fuels with renewable energy, and the other is to reduce carbon intensity of fossil energy. In the case of high technological feasibility, carbon reduction can be promoted by the electrification of renewable energy. Still, the non-electrical use of renewable energy, though likely less economically attractive, is necessary to complement the application of green electricity. In the absence of key technological breakthroughs in renewable energy, carbon emission intensity can be reduced at both inter-industry and inner-industry levels by improving energy efficiency and minimising energy waste, thereby smoothing the transition. In a word, in the process of carbon reduction, the energy sector needs to take both technological and economic feasibilities of renewable energy into consideration to achieve the relative advantage of renewable energy over fossil fuels and thus integrate the energy sector to align with climate change.

3.2. Auxiliary solutions to carbon reduction in the energy sector

In addition to industrial solutions of carbon reduction, the supply-side solutions also include how the low-carbon transition of the energy supply is guided and supported from the supply side. Therefore, auxiliary solutions to carbon reduction are crucial for aligning the energy sector with climate mitigation goals. During the process, a series of challenges emerge, and hence, there is a need for financing, fiscal, legal, and intelligent support to promote the transition. In this regard, this section examines auxiliary solutions from two aspects: promoting a targeted supply of funds and improving support services.

3.2.1. Promoting targeted supply of funds

As a key component of the low-carbon transition in the energy sector, the renewable energy industry is characterised by great uncertainty and requires substantial, long-term investment. Consequently, there is a great need for financing. However, the need for funds and investments is hardly met with current financing and fiscal solutions. On one hand, challenges such as insufficient green financing, difficulty in fund access, and mismatch of financing terms restrict the performance of low-carbon technologies. On the other hand, the lack of fiscal support makes it difficult for the renewable energy industry at the current stage to confront the challenges brought by the fossil fuel industry and market failure. Therefore, to improve the provision of low-carbon energy, it is necessary to promote the effective supply of funds with financing solutions and macro-guidance of funds with fiscal solutions.

Admittedly, whether for the R&D or deployment of renewable energy, there is a great need for funds “to get the projects off the ground and running.” In contrast, the financing of renewable energy faces a series of challenges (Walsh, 2014). Firstly, renewable energy projects are subject to high upfront costs and high sensitivity to interest rates but often lack good collateral, which makes the projects less attractive to investors. Secondly, the traditional financial market, with its limited range of financial instruments, is unable to address the complex and diverse financial needs of the renewable energy industry (Eti et al., 2024). Thirdly, the renewable energy industry lacks effective measures to respond to financial and economic risks, further increasing its risk exposure (Wang et al., 2022). Therefore, financing solutions for low-carbon energy supply need financing channel expansion and innovation of financing mechanisms. On one hand, the motivation of public and institutional investments is important for green financing expansion. Particularly, these investments can help advance renewable energy technologies (RETs) from concept to commercialisation, as they are better equipped to address risks associated with R&D and information asymmetry. In 2022, for example, the world invested $154 billion in nature-based solutions, with public finance contributing 83% of the total (UNEP, 2022). On the other hand, similarly, innovative financing mechanisms are supposed to promote long-term, low-cost, stable financing by, for example, developing green mortgages and green insurance to reduce credit risks, establishing community-based trust funds to provide flexible and customised service, and initiating syndication to further split risks. In the case of the US, the Inflation Reduction Act of 2022 includes energy price insurance mechanisms with substantial tax credits and subsidies to reduce the costs and risks of renewable energy production.

Meanwhile, financing for the renewable energy sector is also confronted with challenges of market failures, such as strong market power of fossil energy groups, externalised environmental costs, limited market incentives, and high cost of capital for renewable energy, so fiscal solutions will aim at optimising the allocation of resources to overcome the additional costs brought by the transition and provide guidance for funds. Subsidies and taxes are effective approaches to internalising the price of carbon emissions and reallocating capital resources by subsidising the renewable energy industry and increasing taxes on the fossil energy industry (Meng and Yu, 2023). It should be noted, however, that to maintain a balance between tax and subsidy, mere reliance on tax or subsidy may still lead to investment inefficiencies. In addition to that, fiscal support should also involve the improvement of the identification of renewable energy and green technology industries to reduce the distortion of capital supply from greenwashing[3]. Specifically, identification such as ecolabelling, the green certificate, and ESG data exposure provides tools for tracking the carbon footprint of energy industries and keeping continuous monitoring, which would be helpful to provide a reference for subsidy and tax by promoting the targeted supply of funds. For instance, the Danish Ministry of Environment appoints Ecolabelling Denmark, responsible for EU Ecolabel and the Nordic Swan Ecolabel, to certify products and services that meet environmental requirements.

3.2.2. Improving supporting services

Beyond the provision of targeted funds, the external environment is also indispensable for empowering the transition and increasing technological and economic feasibility. Particularly, the supply of supporting services—such as legal and intelligent services—not only fosters a favourable institutional environment by promoting market access to renewable energy, protecting renewable energy intellectual property (thereof IP), and improving regulatory compliance but increases the technological feasibility of low-carbon/carbon-free technologies and hence flattens the path to the transition through preparation for innovation and expansion of the talent pool.

The need for legal services is mainly divided into two categories: legislative and regulatory support. For the former, the need comes from the update of legal measures compatible with renewable energy, protection of RETs intellectual properties, and compatibility between renewable energy and existing energy systems (Oduro, Uzougbo, and Ugwu, 2024). For the latter, the challenges are brought by access to renewable energy projects, constraints on investment, and uncertainty in environmental performance (Grove and Clouse, 2021). Accordingly, the legislative solutions should first simplify legal procedures (especially for licensing), increase the consistency of law when crossing jurisdictional areas, and establish a clear legal framework to improve the stability and reliability of legal support. Apart from that, intellectual property protection should be strengthened but balanced. Undeniably, IP protection will guarantee the returns of RETs as a general-purpose technology, but the protection can potentially hinder the adoption of renewable energy by increasing the cost. For regulatory support, similarly, regulation should make a trade-off between motivating renewable options and improving compatibility with environmental sustainability, which might need a closer combination with transparency improvement and data exposure.

For example, UK enacted The Energy Act 2023, a major new legal framework that establishes modified rules for energy production, security and sectoral regulation. The Act introduces new frameworks and mechanisms to support green technologies such as low-carbon hydrogen projects and seeks to facilitate speedier deployment of or projects by, for example, making changes to environmental regulations for offshore wind. Likewise, on 8th November 2024, the Energy Law of the People's Republic of China is passed and will be brought into force on 1st January 2025. The law sets out requirements in a number of areas, ranging from energy structure to green energy consumption and is expected to promote the development of the renewable energy industry against climate goals of carbon peak and carbon neutrality.

Finally, intelligent support for the low-carbon transition encompasses not only the accumulation and innovation of technologies but also the development of human capital. From the perspective of technological innovation, on one hand, the disconnection between basic research and applied R&D makes it difficult for knowledge tanks to support technological breakthroughs; on the other hand, there is a "valley of death" from the conceptualisation of RETs to industrialisation and marketisation (Raihan et al., 2024).In terms of human capital, there is a significant demand for green human capital to master clean technologies and be familiar with

[3] Greenwashing refers to that a company makes misleading or exaggerated claims about the environmental impact of their products or services.

environmental policies and standards. However, a significant gap remains between education and industrial needs. In this sense, the connection between education, innovation, and industrialisation can be strengthened with the industry-university-research (IUR) cooperation, where universities serve as research centres supplying technologies to the renewable energy industry, by which education and innovation make a good match. Take the University of Edinburgh, for example, the university invests over £3 million of quality research funding to drive the development of innovative energy technologies in cooperation with the Tyseley Energy Park, an energy innovation zone focused on energy storage, clean transport fuels, and related advancements. Concerning the gap between basic research and technological application, a possible solution is to promote cooperation between upstream and downstream industries with complementary advantages and resource sharing and to bridge the technology supply with demands.

In summary, improving the technological and economic feasibility of the industrial solutions mentioned above, auxiliary solutions are expected to complement the former in terms of financing, fiscal, legal, and intelligent support. On one hand, the supply of low-carbon energy comes with a large capital demand but high uncertainty. Therefore, it is necessary not only to expand the financing channels of public and institutional investment but also to provide long-term, stable, and reliable funds compatible with the characteristics of the renewable energy industry. On the other hand, the effective supply of capital as a driver of low-carbon transition requires fiscal guidance to overcome the distortion of financing, especially from market failure and additional costs. In terms of supporting services, improvements in legislation and regulation help create a favourable institutional environment where the transition is promoted smoothly. Particularly, the stability and consistency of laws are essential to empower the development of a clean energy supply. At the same time, IP protection and regulation, though equally important, are supposed to be carefully balanced between different needs. Finally, in terms of intelligent support, the university-industry partnerships contribute to bridging training and research and filling the talent gap, while supply chain would be a good opportunity to accelerate the process from conceptualisation to application. In short, the auxiliary solutions are, as indicated, a complement to industrial solutions—together, they will leverage the huge potential from the supply side and promote the low-carbon transition of the energy sector quickly and smoothly.

4. Concluding remark

The study attempts to explore the supply-side solutions to carbon emission reduction in the energy sector by drawing a blueprint for low-carbon energy supply solutions and identifying the logic behind each strategy and the solutions as a whole. The article divides the supply-side solutions into industrial solutions and auxiliary solutions in accordance with their connection with the energy industry. Based on the economic and technological feasibility of renewable energy technology, industrial solutions can be further divided into electrical and non-electrical uses of renewable energy, industrial integration and cooperation, and cleaner use of fossil fuels. Concerning the support for improving the feasibility, auxiliary solutions include financial, fiscal, legal, and intellectual support. The article finds that the low-carbon transition in the energy sector displays a huge and systematic need for supply-side solutions. While aligning the energy sector and the goal of carbon reduction is a key component of the supply-side solutions. Still, the solutions are supposed to move beyond and pay attention to the promotion of the process as a whole. Meanwhile, even though industrial solutions have rich policy implications and a basic logic for implementation, the technological and economic feasibility of renewable energy remains pivotal. In addition to that, the study also concludes that there are complex dynamics in the low-carbon transition of the energy sector, indicating that the promotion of carbon reduction is supposed to be carried out in a quick but smooth manner.

The study has potential limitations. Despite an attempt to reconceptualise the supply-side solutions to carbon reduction in the energy sector, it remains primarily focused on the intersection of technological and economic solutions. On one hand, the study starts from the supply of low-carbon energy motivated by renewable energy technologies, presuming technological and economic feasibility as the rationale for selecting solutions. On the other hand, the study fails to include other potential topics, e.g., culture and entrepreneurship, into the discussion nor contribute to filling the gap of why the supply-side solutions have long been underestimated, such as a shift to supply-orientated national accounting standard. Meanwhile, the study pays limited attention to the interaction and synergy between supply-side and demand-side solutions in promoting carbon reduction, despite the collective influence of energy supply and consumption dynamics on the process. However, the article still contributes to drawing a blueprint of current practices to provide a policy toolkit accordingly and illustrating the rationale for choosing different strategies of the supply-side solutions to bridge the gap between achieving climate goals and harmonising the transition.

Moving forward, the further discussion may concentrate on the following topics. Firstly, how effective are supply-side and demand-side solutions in reducing carbon emissions, and what contributes to the difference in effectiveness, For instance, technological breakthroughs like renewable energy technology potentially promote the alignment with climate goals in the long term but require a long period of R&D and investment beforehand and thus are less likely to be effective in the short term. Secondly, how does the political economy reshape the discussion of the supply-side solutions versus demand-side solutions in the energy sector and dominate the discourse, which would be helpful to complement current research of productive factors and contribute to the discussion of a just and sustainable transition, Thirdly, how do the supply-side solutions to carbon reduction in the energy sector respond to multiple development goals, such as economic growth, equality, and climate goals, in a national case study, which would be important for identifying the dynamics between different development goals and promoting a better trade-off wherever there is a conflict.

References

1. Aldunce, P., Blanco, G., Calvin, K., Cheung, W., Dasgupta, D., Denton, F., Diongue-Niang, A., Dodman, D., Garschagen, M., Geden, O., Hayward, B., Jones, C., Jotzo, F., Krinner, G., Lasco, R., Lee, J., Meinshausen, M., Mukherji, A., Otto, F., Revi, A., Roy, J., Slangen, A., Sörensson, A. A., Thorne, P., Trisos, C., Van Vuuren, D., Wei, Y. M., Winkler, H., Zommers, Z. (2023) *The Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Available at: https://www.ipcc.ch/assessment-report/ar6/ (Accessed: 10 November 2024).
2. United Nations–Facts and Figures (https://www.un.org/en/actnow/facts-and-figures#:~:text=Home%20energy,-Electricity%20drives%20our&text=The%20energy%20supply%20sector%20(electricity,are%20supplied%20from%20fossil%20fuels).
3. Greenhouse Gas Emissions from Energy Data Explorer (https://www.iea.org/data-and-statistics/data-tools/greenhouse-gas-emissions-from-energy-data-explorer).
4. 3 Charts that Show Countries and Sectors with the Highest Greenhouse Gas Emissions (https://www.weforum.org/stories/2020/12/climate-change-greenhouse-gas-emissions-environment-paris-agreement/#:~:text=2.,to%20net%20zero%20by%202050).
5. Creutzig, F., Roy, J., Lamb, W.F., Azevedo, I.M., Bruine de Bruin, W., Dalkmann, H., Edelenbosch, O.Y., Geels, F.W., Grubler, A., Hepburn, C. and Hertwich, E.G. (2018) 'Towards Demand-Side Solutions for Mitigating Climate Change', Nature Climate Change, 8(4), pp.260-263.
6. Mayer, P., Heer, M., Shu, D.Y., Zielonka, N., Leenders, L., Baader, F.J. and Bardow, A. (2024) 'Flexibility from Industrial Demand-Side Management in Net-Zero Sector-Coupled National Energy Systems'. Frontiers in Energy Research, 12, pp.1443506.
7. Sinn, H.W. (2008) 'Public Policies Against Global Warming: A Supply Side Approach', International Tax and Public Finance, 15, pp.360-394.
8. Trencher, G., Rinscheid, A., Rosenbloom, D., Koppenborg, F., Truong, N. and Temocin, P. (2023) 'The Evolution of "Phase-Out" as a Bridging Concept for Sustainability: From Pollution to Climate Change', One Earth, 6(7), pp.854-871.
9. Bohm, P. (1993) 'Incomplete international cooperation to reduce CO2 emissions: alternative policies', Journal of Environmental Economics and Management, 24(3), pp.258-271.
10. Green, F. and Denniss, R. (2018) 'Cutting with both arms of the scissors: the economic and political case for restrictive supply-side climate policies', Climatic Change, 150(1), pp.73-87.
11. Le Billon, P. and Kristoffersen, B. (2020) 'Just cuts for fossil fuels? Supply-side carbon constraints and energy transition', Environment and Planning A: Economy and Space, 52(6), pp.1072-1092.
12. Lazarus, M., Erickson, P. and Tempest, K. (2022) *Supply-side climate policy: the road less taken*. Stockholm Environment Institute.
13. Scott, K., Smith, C.J., Lowe, J.A. and Garcia-Carreras, L. (2022) 'Demand vs supply-side approaches to mitigation: What final energy demand assumptions are made to meet 1.5 and 2° C targets?', Global Environmental Change, 72, pp.102448.
14. Quiggin, D. (2023) 'Net zero and the role of the aviation industry'.
15. Zhao, J., Li, F. and Zhang, Q. (2024) 'Impacts of renewable energy resources on the weather vulnerability of power systems', Nature Energy, pp.1-8.