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PRESIDENT'S MESSAGE

Dear IAEE members, As I write this message, I feel completely energized by the 46th International Conference in Paris last June. This conference was a remarkable success and left me with the sentiment that IAEE is in the right direction to grow and flourish. With almost 700 registered delegates, this was one of the largest conferences of IAEE. We convened at the impressive Palais des Congrès to engage in rich discussions about the future of global energy. A particular highlight was the gala dinner at the iconic Paris City Hall—a stunning showcase of French history, architecture, and elegance. It is an experience we will surely remember forever.

I would like to extend my heartfelt congratulations to the French IAEE Affiliate, particularly to FAEE President Christophe Bonnery and the Paris Conference Chairs, Cédric Clastres and Olivier Massol. The success of the 46th International Conference was the result of tireless effort and commitment from many individuals who believe deeply in your leadership and in the mission of the IAEE.

The conference highlighted the increasingly complex and dynamic nature of global energy markets. We are witnessing profound transformations across technology, geopolitics, regulation, and business models. Several key insights emerged: i) Energy security is once again taking center stage in policy discussions, particularly as geopolitical tensions escalate. Our gathering in Paris coincided with the ongoing conflict in the Middle East, underscoring this urgency. Furthermore, as decarbonization progresses through greater reliance on variable renewable sources, ensuring reliable power supply becomes even more critical. i) Electricity demand is poised to grow rapidly, fueled by digitalization and the electrification of economies. iii) The pace and direction of these changes vary greatly between developed and developing countries. It is essential that we deepen our focus on combatting energy poverty and fostering a just energy transition.

While in Paris, we also held a productive IAEE Council Meeting, with rich discussions and important decisions regarding the Association's strategic directions. In parallel, we advanced preparations for our upcoming conferences through a series of focused planning meetings.

Looking ahead, our regional and international meetings promise to be equally stimulating. This December, we will gather in Antalya, Turkey, for the Middle East and Central Asia (MECA) Conference (https://www.iaee2025.org.tr/)—an excellent opportunity to explore the region's evolving energy geopolitics. The next European IAEE Conference will take place in Munich, Germany, from 6–9 September 2026. This promises to be another must-attend event to discuss Europe's energy future.

And last but not least, we are delighted to announce that the 47th IAEE International Conference will take place in Santiago, Chile, in July 2026, under the leadership of Professor Ricardo Raineri of the Pontifical Catholic University of Chile. Our planning meeting in Paris laid a strong foundation for what I am confident will be an outstanding conference.

Hosting our flagship event in Chile not only reaffirms IAEE's strategic commitment to expanding its global presence, but also offers a unique opportunity to explore global energy challenges from a Latin American perspective. Chile stands out as a regional leader in the energy transition and exemplifies how prosperity and sustainability can go hand in hand.

Let us all begin preparing for what promises to be a memorable gathering in Santiago. I look forward to seeing you there!

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Editor's Notes

Many thanks to our members for their insight on the topic of "The New Geoeconomics of Energy Transition."

Since 2020, there has been a growing global consensus on the need to promote and accelerate the energy transition. This consensus materialized in the form of countries and companies aligning around the goals of net-zero emissions by 2050. A process of reviewing energy transition policies and strategies seems to be emerging. The new Trump administration the USA brought a radical review of the American policy of promoting the decarbonization of the economy. In addition, growing geopolitical rivalry and escalating trade disputes creates new challenges for the energy transition.

Although decarbonizing the economy is a necessity for all countries, we are beginning to see in practice that the costs and benefits of decarbonization are not the same for all the countries. Asymmetries in the competitiveness of countries in renewable energy sources, both from the point of view of production costs and from the point of view of development the value chain, are issues that can no longer be ignored in the debate on energy transition.

Some important questions need to be addressed in the new geoeconomics of energy transition. First, how does increasing trade disputes and geopolitical rivalry affect the development of renewable industries and the decarbonization technologies worldwide? What are the competitive advantages (and disadvantages) of different countries and regions to promote energy transition? What are the best strategies to develop the energy transition value chains? How does the dominance of technology and access to critical material define the ability for promoting energy transition in different countries? These are some of the questions associated with the new geoeconomics of energy transition.

Gavin Flanagan explores how global strategic shifts may undermine net-zero goals, reinforcing the Global North's competitive advantages while fostering asymmetry in climate trajectories. This imbalance risks an unequal divergence in climate goals, ultimately hindering a fair and equitable global energy transition.

Tooraj Jamasb, Dani-Davi-Arderius, Natsuko Toba, and **Anupama Sen** explain that the European Union is decarbonising its energy sector amidst a changing geopolitical context. This article focuses on the nexus of three inter-related policy pillars; industrial strategy-critical materials-innovation. They investigate the elements of this 'policy trilogy' and present some recommendations.

Meenakshi Gautam examines how geopolitical rivalries and trade disputes are reshaping the global renewable energy landscape and influencing the deployment of decarbonization technologies. With countries increasingly reliant on critical minerals and clean technologies, the transition away from fossil fuels is no longer just an environmental imperative but a strategic geopolitical shift. The U.S.-China-EU power dynamic has led to both innovation and fragmentation in green technology supply chains, with protectionist policies raising costs and limiting access especially in the Global South. Regional case studies of China, the European Union, Africa, and Saudi Arabia highlight varying opportunities and vulnerabilities shaped by trade barriers, energy security concerns, and shifting alliances. While competition has driven down costs and spurred technological advances, it also threatens to create a divided global energy transition. The article concludes with key policy recommendations: fostering international cooperation, easing trade barriers, promoting technology transfers, and ensuring sustainable and equitable access to critical resources. Achieving a successful, inclusive net-zero transition will require balancing national interests with global climate goals through diplomacy, equity, and innovation.

Aditi Sarkar asserts that critical minerals are the dominating factor in the new geoeconomics of energy transition. This essay analyzes how China became the global powerhouse of critical minerals and its effects on the economics of energy transition.

Luis Renato Amórtegui Rodríguez aims to show how fossil primary energies will continue to play a smaller role in the global energy mix by 2050 compared to renewable energies, despite their progressive decline due to lower demand. This is due to the strategies and policies adopted by countries within the current energy transition aimed at decarbonizing the global energy system by 2050 within the framework of the Paris Agreement. This is because CO2 emissions into the atmosphere from the massive consumption of oil, natural gas, and coal have contributed to global warming.

Carey King posits that geopolitics and geoeconomics are largely about one country, or an alliance of a few countries, asserting social power and rules upon those not part of the alliance. This social power, the a large degree, derives from the control and the ability to extract energy from the environment.

Robert V. Parsons, Maryna Klymchuk and **Paul D. Larson** state that there is a growing, global need to reduce greenhouse-gas (GHG) emissions, amidst emerging geopolitical and economic turmoil.

Since 2015, Canada has set reduction of emissions as a priority, but progress has been slow. Canada has also been facing trade barriers; from China starting in 2019, and recently from the United States, in the form of tariffs. Despite these obstacles, there are opportunities, such as using Canadian canola to produce sustainable aviation fuel (SAF) to reduce emissions from civil aviation. This article outlines and explores these obstacles and opportunities, with respect to the energy transition.

Anurag Mandalika and **Brian Snyder** report that trade of biofuels and biomass feedstocks have become increasingly globalized over the past decades as economies pursue varied decarbonization strategies. Due to its large resource base, the United States exports a variety of biofuels and feedstocks, however, the international trade of these commodities may be impacted as a part of the ongoing trade disputes between the U.S. and its trading partners. In this paper, we consider the potential impact of tariffs (and retaliatory tariffs) on the biomass and biofuels industry in the U.S. We analyze the flow of important biofuels such as fuel alcohol (ethanol), biomass-based diesel fuel (BBD, which includes renewable diesel and biodiesel), densified biomass fuel (DBF or wood pellets), etc. Heightened trade barriers are likely to affect not just biomass-based fuels, but also the feedstocks that are used to manufacture biofuels. Their preliminary analysis shows that feedstocks for biofuels (which have competing uses for food and feed) such as soybeans and corn endure a greater effective tariff rate in comparison to finished biofuels (e.g., fuel ethanol or biomass-based diesel). While international trade will likely be impacted, we also consider the potential for increased domestic use of these feedstocks as a result of decreasing globalized energy and feedstock flows. Opportunities for increased decarbonization of transportation sectors may exist through greater utilization of these feedstocks for biofuel production instead of producing a glut of biomass created due to trading barriers. As an example, were all soybean exports utilized domestically for BBD production (in the face of unattractive trade barriers), domestic producers can increase their capacity between 31 and 102-fold for renewable diesel and biodiesel, respectively (notwithstanding other barriers towards such an increase in production).

Sangita Kannan and **Michael Toman** inform us that concerns about the security of EV battery mineral supplies arise because China has a large market share in processing most of the necessary minerals. Geopolitical risks reflect the possibility of supply cuts aimed at individual countries due to conflicts. However, China's ability to control the market allocation of battery minerals is unlikely to be sufficient to sustain targeted supply cuts. A greater concern is China's exercise of market power over foreign buyers to increase profits. However, the record on such actions by China is mixed. A costly build-up of non-Chinese capacity for battery mineral processing will be needed to mitigate market power.

Remembering John Felmy

John C. Felmy, 70, of Olney, MD, passed away on June 13, 2025, in Sandy Spring, MD, after a lengthy illness. John was born in Clearfield, PA, to Mary Felmy and Norwood Brosius. He grew up in Jersey Shore, PA, and the surrounding area, where he was known to his childhood and college friends and family as "Smokey". He was a graduate of Jersey Shore High School, received a BA and MA in Economics from Penn State University, and a Ph.D. in Economics from the University of Maryland.

Mr. Felmy had more than three decades' experience in energy, economic, and environmental analysis. John served as the chief economist of the American Petroleum Institute (API) from 2000 to 2016. He was responsible for overseeing economic, statistical, and policy analysis of the Institute. Earlier in his career he worked for DRI/McGraw Hill, ICF Consulting, and Princeton Economic Research. John was known for his impeccable insights on energy markets, reporting on both International and national markets with clarity and penetrating understanding. John was a deeply knowledgeable expert on the petroleum industry and the overall energy sector, and was tireless in his passion to educate the public. As chief economist of API, he traveled the country giving hundreds of presentations and interviews to members of Congress and their staffs, Federal and State agencies, the media, professional organizations, universities, and many others.

John was a member of several professional associations including the American Economic Association, the National Association for Business Economics, and the International Association for Energy Economics. In 2000 he was elected President of the National Capital Area Chapter of the U.S. Association for Energy Economics (NCAC-USAEE) and was later recognized for his accomplishments in the field of energy economics by being named a Senior Fellow.

John never forgot his Pennsylvania roots. He regaled anyone who would listen with stories of growing up in the hills of Pennsylvania, fishing with his brother, working alongside his father, and surviving the life-altering effects of the Hurricane Agnes floods. Supporter of all things related to Penn State, he was a devoted fan of Penn State football. As an undergraduate, he was president of the Debate Society, where he honed the skills that would serve him well in his later career. John was a member of Penn State's Phi Kappa Tau fraternity where he made many life-long friends and was a consistent donor to their many philanthropic events.

John was the beloved husband of Mary Anne Normile for more than 46 years. John was preceded in death by his brother, Andrew Felmy of Pasco, WA, and his parents. John also leaves behind a large extended family including several sisters- and brothers-in-law, nieces, nephews, and great nieces and nephews. John will be missed greatly by his family and a wide range of friends.

Information on a celebration of John's life will be forthcoming. Interment will be private.

In lieu of flowers, donations in John's memory may be made to the Penn State Pattee-Paterno Library at raise.psu.edu/JohnFelmyMemorial.

Net Zero Divide: The Geopolitical and Economic Landscapes of the Energy Transition on the Global North and South

BY GAVIN FLANAGAN

Abstract

This article explores how global strategic shifts may undermine net-zero goals, reinforcing the Global North's competitive advantages while fostering asymmetry in climate trajectories. This imbalance risks an unequal divergence in climate goals, ultimately hindering a fair and equitable global energy transition.

The Global Energy Transition: Emerging Trends and Geopolitical Realities

The urgency behind the goal of net-zero emissions stems from overwhelming scientific evidence that continued climate warming will impose irreversible ecological and economic costs, an understanding that is now widely acknowledged in many governments and organizations. Changing sentiment on global warming led to international cooperation through historical landmark events such as the United Nations Framework Convention on Climate Change (UNFCCC) and the Paris Agreement, where nearly 200 nations pledged to curb emissions and work toward net-zero carbon emissions by 2050, marking a turning point in global climate governance. Subsequent Conferences of the Parties (COP) refined the framework, shaping climate finance mechanisms, and setting legal obligations for emissions reductions. Since international cooperation on climate change began, advancements in the reduction of carbon emissions have been documented, with the World Economic Forum's Energy Transition Index (ETI) reporting that since 2015, "out of 120 countries, 107 have shown progress over the past decade, with 30 countries seeing their scores increase by more than 10%."

Despite the efforts to combat climate change, new trends, challenges, and opportunities have emerged on the global stage, prompting renewed discussions on short and long-term outlooks and priorities. Recent global developments, including concerns over energy security, the rise of artificial intelligence, and international trade relations have become increasingly prominent. These developments have caused governments, businesses, and public sentiments to change, which may jeopardize the energy transitions goals. A recent analysis of ETI scores shows that "only 20 countries improved scores across all three dimensions in the past year" (WEF, 2024), suggesting that priorities may be shifting. While climate change has long been perceived as a global public good (Andre, Boneva, Chopra, & Falk, 2024), the pathway to net zero may be evolving in response to these new developments and changing sentiments.

The global push toward Net Zero has been a defining objective for many governments, industries, and international organizations. Recent developments and geopolitical shifts have introduced new complexities that are reshaping the trajectory and priorities of the transition. As nations navigate these new challenges, several key global trends have emerged as particularly impactful:

1. An increased focus on energy security and the need to secure critical minerals and supply chains (Kim, Jaumotte, Panton, & Schwerhoff, 2025).
2. The pursuit of a first-mover advantage in the global race for artificial intelligence (Qutbah, 2025).
3. Increased trade recalibrations, disputes, and negotiation ensuing uncertainties and consequentially heightening volatility in financial markets. (WEF, 2025).

These interconnected trends can collectively shape the trajectory of the global energy transition. While decarbonization remains a widely acknowledged global goal, emerging trends indicate a shift in priorities that present lucrative opportunities and substantial opportunity costs that cannot be disregarded. These trends can influence the effectiveness of transition efforts and carry long-term implications, an effect that Gross and Finley observe, "a cooperative and open trade market would lead to a faster and less expensive energy transition," but rising "geopolitical tensions and rivalries will likely make this ideal solution unreachable" (Gross & Finley, 2025).

As a result of these changes, the trajectory of the climate transition appears to be shifting. The Global North, leveraging its economic and political competitive advantages, is well-positioned to capitalize on the evolving landscape, while the Global South, constrained by financial and structural limitations, remains unable to adapt in a similar fashion, potentially deepening the divide between the two regions. These changes may have significant long-term consequences: without substantial support and collaboration from the Global North, the Global South will struggle to decarbonize while maintaining its economic development, increasing carbon emissions, and jeopardizing climate targets. Leading to disparate climate reduction achievements between the Global North and South, reinforcing asymmetries in climate transition efforts and the need for a more equitable approach to sustainable development.

Challenges of the Global North and South

Understanding the divide between the Global North and Global South is essential to analyzing the dynamics of the energy transition. The Global North generally comprises economically developed, industrialized nations with advanced technologies, high living standards, and significant influence in global policymaking. Countries such as the United States, members of the European Union, and parts of East Asia hold competitive advantages in renewable energy adoption, research, and climate policy leadership.

In contrast, the Global South includes developing nations that often face economic and infrastructure challenges preventing change, limiting their capacity to adopt clean energy technologies. Many rely heavily on natural resource exports and grapple with energy access and affordability, all while attempting to balance economic growth and sustainability (Hickel et al., 2022).

While the Global North sets ambitious climate targets and drives innovation, the Global South must navigate developmental priorities alongside sustainability goals. Given historical context and current trends, energy transition outcomes are likely to diverge significantly between the two regions. The assumption that access to increase capital or technology alone can ensure successful transitions in the Global South reflects an overly optimistic view that risks deepening the existing divide.

This perception underestimates the significant constraints faced by the Global South in its climate change related efforts. In a paper analyzing 172 regional mitigation scenarios consistent with the Paris Agreement targets, Hickel and Slameršak found that “OECD countries and the rest of Europe consume 2.3 times more energy than the average in the Global South (119 GJ per capita vs. 52 GJ per capita)” and that “only 11 of the 172 scenarios analyzed have the Global North–Global South energy gap declining to less than 30 gigajoules per capita per year by the end of the century” (Hickel, J., & Slameršak, 2022). Their research demonstrates that the global framework set forth in the Paris Agreement does not adequately address the complex and divergent realities of the Global North and South when it comes to energy transition efforts.

While the Global North benefits from centuries of economic and institutional development, its competitive advantages are being leveraged in a multifaceted strategy in reprioritizing climate change goals. However, this shift risks deprioritizing collaboration, investment, and self-sufficiency, factors that the World Economic Forum (Majid, 2025) identifies as essential to a successful energy transition in the Global South.

Overlooking the Global South’s constraints could intensify climate change and obstruct energy transition. Without significant subsidies and technological cooperation, the Global South may rationally reprioritize its energy supply and demand goals, reinforcing “domestically available coal, oil, and gas serve[ing] as critical pillars for ensuring the security of supply” as they “are primary sources of revenue for numerous countries.” If clean energy technologies fail to become cost-competitive with carbon-intensive alternatives, adjusting market incentives alone will be insufficient for a sustainable transition.

Beyond market mechanisms, structural and economic issues facing the Global South, the realities of the region must also be addressed to ensure a stable and secure energy transition. A “rapid phaseout of fossil fuels could result in widespread unemployment, political unrest, and destabilization, all counterproductive to addressing climate change” (Singh & Arya, 2024). A comprehensive strategy is needed, one that incorporates both targeted market interventions and economic aid for success in the long term.

The Global Energy Transition in a Fragmented Landscape

The global energy transition is reshaping geopolitical dynamics, and the gap between nations capable of independently meeting climate targets and those reliant on external support has widened. The differences between the Global North and Souths’ economic structures, industrial capacity, and policy frameworks determine the feasibility of sustainability goals, creating divergent trajectories for advanced and emerging economies.

Among the most influential Global North policies are the U.S. Inflation Reduction Act (IRA) and the EU’s European Green Deal. The IRA allocates nearly $400 billion to clean energy, targeting investment in renewables, EVs, hydrogen, and carbon capture (Kumar et al., 2022). The European Green Deal mobilizes €1 trillion over a decade to promote renewable energy, efficiency, and environmental policies (European Commission, n.d.)..

Beyond financial and industrial strength, the Global North wields institutional, military, and technological leverage. Influence over capital markets facilitates favorable investment conditions, while geopolitical dominance enables access to critical minerals like lithium and rare earth elements, at favorable terms, which are vital for renewable technologies and battery systems.

While these advantages allow the Global North to advance their sustainability goals, they also contribute to structural imbalances in global energy markets. Many developing economies in the Global South face difficulties in securing liquid markets, specialized labor supply, or deploying advanced technology at comparable scales to the North, reinforcing the inequalities in climate adaptation. Addressing this divide requires international cooperation, equitable resource allocation, and strategic policy alignment to ensure a balanced and inclusive global energy transition.

The New Geopolitical Landscape: Intensifying Divides in the Energy Transition

Since the UNFCCC and Paris Accords, the energy transition has evolved amid rising geopolitical uncertainty. While the Global North can navigate risks more effectively, the Global South faces heightened vulnerability. Understanding these dynamics is critical for evaluating global energy transition outcomes. Wang et al. (2024) find that “there is a negative correlation between geopolitical threats, geopolitical acts, geopolitical risks and

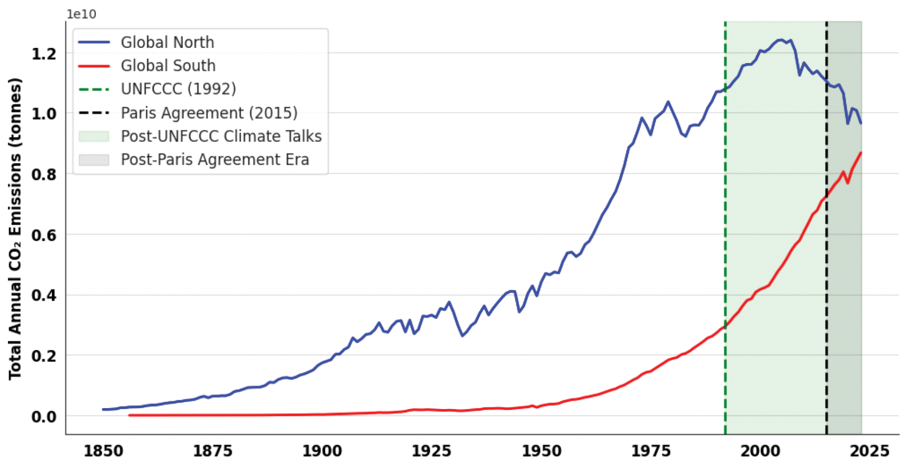

Figure 1: CO_2 Emission Trends in the Global North and South, 1850-2023
Note: Emissions are in metric tons of CO_2 per year. Regions are classified based on economic development, energy infrastructure, and reliance on fossil fuels: the Global North includes developed, high-income nations with advanced energy systems; the Global South includes emerging and developing economies often reliant on fossil fuels or facing energy access challenges.
Source: https://ourworldindata.org/co2-emissions

energy transition" and that "geopolitical risk has a negative impact on the energy transition and slows down the process… as geopolitical risk increases, the elasticity of energy transition to geopolitical risk increases."

Zhu et al. (2025) further observe that "geopolitical risk negatively impacts energy transition[s] more in developed countries due to their high dependence on the international energy market than in non-developed countries, where internal economic and infrastructural factors more influence energy policies." They note that while geopolitical risks have slowed the transition in the Eastern Hemisphere due to reliance on transnational energy chains, "Western Hemisphere countries [have used] geopolitical risks to transition to energy independence," citing examples like U.S. trade renegotiations and the EU's ban on Russian seaborne oil and the creation of an EU Gas Purchasing Platform (Marhold, 2023).

Additionally, Zhu et al. (2025) explain that "large natural resource rents considerably boost geopolitical risk dampening… resource-based economies are more inclined to safeguard old energy supplies than promote renewable energy options amid global conflicts." This reveals a core divide: while the Global North possesses the capacity to advance clean energy, resource-dependent Global South economies often remain tethered to fossil fuels as a risk management strategy.

Energy transitions traditionally follow a historical pattern: nations initially rely on low-cost, high-density fuels before shifting to cleaner sources as institutional strength and investment grow. Yet, many Global South countries face limited capital access, specialized labor shortages, and weak governance, stalling renewable adoption. In the absence of sustained international support, these nations may prioritize low-cost fossil fuels such as coal (South Africa, Indonesia, India, China) and heavy crude oil (Venezuela, Nigeria, Mexico) to meet short-term demand, reinforcing environmental and opportunity costs.

Emissions trends underscore this divergence. According to the European Commission's *GHG Emissions of All World Countries 2024*, "top emitters, in 2023 China, India, Russia, and Brazil increased their emissions compared to 2022, with India having the largest increase in relative terms (+6.1%) and China the largest absolute increase by 784 Mt CO_2 eq." The report also states that "global GHG emissions… have increased by nearly 1.5% annually on average since 1990, and they were 61.8% higher in 2023 than in 1990." Among major emitters, China, India, Russia, and Brazil saw increases, while the USA (–1.4%) and EU27 (–7.5%) saw declines (Crippa et al., 2024).

These patterns of emissions are further contextualized in Figure 1, which illustrates the historical divergence of CO_2 emissions between the Global North and Global South from 1850 to 2023. The figure demonstrates how emissions from the Global South have sharply increased since the 1990s, coinciding with accelerated industrialization, while emissions in the Global North have plateaued or declined post-2005. Despite the implementation of major climate accords such as the UNFCCC (1992) and the Paris Agreement (2015), emissions trajectories suggest that mitigation efforts have had an uneven impact, with the Global South still on a steep upward path. This divergence highlights the structural imbalance in global energy and climate politics: while the Global North had decades of high-emission growth before transitioning toward cleaner alternatives, the Global South is now attempting to industrialize in a more carbon-constrained world, often without the same financial and institutional support.

Summary

As global complexities continue to evolve, the solutions of tomorrow must adapt accordingly. The pursuit of net-zero emissions and the energy transition has shaped national strategies for decades. However, recent developments, including heightened concerns over energy security, the growing influence of artificial intelligence, and the recalibration of international trade policies, have introduced new uncertainties that are redefining the geopolitical and geoeconomic landscape. Highlighting the systemic imbalances between the Global North and South, producing divergent realities in the result for achieving net-zero emissions for both regions.

Advanced economies in the Global North, supported by technological innovation, geopolitical leverage, and financial resources, are accelerating for adjusting their energy transitions while meeting emerging trends. In contrast, the Global South, face significant obstacles in achieving a sustainable energy transition without compromising economic growth and internal stability. Under conditions of heightened uncertainty, limited access to investment, lack of technical expertise, and overall support from the Global North, the Global South may continue to rely on carbon-intensive resources to meet energy demand, increasing abatement costs, and deepening reliance on fossil fuel infrastructure.

If current trends persist, global efforts to stabilize energy markets and mitigate climate change risks will be increasingly challenged. Bridging the gap between the Global North and South will require strategic investments in energy infrastructure, innovative financing mechanisms, and technology transfers. Without these interventions, disparities in energy transition pathways will deepen economic and energy inequalities, further complicating global climate objectives.

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Geopolitics and Green Transition Trilogy in the EU: Industrial Strategy, Critical Minerals, and Innovation

BY TOORAJ JAMASB, DANIEL DAVI-ARDERIUS, NATSUKO TOBA, AND ANUPAMA SEN

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Abstract

The European Union is decarbonising its energy sector amidst a changing geopolitical context. This article focuses on the nexus of three inter-related policy pillars; industrial strategy-critical materials-innovation. We investigate the elements of this 'policy trilogy' and present some recommendations.

1. Introduction

The European Union's (EU) decarbonisation and Green Deal policies sit within a changing geopolitical energy context and can be characterised as a 'trilogy' comprising (i) industrial strategy, (ii) critical materials, and (iii) innovation. The energy 'trilemma' (security, sustainability and affordability) conventionally faced by policymakers now need to be pursued within the context of this emerging 'trilogy' (Figure 1). Both the trilemma and the trilogy demonstrate features of public goods, meaning that markets alone are unlikely to deliver the efficient amount and right balance of each of their components. For example, competitive pressures and lack of access to critical materials may incentivise firms to innovate, but industrial strategy may not necessarily support firms that have the greatest potential for efficiency and innovation.

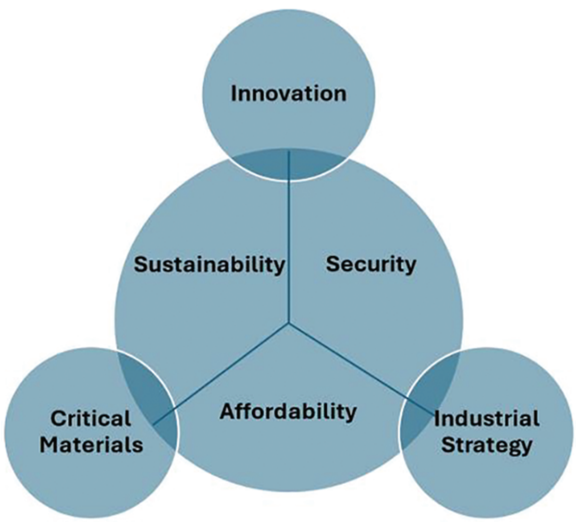

Figure 1: Energy Trilemma within Trilogy Framework. Source: Authors.

At the same time, industrial strategy may be able to initially support the most promising firms, which may lead them to become complacent and reduce their incentives for further innovations or for the efficient procurement, allocation and use of critical and other materials. In this case, firms supported by the industrial strategy may instead focus on increasing their dominant market power. Such consequences are detrimental to the energy Trilemma.

Thus, optimising the trilogy will require carefully thought-out policy interventions, which may be sub-optimal from a narrow economic efficiency point of view in the sense that market values capture only part of full economic (or social) values. However, deviations from efficiency occur frequently in economic policy making and guided by higher-level geopolitical and security considerations.

The new geopolitical context can weaken some established multilateral trading blocs, leading to the use of less formal and more unilateral diplomatic and trade measures (Hegde, Wouters, & Raina, 2021). This trend may have implications for global trading in critical minerals, energy (fossil and clean fuels and electricity), infrastructure equipment, and in the development of new technologies as seen in the EU's renewed focus on industrial competitiveness. As new competing geo-politically motivated trade blocs emerge, more may follow, leading to segmentation of global trade markets that have historically been based on the economic principles of comparative and competitive advantages among countries, and the associated supply chains, thus constraining innovation.

EU industrial strategy, innovation and raw materials also influence the pursuit of the three dimensions of the original energy trilemma. For example, securing critical minerals within the EU through deep-sea mining could risk the affordability of end-products, and might impact sustainability of the marine environment and biodiversity if not pursued in a reasonable and sustainable manner; a better alternative would be to pursue procurement through global trade based on economic sustainability, rather than geopolitics.

Given this context, this article addresses two major questions. First, how could an EU strategy adapt to recent geopolitical changes? We consider the period

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starting with the Russian invasion of Ukraine in 2022 followed by increasing global instabilities and trade tensions, aggravated by import tariffs implemented in the United Sates (US) since early 2025.[1] And second, what are the resulting implications for industrial competitiveness, decarbonisation of the economy, and efficient 'green' energy supply chains? This article considers issues and options relating to the three pillars of the trilogy, in relation to the energy trilemma framework, through a lens of economic and policy analysis.

2. Industrial strategy and competitiveness

In February 2023, the European Commission introduced 'A Green Deal Industrial Plan for the Net-Zero Age'[2], accompanied by measures for strengthening Europe's net-zero technology products manufacturing ecosystem (Net Zero Industry Act), a framework for ensuring secure and sustainable supply of critical raw materials for energy, and a reform of electricity market design.

The Draghi Report in 2024 analysed the competitiveness of EU industry and strategy (European Commission, 2024a). It highlighted the market price of electricity in the EU higher than those of China, and the US, with a combination of the generation mix, resource endowments, technology costs and political economy at times favouring technologies with higher economic costs. In 2024, coal formed the highest share of the electricity generation mix in China (58.4%), in the US it was natural gas (42.6%), and in the EU it was renewable energy sources (RES), 48.7% (IEA, 2025a).

Global installed capacity of RES has been increasing every year (IRENA, 2024). In 2024, RES made up almost three-quarters of the overall increase in global power generation (IEA, 2025a). Access to low-cost new energy technologies will be an important factor in global industrial competitiveness (European Commission, 2025).

Global value chains of trade, partnerships, and research and innovation (R&I) could promote overall global competitiveness and net global welfare gains. For instance, in 2020, mobile phone manufacturing for a global major company involved suppliers in 43 countries across six continents (Ross, 2020). Similarly, it has been suggested that international cooperation between the US, EU, and China could bring forward the point at which electric vehicles (EVs) reach market cost parity with internal combustion engine (ICE) vehicles (Lam & Mecure, 2022). Simulations show that global supply chains for solar panels resulted in faster learning and lower global market prices than fully domestically supplied markets (Helveston, He, & Davidson, 2022).

On the other hand, in a scenario where the global market for critical energy equipment is segmented into trading blocs, there may be a global net welfare loss as supply and value chains will be rearranged according to geopolitically-driven industrial strategy priorities. In this scenario, the EU trading bloc would be a sizable proportion of the global market, though not the largest. For instance, by 2050, projections show India's electricity generation will exceed that of the EU, and China's renewable electricity generation will be about four times that of the EU (IEA, 2024). While some blocs will win, others will lose, to varying extents, resulting in widening equity gaps across the globe, and potentially leading to instabilities.

The energy crisis after the Russia-Ukraine war has widened the economic boundaries between the energy and the public sectors as considerable resources have been required to support consumers and the green transition. The magnitude of required investments combined with new uncertainty about the progress

Table 1: Policy recommendations - Industrial Strategy and Competitiveness

Policy recommendation	Potential benefits
Develop demand-side electrification, green fuels, and energy efficiency activities.	• Lower energy costs • Stimulate employment in new economic activities[3] • Reduce uncertainty in expanding manufacturing capacity and 'anticipatory investments' • Stimulate upstream investments in the value chain[4] • Increase bankability of new projects • Improve competitiveness as suppliers compete for market share
Where specific EU energy equipment lags other trade blocks on quality and cost, leverage the scale of the EU market to promote foreign direct investments in energy equipment manufacture – for instance, joint ventures (JVs), to promote technology transfer and risk sharing in EU markets.	• Reduce the market and technology risk of investments for foreign investors in introducing new energy equipment and technology transfer in EU market • Take advantage of the experience of other regions in energy equipment manufacture[5]
Improve regulatory predictabilities and reduce uncertainties to promote anticipatory investments in electricity networks and other infrastructures.	• Reduce time to commission new investments, which reduces uncertainty and financing risks[6] • Lower and more predictable network costs for new economic activities.
Develop demand-side flexibility solutions, including storage.	• Lower RES curtailment during surplus production[7] • Smooth peak electricity prices[8] • More efficient use of electricity networks • Deferred or cost saving of redundant grid construction and upgrades, higher system resilience, resource adequacy and lower GHG emissions[9] • Consumer electricity bills and costs savings[10]
Prioritize projects that require minimum financial support in relation to required total investment.	• Take better advantage of nearing commercial viability technologies • Improve efficiency and efficacy of public financial support such as Connecting Europe Facility (CEF)

of green transition portends careful thinking around 'anticipatory investments' for regulators and industry. In addition, EU integration projects present a 'cross border cost allocation (CBCA)' dimension that requires special instruments (Sen et al., 2024).

The support for consumers and the green transition needs to be strategically designed as support to energy prices may undermine progress. For example, subsidies on retail tariffs should be refocused on encouraging demand-side flexibility and efficiency, which could enable the green transition in addition to reducing electricity bills. This effect was seen in the UK after the energy crisis precipitated by Russia's invasion, with an increase in demand flexibility services provided by companies to consumers. In the EU, high electricity and gas prices and new incentives in the aftermath of the invasion drove rapid growth in solar PV installation. However, outside of three largest markets (Germany, Italy and Spain), annual PV additions declined in over 15 member states in 2024, as lower energy prices and reduced policy support slowed growth (IEA, 2025b).

3. Innovation

The formation of competing trading blocs could segment and rearrange established industrial energy supply chains. This trend could also affect the scale of R&I networks, and some collaborations may give way to competition among former collaborators. Multinational companies with research centres around the world may be forced to reorganise their innovation activities. This trend may reduce the global rate of innovation in terms of learning-by-research and the diversity of complementary attributes. The economic cost of foregone innovation for global decarbonisation can be substantial, as trading blocs aim to innovate independently.

The economies of the EU are diverse and establishing new R&I infrastructures could be an opportunity to create high value-added jobs and innovations that deliver solutions specific to the EU, laying the foundations for future 'green' growth. As global geopolitical conditions improve, EU technologies could be marketable to other countries, as the EU is regarded as a global leader in promoting sustainability and the 'green' economy.

Increasing the utilisation of existing technologies and promoting the commercialisation of technologies that are nearly at maturity could optimise funding costs, especially with a stronger focus on market mechanisms. For instance, while next generation of inverter-based resources (IBRs) for RES can enable stable operations of highly decarbonised grids, the potential to leverage existing conventional and advanced IBRs is overlooked. Most power systems do not yet require new advanced IBRs to support the grid, often using existing IBRs as legacy units, even though some systems have the technical capability to deliver services and be marketed (EPRI, 2025). Another example is long duration energy storage (LDES), which is yet to be fully commercialised at low cost. [11] The utilisation and support of existing and near-market innovations with high technology readiness levels (TRLs) are as important as supporting emerging technologies.

Table 2: Policy recommendations - Innovation

Policy recommendation	Potential benefits
Increase investment levels in R&I and consider new models of organising and funding R&I in the EU	• Increases the scale of R&I capacity and scale which is important for energy but is beyond the reach of smaller utilities[12]
Measure and benchmark performance of regulatory incentives for innovation in the grid	• Incentivises network companies to become innovation facilitators, effectively channelling regulatory incentives to suppliers, service providers and research institutions that traditionally show higher patenting activity[13]
Prioritise 'market pull' and learning-by-doing R&I for existing and near-market technologies to achieve cost reduction	• More efficient allocation of public funds for technology promotion[14]
Prioritise 'technology push' and learning-by-research R&I to support emerging technologies	• Helps technologies progress faster from the 'emerging' to 'evolving stage'[15]
Widen the use of regulatory sandbox to trial non-mature solutions related to equipment for grid and RES	• More efficient regulatory developments. • Less uncertainty when revising and updating regulation[16]

Furthermore, designs of new support mechanisms for R&I would benefit from thorough evaluations of the organization, efficiency and efficacy of existing and past R&I support. Such evaluations would include a full cycle, such as proposal, selection, implementation, monitoring, reporting and verification, etc. to help improve outcomes for the new R&I programs.

The measures outlined under the industrial strategy pillar can leverage the scale of the EU market for R&I. A larger EU market with inward international investment in energy equipment manufacturing and standardisation could increase the incentive to invest in R&I. This increase could in turn raise the potential for cost reduction through learning-by-doing. Similarly, the development of the demand-side for green technologies and fuels can be supported by R&I through learning-by-research (market-pull) measures (Jamasb, 2007). Finally, bridging policies and financial support can align the demand and supply sides and reduce the likelihood of losing emerging technologies in the 'valley of death' (Gbadegeshin, et al., 2022).

4. Critical Materials

Geopolitical competition over scarce critical materials that can help deliver a global public good (i.e., climate change) to achieve narrow industrial policy objectives, is unlikely to lead to the optimal use of these resources. From a global welfare maximising and climate change perspective, collaborative approaches are preferable and deliver better outcomes than uncontrolled competition among trade blocs. Therefore, collaborative multilateral solutions based on a fair distribution of the value-added emanating from these minerals among exporting and importing countries would be likely to deliver more sustainable outcomes and need to be considered.[17]

Many critical energy minerals are concentrated in a small number of countries.[18] In the absence of exporter-importer collaboratives, a possible outcome is the formation of Organization of the Petroleum Exporting Countries-like exporting blocks for different minerals (Ghorbani, et al., 2024). An example is the formation of BRICS+6 in relation to critical minerals (Vivoda, Matthews, & McGregor, 2024). However, past attempts of metal producer clubs had not been sustainable or successful, such as Intergovernmental. Council of Copper Exporting Countries, Association of Iron Ore Exporting Countries and Primary Tungsten Association.

Ongoing technological changes and policies on recycling and waste minimisation affect the demand for the types and amounts of critical minerals and could limit the growth of the critical minerals market. Unlike crude oil, critical minerals are highly heterogeneous, making cartelisation or monopolisation strategies unsustainable. High market concentration poses risk of supply shortfalls and the exporting countries' dependence on mineral export revenues. Furthermore, as of 2025, 55% of strategic minerals are under some form of export restrictions, half of which are produced as by-products, limiting the flexibility of their supply and amplifying supply risks (IEA, 2025b).

EU Industrial policies such as the European Critical Raw Materials Act, secure supply chains innovation (extracting, processing, recycling) and set a limit of 65% of EU's annual needs of each strategic raw material at stages of processing coming from a single third country. From the economic efficiency point of view, competition allowing exit and entry and diversification could achieve continuing technological change and cost reduction more effectively than cartelisation of the supply and demand sides. Innovative policy tools can be explored, such as standards and regulations; for example, EU battery passports could support the sustainability of a battery throughout its lifecycle. Innovative market mechanisms are also emerging, such as London Metal Exchange (LME) exploring the potential for producing sustainable metal premia for LME-approved brands. For example, LME aims to monetise positive externalities of critical minerals with 'low-carbon' nickel.

Further research into sustainable exploration, alongside the development of circular economy strategies in key end-use sectors, such as RES and EVs, may also generate substantial national and global returns. R&I and commercialisation of technologies using fewer (or no) critical minerals could also be prioritised. For example, sodium-ion batteries could be explored as a potentially cheaper alternative to lithium iron phosphate (LFP) due to the latter's high cost, uneven geographic distribution, and environmentally damaging extraction process. Sodium-ion cathodes rely on a new supply chain for sodium instead of lithium, which is predominantly sourced from soda ash. Europe is among the major producers, with 20% of global production, driven by Türkiye producing almost 80% of this production from natural soda ash.

Table 3: Policy Recommendations – Critical Materials

Policy recommendation	Potential benefits
Promote research into modern and sustainable exploration, extraction, and use of raw materials in Europe (e.g. sustainable critical minerals and circular economy strategies)	• Generate substantial national and global returns • Lower risk on the currency exchange rate from imports • Improves security of supply[19]
Support R&I and commercialisation of technologies requiring less critical minerals or finding alternatives	• Lower dependence on critical materials • Less market power for agents that possess dominant critical raw materials
Innovation in circular economy and recycling critical minerals	• Improves security of supply[20] • Reduce dependence on materials from abroad
Consider bloc-to-bloc coordination or trade and investment agreement[21]	• Sharing of technical know-how for collaborative competitions that enables access to critical raw materials and innovations[22]
Implement technical and sustainability standards and regulations for critical raw materials value chain	• Improve competitiveness and sustainability of the European industry related to critical raw materials[23]

5. Conclusion

As the EU continues to decarbonise, recent changes in the geopolitical context imply that it will need to adapt the three pillars or 'trilogy' of its policy (industrial strategy, innovation, and critical minerals) to fit the new geopolitical context and ensure an efficient amount and right balance of each among them. To continue with the path of decarbonization, it is necessary to have access to critical materials but also implement efficient and effective R&I to strengthen EU competitiveness. Such access and R&I become more challenging since the global geopolitical changes are reconfiguring historical alliances and redefining new global supply chains.

The implementation of recommended policies in this article must be agile to mitigate the risk of increasing vulnerabilities to geopolitical shocks and/or fragmentations. The implementation inevitably requires political leadership to set a clear, viable and pragmatic roadmap at EU level. Moreover, EU must strive to set new global strategic alliances to guarantee access to critical materials, innovation and capital. A successful policy would strengthen exports of high-value-added technology, which would also improve Europe's economic development and could maintain EU as a global leader of green transition that the other regions could learn and benefit from.

As a next step, we recommend conducting specific studies and estimates to design the details of the policy recommendations into strategic roadmap and action plan.

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Notes

[1] Up to the time of drafting this article as of May 2025.

[2] European Commission (2023) eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:52023DC0062

[3] Tamba et al. (2022)

[4] IEA (2023)

[5] ACER & CEER (2024).

[6] ACER & CEER (2024).

[7] PXiSE (2024).

[8] Jamasb, Nepal, & Davi-Arderius (2024).

[9] PXiSE (2021); Hledik & Peters (2023); Deloitte (2024); PXiSE (2024); Anaya & Pollitt (2021); Anaya & Pollitt (2022).

[10] Asmus & Kelly (2021); PXiSE (2021).

[11] The Long Duration Energy Storage Council. https://www.ldescouncil.com/

[12] Jamasb, Llorca, Meeus, & Schittekatte (2023)

[13] Ribeiro & Jamasb (2025).

[14] Jamasb (2007).

[15] Jamasb (2007).

[16] Schittekatte, Meeus, Jamasb, & Llorca (2021)

[17] The solutions would need to be within the bounds of ownership and regulation of natural resources within national boundaries.

[18] For example, Brazil produces 98% of the world's active niobium reserve; global cobalt reserves are concentrated in the Democratic Republic of Congo (DRC); Argentina, Bolivia, and Chile, known as the "lithium triangle", together hold half of the world's lithium reserves; Indonesia controls over 20% of the world's nickel reserves; Mozambique controls more than half of the global graphite reserves; Russia has nearly half of global palladium deposits; and China holds reserves of rare earth oxides, and 34% of the world's copper reserves (Foreign Affairs Committee, 2023; Romani, Comincioli, & Vergalli, 2024).

[19] Maisel, Neef, Marscheider-Weidemann, & Nissen (2023)

[20] Lotric, Sekavcnik, Kustrin, & Mori (2021)

[21] European Comission (2024b)

[22] Vivoda (2023)

[23] CEN-CENELEC (2023)

Geoeconomics of Clean Energy: Trade Conflicts, Strategic Rivalries, and the Fragmentation of Global Decarbonization Pathways

BY MEENAKSHI GAUTAM

Abstract

This article examines how geopolitical rivalries and trade disputes are reshaping the global renewable energy landscape and influencing the deployment of decarbonization technologies. With countries increasingly reliant on critical minerals and clean technologies, the transition away from fossil fuels is no longer just an environmental imperative but a strategic geopolitical shift. The U.S.-China-EU power dynamic has led to both innovation and fragmentation in green technology supply chains, with protectionist policies raising costs and limiting access especially in the Global South. Regional case studies of China, the European Union, Africa, and Saudi Arabia highlight varying opportunities and vulnerabilities shaped by trade barriers, energy security concerns, and shifting alliances. While competition has driven down costs and spurred technological advances, it also threatens to create a divided global energy transition. The article concludes with key policy recommendations: fostering international cooperation, easing trade barriers, promoting technology transfers, and ensuring sustainable and equitable access to critical resources. Achieving a successful, inclusive net-zero transition will require balancing national interests with global climate goals through diplomacy, equity, and innovation.

Introduction

Renewable energy and decarbonization technologies are central to combating climate change, with renewables like solar and wind contributing 29% of global electricity in 2022, projected to reach 35% by 2025 (IEA, 2023). Investments in renewables hit $623 billion in 2023, reflecting their economic and environmental importance (Bloomberg NEF, 2024). Decarbonization technologies, such as green hydrogen and carbon capture, are vital for net-zero targets, with green hydrogen potentially meeting 10% of global energy demand by 2050 (IRENA, 2022). However, trade disputes, like U.S.-China tariffs on solar panels, and geopolitical rivalries among the U.S., EU, and China disrupt supply chains and technology diffusion (Lewis, 2019). This article explores how these tensions shape renewable energy industries and decarbonization efforts, analysing geopolitical contexts, trade impacts, rivalry's role, regional case studies, and policy implications.

1. Geopolitical Context of Renewable Energy and Decarbonization

The transition from fossil fuels to renewable energy constitutes not merely an energy shift but a reconfiguration of global power dynamics. Countries are now competing for dominance over essential minerals such as lithium, cobalt, and rare earth elements, rather than relying on oil and gas. These are essential for the production of solar panels, wind turbines, and batteries.

The IEA (2023) forecasts that the demand for these minerals would treble by 2040 under existing policy, emphasising their strategic significance. In 2023, investments in renewable energy reached $623 billion, primarily due to the surge in solar and wind energy (Bloomberg NEF, 2024).This transition introduces a novel power dynamic "geoeconomics," wherein nations seek autonomy by managing technology, and "geopolitics," through which influence is exerted via commerce and innovation. An exemplary instance? China. It commands solar industry, with more than 80% of the global capacity. This reallocates influence from resource-abundant nations to technologically advanced ones (Wood Mackenzie, 2023). However, it also engenders weaknesses. Disruptions in supply chains adversely affect energy security, underscoring the significance of comprehending global energy politics.

2. Trade Disputes and the Impact on Renewable Energy Sectors

Trade disputes substantially hinder renewable energy sectors by escalating expenses and delaying initiatives. The U.S.-China trade conflict exemplifies this, as U.S. tariffs reaching 50% on Chinese solar imports in 2024 increase installation expenses and encourage panel stockpiling (Carnegie Endowment, 2025). China's dominance of 80% of the global solar panel components industry, encompassing polysilicon and wafers, leads to supply chain vulnerabilities, since trade barriers or export restrictions on rare earths might destabilise global markets (Wood Mackenzie, 2023; Reuters, 2021). Environmental policies reduce these effects; the U.S. Inflation Reduction Act (IRA) of 2022 promotes domestic manufacturing, thus reducing dependence on imports (White House, 2022), whereas the EU's Carbon Border Adjustment Mechanism (CBAM) promotes cleaner imports but poses potential trade conflicts (European Commission, 2023). Nonetheless, regional trade agreements such as the Regional Comprehensive Economic Partnership may emphasise growth in lieu of sustainability, thereby exacerbating emissions if left unregulated (UNCTAD, 2022). These conflicts aggravate "greenflation," rendering renewable energy less accessible, particularly in developing countries.

3. The Impact of Geopolitical Rivalry on the Development of Renewable Energy

Innovation and fragmentation in the development of renewable energy are both influenced by the geopolitical rivalry between the United States, the European Union, and China. China's Made in China 2025 initiative is designed to establish itself as a leader in high-tech sectors, including renewables, while the U.S. IRA and EU Green Deal Industrial Plan support domestic sustainable tech (State Council of China, 2015; White House, 2022; European Commission, 2023). This competition has resulted in a reduction in the cost of solar panels, as China's investments have made renewable energy sources more accessible (IRENA, 2022). Nevertheless, protectionist policies, such as the United States' restrictions on Chinese technology, exacerbate inequalities by restricting the diffusion of technology to developing nations. The European Union's renewable energy target was expedited to 42.5% by 2030 as a result of the Russia-Ukraine conflict, which decreased its dependence on Russian gas (European Commission, 2023). Global energy markets are transformed by strategic alliances, such as Saudi Arabia's renewable partnerships with China (Carnegie Endowment, 2025). Although rivalry encourages innovation, it poses a risk of fragmenting supply chains and impeding global decarbonisation initiatives.

4. Regional Case Studies: A Wide Range of Effects

China: Dominance and Dependence

Wood Mackenzie (2023) notes that tariffs imposed by the United States and the European Union are impeding China's export markets, despite the fact that it manufactures over 80% of the world's solar panels. The vulnerabilities in Xinjiang, a critical polysilicon centre, are further exacerbated by potential sanctions and geopolitical risks (IEA, 2022). The Belt and Road Initiative (BRI) prioritises renewable initiatives, with solar, wind, and hydro comprising 55% of energy investments in 2023. Nevertheless, it has the potential to create economic dependency in associate countries (Climate Change News, 2023). Cost reductions are the responsibility of China's leadership; however, it must also address trade and geopolitical challenges (Tang et al., 2015).

The European Union: A Crisis-Induced Accelerated Transition

The European Union's response to the Russia-Ukraine conflict is a 42.5% renewable energy target by 2030, which is motivated by the necessity of replacing Russian gas (European Commission, 2023). The Green Deal Industrial Plan advocates for the advancement of indigenous renewable technology by opposing U.S. IRA incentives. Nevertheless, the European Commission (2023) has identified supply chain hazards associated with the dependence on Chinese solar panels. The EU maintains a balance between energy security and climate objectives, despite the persistence of regional disparities in infrastructure.

The opportunities and challenges of Africa

30% of the world's critical mineral reserves, which are essential for renewable energy, are located in Africa. Nevertheless, the U.S.-China rivalry is the cause of the region's severe lack of infrastructure and technology access (IMF, 2024). Despite the fact that countries like the Democratic Republic of Congo leverage mineral agreements, the adoption of green technology is impeded by trade disputes (SAIIA, 2023). Geopolitical neutrality may yield more advantageous terms; nevertheless, sustainable development necessitates investments in local processing activities.

Saudi Arabia: Diversification Through Renewables

Saudi Arabia's Vision 2030 targets 50% renewable energy by 2030, with Chinese partnerships driving projects like the Sudair Solar PV plant (Vision 2030, 2016; ACWA Power, 2021). These ties shift geopolitical alignments, challenging U.S. influence. Trade disputes could disrupt technology imports, but Saudi Arabia's strategic pivot enhances its role in the global energy transition.

5. Implications for Global Decarbonization and Policy Recommendations

Trade disputes and geopolitical rivalry pose significant challenges to decarbonization by increasing costs and limiting technology access, particularly for developing nations. Protectionism fragments supply chains, while mineral dependencies create vulnerabilities. However, competition drives innovation, as seen in cost reductions from Chinese solar production (IRENA, 2022). To address these issues, the following policies are recommended:

- Enhance Multilateral Trade Agreements: Reduce tariffs on clean technologies to improve access, fostering global collaboration (UNCTAD, 2022).
- Promote Technology Transfers: Encourage licensing and joint ventures to bridge technology gaps in developing nations (IRENA, 2022).
- Establish Critical Mineral Alliances: Create international frameworks for stable, sustainable mineral supply chains (IEA, 2023).
- Support Local Manufacturing: Incentivize clean tech production in mineral-rich regions to boost economic resilience (IMF, 2024).
- Enforce Sustainability Standards: Implement responsible mining practices to minimize environmental and social impacts (UNEP, 2024).

The future of decarbonization hinges on balancing national interests with global climate goals through diplomacy and equitable policies, ensuring an inclusive energy transition.

Conclusion

This article has illuminated the intricate ways in which trade disputes and geopolitical rivalries shape the trajectory of renewable energy industries and decarbonization technologies globally. Trade disputes, such as the U.S. tariffs of up to 50% on Chinese solar imports in 2024, have disrupted supply chains, escalated costs, and delayed renewable energy projects, contributing to "greenflation" that disproportionately affects developing nations (Carnegie Endowment, 2025). Simultaneously, geopolitical rivalries among major powers the U.S., EU, and China have driven significant innovation, as evidenced by the rapid decline in solar panel prices due to China's manufacturing scale, which produces over 80% of global panels (Wood Mackenzie, 2023). Yet, these rivalries also foster protectionist policies, such as U.S. restrictions on Chinese clean technology, limiting technology diffusion to regions like Africa, where access to green tech remains constrained despite abundant mineral resources (IMF, 2024). Regional case studies further highlight this complexity: China's solar dominance is tempered by trade barriers and geopolitical risks in Xinjiang, the EU accelerates its 42.5% renewable energy target by 2030 in response to the Russia-Ukraine conflict, Africa navigates opportunities and challenges in leveraging its 30% share of global critical minerals, and Saudi Arabia strategically diversifies through Chinese partnerships under Vision 2030 (European Commission, 2023; SAIIA, 2023; Vision 2030, 2016). These findings underscore the dual role of trade and geopolitics as both catalysts for progress and barriers to equitable decarbonization.

The significance of these dynamics is profound in the global fight against climate change. Renewable energy and decarbonization technologies are indispensable for achieving the Paris Agreement's goal of limiting global warming to 1.5°C. The International Energy Agency's Net Zero by 2050 scenario projects that renewables must supply over 60% of global electricity by 2030, a target that demands unprecedented deployment of clean energy technologies (IEA, 2022). However, trade disputes and geopolitical tensions threaten to derail this progress by increasing costs, fragmenting supply chains, and perpetuating inequalities in technology access. Failure to address these challenges risks delaying the global energy transition, exacerbating climate impacts, and undermining sustainable development goals, particularly in vulnerable regions where energy poverty remains a pressing issue.

The interplay between trade policies, geopolitical strategies, and clean energy development presents both challenges and opportunities. On one hand, geopolitical competition has lowered costs and accelerated technological advancements, making renewables more accessible in some markets. For instance, China's investments have reduced solar panel costs by 80% over the past decade, benefiting global adoption (IRENA, 2022). On the other hand, protectionism and resource nationalism can create a fragmented energy landscape, where wealthier nations advance rapidly while others lag, deepening global disparities. This fragmentation could lead to a two-tiered energy system, where developed nations achieve net-zero targets while developing countries remain reliant on fossil fuels, perpetuating environmental and economic inequities. The qualitative analysis in this article highlights the need for a balanced approach that harnesses the benefits of competition while mitigating its divisive impacts.

To navigate these complexities, policymakers must prioritize international cooperation and equitable access to clean energy technologies. Reducing trade barriers, such as tariffs on environmental goods, can enhance affordability and accelerate deployment, particularly in low-income countries. Multilateral frameworks, inspired by initiatives like the World Trade Organization's negotiations on environmental goods, could facilitate the free flow of renewable technologies, building on the Asia-Pacific Economic Cooperation's commitment to reduce tariffs on 54 environmental products (World Trade Organization). Promoting technology transfers through licensing agreements and joint ventures can bridge the gap for developing nations, enabling them to build local capacity and participate in the global energy transition. Additionally, establishing international alliances for critical minerals, as suggested by the IEA, can ensure stable and sustainable supply chains, reducing dependency on single nations and mitigating geopolitical risks (IEA, 2023). Investing in research to diversify supply chains and develop alternative materials can further enhance resilience. Finally, enforcing sustainability standards in mining and manufacturing, as advocated by the United Nations Environment Programme, is essential to minimize environmental and social harms, ensuring that the energy transition aligns with broader sustainability goals (UNEP, 2024).

Looking forward, the global energy transition is as much a geopolitical endeavour as it is a technological one. While trade disputes and geopolitical rivalries pose significant hurdles, they also offer opportunities for strategic partnerships and innovation. By fostering collaboration, promoting equitable access, and implementing sustainable practices, the global community can overcome these challenges and achieve a successful, inclusive transition to a low-carbon future. Policymakers, researchers, and stakeholders must work together to address the geopolitical dimensions alongside technological advancements, ensuring that the benefits of renewable energy and decarbonization are realized worldwide. The path to net-zero emissions demands not only innovation but also diplomacy, equity, and a shared commitment to a sustainable planet.

China's Role in Energy Transition

BY ADITI SARKAR

Critical minerals is the dominating factor in the new geo-economics of energy transition. This essay analyzes how China became the global powerhouse of critical minerals and its effects on the economics of energy transition.

I. Introduction

News articles showcase increasing tensions on critical minerals, especially with China's role in the center:

1. China proposes further export curbs on battery, critical minerals tech- Reuters, Jan 2, 2025[1]
2. China's Critical Minerals Embargo Is Even Tougher Than Expected- New York Times, Dec. 9, 2024[2]

These developments underscore a growing concern: consolidation of critical mineral market power in China and the influence it has. As society progresses forward in this digital age coupled with the push for decarbonization globally, access and refinement of these materials have become a major security and economic concern.

II. Definition

Minerals are critical components in electronic devices and clean energy technologies. In the US, the Energy Act of 2020 has defined critical minerals as minerals that have economic or national security importance (USGS, 2025). Key examples of these minerals include:

- Cobalt and lithium- used in electronic devices such as batteries
- Silicon- used in solar panels and semiconductors

As the global economy transitions to advanced electronics—including electric vehicles (EVs), renewable energy, and advanced electronics—the demand for minerals such as lithium, cobalt, nickel, and rare earth elements is increasing dramatically. These minerals are essential components of high-capacity batteries, semiconductors, solar panels, and wind turbines.

Deposits of critical minerals, however, is geographically limited. Some of these minerals are in limited supply and the cost of extracting them can be expensive, both financially and environmentally. According to Center for Sustainable Systems, global demand for these materials are rising exponentially every year due to energy transition[3].

Countries with rich resources include:

i. Democratic Republic of Congo (DRC) with 70% of world cobalt share,
ii. Australia and Chile with more than 70% share of lithium globally
iii. Indonesia with 30% share of nickel globally
iv. Chile and Peru with more than 40% share of copper worldwide

Despite China lacking these resources, it still has an almost monopoly over the market.

III. Stages in Critical Mineral Mining

Critical minerals undergo transformations in various stages of production until they are ready to be used in final products.

The first stage of production, known as upstream activity, is mining raw minerals from the ground which occurs in mineral- rich countries. China has comparative advantage of the upstream industry through the Belt and Road Initiative investments in mining and transportation overseas (Bian et al. 2024).

The next stage is called midstream activities where the minerals are refined and processed so they can be used in the final products. Majority of the refinement firms are located in China. The U.S. Department of Energy observed that China refines 60% of lithium and 80% of cobalt, both of which are core inputs for making high-capacity batteries. In late- midstream stage, firms in China make anodes, cathodes, and collectors with these materials.

These products are then assembled by the downstream industry to make electric vehicles (EVs) among other things (Castillo and Purdy 2022). Thus, even if China does not have deposits, majority of the extracted resources have to be sent to the country for refinement.

China's dominance in midstream and downstream industries hark back to the 1980s when the government prioritized developing rare earth (part of the critical mineral) market. It issued export tax rebates for domestic producers and in the 1990s rare earth minerals as strategic and prohibited foreign investments on it. It cultivated its own market by controlling production and exports of minerals. The growth of midstream and downstream industries was made possible by the support of the upstream sector, enabling them to refine not only rare earth elements but also a broader range of critical minerals. Thus, the government's foresight in the past decades propelled the country forward globally (Foss and Koelsch 2022).

IV. BRI's Influence on Upstream Industry

Despite having limited resources, China has upstream access due to the Belt and Road Initiative (BRI):

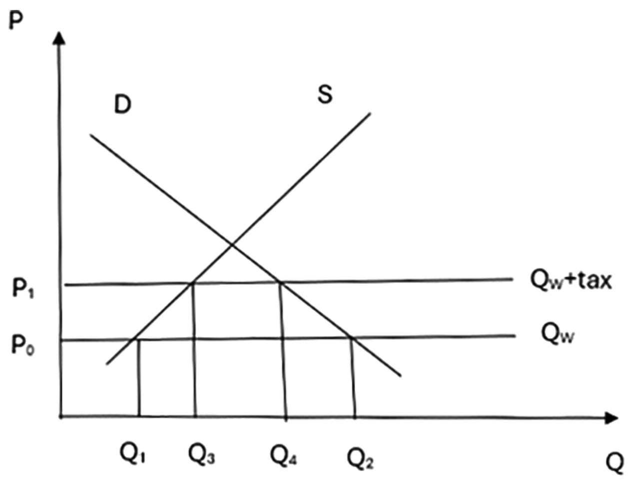
1. China has built a vast trade network for critical minerals. Through the BRI, China has built infrastructure for mining these minerals across countries with vast deposits.
2. This way they got control and ownership of all the minerals. Chinese financing facilitates conditions that prefer China, thus, getting preferential access to mining projects and mining.
3. Through these ties, China has also transferred technological innovations to these developing countries.
4. It has established long-term trade relationships under favorable terms for Chinese firms

With all these moves, China has been able to forge a deep relationship with the resource rich developing countries, extending its influence from mines to markets.

V. The economics behind it

Geoeconomics is the study of economics and political science that focuses on the government's use of economic strength on foreign entities (Clayton et al. 2025). As stated earlier, China is the global economic powerhouse in critical minerals. The market can have an adverse impact if China has any dispute with another country- whether economic, trade, or political. The examples below will illustrate the consequences facing an almost monopoly power with disputes.

Australia has significant resources and still, has to depend on China for majority of the stock of minerals. If for any reason, Australia decides to impose additional taxes on imports from China due to any disagreement, then it will gravely impact the local clean energy industry. Let's look at the graph below which shows the Australian mineral market:



The demand curve is marked D and supply curve as S. It should be noted that D and S refer to Australia's demand and supply. The international price of minerals will not be affected by the country's demand and hence, the international supply curve is completely elastic. It is given by Qw, the horizontal line. In the initial setting, the price is at P_0. The quantity supplied is Q_1 and the quantity demanded is Q_2. Demand is greater than supply and that difference is met by importing the goods. After adding taxes, the price increases to P_1. The quantity supplied locally is Q_3 and the demand has fallen to Q_4. The difference is now met by importing goods. Locally, the suppliers sell at a higher price that is set at the international level. Due to taxes, the prices have increased, and the quantity demanded has fallen. Of course, this is a highly simplified example of the way domestic policies can affect the market. In addition, it is assumed that Australia has the necessary midstream and downstream industry to process the minerals to be used in the final products. This situation would be more complicated in real life.

Now consider a country with minimal resources: Switzerland. If Switzerland has a trade or political dispute with China and it restricts exports of critical minerals, then Switzerland will be left without any supply.

Further, recent events have shown that China has shown tendencies to use this chokepoint as an upper hand while negotiating with other countries or in coercing uncooperative countries. It has declared export controls on critical minerals on several occasions (Jackson 2025; Shivakumar 2025). All of these issues considerably delays progress in transition to clean energy. In the interest of advancement of civilization and progressing towards decarbonization, it is crucial that diplomatic ties are maintained.

VI. Possible Solutions

In response to China's control over the chokepoints, it is imperative that the countries form an alliance and make progress in development of the industry. Other countries need to diversify their source of critical minerals and need to invest in extraction and refining of the minerals. Some countries have started planning and investing. The United States has passed policies in the past that encouraged more production of critical minerals in both US and Canada (IEA 2022). The Inflation Reduction Act of 2022 made provisions for processing, manufacturing, and recycling of these minerals (U.S. DOE 2023). Australia has started building its first mineral refinery as part of its domestic plan to drive the clean energy transition (Chater 2025).

Actions such as these are required, however, it should be noted that these projects will take years to develop. Till then we will be dependent on China.

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Energy basket 2050: reducing share of fossil fuels

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This article aims to show how fossil primary energies will continue to play a smaller role in the global energy mix by 2050 compared to renewable energies, despite their progressive decline due to lower demand. This is due to the strategies and policies adopted by countries within the current energy transition aimed at decarbonizing the global energy system by 2050 within the framework of the Paris Agreement. This is because CO2 emissions into the atmosphere from the massive consumption of oil, natural gas, and coal have contributed to global warming.

For (Smil, 2017), energy is part of the planet's history, and from a biophysical perspective, natural processes and human actions are energy transformations. In this sense, civilization has been characterized by the constant search for greater energy flows for the production of food, raw materials, and goods, as well as to promote mobility and access to information. This has entailed improving the population's quality of life, supporting economic growth, and developing new, more complex social, productive, and political arrangements; as well as controlling larger quantities of energy reserves in more concentrated, versatile, and accessible forms, at lower costs, and with greater efficiency in generating heat, light, and movement.

In this sense, (Rifkin, 1989) argued that the current energy transition is related to the reduced future availability of energy for productive use due to entropy. In the process of harnessing energy, it is transformed into pollution that generates a greenhouse effect through atmospheric emissions and global warming. This is the case with fossil fuels (coal, oil, and natural gas), which are nonrenewable natural resources and finite in terms of their reserves and emit carbon dioxide (CO2) when burned. And as entropy deepens, there will be a shift toward a new energy environment with new technology and social, economic, and political institutions, evolving from an industrial age based on nonrenewable resources to an undefined age based on renewable energy.

(Rifkin, 1989) also outlined that the depletion of nonrenewable energy sources has fractured the energy system, and there is not enough time to remedy this energy shortage. Furthermore, since global warming is not neutralized in the short term, its speed can be reduced to create the conditions for adaptation to changes in the economy and climate. In this regard, at the Belaggio Conference (Italy) in 1987, and at the Conference on Atmospheric Change in Toronto (Canada) in 1988, it was pointed out that, in the absence of a quick technological solution, fossil fuel consumption and, consequently, CO2 emissions should be reduced, in addition to implementing efficiency, recycling, and energy conservation programs.

Given these prospects, climate diplomacy actions are being developed, which are materializing at the 21st Conference of the Parties (COP21) through the Paris Agreement of December 12, 2015. According to (United Nations, 2025a), commitments are defined to address the threats of climate change in the context of sustainable development, with the aim of limiting the increase in global temperature to below 2.0°C compared to pre-industrial levels, as well as strengthening efforts to limit this increase to 1.5°C. These actions are expected to achieve maximum GHG emissions, aiming to balance anthropogenic emissions by sources and their absorption through sinks by the second half of the 21st century.

In relation to the above, (Ottesen, Dieter, Bhagat, & Rola, 2023) point out that this energy transition seeks to replace hydrocarbons (oil and natural gas) in favor of low-carbon or carbon-free energy sources, the speed of which will depend on government policies and the achievement of the objectives of the Paris Climate Agreement. Thus, the COP28 declaration raises for the first time the need to gradually abandon fossil fuels within a reasonable timeframe, so that the era of fossil fuels ends with justice and equity according to (United Nations, 2025b). The imperative to limit the increase in global temperature to 1.5 ° C remains, and the capacity of renewable energies must be tripled, as must energy efficiency be doubled by 2030.

(O'Sullivan & Bordoff, 2024) state that the transition to clean energy is at a very early stage with uncertainties and internal paradoxes generating volatility, and in the face of ambitious measures to combat climate change, political leaders fear the deepening of geopolitical problems, and governments fear the risks to energy security, promoting strategies that include fossil fuels and clean alternatives, in addition to avoiding a shift from dependence on imported oil to imported lithium.

Likewise, a poorly designed clean energy policy can lead to higher costs for consumers, economic anxiety, and a risk to energy reliability and the political will to support climate action. Furthermore, grids and the electrical system must be prepared to cope with the rise of intermittent energy sources (solar and wind), the closure of fossil fuel and nuclear plants, and the increased demand for electric cars, data centers, and artificial intelligence.

Regarding the evolution of the energy transition (Yergin, Orszag, & Arya, 2025), they observe an increase in energy demand, and that renewable sources are not replacing conventional sources, but rather adding to them to support these increased demands. Furthermore, in the context of the current transition, renewable energies are expected to be transformative or replacement, rather than additive, as previous transitions have been. The challenge is to develop a variety of energies in a multidimensional and complex way, due to the differential pace of technologies and regional priorities, shaped by governments and businesses.

In relation to additive energy transitions throughout the history of humanity, (Ritchie, Rosado, & Rose, 2020) support that primary energies (biomass, coal, oil, natural gas, hydraulic, nuclear, wind, solar, biofuels, thermal and other non-conventional renewables) maintain their validity in the energy basket since 1800, changing their participation as their use focuses on certain market niches according to their calorific capacity and characteristics, which has led to complementarity of sources and substitution between them for specific uses according to technological advances, and implied changes in the processes to illuminate, heat, refrigerate, generate electricity and produce fuels (energy vectors), depending on the energy needs of households, companies, industries, transportation and productive sectors, tending to promote the well-being and economic growth of countries.

Returning to (Yergin, Orszag, & Arya, 2025), they argue that concerns about climate change have generated expectations about a rapid abandonment of fossil fuels, but the global energy system is not capable of carrying out a transition at that pace because it is much more difficult, costly, and complex. Furthermore, much of the thinking about the transition was consolidated during the COVID-19 pandemic, when energy demand and carbon emissions plummeted, generating optimism about the energy system's flexibility and capacity for change.

Therefore, achieving the 2050 goal of net-zero emissions requires a more pragmatic plan, because the transition is not only related to energy, but to the reconfiguration and redesign of the entire global economy. And in the face of the goal of replacing most of the current energy system with a completely different one, it must be kept in mind that throughout history, no energy source has decreased in absolute terms for an extended period. While previous transitions were driven by increased functionality and lower costs, these incentives are lacking in much of the energy system; and technological, political, and geopolitical uncertainty makes it difficult to calculate the costs of achieving net-zero emissions by 2050.

In the process of decarbonizing the energy mix, they argue that natural gas is an available option and a better alternative in terms of emissions compared to coal and traditional biomass (wood). Furthermore, they predict that global oil demand will stabilize in the early 2030s, natural gas consumption will continue to increase well into the 2040s, and liquefied natural gas (LNG) production will increase by 65% by 2040, thus meeting energy security needs in Europe, replacing coal in Asia, and boosting economic growth in the Global South.

Regarding the future of the energy transition, the Secretary General of OPEC, at COP28 in Dubai in 2023, according to (Organization of the Petroleum Exporting Countries (OPEC), 2023), argues that due to the interrelation between emissions reduction and energy security, realistic policies are needed that consider all technologies and energies, including hydrocarbons, aimed at satisfying the growing demand for energy and its universal and affordable access. Furthermore, the purpose of the Paris Agreement is the reduction of emissions, and the capacities, circumstances and development priorities of countries must be considered to spread the benefits of the transition.

Complementing OPEC's vision and in light of the evolving energy transition toward renewable energy, the paper explores the position of several international oil companies, taking into account that the expected decline in demand for oil and natural gas to achieve the net-zero emissions goal will affect their interests and lead them to become more sustainable in their production processes and product portfolios, thus maintaining their status as energy companies. These corporations shape energy markets, influence geopolitical strategies, and generate billions of dollars in revenue. They also control large hydrocarbon reserves, invest in technology, and play a fundamental role in global economic stability.

(ExxonMobil, 2025), it seeks to create sustainable energy solutions to improve the quality of life, as well as continue to meet the growing demand for oil, natural gas, and refined products; likewise, to efficiently produce energy (fuels), chemicals, lubricants, and low-emission technologies with new technologies, reducing greenhouse gas emissions and creating sustainable value for society, as well as strengthening energy security through the expansion of low-cost, highly profitable oil and natural gas operations. Low-carbon solutions include carbon capture and storage (CCS), hydrogen, and biofuels.

(Chevron Corporation, 2025)'s purpose is to provide affordable, reliable, and cleaner energy, based on the premise that energy drives human progress, improves lives, and generates positive changes in society. Therefore, it works to increase production to meet growing demand by offering low-carbon energy solutions, while building the lowest-carbon future energy system using innovative technology. Therefore, it seeks to expand its oil and natural gas business, reduce the carbon intensity of its operations, and develop new businesses in renewable fuels, carbon capture and offsetting, hydrogen, and power generation for emerging technologies.

In the case of (Shell plc, 2025), it defined a strategy to generate more value with fewer emissions, offering safe and reliable products for the present and during the energy transition, aimed at meeting the changing needs of customers. Along with traditional fuels and lubricants, it seeks to offer low-emission energy solutions, such as electric vehicle charging, biofuels, hydrogen, and carbon capture and storage; it also generates and markets energy from renewable sources: wind and solar, and natural gas due to its low emissions; and it enters the carbon credit business, seeking to reduce emissions from oil and natural gas assets, as well as net carbon intensity (NCI).

(BP plc, 2025)'s purpose is to provide energy in the context of energy transition, which will last several decades, due to its ability to operate in increasingly complex energy markets and systems. Its strategy includes investments in biogas, biofuels, and electric vehicle charging, developing innovative partnerships in renewable energy, as well as in hydrogen and carbon capture projects to decarbonize operations. Given the increase in global energy demand, it plans to expand its fossil fuel and low-carbon energy business, seeking to reduce emissions and transform oil, natural gas, and refining operations to boost efficiency.

According to the list of the ten (10) largest oil companies in the world by market capitalization (Energy, Oil & Gas Magazine, 2025), ExxonMobil is second with $ 490 billion USD, Chevron Corporation is third with $ 281 billion USD, Shell is fifth with $ 220 billion USD and BP is ninth with $ 97 billion USD; this ranking is topped by Saudi Aramco, with a capitalization of $ 1.7 trillion USD.

(Aramco, 2025), considering the forecast for global population growth and the need for more energy to meet this growing demand, envisions that all energy sources will be needed; and because alternative energies will not be able to meet future demand despite their advances, hydrocarbons will be essential during the transition to a low-emission global economy. However, the company has a responsibility to help achieve a net-zero emissions economy by providing reliable, affordable, and more sustainable energy, utilizing the potential of technology to reduce emissions, also, to continue expanding and diversifying the energy product portfolio, and managing the extensive hydrocarbon reserves, optimizing production to increase their long-term value.

In this context, (O'Sullivan & Bordoff, 2024) argue that the transition must continue its ambitious implementation because carbon emissions continue to increase and the threat of climate change must be mitigated through decarbonization. Additionally, the transition should not be considered a means to solve global problems, nor to an end, i.e., achieving net-zero emissions by mid-century according to the 2015 Paris Agreement. As the energy system is intertwined with geopolitics, its transformation is an opportunity to address climate change, reduce inequalities, diversify and strengthen supply chains, create export markets for US companies, and reduce dependence on China. In this way, climate and geopolitical objectives are combined by replacing the fuel sources that drive the entire global economy and increasing the energy supply to ensure more prosperous lives.

Regarding the projected share of primary energy for 2050, Table A.1b: World energy supply from the (International Energy Agency, 2025, pág. 302), was taken as a reference, corresponding to the Announced Pledges scenario, through which it is visualized that renewable energies will have a share of 53% (solar: 19%, wind: 10%, hydraulic: 4% and modern bioenergy: 15%), fossil energies (oil: 16%, natural gas: 14% and

				Announced Pledges (EJ)				Shares (%)		
	2010	2022	2023	2030	2035	2040	2050	2023	2030	2050
Total energy supply	536	629	642	641	624	620	635	100	100	100
Renewables	43	74	78	140	197	251	336	12	22	53
Solar	1	6	8	31	55	81	120	1	5	19
Wind	1	8	8	21	34	46	66	1	3	10
Hydro	12	16	15	18	20	22	25	2	3	4
Modern solid bioenergy	23	34	36	48	56	64	73	6	7	11
Modern liquid bioenergy	2	4	5	10	12	14	14	1	2	2
Modern gaseous bioenergy	1	1	1	4	6	8	12	0	1	2
Traditional use of biomass	21	19	19	6	5	3	2	3	1	0
Nuclear	30	29	30	39	49	59	69	5	6	11
Natural gas	115	144	145	138	121	106	86	23	22	14
Unabated	109	136	137	128	108	90	65	21	20	10
With CCUS	0	1	1	2	5	7	13	0	0	2
Oil	173	187	192	178	156	133	100	30	28	16
Non-energy use	26	30	31	34	35	35	34	5	5	5
Coal	153	172	175	138	95	66	40	27	22	6
Unabated	151	169	172	134	87	56	28	27	21	4
With CCUS	-	0	0	0	4	6	10	0	0	2

Fuente: (International Energy Agency, 2025, pág. 302) coal: 6%) 36% and nuclear energy 11%. Regarding a 12% share of renewable energies in the energy basket in 2023, fossil energies with 80% (oil: 30%, natural gas: 23% and coal: 27%) and nuclear energy with 5%.

In this way, it can be seen how hydrocarbons and other sources will remain relevant until 2050, varying their share depending on their use due to the evolving energy transition toward renewable sources. Among the assumptions, it is identified that carbon capture, utilization, and storage (CCUS) technologies will be used in the production and consumption of natural gas and coal, oil will not be used as a fuel, and nuclear energy is experiencing a new boom.

However, the Stated Policies Scenario (STEPS) in Table A.1a: World energy supply, (International Energy Agency, 2025, pág. 296) shows that fossil fuels will contribute 58%, renewables 33% and nuclear energy 7%. However, the Net Zero Emissions by 2050 (NZE) scenario in Table A.1c: World energy supply, (International Energy Agency, 2025, pág. 308) shows that fossil fuels will contribute 15%, renewables 71% and nuclear energy 14%.

Finally, as this article has shown, renewable energies are not meeting the growing global energy demand due to population growth. Therefore, fuels will continue to play a fundamental role in the global energy mix in the medium term, as energy analysts and international oil companies have stated. In this context, the vision of a 2050 energy mix without fossil fuels is not possible because it is not envisioned under the conditions of technological development and the pace of growth of renewable energies.

Additionally, the history of the energy mix over the last two (2) centuries shows that no source has been replaced, except in specific sectors, leading to the continued existence of all of them since their emergence. All this, even though an energy transition characterized by the replacement of fossil fuels with renewables is expected, contrary to the cumulative processes of previous transitions, in which all primary energy sources meet the needs, supporting energy security, national interests, and promoting the well-being of the population and the economic growth of countries.

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Answering Questions of Geoeconomics requires the Basics of Energy

BY CAREY KING

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Abstract

Geopolitics and geoeconomics is largely about one country, or an alliance of a few countries, asserting social power and rules upon those not part of the alliance. This social power, to a large degree, derives from the control and the ability to extract energy from the environment.

In this article I make the case that evolutionary pressures help explain why it has proven extremely difficult for national economies to cooperate on climate mitigation such that greenhouse gas emissions are actually declining. In doing so I make connections among energy, efficiency, economic output, social (geopolitical) power, and evolution. These connections help explain increasing trade disputes and geopolitical rivalry affecting energy trade and decarbonization of the economy.

In his 1975 book *Energy and Structure*, anthropologist Richard Adams stated that "It is the actor's control of the environment that constitutes the base of social power ..." and "... control over the environment is a physical matter. An actor either has it or does not... . Power over an individual is a psychological facet of a social relationship ..."

At its core, the economy is about human actors with social power making decisions that influence physical control over the environment. Human actors with control over the environment can have the social power to make decisions that others must follow and avoid constraints that others try to impose. This control includes extracting energy and material resources, converting them into fuels and products that include phones, rockets, and renewable electricity generation technologies.

Examples abound to indicate how many of the most fundamental long-term energy and economic trends are underpin by actors with physical control exerting social power.

In the earliest agricultural civilizations, control over floodwaters enabled nobles and kings to accumulate masses of farmer citizens beholden to them for sustenance.

In the middle of the 20th Century, control over the extraction rate of oil in prolific Texas oil fields gave the Texas Railroad Commission (TX RRC) the social power to regulate oil prices. By the early 1970s, at the time of (then) peak U.S. oil extraction, the TX RRC no longer had that control and thus the social power to influence oil prices. This social power shifted to the Organization of Petroleum Exporting Countries (OPEC), with Saudi Arabia as the most influential actor. Over the last two decades, the commercialization of technology in the form of hydraulic fracturing and horizontal drilling has enabled the U.S. to again top the world list of the oil extraction by country. "Energy dominance" is a phrase uttered by the U.S. Executive Branch, with one stated goal as to "... restore peace through strength by wielding our [U.S.] commercial and diplomatic levers to end wars across the world."[1]

Since the mid-2000s, China has invested to obtain a large majority share of control over the materials extraction, processing, and manufacturing of several necessary materials and parts of the supply chain for manufacturing of solar photovoltaic (PV) panels, high performance metal alloys used in combustion turbines, and permanent magnets used in electrical generators and motors. PV panels, turbines, and electrical generators are all machines that enable control to extract resources, transport people and products, and make more machines. Diplomats from other countries worry how much China will use this control over rare earth material to exert social power, as it did with Japan in 2010 and threatened to do to the U.S. in response to increased import tariffs on Chinese imports.

After the Russian invasion of Ukraine in 2021, one U.S. response was to attempt to exert social power over the sale of Russian oil and gas by preventing Russia access to the SWIFT banking system. The sanctions have not materially affected Russia's economy. Remember the order of causality: control first, social power second. Russia has control over oil and natural gas that China, India, and other countries want, and thus they found the social power to trade hydrocarbons in roubles and yuan rather than via SWIFT in U.S. dollars or other Western currencies.

Control over physical resources is more important than the currency used for accounting their exchange.

We nave not decoupled money or economic output from physical resources. For those who claim that the economy can absolutely decouple economic output from energy and materials inputs, the concept of geoeconomics should force a rethink. As a biophysical and ecological economist, absolute decoupling goes against a core tenet. Biophysical and ecological economists consider the material and energetic basis of the economy as a starting point for explaining the physical, social, and financial aspects of the economy. Energy and materials are not side notes to consider as externalities.

Because materials and energy resources exist somewhere on the Earth, those countries with control of material and energy resources and processing can have social power over those that don't.

It matters where materials and capital physically reside. It always has, and always will.

With this backdrop, what can macroeconomic models say on the question of country leaders attempting to impose political (social) power over national rivals when it comes to shifting to a low-carbon energy supply?

Macroeconomic models should be able to say more than they usually do. To inform national governments with low-carbon scenarios, macroeconomic models need consistent relationships between energy use, energy efficiency, work, gross domestic product (GDP), and technological change. The key words are work and energy efficiency. Here, when I write "work", I don't mean concepts related to jobs, labor, and wages. While it is vitally important to consider economic distribution to people working for a living, in the rest of this article, I focus on work in the sense of physics—in the sense of thermodynamics.

Work is the useful output of machines, as well as muscles in animals and humans, in terms of moving and rearranging matter. Pre-industrial economies were dominated by work output from muscles, and the fuel input is food. Industrial economies are dominated by work output from machines, such as cars, industrial boilers, and power plants, and the fuel inputs are in the forms of refined fossil fuels, wind, and the sun.

By definition, the efficiency at which machines produce work equals the work output divided by the energy content of the input fuel. Energy analysts have estimated the total work output of most of the economies in the world.[2] The more technical way to describe this estimated work output of economies is "useful exergy." In explaining the term useful exergy, two points are relevant.

First, useful exergy *is not* a measure of the final work done by the machines and muscles in the economy. Useful exergy *is* an estimate of energy use at the furthest end of the supply chain that we could expect to measure it *and* still use units of energy, such as joules. Consider an industrial plant that converts feedstocks, such as natural gas, into plastic. The real work done would be quantified by the rearrangement of carbon, hydrogen, and other molecules into plastics, such as polyethylene terephthalate, or PET, that we use for clothing and bottles. The *useful exergy* of the industrial plant is the heat generation required to make the plastic. We can readily measure the exergy content of the heat, but this is not as straightforward for the plastic material itself.

This brings me to the second point: what is exergy? Exergy is quantification of energy that accounts for the second law of thermodynamics. In effect, it is a quality-adjusted quantification of energy. Consider that 1 kWh of the heat from burning fossil fuels cannot be converted into 1 kWh of electricity (by operating a heat engine), but 1 kWh of electricity can be converted to 1 kWh of heat (by dissipating the electricity in a wire).[3] For this reason, while an energy value of 1 kWh electricity equals 1 kWh of heat, the exergy value of the heat is *less than* the exergy value of the electricity.

Why does this "useful exergy versus energy" discussion matter? Because useful exergy output is *much more explanatory* of economic output than is energy input.

Recent research is showing that at the country level, real GDP is nearly proportional to useful exergy. That is to say, if you divide GDP by the useful exergy of a country, there is much less of a change over time than if you compare primary or final energy consumption to GDP. One study of using data from 1900-2000 for the U.S. and three other countries shows that on average, useful exergy intensity (useful exergy/GDP) rises and falls over time, but is nearly constant.[4] In contrast while primary exergy intensity also fluctuates, it has a more consistent decline over time, particularly since World War II.

Why might be an explanation for useful exergy to be highly-correlated with GDP?

One explanation is that GDP is largely a proxy for the work performed by the economy. While we quantify GDP in nominal monetary terms, we estimate inflation indices to calculate GDP in real terms. Useful exergy is always "real". There is no nominal quantification of useful exergy.

Useful exergy helps explain the role of energy (or exergy) efficiency in the economy. By making machines more efficient, the economy overall both performs more work with the same energy input and affords to invest in extracting more primary energy. This positive feedback, or rebound effect, from efficiency to extraction is essentially the same concept as the Jevons Paradox—that over time increased efficiency increases, rather than decreases, total energy extraction rates over time. The global data bear this paradox as correct. Overall, from year to year, we do make machines more efficient and the global economy has been extracting energy at a higher rate.

A second explanation for correlated useful exergy and GDP is that it helps explain total factor productivity (TFP), or the Solow Residual, of Neoclassical growth theory developed by Robert Solow. Notoriously, TFP is usually estimated as responsible for about half of economic growth. Fifty years after his seminal work, Solow himself asked:

> "... it would be interesting to see if any connection can be made, perhaps in a specific industry, between the time series of TFP and an informed narrative of significant innovations and their diffusion. (One can see in principle how TFP should be related to new-product innovations, but it is not clear what would happen in practice.)"[7]

It seems we might be on the brink of relating TFP to "an informed narrative of significant innovations and their diffusion". That is to say, the change in exergy efficiency of machines explains the vast majority of TFP.

The aggregate (economy-wide) U.S. thermodynamic exergy efficiency of all prime movers is highly correlated with the U.S. Federal Reserve's measure of multifactor productivity (similar to total factor productivity).[5] A study of Portugal concludes that the aggregate efficiency of converting final exergy into useful exergy is nearly a full explanation for TFP.[6]

The efficiency-GDP linkage also helps explain why countries seek energy efficient technologies. By becoming more efficient, their economies can perform more thermodynamic work, and this increase in work is an unambiguous expression of enhanced control over the environment. This enhanced physical control relates to higher GDP and can enable more social power over other countries. More control and social power means that a country has a better chance of surviving, in the sense of evolution, and propagating its principles and methods.

This concept is the same as in biology where via natural selection, organisms with higher fitness tend to survive and pass on their genes. Part of increasing fitness is the ability to extract and use more resources from the environment via a concept some call the maximum power principle (MPP). Ecologist Howard Odum, interpreting an idea from Alfred Lotka, states that "This [maximum power] principle says that the more lasting and hence more probably dynamic patterns of energy flow or power (including the patterns of living systems and civilizations) tend to transform and restore the greatest amount of potential energy at the fastest possible rate."[8]

Economist Carsten Herrmann-Pillath states that the economy operates in the same way:

> "... the MPP [maximum power principle] as a principle of natural selection also operates for all extensions such as, in technology, the evolution of artefacts under economic selection, ... That means, a steam engine, together with the human agent using it, is just another manifestation of physical inference devices which evolve, for example, in the direction of higher efficiency. Higher efficiency follows MPP in the sense of maximizing work output ... Ultimately, the steam engine is just one way to increase the steepness of the gradient of energy dissipation, ..."[9]

With this statement, we can now return to the stated purpose at the beginning of the article.

When we use macroeconomic models to help answer questions related to the viability of a low-carbon energy transition, these models should endogenize and be constrained by the observed and historical relationships between energy, efficiency, and GDP (among other metrics that are beyond the scope of this article, such as wages, inequality, and debt levels). If not, we risk being confused that we understand more than we do.

Most macroeconomic models and integrated assessment models (IAMs) used to study the costs and policies for reaching a low-carbon economy assume too many of these energy-related changes and feedbacks as exogenous. That is to say they assume TFP or a pre-determined energy/GDP relationship. Ironically, models that use TFP are insufficient to inform a low-carbon transformation of the energy system, because they assume TFP is independent of endogenous energy changes they seek to explain. This insufficient energy-economy linkage makes a low-carbon energy transition appear trivial in overall cost despite lack of observed real-world progress (i.e., IPCC Working Group III reports global GDP would typically be only 2-6% lower in a 2 °C world in 2100 compared to a baseline scenarios, without climate damages).

Because the useful exergy of an economy is so clearly associated with energy technologies and GDP, it is a crucial concept to include in macroeconomic models for studying a low-carbon transition. Many people observe that over time, the global economy increasingly extracts each primary energy resource at a higher rate. We're consuming more of each of biomass, coal, wind power, etc. over time. Thus, we're not transitioning away from anything.

The evolutionary concepts I've highlighted provide a reasonable explanation—the more energy you extract from the environment, in all forms, the more work can be done by the economy. If each economy is seeking to do more work, and thus be more fit to survive and maintain social power, then collectively all economies combine to consume more primary energy and perform more work.

We need to understand how much a low-carbon transition *goes against this short-term evolutionary pressure* to do more work.

There is a conundrum for transitioning to a low-carbon economy. It is easier to achieve lower emissions by consuming less energy from fossil fuels. However, consuming less energy from fossil fuels means an economy performs less work *unless* it is able to replace that work via a low-carbon energy technology. If an economy's low-carbon supply chain is not able to replace the work output from the high-carbon supply chain, then the economy effectively has less control over the environment and can lose social (geopolitical or geoeconomic) power over other countries. Thus, it can make all the right investments to decarbonize, but then be taken over, to some extent, by a rival that made more work-maximizing investments via an "all of the above" energy strategy.

In many cases, a low-carbon energy system is likely more energy efficient: use of electric light-duty vehicle and heat pumps for heating (at least in relatively mild winter climates). In other cases, a low-carbon energy system is less efficient: installing carbon capture and storage (CCS) on fossil fuel combustion systems *by its technological design* reduces the efficiency for the power plant or industrial system to convert energy into work output. Of course, CCS is not an efficiency-increasing technology, but we should not model it as if it is simply an increased monetary cost that does not also directly decrease economy-wide efficiency.

Scholars studying so-called "degrowth" or "post-growth" are correct in their understanding of the energy-economy relationships. They know we likely cannot fully decouple economic output from energy and materials input, and thus they focus on how to minimize energy use and still have high well-being. There is significant potential to achieve high well-being with lower energy use than currently used in the U.S. and other developed countries.

However, a major question remains. Assuming a country does reach net-zero carbon emissions and its citizens are content, how much energy use is needed to prevent a rival country from imposing its will whether that be an invasion or cutting off of critical imports (food, energy technology, minerals)?

While it is unlikely the scope of macroeconomic models can inform this geopolitical, or geoeconomic, question, there are existing macroeconomic frameworks that can take us a significant step closer. The first step is more fundamental integration of the thermodynamic principles outlined in this article: energy, efficiency, and work. By better integrating these ideas, we'll better understand how low-carbon energy systems affect overall economic energy efficiency, GDP, and maybe eventually, economic fitness and geopolitical cooperation.

Notes

[1] Executive Order, Establishing the National Energy Dominance Council, https://www.whitehouse.gov/presidential-actions/2025/02/establishing-the-national-energy-dominance-council/.

[2] Brockway, Paul E.; Heun, Matthew Kuperus; Marshall, Zeke; Aramendia, Emmanuel; Steenwyk, Paul; Relph, Thomas; Widjanarko, Michelle; Kim, Jeonghoo (James); Sainju, Anjana; and Irtube, Julian (2024). A country-level primary-final-useful (CL-PFU) energy and exergy database: overview of its construction and 1971–2020 world-level efficiency result, *Environmental Research: Energy*, Vol. 1, No. 2, p. 025005.

[3] "... 1 kWh of heat at 30°C is different from 1 kWh of heat at 900°C which is different from 1 kWh of mechanical work. Why are they different? Because 1 kWh of work can be converted into up to 1 kWh of heat at 30°C while 1 kWh of heat at 30°C can be converted into a maximum value of 0.066 kWh of work.... Assuming that the environment is at 10°C." Santos, J., Domingos, T., Sousa, T., & Aubyn, M. S. (2018). Useful exergy is key in obtaining plausible aggregate production functions and recognizing the role of energy in economic growth: Portugal 1960–2009. *Ecological Economics*, 148, 103–12.

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The transition to sustainable aviation fuel (SAF), amidst geopolitical and economic turmoil

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Abstract

There is a growing, global need to reduce greenhouse-gas (GHG) emissions, amidst emerging geopolitical and economic turmoil.

Since 2015, Canada has set reduction of emissions as a priority, but progress has been slow. Canada has also been facing trade barriers; from China starting in 2019, and recently from the United States, in the form of tariffs. Despite these obstacles, there are opportunities, such as using Canadian canola to produce sustainable aviation fuel (SAF) to reduce emissions from civil aviation. This article outlines and explores these obstacles and opportunities, in light of the energy transition.

Introduction

There is an urgent need to reduce greenhouse-gas (GHG) emissions and transition to a zero-emission global economy, in this time of war and other geopolitical disruptions. Since 2015, Canada set emission reduction as a priority, but progress has been slow. Concurrently, Canada faces trade barriers and tariffs from China, starting in 2019, and more recently from the new administration in the United States. Despite these ambitious goals amidst obstacles, there are opportunities for Canada to employ domestic oilseed canola crops to produce renewable drop-in fuels. Such fuels can help industries like aviation and heavy-duty trucking. This paper focuses specifically on sustainable aviation fuel (SAF), using the *three effects model*, i.e. by considering activity, structural and energy efficiency effects.

Impacts on Canola

One Canadian crop hit hard by trade barriers and tariffs is canola. Canola is a specialized oilseed crop developed from rapeseed. Canada is the largest producer and exporter in the world (FAS 2024). In Canada, canola accounts for $24.5 billion in direct economic activity, along with nearly 130,000 jobs (GlobalData 2024). Indeed, canola is larger than the Canadian automotive sector. Though more prominent in the media, automotive accounts for $16.5 billion in economic activity and job numbers similar to those of canola (CVMA n.d.).

Recently, canola has been subjected to periodic trade restrictions by China. Canada was once a major canola exporter to China; however, from 2019 through 2021, imports were restricted, in an apparent response to the detention of a Huawei executive based on an extradition request from the United States. One analysis estimated costs to the industry of between $1.5 and $2.4 billion from lost sales and lower prices (Left Field Commodity Research 2021). Canadian canola also involves genetically-modified organisms (GMO), which are not permitted by the European Union (EU) for human consumption, limiting alternative food markets. More recently, China imposed tariffs on canola in response to Canadian tariffs on Chinese-made electric cars.

Meanwhile, the U. S. tariff situation is volatile and uncertain. Tariff levels of 25% could be more damaging than even higher tariffs from China. Thus, Canada needs new markets and alternative ways to support its canola industry. Locally-produced canola can be used to produce drop-in renewable biofuels for aviation (i.e. SAF) and surface freight transportation (renewable diesel).

Canada's Emissions

Canada's Nationally Determined Contribution (NDC) under the 2015 Paris Agreement was set at reducing total emissions by 40% to 45% by 2030, vis-à-vis 2005 levels (Office of the Prime Minister 2021). However, the most recent National Inventory Report (NIR) from Environment and Climate Change Canada (ECCC 2025) reports 2023 emissions of 694 million tonnes, with updated reference for 2005 of 759 million tonnes. This reflects a reduction of only 8.5%. The Commissioner of Environment and Sustainable Development (2023) bluntly stated the country is not on track, and the

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United Nations Environment Program (2023) revealed that Canada had the largest implementation gap (27%), among G20 countries. NIR data shows that significant national reductions only occurred due to external factors, e.g. the 2008 recession and the 2020 COVID pandemic.

Emissions data by economic sector demonstrate that, in 2023, oil and gas was first in emissions, at 208 million tonnes or 30% of Canada's total (ECCC 2025, Table ES-2). Transportation came in second, at 157 million tonnes or 23% of total emissions. The smallest sector was electricity, with only 49 million tonnes (7% of total). These results contrast with the USA, where transportation was the largest emitting sector in 2022 (at 28%), followed by electricity (at 25%).

Canada's largest increase from 2005 was also the oil and gas sector, up 13 million tonnes or 7%, while the largest decline was electricity, down 67 million tonnes or 58%. Thus, Canada's overall reductions, 65 million tonnes since 2005, are overwhelmingly attributable to electricity, which fell from second largest to lowest major sector. In contrast, transportation emissions remained relatively unchanged since 2005 despite numerous reduction policies and programs. Emissions for all modes of domestic freight transportation, including air, ship, rail and truck, are itemized in the NIR – and remained largely unchanged since 2005 (ECCC 2025, Table 2-13).

Aviation, as well as the other freight modes, relies heavily on middle-distillate fuels, exhibiting relatively higher GHG intensities. Diesel accounts for the largest volume of such fuels, with turbine-based aviation fuel second. On-road diesel fuel consumption for 2023 increased by approximately 2.4% compared to pre-COVID levels in 2019 (Statistics Canada 2024a), to 18.3 billion Litres. Meanwhile aviation fuel consumption for 2023 totalled 8.0 billion Litres, 92% of pre-COVID levels. The importance of aviation fuel in Canada is downplayed since international passenger and cargo emissions are excluded from the NIR (Ferreira 2022). By 2023, emissions from civil aviation in Canada had increased 9% compared to 2005, reaching 98% of 2019 pre-COVID levels (ECCC 2025, Table 2-5).

End-use energy projections from Canada Energy Regulator's Energy Futures 2021 outlook (CER 2021) estimate that by 2030, overall diesel consumption will drop somewhat, while aviation fuel use will continue to rise, reaching nearly 10.6 billion Litres. Thus, a focus on transportation fuel consumption and emissions appears to be a worthwhile priority moving forward.

Reduction Policy Concerns

While the focus here is renewable drop-in fuels produced from canola, it is relevant to first outline other policies designed to reduce emissions – and their success in achieving reduction objectives.

Up until 2025, Canada's emission reduction plans focused on a commodity-based carbon tax, applied to a broad range of fossil fuels (ECCC n.d.) consumed in transportation, including civil aviation. After six years it was withdrawn, largely for political reasons. Instead of employing a Pigouvian approach, wherein adding a charge to cover externalities *might* inspire consumers to reduce their consumption (McKittrick 2016); it was promised that the tax *would* reduce fuel consumption and GHG emissions, i.e., "put a price on carbon, and reduce carbon pollution" (Liberal Party of Canada 2015). Environment and Climate Change Canada (ECCC 2018) suggested the tax would become Canada's largest single reduction measure and, by 2022, would result in a decline of 80 to 90 million tonnes of CO_2eq annually. As seen in the NIR data, the tax failed to achieve reductions as planned, especially in the transportation sector.

Since 2005, the electricity sector has enjoyed success with grid-decarbonization programs, but these were largely provincial rather than federal initiatives (Parsons 2021). By 2021, the federal government began to focus on electricity, after large reductions had already been realized. By 2023, federal tax incentives of around $33 billion were in place, mostly oriented to intermittent renewable sources, e.g. solar and wind (Finance Canada 2023). The major driver appears to have been alignment with directions of the Biden administration (DOE 2023), including the *Inflation Reduction Act* (IRA), rather than Canada's situation (EPA n.d.). Such an approach was more sensible for the United States, given their high electricity emissions compared to Canada.

Canada already had third lowest grid emissions within the G20 (IEA and KEEI 2025), with grid-intensity of about 30% that of the U.S., raising concerns about diminishing reduction returns compared to other sectors. Applications like light-duty electric vehicles and heat pumps are emphasized for electricity, and certainly growing, but still present in small numbers, only around 3% of all light-duty vehicles and home heating capacity (Statistics Canada 2024b, 2025a, NRCan 2023), requiring long lead-times to reach meaningful adoptions. As an exporter, Canada is not short of electrical energy (kWh), but needs to address more pressing concerns associated with grid-interconnections and electrical delivery (kW) capacity (Bowman et al. 2009, Economist 2023). Canada also relies overwhelmingly on imports, for technologies like solar panels, wind turbines, heat pumps and electric cars. The prospect of tariffs severely impacts economic viability. Expecting Canadians to purchase these imported products is not easy in the face of punishing tariffs and economic uncertainties.

More notably, civil aviation and long-haul trucking remain poor candidates for electrification. Electric-based aviation is still at early technology-readiness (Crownhart 2022), not expected to contribute much by 2050 (IATA 2024). In addition, the economic viability of electric long-haul trucking is constrained by multiple factors, and in some instances infeasible (Larson et al. 2024).

Focus on Aviation

The International Air Transport Association (IATA 2021), in response to growing environmental concerns and pressures, announced an ambitious goal of achieving "net-zero" by 2050. For this industry the *three effects model* is a useful analytical tool (SDTC 2009). The three

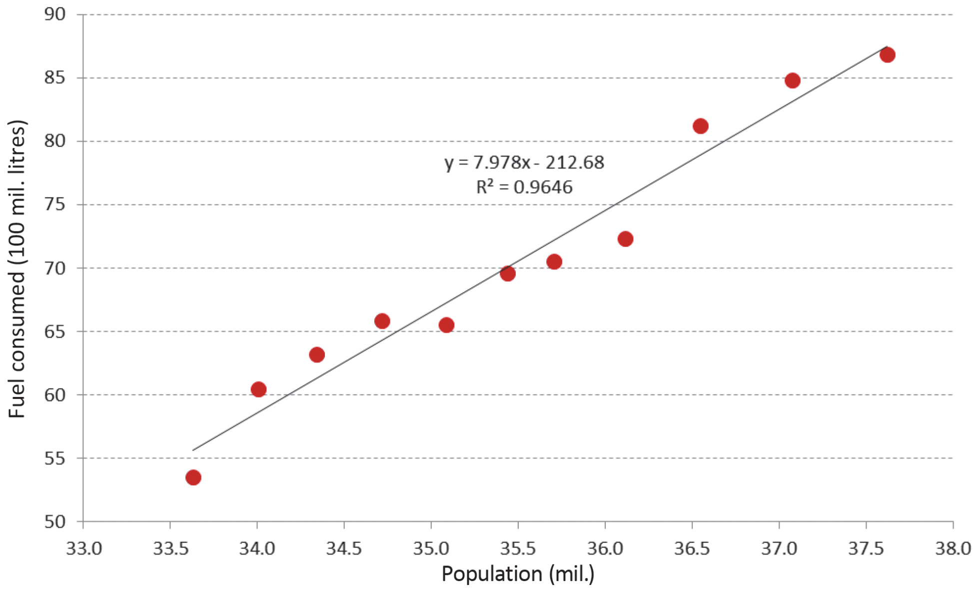

Figure 1: Canadian Aviation Fuel Consumption and Population, 2009-2019

effects are *activity*, driven largely by population; *structural*, e.g. shifts from air travel to travel by train or bus; and energy *efficiency*, i.e. use of technology or policy to reduce energy consumption – and emissions. Aviation sector emissions are strongly linked to activity, with demand expected to grow rapidly through 2030. Historically, activity growth has outpaced efficiency gains associated with new aircraft (IEA n.d.). The sector has been flying into a stiff headwind, yielding increases in energy consumption and GHG emissions, as seen in Canada.

Annual national population is an indicator of activity; more people, more air passenger travel and air cargo movement. Regression analysis of annual turbine-related aviation fuel use in Canada (Statistics Canada 2010, 2015, 2025b), as a function of population (Statistics Canada 2025c) over the eleven years leading up to the pandemic disruption (2009-2019), results in a highly significant relationship (see Figure 1). Note the R-square = 0.9646.

Additional analysis, from 2009 through 2023, excluding the COVID years of 2020 and 2021, yields a positive significant correlation ($F = 12.9$; $p = 0.004$). Using this correlation, along with population projections for the Energy Futures outlook (CER n.d.), yields estimated aviation fuel consumption by 2030 of roughly 10 billion Litres, close to previously projected fuel consumption of 10.6 billion Litres (CER 2023, Figure R4 data). Figure 2 depicts the collapse of civil aviation in Canada during the pandemic (2020-2021) and subsequent recovery, starting in 2022.

Given that improved fuel efficiencies associated with replacement aircraft are overwhelmed by increasing activity, SAF (an energy efficiency effect driver) becomes a good option for emission reduction. In 2022, Canada set an aspirational goal for 10% of aviation fuel to be SAF by 2030 (Transport Canada 2022). Based on conventional fuel projections, this requires about one billion Litres of SAF by 2030; an amount consistently noted by the Canadian Council for Sustainable Aviation Fuels or C-SAF (Allan *et al*. 2023). Currently, Canada is nowhere near this volume. The Rocky Mountain Institute suggests that by 2030 more than 85% of SAF will come via the hydrogenated esters and fatty acids (HEFA) pathway (Shams et al. 2024), which could include conversion of canola. These factors imply that SAF using canola can be a viable contributor to emission reductions in Canada.

Addressing Constraints

To achieve its ambitious goals, Canada needs to reduce GHG emissions. However, the country faces unprecedented trade threats and tariffs, which have eclipsed public concerns about the environment (Hussain 2025). This combination leads to consideration of liquid renewable fuels as an option, in particular SAF for aviation. To move forward with SAF produced from canola, two critical obstacles must be addressed: (1) current federal government incentive policies and (2) requirements of the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA).

Compared to SAF, renewable diesel is a more commonly available product, with relative price compared to conventional diesel varying regionally, either positive or negative, based on recent Department of Energy data from the U.S. (DOE 2025). The price of SAF, on the other hand, tends to be higher than conventional fuel. Information from Europe and North America suggests SAF costs are roughly twice that for conventional fuel, though mostly because production volumes are still very small (Airlines for America n.d., European Union Aviation Safety Agency 2025, Parolini et al. 2025). High costs and

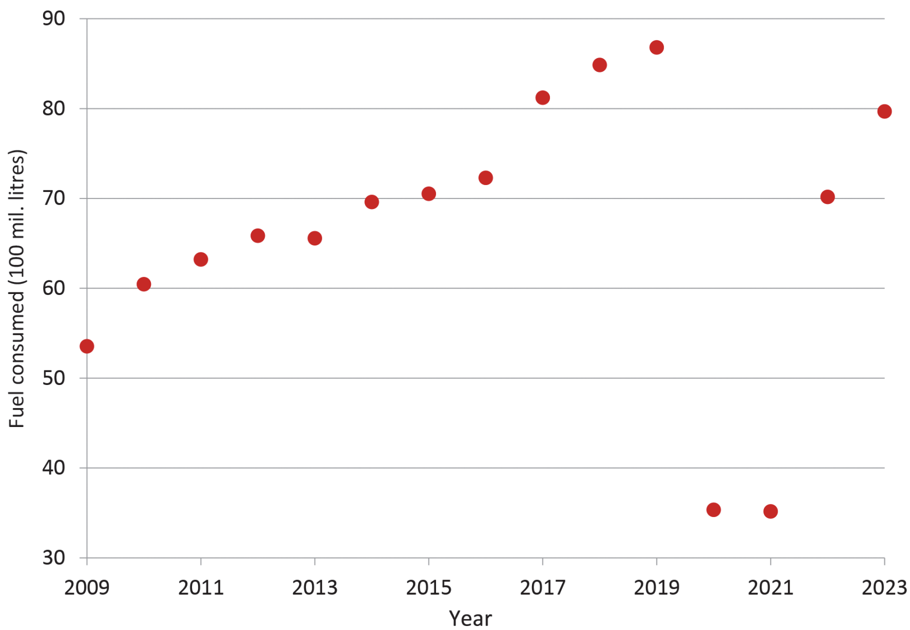

Figure 2: Canadian Civil Aviation – Pandemic Collapse and Recovery

market uncertainties imply that incentives are needed to address investment risks and encourage production.

However, incentives should to be tailored to suit projects. In the U.S. under the IRA, which seems to still be in place, production tax credits (PTC) are available for SAF and renewable diesel. Canada lacks comparable incentives. Incentives roughly matching those for renewable biofuels under the IRA translate to $100 to $170 per tonne (USD). These are within the range of $70 to $190 per tonne reduction (USD) identified by the Specific Mitigation Opportunities Working Group (2016) for middle-distillate fuel-related reductions. Thus, these incentive levels seem reasonable, and worth pursuing. Further work is underway to understand differences in incentives and their effects, as well as developing and proposing a suite of incentives.

Regarding the second obstacle, compliance with stringent CORSIA requirements, this system was initially established in 2016 under the International Civil Aviation Organization (Liao et al. 2022). The intent was to develop a global market-based set of practices for international aviation, which could include offsets, technologies, operational improvements and SAF to address carbon footprints. CORSIA includes a framework for evaluating SAF reduction potential, and confirming compliance for allocation of credit (Prussi et al. 2021). The CORSIA threshold requires demonstrating a minimum 10% reduction.

CORSIA evaluations are based on lifecycle analyses (LCA), expressed as g CO_2e per MJ energy content. A series of "default" LCA emissions values are provided, with oilseed crops assigned less-favorable reduction values, partly due to indirect land use change (ILUC) impact estimates. While the CORSIA process is complex, it allows proponents to submit detailed evaluations of LCA emissions, rather than relying on the defaults.

Addressing CORSIA is less important for fuels used domestically, since national inventories, such as Canada's NIR, do not involve LCA (EPA 2016). But CORSIA compliance is essential for export markets. Further work is underway to understand CORSIA and develop approaches relevant to SAF manufactured in Canada from canola.

Conclusions

Canada's changing circumstances, including slow progress on reducing emissions and emerging trade threats, suggest a need to revisit priorities and policies. One important opportunity is using canola, a major oilseed crop, as the feedstock to produce renewable drop-in fuels, e.g. SAF for aviation and renewable diesel. The benefits include: protecting a major and valuable Canadian agricultural sector; creating value-add and employment opportunities in Canada; and facilitating significant reductions in GHG emissions.

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How might tariffs impact U.S. biomass industries, and are there hidden opportunities for these sectors?

BY ANURAG MANDALIKA AND BRIAN SNYDER

Abstract

Trade of biofuels and biomass feedstocks has become increasingly globalized over the past decades as economies pursue varied decarbonization strategies. Due to its large resource base, the United States exports a variety of biofuels and feedstocks, however, the international trade of these commodities may be impacted as a part of the ongoing trade disputes between the U.S. and its trading partners. In this paper, we consider the potential impact of tariffs (and retaliatory tariffs) on the biomass and biofuels industry in the U.S. We analyze the flow of important biofuels such as fuel alcohol (ethanol), biomass-based diesel fuel (BBD, which includes renewable diesel and biodiesel), densified biomass fuel (DBF or wood pellets), etc. Heightened trade barriers are likely to affect not just biomass-based fuels, but also the feedstocks that are used to manufacture biofuels. Our preliminary analysis shows that feedstocks for biofuels (which have competing uses for food and feed) such as soybeans and corn endure a greater effective tariff rate in comparison to finished biofuels (e.g., fuel ethanol or BBD). While international trade will likely be impacted, we also consider the potential for increased domestic use of these feedstocks as a result of decreasing globalized energy and feedstock flows. Opportunities for increased decarbonization of transportation sectors may exist through greater utilization of these feedstocks for biofuel production instead of producing a glut of biomass created due to trading barriers. As an example, were all soybean exports utilized domestically for BBD production (in the face of unattractive trade barriers), domestic producers can increase their capacity between 31 and 102-fold for renewable diesel and biodiesel, respectively (notwithstanding other barriers towards such an increase in production).

Introduction

In April of 2025, the Trump Administration announced broad-based tariffs on imports that ranged between 10 and 125%. Because tariffs varied across nations, and because products are unequally exported across space, these tariffs have the potential to have very different impacts on different sectors of the economy. In the bioenergy sector, feedstocks and fuels are traded in very different ways and with different nations, and so these tariffs might have markedly different impacts on different parts of the industry and these impacts may affect the supply, demand, and prices of bio-feedstocks and fuels. Here, we use data on the destination of U.S. exports of bio-feedstocks and fuels to provide a high-level analysis of the potential impacts of tariffs on the bioenergy industry in the U.S.

Tariffs can have a variety of impacts on markets. They can raise prices for consumers and disrupt established trade patterns. They can also reduce local production and create a glut for products that were scheduled for export. Finally, tariffs also have the potential to stimulate innovative opportunities, and new domestic markets can potentially absorb the products intended for export that are now uncompetitive if the opportunities are created for their utilization.

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Biofuels are unique energy vectors with regards to their functionality – the feedstocks used for biofuel production have multiple uses, including food and (animal) feed, materials and chemicals, and energy. First-generation biofuels in particular (produced from feedstock which can be considered as edible) have multiple roles to play. We do not advocate for or against tariffs or energy trade policies. Rather, we seek to interpret potential impacts of these policies and identify potential opportunities from these shocks. Winston Churchill is famously attributed to having said '*Never let a good crisis go to waste*'. We take this approach to argue that overcoming uncertainty and international trade barriers by deploying biomass utilization sustainably for increased biofuel production can valorize these feedstocks and lower the emissions associated with the U.S. transportation sector.

The biofuels sector in the U.S. is small, accounting for ~5% of total primary energy consumed, although this share has been rising again. The three main liquid biofuels produced in the U.S. are ethanol, renewable diesel and biodiesel (the latter two can be collectively referred to as biomass-based diesel, BBD). The primary solid biofuel is densified biomass fuel (DBF), and includes pellets, logs, and briquettes made from wood (referred to colloquially as wood pellets). The main feedstocks for producing these biofuels are corn grain (for ethanol), soybean oil, corn oil, canola oil, and used cooking oil (for BBD), and residuals (sawmill, other, and wood product manufacturing), and roundwood and pulpwood (for DBF). Along with the finished biofuel, the bio-based feedstock used for producing these fuels are also traded between nations. While import and export trading persists for all fuels, utility-grade DBF is primarily intended for exports to other countries, with the U.K., countries in the E.U., and Japan being the main importers. In addition, biomass feedstocks like corn and soybeans are among the most heavily traded commodities in the world but are generally used for food rather than fuels.

While biofuels were not directly targeted during the first Trump administration, feedstocks for biofuels production such as soybean exports were impacted. Retaliatory tariffs of 25% imposed by China on U.S. soybeans announced in 2018 led to cancellations of U.S. soybean orders.[1] This was also reflected in a bump in ending stocks for soybeans for the 2018/19 year, and a drop in season-average farm prices.[2]

The second Trump administration has announced the implementation of tariffs on several trading partners, announced a second round of tariffs on nearly all countries, and then suspended the latter round of tariffs for a 90-day period. Biofuels currently imported or exported which will be impacted by tariffs include fuel ethanol, BBD, and DBF. Exports of ethanol from the U.S. totaled 4.67 MMbbl in March 2025 (source: EIA), after reaching a peak of 45.8 MMbbl in 2024.[3] Canada has been the top destination for ethanol exports from the U.S., particularly in 2024, accounting for 16 MMbbl in 2024.[4] More recently, it was reported that ethanol exports fell by 45% for the week ending on April 18, 2025.[5]

The U.S. has been importing renewable diesel since 2012, primarily from the Netherlands and Singapore.[6] The year 2024 marked the largest imports of renewable diesel into the U.S. at 12.3 MMbbl.[6] The recent increase in renewable diesel imports during 2024 has been attributed to a combination of factors, including expansion of Neste's plant in Singapore, and perhaps more importantly, the phasing out of the Blender's Tax Credit (BTC) to the Clean Fuel Production Credit (CFPC), also referred to as the IRS Section 45Z tax credit) in January 2025. Delays by the Treasury Department in releasing full 45Z guidance has led to greater uncertainty regarding available credits.[7] This is evident in the drop in renewable diesel imports in the first months of 2025.[6] Historically, Singapore has been the primary exporter of renewable diesel to the U.S., accounting for 74% of imports, with Canada accounting for most of the remaining imports (18%). All January 2025 imports of renewable diesel into the U.S. originated from Canada at 1,000 bbl. On March 4, tariffs amounting to 10% went into effect on imports of Canadian biofuels into the U.S., with subsequent retaliatory tariffs announced by the Canadian government, with the potential to impact biodiesel imports from the U.S.[4]

DBF is exported from the U.S. to several countries, particularly the UK, multiple E.U. nations (e.g., the Netherlands, Denmark, Belgium-Luxembourg, etc.), Japan, Canada, and China, among others.[8]

To estimate potential impacts of tariffs (and retaliatory tariffs) on sectors associated with the U.S. biofuels (and their feedstocks) industry, we estimate export-weighted tariff rates on individual North American Industry Classification System (NAICS) sectors from the U.S. Census Bureau.[9] While the status of these tariffs is still undergoing temporal changes and several nations have signed individual trade agreements with the U.S., it is a useful exercise to analyze potential economic impacts of any tariffs and retaliatory tariffs on the sectors associated with biofuels production in the U.S.

Analysis

Estimation of export-weighted effective tariff rates

In this section, we analyze the potential impacts of the April 2nd tariffs on eight commodities of importance to the U.S. biofuel industry. We make the assumptions that: (1) there are no second-order effects due to U.S. tariffs (either substitution towards domestic production or switching trading partners to avoid higher tariffs), (2) trade flows remained at 2024 levels, and that trading partners levy retaliatory tariffs at the same level as is imposed by the U.S.

While these assumptions are not realistic, they allow for a preliminary analysis of potential impacts of these trade barriers, and of the susceptibility of various biofuels and the feedstocks that are used to produce them. Table 1 lists several biofuels and feedstock categories assembled according to their NAICS codes, the top importer of these commodities, and the value of all U.S. exports and imports of these commodities. It is evident from Table 1 that the U.S. is a net exporter of biofuels and associated commodities, by ~8.5 times in economic value. That said, the majority of corn and soybeans exported from the U.S. will not be used for

Table 1: Commodities considered in analysis of potential tariff impacts to the biofuels industry in the U.S.

Commodity	Top Importer of U.S. Exports (Share of U.S. Exports)	Value of All U.S. Exports (Billions)	Value of All U.S. Imports (Billions)
1005: Corn (maize)	Mexico (39.8%)	$14.3	$0.3
1201: Soybeans . . .	China (51.9%)	$24.6	$0.4
1507: Soybean oil . . .	Mexico (20.2%)	$0.5	$0.3
1518: Animal or vegetable fats and oils . . .	Mexico (28.6%)	$0.2	$2.4
2207: Ethyl alcohol . . .	Canada (33.3%)	$4.4	$0.4
271020: Petroleum oils . . .	Peru (94.4%)	$0.7	$0.02
3826: Biodiesel . . .	Canada (93.2%)	$0.8	$1.9
440131: Wood pellets . . .	United Kingdom (72.2%)	$1.9	$0.04
Combined	China (27.6%)	$47.4	$5.6

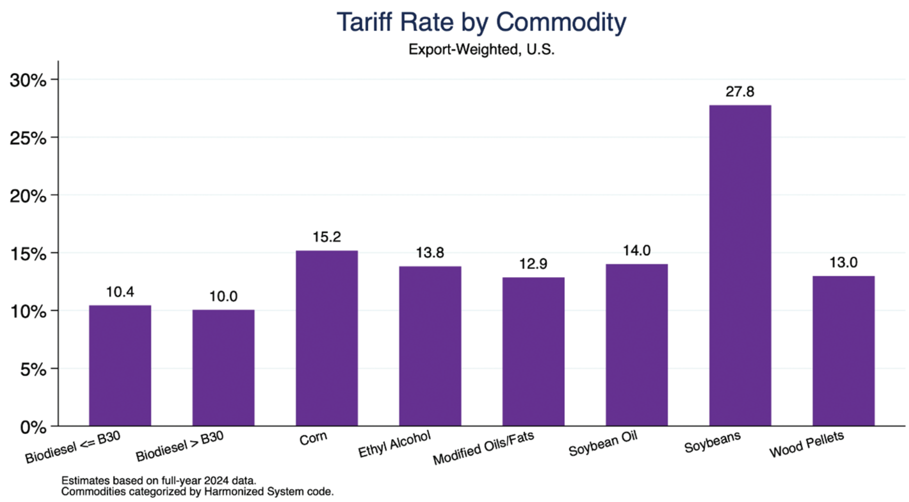

Figure: Calculated export-weighted tariff rates by commodity (industry sectors)

the production of biofuels and are instead used to meet nutritional needs in Mexico, China, and other importing nations.

To compare the potential impact of tariffs of different biomass feedstocks and biofuels, we calculate a weighted average of the country-specific tariffs imposed on April 2nd. These weights reflect the weighted average tariff of a dollar of biobased product exported. The effective tariff is given by the equation below:

$$\frac{\sum_{i=1}^{n} w_i x_i}{\sum_{i=1}^{n} w_i}$$

where i represents each country, w_i represents the value of exports from the U.S. to that country, and x_i represents the U.S.-imposed tariff rate on that country. This methodology assumes that U.S. policies provoke retaliatory tariffs at commensurate levels, as has occurred with China.[10]

Under commensurate global retaliation, agricultural feedstocks—corn (1005) and soybeans (1201)—are subject to the highest effective tariff rate due to their export to high-tariffed nations. Soy faces an effective tariff rate of 27.8% due largely to the scale of soybean trade with China, which is tariffed at 34%. Finished biofuels, on the other hand, are likely to face much lower export-weighted retaliatory tariff rates, as our analysis shows.

Potential for additional domestic biofuel creation

For additional context, the U.S. exported 52.4 MMT of soybeans in 2024.[11] Were all this material used as feedstock to produce BBD, it could have produced an additional 138 billion gallons of renewable diesel or 173.9 billion gallons of B100 biodiesel (Table 2). This calculation assumes that each bushel of soybeans (60 lb) yields 11 bushels of soybean oil,[12] and that it requires 1.26 and 1 kg of oil to yield 1 kg of renewable diesel and biodiesel, respectively.[13] Annual production capacities for renewable diesel (2024) and biodiesel (2023) were 4,328 MMgal and 1,699 MMgal, respectively.[14, 15] This means that diverting soybean exports to domestic BBD production can increase biodiesel production by over 102 times and renewable diesel production by over 31 times current capacity of these fuels. While we do not advocate for this transition in terms of soybean consumption to occur, and there are many factors that dictate commodity utilization, this analysis merely puts perspective on the additional potential for biofuel production.

Table 2: Analysis of the potential for BBD production from U.S. soybean exports

	Renewable Diesel	Biodiesel
Fuel Yield from Soybean Oil (kg feed per kg fuel)	1.26	1
Fuel from U.S. Soybean Exports (billion gallons)	138.0	173.9
Current Capacity (million gallons per year)	4,328	1,699
'Potential for Export-destined Fuel Compared to Current Capacity	31.9 times	102.4 times

Discussion

From this analysis, it is possible that the U.S. will experience another soybean glut similar to what happened when tariffs were implemented during the first Trump Administration. An effective export-weighted tariff rate of ~27% on soybeans could have a number of impacts. It may reduce U.S. exports, reduce U.S. production, or shift U.S. exports to low-tariff countries. These impacts will vary over time and depend on how exporters and producers perceive the permanence of tariffs. It is likely that all these changes will occur, but over different timescales and to different degrees. During the first Trump Administration, American soybean farmers were compensated for losses and Chinese importers temporarily shifted to Brazil for their imports. Although this seems like a plausible consequence of tariffs and retaliatory tariffs, there are also potential opportunities which can be tapped for domestic biofuels production. Our analysis shows the potential for increased biofuels production in this scenario. This sentiment has been echoed previously as an opportunity in the face of economic uncertainty;[16, 17] the opportunity may lie closer to the feedstock rather than finished fuels, given the steeper international trade barrier the former commodities face.

While American soybean exports are primarily used for animal feed in China, they can be diverted to produce additional BBD and advanced fuels such as sustainable aviation fuel (SAF) in the U.S. Demand for BBD, in particular renewable diesel, has risen sharply, driven primarily by the Low Carbon Fuel Standard (LCFS) incentives in the state of California (along with similar initiatives in Washington state and Oregon). At the time of this writing, the Internal Revenue Service (IRS) 45Z tax credit for clean transportation fuels appears to have bipartisan support (similar to support that biofuels have historically enjoyed), with particular emphasis on domestically sourced feedstock.[18, 19] SAF production enjoys the greatest incentives as part of 45Z and there appears to be substantial momentum in expanding its consumption in the aviation sector.[20] Feedstocks such as soybeans which may end up being moored due to trade barriers can be routed to produce BBD and SAF, leading to lower feedstock costs and reducing transportation-related emissions.

Conclusions

Our preliminary analysis suggests that retaliatory export-weighted tariffs may affect biofuel feedstocks more than finished biofuels, although these feedstocks have nutritional uses in import regions. While the primary impact is greater hardship and economic uncertainty for the U.S. agricultural sector, we estimate the potential for utilizing these commodities for biofuel production. Soybeans, which are a large export product from the U.S. to China, are likely to face the largest trade barrier in the form of retaliatory tariffs. The three-way role that soybeans play (as a source of food, feed, and fuel) can allow for this feedstock to be increasingly incorporated into the biofuel production pipeline in the U.S., particularly to meet the increasing demand for BBD and SAF.

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Battery Mineral Security and the Energy Transition

BY SANGITA KANNAN AND MICHAEL TOMAN

Abstract

Concerns about the security of EV battery mineral supplies arise because China has a large market share in processing most of the necessary minerals. Geopolitical risks reflect the possibility of supply cuts aimed at individual countries due to conflicts. However, China's ability to control the market allocation of battery minerals is unlikely to be sufficient to sustain targeted supply cuts. A greater concern is China's exercise of market power over foreign buyers to increase profits. However, the record on such actions by China is mixed. A costly build-up of non-Chinese capacity for battery mineral processing will be needed to mitigate market power.

Global increases in production of battery-powered electric vehicles (EVs) as part of the "energy transition" implies growing demands for the critical minerals used in EV batteries (cobalt, graphite, lithium, manganese, and nickel). Concerns about the security of battery mineral supplies arise because China has a large market share in processing most of the critical minerals needed for EV batteries. (In contrast, extraction of most battery minerals is more geographically diverse; see https://media.rff.org/documents/Report_23-19.pdf). For example, China refined 76 percent of global lithium as of 2020. Its refining capacity grew sevenfold from 2013 to 2020, while refining capacity in the rest of the world (ROW) expanded by only 10 percent.

Two types of concerns have been expressed in relation to China's large market shares:

- **Geopolitical risks:** The possibility of supply cuts aimed at individual countries due to conflicts.
- **Market power:** Manipulation of mineral prices to increase profits while imposing economic costs on dependent buyers. This can include restricting output to inflate prices or flooding markets to deter competitors.

What Evidence do We Have About Geopolitical Risks?

Concerns about geopolitical risks have exerted a strong influence over critical mineral policy generally. At least for EV battery minerals, however, it would be challenging for China to selectively target supply reductions, given the numerous bilateral agreements between mineral processors and buyers. China would have to effectively limit reallocation of supplies across entire markets.

A 2010 dispute between China and Japan led China ostensibly to reduce supplies of certain rare earth minerals, the announcement of which provoked a price jump that persisted well into 2011. However, as we document in our recent RFF report (https://media.rff.org/documents/Report_25-06.pdf), examination of relevant trade statistics by other researchers has revealed no reduction in supplies to Japan during that period, nor any evidence of selective supply cuts to any buyer over 2010-2019. It remains to be seen if the intent to cut supplies of certain rare earth minerals to the United States announced by China in December 2024, and subsequent export licensing restrictions, might be more effective.

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What Evidence do We Have About the Exercise of Market Power by China?

The accompanying figure (also taken from our recent RFF Report) shows how lithium prices surged between 2015 and 2018 due to growing demand. This would have been an attractive opportunity to restrict production and slow refining capacity expansion to drive prices even higher. However, the figure shows that Chinese production of lithium continued to grow rapidly during this period. Even as lithium prices declined from 2018 to 2020, China continued to expand its production. A broadly similar pattern is observed during the lithium price run-up of 2021-2022, and during two cobalt price run-ups in 2006-2008 and 2016-2018.

However, these observations do not rule out China using market power to charge foreign customers more than domestic customers (price discrimination). This would be China's preferred form of market power, since withholding supplies from the market as a whole would raise prices for domestic customers, and the impacts of that would be inconsistent with China's industrial policy for the EV sector.

China has been found responsible for practicing international price discrimination with certain rare earths in a 2012 WTO case resolved in favor of the United States in 2014 (see https://www.wto.org/english/tratop_e/dispu_e/cases_e/ds431_e.htm). China's claim that it needed to restrict exports but not domestic uses to mitigate resource depletion was not accepted. China also has more recently imposed export restrictions for some minerals to meet domestic mineral requirements, consistent with a "China First" approach to protecting domestic supply chains for critical minerals (https://www.iea.org/policies/17933-announcement-on-the-optimisation-and-adjustment-of-temporary-export-control-measures-for-graphite-items).

Unfortunately, obtaining domestic Chinese sales prices to compare with international prices is not easy. All we can say is that price discrimination could again become an issue. It will be less of an issue to the extent that battery mineral spot markets grow in volume and lead to greater price transparency in other processed mineral trade agreements.

There is also concern about China flooding critical mineral markets to drive down prices and thereby

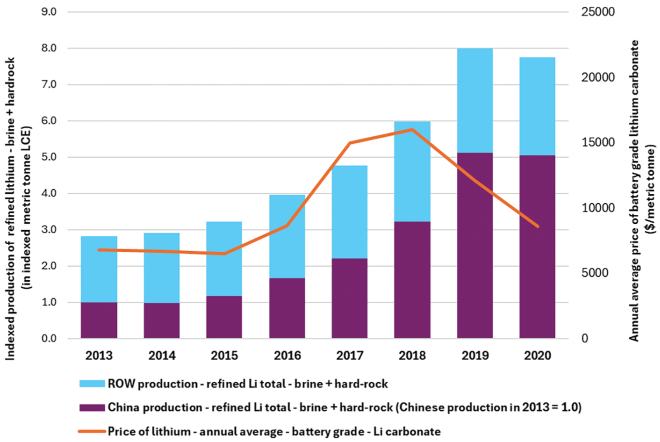

Figure: Refined Lithium Production (Normalized, China and ROW) and Price of Lithium, 2013-2020.
Note: Production numbers are indexed as follows: (a) in 2013, Chinese production is indexed to 1.0 and ROW production was normalized relative to that; and (b) for 2014–2020, both production quantities are constructed by using the ratio of current to previous-year values.

deter international competitors. However, a plausible alternative explanation for China's actions is that they reflect a frequently observed Chinese tendency toward capacity overshooting. Expanding EV production is a national priority for China, and that has led to a strong emphasis on building up domestic mineral refining capacity to secure its own EV supply chains. The emphasis on avoiding too little capacity inherently biases planning toward excess capacity.

Policy Implications

Issues of supply diversity, market power, and investment cost are the considerations that should be driving battery minerals policy in the context of the energy transition. To reduce China's market power over battery minerals, other nations must make substantial investments in battery mineral refining capacity. With lithium, for example, the United States and other countries could be investing in processing capacities for hard rock lithium ore from Australia and lithium-containing brines from Latin America. (As noted, the priority for most battery minerals is diversifying processing versus extraction, given the geographic diversity of the latter.) However, it will be challenging for the rest of the world to do so profitably given China's experience in the sector and its provision of various types of support for investment costs. Potentially costly policy support may well be needed. Thus, care is needed to be confident that the benefits of geographically diversifying battery mineral processing capacity – primarily, reduced Chinese market power – will justify the costs.

It is also important to keep in mind that there are inherent limits to China's market power as demands for battery minerals grow. If it pursues trade restrictions and price increases too aggressively, China will induce more rapid countervailing investment in processing capacity by the rest of the world. Once that capacity is in place, it would be costly for China to try to undercut its use, and its market advantage would be upended.

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