



Climate and Trade Policy for Risk Management: The Need for Geopolitical Analytical Frameworks for Supply Chain and Energy System Modeling

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Abstract

Purpose of review This review contextualizes climate and trade policy and the risks it seeks to mitigate for energy system and supply chain researchers in an era of rising geopolitical tensions by compiling information from various disciplines including international trade, macroeconomics, and energy and carbon modeling.

Recent findings Literature has mostly examined the interaction between climate and trade strategies; however, geopolitics has introduced the need for studies that investigate the effects of policies that aim to address both climate and trade concurrently. Yet, recent studies highlight that there are no analytical frameworks to do so, and energy researchers will need to develop one in order to incorporate geopolitics into energy system planning.

Summary The literature showed that there will be tradeoffs to any type of trade barrier and nations will have to balance economic, innovation, and climate risks. This review aims to guide and encourage energy researchers to develop the analytical frameworks needed to incorporate climate and trade policy and the associated risks into their models.

Keywords Climate and Trade · Energy Systems Modeling · Critical Minerals · Supply Chains · International Trade · Climate Policy · Carbon Leakage · Macroenergy systems · Geopolitical Risk

Introduction

Climate and trade policy, which combines climate and trade strategies into a singular cohesive policy, has emerged as a new geopolitical tool that will affect future energy systems [1, 2]. Energy systems modeling seeks to project how future supply can be built to meet future demand and include cost paradigms that mostly assume straightforward cost curves and material availability [3]. Climate and trade policy affects both costs and supply chains, limiting the efficacy of existing energy system models. As climate and trade policy aims to correct for risk associated with policies that might have improved national climate goals but introduced economic harms; energy systems models are currently ill equipped to model this shift. For instance, the decarbonization of

developed economies is partially a byproduct of the shift of low-cost and in some cases heavy manufacturing to developing countries. Energy systems models were able to capture that most advanced economies have reduced overall and per-capita energy consumption by steadily replacing high-carbon intensity energy generation with low- to zero carbon intensity energy generation via economic carrots such as government incentives (or simply market forces) and policy sticks (e.g., quotas) but have excluded other ramifications of this shift [4].

Political forces across the political spectrum have started to challenge the strategic choice to decarbonize via deindustrialization for four main reasons: 1) *Climate and Weather Risk*: outsourcing energy and labor-intensive industries often leads to worse global environmental and labor outcomes as offshore countries generally use higher carbon emitting energy sources (i.e., carbon leakage) and have worse labor standards [2, 5, 6]; 2) *Economic and Political Risk*: outsourced industries historically formed the economic engine of many regions, especially rural towns, and their disappearance has devastated local economies and pushed millions of people into under- or unemployment [8, 9]; 3) *Competitive*,

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Technological, and Innovation Risk: The research, development, and production of important technologies and key parts of their supply chains are no longer onshore and nations could miss out on key innovations that could drive economic growth [10]; 4) *Concentration and Geopolitical Risk:* if one nation dominates a given technology or supply chain than disruptions in that nation either natural (e.g., weather disruptions brought by climate) or geopolitical will disrupt production in all downstream nations [11–16].

Thus, in recent years many advanced economies have attempted to onshore important future industries, especially renewable energy technologies, which includes lithium-ion battery production, solar cell production, and electric vehicle (EV) production [11, 18]. However, reshoring brings challenges that offshoring sought to answer including increased costs for goods, more internal resource competition (e.g., higher energy, labor, and material costs), and higher national emissions [19, 20]. In other words, there is a cost to resilience from risk, both directly in increased prices and indirectly in more resources being diverted from other industries (e.g., labor and capital), namely service industries, that now constitute most of advanced economies GDP.

In response to this broader global challenge, a new industrial policy arena has emerged: climate and trade. Climate and trade research evolved from work that sought to understand how global supply chains and trade policies could impact national and global climate goals [1, 2]. This area includes theory and analysis of carbon leakage policies like the European Union's Cross Border Adjustment Mechanism (CBAM), technology adoption subsidies like the U.S. Inflation Reduction Act (IRA), and tariffs that balance geopolitical, environmental, and economic concerns into coherent strategies that maximize national benefits [2, 6, 7, 21, 22]. While these policies can operate on wildly different assumptions, zero-sum competition or the need for cooperation, they all recognize that climate and trade policy are now inextricably linked.

Energy systems research must begin to include these geopolitical dynamics into their models to provide accurate analysis and data driven recommendations to policy makers [7, 24–27]. However, this field of research has been slow to build analytical frameworks capable of evaluating how these trade — and now climate and trade policies — will impact energy systems [12]. There is currently a dearth of analytical frameworks that incorporate trade and geopolitics into energy system modeling, and this represents both a fundamental gap and practical need as policy makers look for more information on political and social insights [12, 24, 29, 30].

This review aims to provide additional context in this area by consolidating relevant facts and research literature related to major economies' manufacturing output, energy consumption, carbon intensities, and aggregate and subsector

trade flows. This review will also provide commentary on how policies aimed at reducing one risk (e.g., climate risk and geopolitical risk) can increase another set of risks (e.g., economic and inflation risks) and the need for new, joint modeling paradigms that can provide guidance on how to balance climate and trade objectives.

Manufacturing and Heavy Industry in Major Economies

Globalization has been hypothesized to be responsible for the deindustrialization of advanced economies to the detriment of workers and national security which has increased economic and political risk in offshoring countries [32]. Deindustrialization is a bit of a misnomer, as many advanced economies productivity increases have allowed countries to produce, measured by value-added, either the same or more than they did before “The China Shock” [9, 33]. Nonetheless, globalization has shifted vast amounts of low-cost manufacturing to other countries with lower labor costs (and standards) and environmental standards at the expense of domestic workers who lose out on good paying (relative to the low-wage service jobs that replaced them) blue collar jobs [8, 9, 19, 33, 34]. This section seeks to contextualize how these trends have impacted global manufacturing (Table 1).

Nine nations — China (29%), US (16%), Japan (7%), Germany (5%), India (3%), South Korea (3%), India (3%), Italy (2%), France (2%), UK (2%) individually manufacture at least 2% of the world's manufactured products by value added and combined represent nearly 70% of the global total [34, 36, 37]. Since 2000, the G7's share of global manufacturing has steadily decreased even as manufacturing value-added output has remained the same (Japan, UK), increased modestly (France, Italy, US), or increased by double or more (Germany, India, South Korea) [38]. Over the same time period, China's value-added manufacturing output has increased by an astonishing 680%, so that now it nearly matches G7 output on its own and nearly doubles the market share of the second-place nation, (29%, China vs 16%, US) [36, 38]. Yet, since 2000, manufacturing's share of each major manufacturing nation's GDP (as well as manufacturing employment) has decreased [38, 39] — even in China. As of 2022, the manufacturing sector constitutes less than 25% of the GDP of all major manufacturing nations [39]. Therefore, while manufacturing is important, it is not the main driving force behind these economies and as a result it uses a disproportionate amount of energy relative to its economic impact.

Three heavy industries — chemicals, steel and cement — account for nearly 60% of industrial energy consumption and around 70% of CO₂ emissions even while accounting for only a small fraction of industry value added [40]. In G7 countries, energy intensive industries such as steel and

Table 1 Manufacturing and Trade Volumes (USD Billions) and Percentage of GDP [36, 37]

Country	Year	Manu	Manu % GDP	Exports	X % GDP	Imports	M % GDP	Net Trade
Canada	2004	\$ 147	14%	\$ 317	31%	\$ 280	27%	\$ 37
Canada	2020*	\$ 149	9%	\$ 599	28%	\$ 584	27%	\$ 15
China	2004	\$ 625	32%	\$ 593	30%	\$ 561	29%	\$ 32
China	2022	\$ 4,840	27%	\$ 3,544	20%	\$ 2,707	15%	\$ 838
Germany	2004	\$ 564	20%	\$ 910	32%	\$ 716	25%	\$ 194
Germany	2022	\$ 761	18%	\$ 1,676	40%	\$ 1,583	38%	\$ 93
France	2004	\$ 265	13%	\$ 452	21%	\$ 471	22%	\$ (19)
France	2022	\$ 267	10%	\$ 620	22%	\$ 823	29%	\$ (203)
United Kingdom	2004	\$ 265	11%	\$ 350	14%	\$ 470	19%	\$ (120)
United Kingdom	2022	\$ 252	8%	\$ 533	17%	\$ 824	26%	\$ (291)
India	2004	\$ 112	16%	\$ 77	11%	\$ 100	14%	\$ (23)
India	2022	\$ 440	13%	\$ 453	14%	\$ 720	22%	\$ (267)
Italy	2004	\$ 288	16%	\$ 354	20%	\$ 355	20%	\$ (2)
Italy	2022	\$ 322	15%	\$ 659	31%	\$ 694	33%	\$ (36)
Japan	2004	\$ 1,030	21%	\$ 566	12%	\$ 455	9%	\$ 111
Japan	2022	\$ 818	19%	\$ 747	18%	\$ 897	21%	\$ (150)
Korea, Rep	2004	\$ 207	26%	\$ 254	32%	\$ 224	28%	\$ 29
Korea, Rep	2022	\$ 429	26%	\$ 684	41%	\$ 731	44%	\$ (48)
United States	2004	\$ 1,610	13%	\$ 815	7%	\$ 1,526	13%	\$ (711)
United States	2021*	\$ 2,500	11%	\$ 2,065	8%	\$ 3,372	13%	\$ (1,307)

chemical production volume have largely stagnated [41, 42]. China alone produces over half of the world's steel and cement, and the vast majority of it is used domestically [41, 43–45]. China also dominates chemicals production, comprising 43% of world chemical shares (2023) whereas the EU and US combined make up less than 25%. Thus, the ceding of heavy industry from developed to developing countries reduced the industrial energy consumption in developed countries at the expense of an increase in global emissions [47, 48]. Yet, there is evidence that this commodity “supercycle” is ending as China slows down its rapid urbanization, but a new commodity supercycle for critical minerals could be beginning [46]. Almost universally in developed countries, since 2000, the energy consumption by industry has decreased, with South Korea and Canada being the exceptions due to increased metal and oil production respectively [47, 48]. While part of this is due to improving energy efficiency much of it is no doubt due to offshoring energy intensive industries which has implications for climate and trade policy design.

Energy Consumption and Carbon Emissions in Major Manufacturing Economies

Increased global emissions increases climate and weather risk by contributing to climate change which in turn increases the number of severe weather events. Yet, energy consumption per capita, carbon emissions per capita, and overall carbon intensity have decreased in all G7 nations

since 2000 [47] as shown in Table 2. Furthermore, overall energy consumption and carbon emissions have also decreased for all G7 nations in that timeframe except Canada [47]. On the other hand, China uses a staggering 4.4x as much energy as it did in 1990, India 3.6x, South Korea 3x, Indonesia 3x, and Brazil 2.25x. Mexico and Russia are the only major manufacturing developing economies that did not at least double their energy usage since 1990 with Mexico only increasing by 47% and Russia actually decreasing by 8%. Carbon emissions have increased even more rapidly than energy consumption with Chinese, Indian, and Indonesian emissions increasing by approximately 5x due to a heavy increase in coal for electricity production and industry heat and oil for transportation. South Korean, Brazilian and Mexican emissions increased slower than their energy consumption at 2.4x, 2.4x, and 1.5x rates respectively and Russian emissions declined by 25% as these countries mainly power their electricity and industrial sectors with natural gas and a substantial amount of nuclear (and hydro in Brazil's case) which arrests the dramatic emissions increases [47].

Therefore, developed countries were able to achieve lower energy consumption and carbon emissions due to increased energy efficiency, the increase in low- to zero-carbon energy sources, and more efficient (and productive) manufacturing [48]. On the other hand, the developing countries have increased their industrial output mostly powered by coal which has driven vast energy and emissions increases.

China, India, and Indonesia, three developing economies with massive manufacturing outputs and populations, have

Table 2 Total Energy Supply (Petajoules), Percent Mix, and Carbon Intensity (g CO₂ / MJ) [47]

Country	Year	Total Energy Supply	% Non-Fossil	% Coal	Carbon Intensity
Brazil	2000	7,716	41%	7%	38.2
Brazil	2022	12,532	49%	5%	33.0
Canada	2000	10,690	24%	12%	47.1
Canada	2022	12,627	24%	3%	41.4
China	2000	47,475	20%	59%	64.8
China	2022	159,126	13%	61%	66.7
France	2000	10,784	48%	6%	33.5
France	2022	8,785	50%	4%	31.3
Germany	2000	14,082	16%	25%	57.1
Germany	2022	11,454	22%	20%	51.9
India	2000	17,490	33%	35%	50.9
India	2022	42,515	25%	46%	59.2
Indonesia	2000	5,299	24%	9%	48.1
Indonesia	2022	10,921	23%	36%	59.7
Italy	2000	7,022	6%	7%	59.9
Italy	2022	5,804	19%	5%	53.5
Japan	2000	21,599	19%	19%	52.8
Japan	2022	16,428	13%	28%	57.1
Korea, Rep	2000	7,779	16%	21%	53.7
Korea, Rep	2022	11,710	20%	24%	46.9
Mexico	2000	6,312	13%	5%	57.0
Mexico	2022	7,646	12%	5%	49.7
Russia	2000	25,982	9%	19%	56.7
Russia	2022	33,883	11%	16%	47.9
United Kingdom	2000	9,285	11%	16%	56.1
United Kingdom	2022	6,426	23%	3%	48.2
United States	2000	95,038	14%	23%	60.3
United States	2022	90,830	18%	11%	50.7

high (2022) carbon intensities well above the carbon intensities of most developed countries. However, not all developing countries have high carbon intensities, including some that have experienced rapid growth. For example, Brazil has a relatively low (2022) carbon intensity, even among developed economies because it derives a large portion of its energy from biofuels and hydro. Mexico's (2022) carbon intensity is actually less than the US's. Russia's (2022) carbon intensity was less than Germany, Italy, and the UK [47].

This implies that while developed countries might have better energy efficiency, supported by the reductions in energy consumption and carbon emissions, they do not have an inherent advantage in carbon intensity. In fact, carbon intensity seems to have some regional correlations because the Asia Pacific countries use more coal than other regions that have more ample natural gas supplies. This is even true

for developed Japan which has a (2022) carbon intensity nearly as high as the developing countries in the area. South Korea mitigates this regional disparity by utilizing significant nuclear resources to achieve a (2022) lower carbon intensity than Japan which has reduced its nuclear energy production. The role of nuclear in reducing carbon intensity can also be observed in western economies where France achieves its relatively extremely low (2022) carbon intensity by utilizing massive nuclear power. Beyond nuclear, generating significant quantities of electricity from hydro as is the case in Canada and Brazil also reduces carbon intensities. Currently, renewable energy sources like solar and wind make negligible contributions to total energy supplies and carbon intensity reductions. However, as their adoption increases, they will likely have disproportionately positive impacts on coal reliant economies.

The carbon intensity data has important implications for carbon trade policies like CBAM which aim to reduce the carbon emissions associated with commodity production [6, 7, 17, 22, 49, 50]. Currently, Asia Pacific countries, especially China, which dominate the production of these goods have high carbon intensities. Yet, if they can reduce their emissions by substituting coal for natural gas, nuclear, or renewable production their carbon intensities could quickly improve beyond that of EU nations. Furthermore, while Asia Pacific exporters have high average carbon intensities, they do have low carbon intensive sources they can use to produce exports. This is further highlighted in research on carbon tax leakages which when designed improperly have been shown to hurt growth for limited to no emissions benefits [6, 17, 22, 51, 52].

Global Trade and Intermediate Goods

The value of global trade has increased steadily since 2000 which has lengthened supply chains and, in some cases, concentrated them leading to concentration and geopolitical risks [36, 37]. Gross imports and exports for all major economies (G7, China, India, and South Korea) have increased. However, exports and imports as a percentage of GDP varies wildly among these economies. Since 2000, China and Canada's exports and imports as fraction of their GDP have fallen modestly, the US has shares virtually remain the same, Germany, Italy, India, South Korea, and Japan have seen their import and export percentages explode, and the UK and France have witnessed a drop or stagnation of export percentage but a noticeable increase in import percentage [37]. This illustrates that as the economy has globalized, trade has become more important for most major economies [53]. It also shows that China and North American economies have become more self-reliant even as gross imports and exports increased. Lastly, it shows how the more trade reliant major manufacturing nations (Germany, Italy, India,

South Korea, and Japan) have made producing goods for export a major part of their economies, opening them up to various geopolitical and trade risks for both the supplies needed to manufacture goods and the markets to sell them in.

While percentages are insightful, the magnitude of trade flows hints at some of the challenges climate trade policies aim to address. The three largest exporters and importers, China, US and Germany, have dramatically increased exports since 2000, when no nation exported or imported more than a \$1 trillion worth of goods, to 2023 when these three have been the first and only to exceed that mark [36]. However, the growth percentage of exports and imports in that time period highlights a major divergence. China and India have increased by their imports and exports by at least 10x since 2000, the next largest increase was South Korea with a 4x increase. All other countries have only increased between 2x and 3x in the same timeframe. Thus, due to China and India's massive increase in GDP the raw value of exports and imports for both countries increased dramatically. In China's case, this occurred even as trade's fraction of GDP decreased.

Today, China is the largest exporter in the world exporting nearly \$3.5 trillion worth of (2023) goods compared to ~\$2 trillion (2023) for the US and \$1.7 trillion (2023) for Germany [34, 36]. China is also the second largest importer, importing \$2.5 trillion (2023) compared to first place US's \$3.1 trillion (2023) and third place Germany's \$1.5 trillion (2023). Net trade for these countries is also vastly different than other large economies. In 2023, China had a goods trade surplus of over \$800 billion with the next closest goods trade surplus being Germany with a goods trade surplus near \$250 billion, no other country had a goods trade surplus higher than \$50 billion. On the other side, in 2023, the United States had a goods trade deficit of over \$1 trillion with the next highest goods trade deficit being less than \$275 billion.

Intermediate good flows, the trade of goods that are produced from raw materials but used as inputs to final goods, are essential to modern global supply chains and their flows are perhaps more important than gross trade [54, 55]. The trade flows of intermediate goods are harder to discern, and economists have developed databases and models to trace the "hidden exposure" of foreign suppliers in international supply chains [56]. This work has shown that the intermediate goods are also dominated by China as China produces over 40% of all intermediate goods [34, 56]. This has profound implications for current and future trade, as even if final products are produced locally, they still require significant imports from geopolitical competitors.

These general trends provide context for the manufacturing subsector trade flows that will be critical for the energy technologies of the future. Namely, that the Chinese dominates aggregate and intermediate good trade flows, with the

US also being a major exporter but a net importer, and Germany fighting to keep its export led economy near the leaders. Literature shows that the manufacturing sector is key innovation driver and accounts for disproportionate share of productivity growth and innovation [10, 32, 57, 58]. Therefore, the largest producers of certain subsectors are likely to have key innovation and technological advantages.

The Future Energy Systems and Technologies: Trade Flows and Potential Risks

Innovation fuels productivity and economic growth and the lack thereof leads to competitive and technological risks. Six key decarbonization technologies of the future could represent over \$2 trillion in value [60, 61, 62]: solar, wind turbines, batteries, electric vehicles, electrolyzers, and heat pumps. China has also recognized the importance of the new energy technologies and has made a strategic shift, focusing on manufacturing the new big three of solar, EVs, and lithium-ion batteries to supplant the old big three of furniture, appliances, and clothing [63]. To provide context on how the three major trading regions (EU, China, and the US) are currently represented in these technologies, Fig. 1 shows the trade flows of selected two-digit Standard International Trade Codes (SITC) that contain these technologies: electrical machinery (SITC: 77), industrial machinery (SITC: 74), power machinery (SITC: 71), road vehicles (SITC: 78) [64]. Furthermore, fuel and major commodity trade flows can also be tracked with this system these include: coal (SITC: 32), petroleum products (SITC: 33), hydrocarbon gases (SITC: 34), plastics (SITC: 57), chemicals (SITC: 59) iron and steel (2-digit SITC: 67), and nonferrous metals (SITC: 68).

China and the EU export nearly equal amounts of electrical machinery (which includes solar and lithium-ion battery cells) and the EU dominates industrial machinery (which includes heat pumps). The EU and China also import electric machinery (likely the components needed to manufacture its own). The also EU imports and exports, in nearly equal portions, more power generating equipment (which includes wind turbines) and road vehicles (which include EVs). Both the EU and China are net importers of petroleum products and recently natural gas due to the lack of sufficient resources to power their industries. Interestingly, even though the EU exports more iron and steel, chemicals, and plastics than China or the US, they import even more. Note that, this includes intra-EU trade showing how the bloc's economies are interconnected. In contrast, the US exports relatively few finished goods and is only a comparatively major exporter of petroleum products and natural gas. The US imports relatively large portions of road vehicles, electrical machinery, industrial machinery, and power machinery which could indicate that its own industries in these areas are either insufficient to meet local demand, that they are

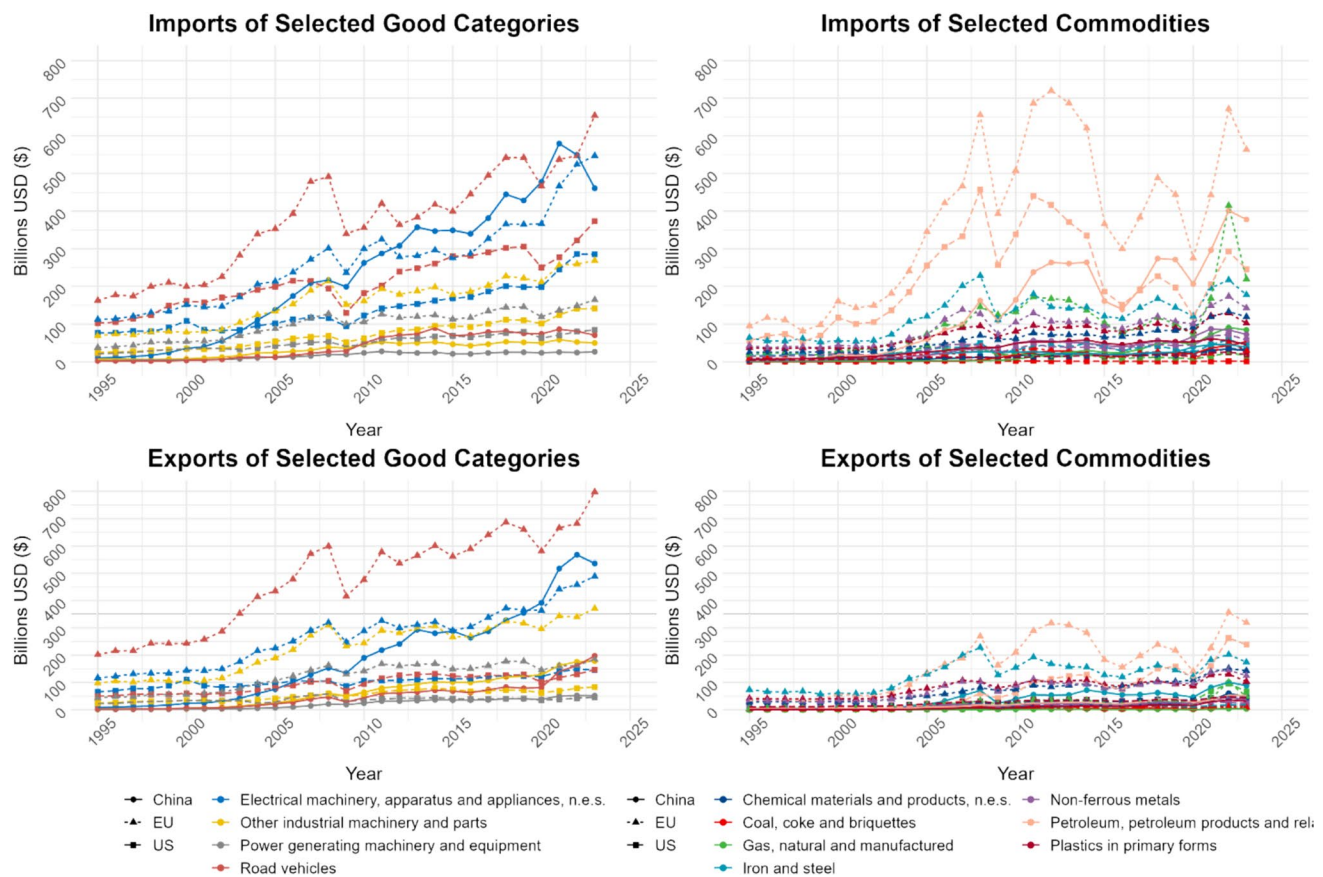


Fig. 1 Imports and Exports of Selected Goods and Commodities by Region [36, 37]

more expensive and of lower quality than global competitors, or that they are importing large quantities of intermediate goods.

Furthermore, the macro numbers imply that China and EU are competing for global market share in these categories and rely on component imports to make higher value-added products. The fact the US is a significant net importer of these subsectors while China and the EU are mostly net exporters indicates that they are leading technologically and in cost. However, the US position as a fossil fuel exporter, in the near term, gives it a strategic energy advantage that could help to offset this deficit.

This high-level view is supported by emerging literature on trade in intermediate goods and the battle for these key supply chains of the future [19, 25–27, 34, 54, 56, 65]. For instance, China has started to dominate production of intermediate goods which makes them essential for EU and even US manufacturing [34, 54, 56]. Furthermore, China has started to dominate the refining market for critical minerals (e.g., lithium, cobalt, and rare earth elements), the new energy technology component market, and the extraction market for mineral supplies [11, 27, 66, 67]. From there China plans to leverage their unmatched industrial capacity

to accelerate the cost production and technological innovation learning curves for solar cells, lithium-ion batteries, EVs, and even wind turbines faster than anywhere else in the world. The EU leads in wind turbine production, road vehicle manufacturing (though they are falling behind in EVs), and electrical and industrial machinery which they hope to lean on to pivot to the technologies of the future [11, 18]. However, they have almost no production capacity in solar cells, lithium-ion batteries, and have only recently started to produce heat pumps as a reaction to the natural gas supply shock which puts them at a disadvantage [68].

The US has started to recognize the risk of being technologically behind and having to rely on imports in the race to build the new energy technologies and have implemented subsidy and tariff policies to encourage US production to varying effect [6, 17, 22, 69, 70]. The subsidies for EVs and their sourcing requirements have encouraged automakers to build factories in the US which has increased supply [72, 73]. However, even though demand has increased, it has not increased at the speed that companies wanted to see. Meanwhile, Chinese EV automakers have increased worldwide market share at blistering speeds and only tariffs are keeping them out of the US market [74]. In other key technologies

like solar, wind, lithium-ion batteries for stationary storage, and heat pumps there is limited domestic production, but subsidies have increased demand so that both investment and imports have increased [75, 76]. Supporters of the tariffs believe that they help give domestic manufacturers time to build competitive operations, that the US needs to have its own supply chain for energy and national security reasons, and that the US can produce these technologies more cleanly than other nations [75, 77, 78]. Detractors argue that US and the world need to deploy these technologies as quickly as possible and by extension as cheaply as possible from whatever source, that the security issues are overblown, and that the even if we could produce these technologies with fewer emissions the manufacturing emissions savings are dwarfed by the operational emission savings [20, 65, 80–83]. Understanding how to balance supply chain and security risk, the risk of missing out on innovation, and the climate and weather risk is critical for policymakers and by extension the energy system modelers who aim to provide data driven insights.

Further complicating this dynamic is the second Trump administration which is opposed to the IRA subsidies, aims to pare them back, and instead promote a tariff forward approach [84, 85]. This strategy could lead to more US production of certain goods dominated by imports and with the investments already made by automakers should not affect the supply of EVs; however, research shows it could increase costs and put US manufacturers further behind the cost and technological curves due to less competition, not even considering the economic effects of likely retaliation [81, 87, 88]. This could have major consequences for future competitiveness as a secure and cheap energy is a major competitive advantage and the new energy technologies promise cheaper, more efficient, and cleaner energy. Thus, if US manufacturers produce inferior and more expensive products and imports are discouraged then the adoption of these technologies will decrease slowing down the energy transition, and exposing the US to the risks associated with the legacy energy system including fuel insecurity and volatile pricing. However, if the alternative is a dominant position by China, then the US will be subject to market share and geopolitical risks as well as the risk of concentrating industry in one location and being subject to a single extreme weather event knocking out production for extended periods of time [11, 18, 89].

Climate and Trade and Energy Systems

Climate and trade policies, that concurrently seek to influence trade and climate, are relatively new and the literature that accounts for both climate and trade typically focused on trade's impact on climate goals irrespective of national climate policies or vice versa [12, 24, 90]. This includes the impacts of climate policy on national manufacturing and the impact of climate and trade trends on jobs [2, 31, 35, 71, 77, 79, 86].

Other relevant literature includes the impact of trade policy on innovation, especially in energy technology such as how trade policy can shape the geography of innovation in energy technology and how it can be used as a tool to help domestic industries compete for the industries of the future (a historic justification for tariffs) [7, 10, 13, 59, 91–94]. These studies have shown that industrial policy can increase domestic production, innovation, and employment but with a cost to global cooperation which could increase costs and lower the speed of carbon reduction.

Energy systems modeling -- which includes the subfield macroenergy systems which that investigates large-scale, systems-level, long-term aspects of energy systems and their implications for other systems -- uses multiple different modeling methods including partial and general equilibrium models and simulation models but the most popular are optimization-based models like capacity expansion models [31, 96]. As energy systems and their interactions with other systems become more complex there have been calls to integrate other system models and to create better mathematical structures to represent spatial and temporal elements with higher resolution [97]. Nonetheless, all of these models are dependent on cost and supply chain (i.e. availability) parameters that will be heavily affected by climate and trade policies and are currently not represented endogenously in models. Models instead use scenario analysis rather than integrate the emerging complicated temporal and spatial cost paradigms for new energy technologies [66, 98].

As the connection between climate and trade has become more clear, recent literature has started to investigate how policies aim to directly affect both climate and trade goals. These include managing carbon leakage via direct trade policies (e.g. border adjustments) like CBAM; how trade policies (and recently climate and trade policies), which are essentially custom trade barriers, will affect the geopolitics of trade and supply chain; and general discussions of trade and climate on geopolitics [2, 7, 12, 17, 21, 23, 24, 28, 29, 58, 93, 99, 100]. These studies show that direct climate and trade policies like CBAM, a tax on carbon intensive commodity imports, and indirect climate and trade policies like subsidies that favor domestic production or tariffs that target emerging energy technologies, can mitigate certain types of risk while introducing others. Yet, there are few analytical frameworks to evaluate these impacts [12, 90]. Energy researchers, especially energy modeling researchers, must develop these frameworks to provide insights to policy makers.

Conclusion

As trade wars intensify, the climate changes, and new technologies emerge, nations will have to develop new strategies to manage the increasing risks. Climate and trade

policies have been introduced as a strategy that could provide a framework for protecting domestic industries limiting economic and political risk, mitigating climate change risk by reducing global emissions, and encouraging innovation in new energy technologies. However, they introduce new risks and could disrupt global supply chains.

The world's manufacturing supply chains have become more integrated and have varying carbon intensities driven by the dominant region fuel. Therefore, different climate trade policy strategies might be more effective than others. CBAM, a climate trade policy that essentially taxes needed manufacturing inputs (i.e. commodities) in order to reduce carbon leakage, could increase costs while providing limited benefits for global emissions [6, 7]. Furthermore, literature shows that import tariffs on intermediate goods and commodities has disproportionate effects on net exporters [2, 6, 17]. Thus, these policies could exacerbate economic competitiveness and inflation risks in order to mitigate climate, geopolitical, and concentration risks. The effect of tariffs and subsidies that aim to encourage domestic production are even harder to predict. On the one hand, tariffs increase the costs of technologies slowing adoption which exacerbates climate and weather risks [20, 82]. However, subsidies could equal or even overcome the cost increases, helping to mitigate the risks associated with relying on one nation controlling a critical supply chain (monopoly and geopolitical risks) and the risk of missing out on a major technology innovation (innovation and economy risk) [11, 18, 21, 58]. Both policies are subject to retaliation from other trade partners and are more costly than an environment without them, even if the higher customer cost still led to increased adoption [14, 15, 90]. For the US, because of the lead China and even the EU have in the subsectors that include the new energy technologies of the future, managing the geopolitical/security and innovation risks has become the priority.

Energy system modelers will have to learn how to incorporate these geopolitical and trade scenarios in their models to give data driven insights. There is literature in the trade and climate space on models that indirectly incorporate both climate impacts on trade which include multisector models, supply chain modeling of energy minerals, and discussions on how to integrate geopolitics into energy research [12, 24, 29, 31, 66, 69, 89, 95, 99, 100]. However, there is limited existing literature on the impact of concurrent climate and trade policies. Furthermore, there are no analytical frameworks or studies that explicitly model the impacts of climate and trade policies or general geopolitics into energy systems models. This review aimed to highlight this gap, provide necessary context, and to encourage researchers to start incorporating these important features into their models.

Key References

- Jakob M. Climate policy and international trade – A critical appraisal of the literature. *Energy Policy*. 2021; 156:112,399.
 - Provides an overarching view of climate and trade literature and important concepts.
- Jakob M, Overland I. Green industrial policy can strengthen carbon pricing but not replace it. *Energy Res Soc Sci*. 2024;116:103,669.
 - Highlights recent developments for climate policy and discusses and provides literature for their impacts on trade
- Jakob M, Afionis S, Åhman M, Antoci A, Arens M, Ascensão F, et al. How trade policy can support the climate agenda. *Science*. 2022 [cited 2025 Feb 19];376:1401–3. Available from: <https://www.science.org/doi/https://doi.org/10.1126/science.abo4207>
 - Clearly makes the case for how trade policies impact climate and how well designed trade policies are also climate policies.
- Yang Y, Xia S, Qian X. Geopolitics of the energy transition. *Journal of Geographical Sciences* [Internet]. 2023 [cited 2025 Feb 9]; 33:683–704. Available from: <https://link.springer.com/article/https://doi.org/10.1007/s11442-023-2101-2>.
 - Highlights the rising importance of geopolitics in the energy transition and notes that new analytical frameworks are needed.
- Davidson MR, Karplus VJ, Lewis JI, Nahm J, Wang A. Risks of decoupling from China on low-carbon technologies. *Science* (1979) [Internet]. 2022 [cited 2025 Feb 19];377:1266–9. Available from: <https://www.science.org/doi/https://doi.org/10.1126/science.abq5446>
 - Highlights how policies that restrict trade can negatively impact climate goals.
- Baldwin R. China is the world's sole manufacturing superpower: A line sketch of the rise | CEPR [Internet]. CEPR | Vox EU. 2024 [cited 2025 Feb 9]. Available from: <https://cepr.org/voxeu/columns/china-worlds-sole-manufacturing-superpower-line-sketch-rise>
 - Provides critical context on manufacturing that is necessary for future energy system and supply chain modelers to understand

- The CSIS Economic Security and Technology Department. Staying Ahead in the Global Technology Race: A Roadmap for Economic Security [Internet]. 2024 Oct. Available from: <https://www.csis.org/analysis/staying-ahead-global-technology-race-roadmap-economic-security>.
 - Provides critical context on the competition for the energy technologies of the future that is necessary for energy system modelers to understand
- IEA. Energy Technology Perspectives [Internet]. Paris; 2024. Available from: www.iea.org
 - Provides technical context for what the energy technologies of the future are and their economic potential that is necessary for energy system modelers to understand.
- Yu X. China Economics: Out With the Old Three and In With the New Three [Internet]. Citi Research. 2023 [cited 2025 Feb 9]. Available from: <https://www.citigroup.com/global/insights/china-economics-out-with-the-old-three-and-in-with-the-new-three>.
 - Provides critical context on what the energy technologies of the future are and how they will shape future economies that is necessary for energy system modelers to understand.
- Tsafos N. China's Climate Change Strategy and U.S.-China Competition [Internet]. Center for Strategic and International Studies. 2022 [cited 2025 Feb 9]. Available from: <https://www.csis.org/analysis/chinas-climate-change-strategy-and-us-china-competition>.
 - Provides critical context on the competition for the energy technologies of the future that is necessary for energy system modelers to understand.

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Declarations

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References

1. Jakob M. Chapter 1: Introduction to the Handbook on Trade Policy and Climate Change. In: Jakob M, editor. Handbook on Trade Policy and Climate Change [Internet]. Edward Elgar Publishing; 2022 [cited 2025 Feb 19]. p. 1–338. Available from: <https://www.elgaronline.com/edcollbook/edcoll/9781839103230/9781839103230.xml>
2. Jakob M. Climate policy and international trade – A critical appraisal of the literature. *Energy Policy*. 2021;156:112399.
3. Herbst A, Toro F, Reitze F, Jochem E. Introduction to Energy Systems Modelling. *Swiss J Econ Stat* [Internet]. 2012 [cited 2025 Feb 20];148:111–35. <https://doi.org/10.1007/BF03399363>
4. Bistline J, Blanford G, Brown M, Burtraw D, Domeshek M, Farbes J, et al. Emissions and energy impacts of the Inflation Reduction Act. *Science* (1979) [Internet]. 2023 [cited 2025 Feb 20];380:1324–7. <https://doi.org/10.1126/science.adg3781>
5. Leisner J, Munch J, Nielsen A, Schaur G. The Impact of Offshoring and Import Competition on Firm-Level Carbon Emissions. *SSRN Electronic Journal* [Internet]. 2023 [cited 2025 Feb 9]; Available from: <https://papers.ssrn.com/abstract=4614729>
6. Mehling M, Jakob M. Subsidy-Related Aspects of the EU Carbon Border Adjustment Mechanism (CBAM). *Journal of World Trade*. 2024;58:361–86.
7. Jakob M, Mehling M. Addressing Competitiveness Concerns of EU exporters with Industrial Policy: The Role of Innovation Support. *World Trade Review* [Internet]. 2025 [cited 2025 Feb 11];1–20. Available from: <https://www.cambridge.org/core/journals/world-trade-review/article/addressing-competitiveness-concerns-of-eu-exporters-with-industrial-policy-the-role-of-innovation-support/229FFCDB0466B82BB14EE665E0A35259>
8. Autor David Dorn Gordon Hanson DH, Brandt L, Caliendo L, Esposito F, Ferman B, Redding S, et al. On the Persistence of the China Shock. 2021 [cited 2025 Feb 9]; Available from: <https://www.nber.org/papers/w29401>
9. Autor DH, Dorn D, Hanson GH. The China Shock: Learning from Labor Market Adjustment to Large Changes in Trade. 2016 [cited 2025 Feb 9]; Available from: <https://www.nber.org/papers/w21906>
10. Fuchs ERH, Combemale C, Whitefoot KS, Glennon B. The “Weighty” Manufacturing Sector: Transforming Raw Materials into Physical Goods. Chatterji A, Lerner J, Stern S, Andrews MJ, editors. *The Role of Innovation and Entrepreneurship in Economic Growth* [Internet]. 2022 [cited 2025 Feb 9];620. Available from: <https://www.nber.org/books-and-chapters/role-innovation-and-entrepreneurship-economic-growth/weighty-manufacturing-sector-transforming-raw-materials-physical-goods>
11. Tsafos N. China's Climate Change Strategy and U.S.-China Competition [Internet]. Center for Strategic and International Studies. 2022 [cited 2025 Feb 9]. Available from: <https://www.csis.org/analysis/chinas-climate-change-strategy-and-us-china-competition>
12. Yang Y, Xia S, Qian X. Geopolitics of the energy transition. *Journal of Geographical Sciences* [Internet]. 2023 [cited 2025 Feb 9];33:683–704. <https://doi.org/10.1007/s11442-023-2101-2>
13. Ebaidalla EM. The impact of taxation, technological innovation and trade openness on renewable energy investment: Evidence from the top renewable energy producing countries. *Energy*. 2024;306:132539.

14. Lewis JI. The Rise of Renewable Energy Protectionism: Emerging Trade Conflicts and Implications for Low Carbon Development. *Glob Environ Polit* [Internet]. 2014 [cited 2025 Feb 19];14:10–35. https://doi.org/10.1162/GLEP_a_00255
15. Allan B, Lewis JI, Oatley T. Green Industrial Policy and the Global Transformation of Climate Politics. *Glob Environ Polit* [Internet]. 2021 [cited 2025 Feb 19];21:1–19. https://doi.org/10.1162/glep_a_00640
16. Beaufils T, Ward H, Jakob M, Wenz L. Assessing different European Carbon Border Adjustment Mechanism implementations and their impact on trade partners. *Communications Earth & Environment* 2023 4:1 [Internet]. 2023 [cited 2025 Feb 19];4:1–9. Available from: <https://www.nature.com/articles/s43247-023-00788-4>
17. Jakob M, Overland I. Green industrial policy can strengthen carbon pricing but not replace it. *Energy Res Soc Sci*. 2024;116:103669.
18. Tsafos N. How the Energy Transition Will Rewire the World. Center for Strategic and International Studies. 2022.
19. Baldwin R. Trade And Industrialisation After Globalisation's 2nd Unbundling: How Building And Joining A Supply Chain Are Different And Why It Matters. 2011 [cited 2025 Feb 9]; Available from: <https://www.nber.org/papers/w17716>
20. Davidson MR, Karplus VJ, Lewis JI, Nahm J, Wang A. Risks of decoupling from China on low-carbon technologies. *Science* (1979) [Internet]. 2022 [cited 2025 Feb 19];377:1266–9. <https://doi.org/10.1126/science.abq5446>
21. Elkerbout M, Nehrkorn K, Pizer W. Climate and Trade in a World of Resurgent Industrial Policy [Internet]. Resources. 2024 [cited 2025 Feb 9]. Available from: <https://www.resources.org/common-resources/climate-and-trade-in-a-world-of-resurgent-industrial-policy/>
22. Elkerbout M, Nehrkorn K. Trade-Friendly Climate Policies: The Promise of “Interoperability” [Internet]. 2024. Available from: <https://www.rff.org/publications/working-papers/trade-friendly-climate-policies-the-promise-of-interoperability/>
23. Balogh JM, Mizik T. Trade–Climate Nexus: A Systematic Review of the Literature. *Economies* 2021, Vol 9, Page 99 [Internet]. 2021 [cited 2025 Feb 11];9:99. Available from: <https://www.mdpi.com/2227-7099/9/3/99/html>
24. Palle A. Bringing geopolitics to energy transition research. *Energy Res Soc Sci*. 2021;81:102233.
25. Eweade BS, Güngör H. Climate policy uncertainty and energy impacts on trade openness and foreign direct investment in the United States: Evidence from the RALS co-integration test. *Nat Resour Forum* [Internet]. 2024 [cited 2025 Feb 11]; <https://doi.org/10.1111/1477-8947.12496>
26. Gakuru E, Yang S, Namahoro JP, Nie P, Bunje MY, Aslam N. Energy-focused green climate policies and trade nexus: Do heterogeneous effects on clean energy poverty matter? *Energy*. 2024;294:130836.
27. Guo K, Luan L, Cai X, Zhang D, Ji Q. Energy trade stability of China: Policy options with increasing climate risks. *Energy Policy*. 2024;184:113858.
28. Ahmed Z. Domestic-Level Climate and Trade Policy Interaction in Bangladesh. *International Law, Climate Change and Bangladesh* [Internet]. 2024 [cited 2025 Feb 11];259–78. https://doi.org/10.1007/978-3-031-71297-5_12
29. Vakulchuk R, Overland I, Scholten D. Renewable energy and geopolitics: A review. *Renew Sustain Energy Rev*. 2020;122:109547.
30. Brown Jon M, Becker Jared, Carbone Teagan, Goforth James, McFarland Destenie, Nock Kristina, Pitman Daniel C, Steinberg ML, Brown ML, Becker JM, Carbone J, Goforth T, McFarland J, et al. Tax Credits for Clean Electricity: The Distributional Impacts of Supply-Push Policies in the Power Sector. 2023 [cited 2025 Feb 9]; Available from: <https://www.nber.org/papers/w31621>
31. Hanna R, Gross R. How do energy systems model and scenario studies explicitly represent socio-economic, political and technological disruption and discontinuity? Implications for policy and practitioners. *Energy Policy*. 2021;149:111984.
32. Rodrik D. Premature Deindustrialization. 2015 [cited 2025 Feb 9]; Available from: <https://www.nber.org/papers/w20935>
33. Rose SJ. Do Not Blame Trade for the Decline in Manufacturing Jobs [Internet]. 2021 Oct. Available from: <https://www.csis.org/analysis/do-not-blame-trade-decline-manufacturing-jobs>
34. Baldwin R. China is the world's sole manufacturing superpower: A line sketch of the rise | CEPR [Internet]. CEPR | Vox EU. 2024 [cited 2025 Feb 9]. Available from: <https://cepr.org/voxeu/columns/china-worlds-sole-manufacturing-superpower-line-sketch-rise>
35. Scott RE, Wilson V, Kandra J, Perez D. Botched policy responses to globalization have decimated manufacturing employment with often overlooked costs for Black, Brown, and other workers of color [Internet]. 2021 Jan. Available from: <https://www.epi.org/publication/botched-policy-responses-to-globalization/>
36. World Bank. World Bank Open Data | Data [Internet]. World Bank. 2025 [cited 2025 Feb 9]. Available from: <https://data.worldbank.org/>
37. World Bank. World Integrated Trade Solution (WITS) | Data on Export, Import, Tariff, NTM [Internet]. World Bank. 2025 [cited 2025 Feb 9]. Available from: <https://wits.worldbank.org/Default.aspx?lang=en>
38. UNCTAD. UNCTAD Data Hub [Internet]. UN Trade and Development. 2025 [cited 2025 Feb 9]. Available from: <https://unctadstat.unctad.org/EN/Index.html>
39. WTO. Trade Statistics - World Trade Statistical Review [Internet]. 2024 [cited 2025 Feb 9]. Available from: https://www.wto.org/english/res_e/statistics_e/wts_e.htm
40. IEA. Achieving Net Zero Heavy Industry Sectors in G7 Members – Analysis - IEA [Internet]. Paris; 2022 May. Available from: <https://www.iea.org/reports/achieving-net-zero-heavy-industry-sectors-in-g7-members>
41. World Steel Association. Data [Internet]. 2025 [cited 2025 Feb 9]. Available from: <https://worldsteel.org/data/>
42. The European Chemical Industry Council. Profile - cefic.org [Internet]. 2023 [cited 2025 Feb 9]. Available from: <https://cefic.org/a-pillar-of-the-european-economy/facts-and-figures-of-the-european-chemical-industry/profile/>
43. Ritchie H. China uses as much cement in two years as the US did over the 20th century [Internet]. Sustainability by Numbers. 2023 [cited 2025 Feb 9]. Available from: <https://www.sustainabilitybynumbers.com/p/china-us-cement>
44. National Minerals Information Center. Cement - Historical Statistics (Data Series 140) [Internet]. US Geographical Survey. 2024 [cited 2025 Feb 9]. Available from: <https://www.usgs.gov/media/files/cement-historical-statistics-data-series-140>
45. Swanson A. How China used more cement in 3 years than the U.S. did in the entire 20th Century - The Washington Post [Internet]. Washington Post. 2015 [cited 2025 Feb 9]. Available from: <https://www.washingtonpost.com/news/wonk/wp/2015/03/24/how-china-used-more-cement-in-3-years-than-the-u-s-did-in-the-entire-20th-century/>
46. Hook L, Leahy J, Ding W. The China commodities supercycle is over. Will there be another? [Internet]. Financial Times. 2025 [cited 2025 Feb 19]. Available from: <https://www.ft.com/content/8ae50718-31ce-4e18-8491-33a600bbd3a5>
47. IEA. Energy Statistics Data Browser – Data Tools [Internet]. IEA. 2023 [cited 2025 Feb 9]. Available from: <https://www.iea.org/data-and-statistics/data-tools/energy-statistics-data-browser?country=WORLD&fuel=Energy%20supply&indicator=TESbySource>

48. IEA. Energy End-uses and Efficiency Indicators [Internet]. 2025 [cited 2025 Feb 9]. Available from: <https://www.iea.org/data-and-statistics/data-tools/energy-end-uses-and-efficiency-indicators-data-explorer>
49. Carbon Trust. CBAM: What it means for businesses | The Carbon Trust [Internet]. 2025 [cited 2025 Feb 9]. Available from: <https://www.carbontrust.com/our-work-and-impact/guides-reports-and-tools/cbam-what-it-means-for-businesses>
50. Arp R. CBAM: What it means for exporters of steel, iron and aluminium | The Carbon Trust [Internet]. Carbon Trust. 2025 [cited 2025 Feb 9]. Available from: <https://www.carbontrust.com/news-and-insights/insights/cbam-what-it-means-for-exporters-of-steel-iron-and-aluminium>
51. Conte B, Desmet K, Rossi-Hansberg E, Rossi E, The -Hansberg, Griffin KC. On the Geographic Implications of Carbon Taxes. 2022 [cited 2025 Feb 9]; Available from: <https://www.nber.org/papers/w30678>
52. Weisbach D, Kortum SS, Wang M, Yao Y. Trade, Leakage, and the Design of a Carbon Tax. 2022 [cited 2025 Feb 9]; Available from: <https://www.nber.org/papers/w30244>
53. Antràs P. De-Globalisation? Global Value Chains in the Post-COVID-19 Age. 2020 [cited 2025 Feb 9]; Available from: <https://www.nber.org/papers/w28115>
54. Baldwin R, Freeman R, Theodorakopoulos A. Horses for Courses: Measuring Foreign Supply Chain Exposure. 2022 [cited 2025 Feb 19]; Available from: <https://www.nber.org/papers/w30525>
55. Baldwin R. The peak globalisation myth: Part 1 [Internet]. Center for Economic Policy Research. 2022 [cited 2025 Feb 19]. Available from: <https://cepr.org/voxeu/columns/peak-globalisation-myth-part-1>
56. Baldwin R, Freeman R, Theodorakopoulos A, Theodorakopoulos Bank Of England A. Hidden Exposure: Measuring US Supply Chain Reliance. 2023 [cited 2025 Feb 19]; Available from: <https://www.nber.org/papers/w31820>
57. The CSIS Economic Security and Technology Department. Staying Ahead in the Global Technology Race: A Roadmap for Economic Security [Internet]. 2024 Oct. Available from: <https://www.csis.org/analysis/staying-ahead-global-technology-race-roadmap-economic-security>
58. Zhang KH. Geoeconomics of US-China tech rivalry and industrial policy. *Asia and the Global Economy*. 2024;4:100098.
59. Unconditional Convergence in Manufacturing. *Quarterly Journal of Economics*. 2013;128.
60. IEA. Energy Technology Perspectives [Internet]. Paris; 2024. Available from: www.iea.org
61. Chetwynd G. China to tighten grip on \$2 trillion global clean-tech market: IEA | Recharge [Internet]. Recharge News. 2024 [cited 2025 Feb 9]. Available from: <https://www.rechargenews.com/energy-transition/china-to-tighten-grip-on-2-trillion-global-clean-tech-market-ia/2-1-1731622>
62. Saraiya K. Global clean energy tech market to reach USD 2 trillion by 2035, driven by major investments [Internet]. *Economics Times Manufacturing*. 2024 [cited 2025 Feb 9]. Available from: <https://manufacturing.economictimes.indiatimes.com/news/energy/global-clean-energy-tech-market-to-reach-usd-2-trillion-by-2035-driven-by-major-investments/114927157>
63. Yu X. China Economics: Out With the Old Three and In With the New Three [Internet]. Citi Research. 2023 [cited 2025 Feb 9]. Available from: <https://www.citigroup.com/global/insights/china-economics-out-with-the-old-three-and-in-with-the-new-three>
64. USITC. Commodity Description Lookup DataWeb [Internet]. US International Trade Commission. 2025 [cited 2025 Feb 9]. Available from: <https://dataweb-legacy.usitc.gov/classification/commodity-description/SITC/2>
65. Ben-Achour S. China dominates the solar industry. Can the U.S. catch up? - Marketplace [Internet]. Marketplace. 2021 [cited 2025 Feb 10]. Available from: <https://www.marketplace.org/2021/07/07/china-dominates-solar-energy-industry-can-us-catch-up/>
66. Jones EC. Lithium Supply Chain Optimization: A Global Analysis of Critical Minerals for Batteries. *Energies* 2024, Vol 17, Page 2685 [Internet]. 2024 [cited 2025 Feb 9];17:2685. Available from: <https://www.mdpi.com/1996-1073/17/11/2685/html>
67. IEA. The Role of Critical Minerals in Clean Energy Transitions – Analysis - IEA [Internet]. Paris; 2021 May. Available from: <https://www.iea.org/reports/the-role-of-critical-minerals-in-clean-energy-transitions>
68. European Commission. Delivering the European Green Deal - European Commission [Internet]. 2025 [cited 2025 Feb 9]. Available from: https://commission.europa.eu/strategy-and-policy/priorities-2019-2024/european-green-deal/delivering-european-green-deal_en
69. Ghorbani Y, Zhang SE, Bourdeau JE, Chipangamate NS, Rose DH, Valodia I, et al. The strategic role of lithium in the green energy transition: Towards an OPEC-style framework for green energy-mineral exporting countries (GEMEC). *Resour Policy*. 2024;90:104737.
70. The Observatory of Economic Complexity. Green Shift: How Renewable Energy is Powering a Global Trade [Internet]. 2022 [cited 2025 Feb 9]. Available from: <https://oec.world/en/blog/green-shift-how-renewable-energy-is-powering-a-global-trade-revolution>
71. Popp D, Vona F, Marin G, Chen Z. The Employment Impact of Green Fiscal Push: Evidence from the American Recovery Act. 2020 [cited 2025 Feb 9]; Available from: <https://www.nber.org/papers/w27321>
72. Bistline J, Blanford G, Brown M, Burtraw D, Domeshek M, Farbes J, et al. Emissions and energy impacts of the Inflation Reduction Act. *Science* (1979) [Internet]. 2023 [cited 2025 Feb 9];380:1324–7. Available from: <https://rooseveltinstitute.org/blog/two-years-later-how-the-ira-is-boosting-green-energy-public-health-and-economic-equity/>
73. Bustamante AR. Two Years Later: How the IRA Is Boosting Green Energy, Public Health, and Economic Equity - Roosevelt Institute [Internet]. The Roosevelt Institute. 2024 [cited 2025 Feb 9]. Available from: <https://rooseveltinstitute.org/blog/two-years-later-how-the-ira-is-boosting-green-energy-public-health-and-economic-equity/>
74. IEA. Global EV Outlook 2024 [Internet]. Paris; 2024. Available from: <https://www.iea.org/reports/global-ev-outlook-2024>
75. Feldman D, Zuboy J, Dummit K, Stright D, Heine M, Grossman S, et al. Quarterly Solar Industry Update [Internet]. Department of Energy. 2024 [cited 2025 Feb 9]. Available from: <https://www.energy.gov/eere/solar/quarterly-solar-industry-update>
76. IEA. Solar PV Global Supply Chains – Analysis - IEA [Internet]. Paris; 2022 Jul. Available from: <https://www.iea.org/reports/solar-pv-global-supply-chains>
77. Anselmo J. US solar panel manufacturing jumps 4-fold after Inflation Reduction Act | Utility Dive [Internet]. 2024 [cited 2025 Feb 9]. Available from: <https://www.utilitydive.com/news/us-solar-panel-manufacturing-capacity-q2-tariff-impact/727360/>
78. Bollinger B, Gerarden T, Gillingham K, Vollmer D, Xu D. Strategic Avoidance and Welfare Impacts of Solar Panel Tariffs [Internet]. 2024. Available from: <https://cowles.yale.edu/sites/default/files/2024-05/Gerarden-solar-tariffs.pdf>
79. Ben-Achour S. Why U.S. solar manufacturing sector can't agree on tariff policy - Marketplace [Internet]. Marketplace. 2024 [cited 2025 Feb 9]. Available from: <https://www.marketplace.org/2024/10/29/us-solar-manufacturing-tariffs-china-imports-supply-chain/>

80. Waldman S, Chemnick J, Storrow B. How tariffs threaten Biden's climate goals [Internet]. E&E News. 2024 [cited 2025 Feb 9]. Available from: <https://www.eenews.net/articles/how-tariffs-threaten-bidens-climate-goals/>
81. Gordon N, McBride M. The New U.S. Clean Tech Tariffs Will Have Global Impacts | Carnegie Endowment for International Peace [Internet]. Emissary. 2024 [cited 2025 Feb 10]. Available from: <https://carnegieendowment.org/emissary/2024/05/ev-battery-china-tariffs-biden-global-impact?lang=en>
82. Helveston JP, He G, Davidson MR. Quantifying the cost savings of global solar photovoltaic supply chains. *Nature* 2022 612:7938 [Internet]. 2022 [cited 2025 Feb 19];612:83–7. Available from: <https://www.nature.com/articles/s41586-022-05316-6>
83. Jakob M, Afionis S, Åhman M, Antoci A, Arens M, Ascensão F, et al. How trade policy can support the climate agenda. *Science* (1979) [Internet]. 2022 [cited 2025 Feb 19];376:1401–3. <https://doi.org/10.1126/science.abo4207>
84. Cui J, Wu J, Murphy J. What Trump's proposed tariffs mean for U.S. trade, in five charts [Internet]. NBC News. 2025 [cited 2025 Feb 9]. Available from: <https://www.nbcnews.com/data-graphics/trumps-proposed-tariffs-mean-us-trade-five-charts-rcna189122>
85. Krugman P. Can Trump Reduce the Trade Deficit? [Internet]. Stone Center on Socio-Economic Inequality. 2024 [cited 2025 Feb 9]. Available from: <https://stonecenter.gc.cuny.edu/can-trump-reduce-the-trade-deficit-paul-krugman/>
86. Reuters. Trump aims at Biden's Inflation Reduction Act: EVs, clean energy and manufacturing | Reuters [Internet]. Reuters. 2024 [cited 2025 Feb 10]. Available from: <https://www.reuters.com/world/us/trump-aims-bidens-inflation-reduction-act-evs-clean-energy-manufacturing-2024-12-20/>
87. Grossman GM, Helpman E, Redding SJ. When Tariffs Disrupt Global Supply Chains. *American Economic Review*. 2024;114:988–1029.
88. Handley K, Kamal F, Monarch R, Bureau US. Rising Import Tariffs, Falling Export Growth: When Modern Supply Chains Meet Old-Style Protectionism. 2020 [cited 2025 Feb 9]; Available from: <https://www.nber.org/papers/w26611>
89. Apergi M, Zimmermann E, Weko S, Lilliestam J. Is renewable energy technology trade more or less conflictive than other trade? *Energy Policy*. 2023;177:113538.
90. Jakob M. The political economy of carbon border adjustment in the EU. *Oxf Rev Econ Policy* [Internet]. 2023 [cited 2025 Feb 19];39:134–46. <https://doi.org/10.1093/oxrep/grac044>
91. Autor D, Dorn D, Hanson GH, Pisano G, Shu P. Foreign Competition and Domestic Innovation: Evidence from U.S. Patents. 2016 [cited 2025 Feb 9]; Available from: <https://www.nber.org/papers/w22879>
92. Bloom N, Draca M, Reenen J Van. Trade Induced Technical Change? The Impact of Chinese Imports on Innovation, IT and Productivity. 2011 [cited 2025 Feb 9]; Available from: <https://www.nber.org/papers/w16717>
93. Jakob M, Mehling M. Addressing Competitiveness Concerns of EU exporters with Industrial Policy: The Role of Innovation Support. *World Trade Review* [Internet]. 2025 [cited 2025 Feb 19];1–20. Available from: <https://www.cambridge.org/core/journals/world-trade-review/article/addressing-competitiveness-concerns-of-eu-exporters-with-industrial-policy-the-role-of-innovation-support/229FFCDB0466B82BB14EE665E0A35259>
94. Rodrik D. Manufacturing is special [Internet]. Center for Economic Policy Research. 2011 [cited 2025 Feb 9]. Available from: <https://cepr.org/voxeu/columns/manufacturing-special>
95. Caceres C, Cerdeiro MrDA, Mano R. Trade Wars and Trade Deals: Estimated Effects using a Multi-Sector Model. *IMF Working Papers* [Internet]. 2019 [cited 2025 Feb 9]; Available from: <https://ideas.repec.org/p/imf/imfwpa/2019-143.html>
96. Moglen R, Chawla KP, Levi P, Sun Y, Phillips O, Leibowicz BD, et al. The state of macro-energy systems research: Common critiques, current progress, and research priorities. *iScience*. 2023;26:106325.
97. Levin T, Bistline J, Sioshansi R, Cole WJ, Kwon J, Burger SP, et al. Energy storage solutions to decarbonize electricity through enhanced capacity expansion modelling. *Nature Energy* 2023 8:11 [Internet]. 2023 [cited 2025 Feb 20];8:1199–208. Available from: <https://www.nature.com/articles/s41560-023-01340-6>
98. Jones EC, Leibowicz BD. Contributions of shared autonomous vehicles to climate change mitigation. *Transp Res D Transp Environ*. 2019;72:279–98.
99. Yarlagadda B, Wild T, Zhao X, Clarke L, Cui R, Khan Z, et al. Trade and Climate Mitigation Interactions Create Agro-Economic Opportunities With Social and Environmental Trade-Offs in Latin America and the Caribbean. *Earth's Future* [Internet]. 2023 [cited 2025 Feb 11];11:e2022EF003063. <https://doi.org/10.1029/2022EF003063>
100. Owen JR, Kemp D, Schuele W, Loginova J. Misalignment between national resource inventories and policy actions drives unevenness in the energy transition. *Communications Earth & Environment* 2023 4:1 [Internet]. 2023 [cited 2025 Feb 9];4:1–12. Available from: <https://www.nature.com/articles/s43247-023-01134-4>

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