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How harmful are fossil fuel subsidies to the diffusion of low-carbon energy technologies?

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ABSTRACT

Global fossil fuels subsidies remain large despite the evident environmental and economic gains from their removal. The increasing attempts to avert climate change-related challenges while creating economic opportunities are promoting energy transition through investments in low-carbon energy technologies and their diffusion. Yet, the existing literature has not assessed how fossil fuel subsidies influence the international trade and diffusion of low-carbon energy technologies. This investigation attempts to shed light on this question by studying the relationship between fossil fuel subsidies and the diffusion of low-carbon technologies using an unbalanced panel for 167 countries and the period 2017 to 2021. By relying on the theoretical framework of gravity model of international trade, we apply the Poisson Pseudo-Maximum Likelihood (PPML) estimator. The results establish a link between international trade in energy technologies and fossil fuel subsidies. The results reveal that fossil fuel subsidies reduce import demand for low-carbon energy technologies and also discourage exports of these goods. Disaggregated analysis shows that especially explicit subsidies reduce the diffusion of low-carbon energy technologies to importing countries. In comparison, both explicit and implicit subsidies are responsible for increasing exports and imports in conventional energy technologies. Meanwhile, implicit subsidies related to air pollution have a negative effect on trade in all energy technologies. Additionally, explicit subsidies for coal and electricity reduce low-carbon exports while subsidies for electricity and natural gas reduce import demand for low-carbon energy technologies.

1. Introduction

Governments across the globe often grant some economic concession to firms, households, and organizations in the form of subsidies to address challenges of access to essential commodities or to promote target aims that are in the interest of the public. The energy sector is critical to the economic progress of any nation and access to affordable energy is imperative for economic activities. The access to energy as well as its affordability have also been incorporated into the United Nations (UN) Sustainable Development Goals (SGD-7). Hence, many governments subsidize fuel prices, and fossil fuel subsidy reforms often face political opposition (Rentschler and Bazilian, 2017). At the moment, fossil fuels continue to account for over 80 % of the world's total energy consumption (Energy Institute, 2024), and global fossil fuels subsidies remain large at about 7.1 % of global GDP in 2022 (Black et al., 2023).

Yet, fossil fuel subsidies lead to overconsumption of fossil fuels, accelerate climate change, contribute to domestic environmental and health problems, and constitute a fiscal burden (Antimiani et al., 2023; Arzaghi and Squalli, 2023; Black et al., 2023; Coady et al., 2017; Dartanto, 2013; Ofori, 2023). Especially climate change mitigation efforts call for immediate phase-out of fossil fuel subsidies or significant subsidy reforms (Rentschler and Bazilian, 2017). Fossil fuel subsidies can also distort international trade (Moerenhout, 2020). Moerenhout and Irschlinger (2020) and Burniaux et al. (2011) argue that the removal of fossil fuel subsidies would reduce international trade in especially coal and natural gas, although subsidy phase-out would leave global international trade volume largely unchanged. However, Moerenhout (2020) notes that these analyses ignore the impacts on trade in low-carbon

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energy and related technologies. Yet, the global diffusion of these low-carbon technological innovations is considered essential for sustainable energy transition goals and climate change mitigation efforts in general (Alola and Rahko, 2024; Onifade and Alola, 2022; Probst et al., 2021). Although conventional energy technologies form a much larger share of the total trade in energy technologies, the volume of trade in low-carbon technologies, including low-carbon transport, low-carbon heat, and clean power among others, is growing (Gosens, 2020). The present study contributes to the literature by scrutinizing how harmful or otherwise are fossil fuel subsidies to the diffusion of low-carbon energy technologies through international trade.

Previous literature has shown that environmental regulation and taxes are important determinants of green trade (Costantini and Crespi, 2008; Costantini and Mazzanti, 2012; Kang and Lee, 2021) and waste (Kellenberg, 2015; Neves et al., 2024). Furthermore, Kuik et al. (2019) and Groba and Cao (2015) have explored, how renewable energy policies and subsidies impact the international trade in renewable energy technologies. Yet, these studies have not assessed the trade impacts of fossil fuel subsidies which are a related but distinct policy tool. Historical evidence by Steenblik and Mateo (2020) shows that phasing out coal production subsidies in Europe led to an initial increase in coal imports, but with time imports turned to decline along with total coal consumption, i.e., coal and coal trade were replaced by cleaner alternatives. Although prior studies have focused on environmental policies as a determinant of green trade, there is sparse information in the literature regarding the trade impacts of fossil fuel subsidies. Yet, the related research evidence implies that fossil fuel subsidies are likely to influence the trade in low-carbon energy technologies, but the magnitude of effects remains to be empirically verified.

Therefore, by navigating the existing gap in the literature, this study examines the role of fossil fuel subsidies on international trade in low-carbon energy technologies. The objective of this investigation is addressed by analyzing a panel of 167 countries for the period 2017 to 2021. We compare the disaggregated impacts of explicit and implicit fossil fuel subsidies and further compare subsidies associated with main energy forms, i.e., subsidies on oil, natural gas, electricity, and coal. Moreover, the effects of subsidies are also analyzed by contrasting the trade in low-carbon energy technologies with trade in conventional energy technologies. Given this practical intuition and the employed approach, the outcomes of the investigation offer vital policy insight. Especially, policy implications related to global diffusion of low-carbon energy technologies and clean transition policies are discussed.

The other segments of the study are arranged as follows. Section 2 provides a review of the extant studies and Section 3 summarizes the data and methods of investigation. The discussion of results and concluding remarks are provided in Section 4 and Section 5, respectively.

2. Literature review

2.1. Theoretical motivation

The theoretical underpinning for the current study is drawn from the substitution and income effects that fossil fuel subsidies can trigger in terms of defining the costs of energy and tendencies to adjust supply or demand among alternative energy sources. Fossil fuel subsidies may be subsidies to energy producers, and relate to exploration, extraction, production, or transformation, or subsidies may target energy users, i.e., households or firms (Moerenhout and Irschlinger, 2020). Production subsidies lower the relative price of fossil fuels; thus, the relative price of alternative and renewable energy is increased. This implies that fossil fuel subsidy removal should increase the demand for alternative and renewable energy products and related technologies via the dynamics of the substitution effect. Subsidies to energy users again alter the relative prices in favor of fossil fuels. The subsidies to energy users may also improve their purchasing power, which may increase demand for all products including alternative and renewable energy products via the dynamics of the income effect. This second effect counteracts the first, but, overall, we should expect that higher fossil fuel subsidies will lead to a lower demand for low-carbon energy products and technologies. In the context of international trade, this implies that the higher the fossil fuel subsidies, the lower the levels of low-carbon energy technology imports will be. In essence, higher fossil fuel subsidies are expected to support the imports of conventional energy technologies that are related to higher fossil fuel use.

Fossil fuel subsidies also have an influence on the downstream industries, in particular, manufacturing sectors that rely on these fuels or other energy-intensive production inputs in their production. Thus, by lowering the costs of production inputs, fossil fuel subsidies support the international competitiveness of such industries (Burniaux et al., 2011; Moerenhout, 2020; Rentschler et al., 2017). These may also include sectors active in the manufacturing of low-carbon energy technology products, some of which require energy-intensive inputs. In contrast, the literature on green trade and environmental regulation has emphasized that, in line with the Porter hypothesis, domestic environmental policies may support the domestic competitiveness in green goods production (Costantini and Crespi, 2008; Costantini and Mazzanti, 2012; Kang and Lee, 2021; Porter and Van der Linde, 1995). The arguments following the Porter hypothesis suggest that stricter environmental regulation, such as carbon pricing that increases the prices of fossil fuels, i.e., or lower implicit subsidies for fossil fuel, motivates regulated firms to innovate, which will improve their competitiveness and, eventually, the competitiveness of the economy as a whole. These two theoretical arguments are contradictory. If the second argument dominates, it would suggest that fossil fuel subsidies have a negative impact on low-carbon exports and the negative impact on imports would be even stronger than the pure substitution effect would predict. However, if the first argument dominates, then the fossil fuel subsidies as indirect subsidies to all manufacturing activities could counteract the negative substitution effect and the effect of subsidies on low-carbon exports and imports would be theoretically ambiguous.

In the context of conventional energy technologies, we should expect that fossil fuel subsidies should support the development of such production by lowering the costs of production inputs. In addition, as implicit fossil fuel subsidies reflect a lack of environmental policies and a price on carbon, such a policy mix is likely to favor the development of gray industries. Thus, both arguments suggest that higher fossil fuel subsidies should be related to higher exports of conventional energy technologies.

Fossil fuel subsidies may be disaggregated into explicit and implicit subsidies (Coady et al., 2017). Explicit fossil fuel subsidies reflect undercharging for supply costs, whereas implicit subsidies are related to the negative externalities of fossil fuel use that are not included in the price of these fuels. These negative externalities include impacts on local air pollution and global warming, but also transportation externalities such as congestion. Hence, the implicit subsidies are typically lower in countries that have adopted carbon tax or cap-and-trade schemes to put a price on carbon. Furthermore, these subsidies may be disaggregated based on which fossil fuel they subsidize and which negative externality the fossil fuel prices, or related policy instruments, fail to include. While we expect that the above theoretical arguments apply to all subsidy types, there may be differences in the magnitude of effects, which remains to be empirically verified.

2.2. Review of empirical studies

The review of the empirical literature reveals an existing gap that the current research seeks to fill. Environmental taxes and other policy indicators have dominated the discussion in the available empirical evidence on the determinants of green trade. We provide a review of the findings and implications from the available relevant literature to establish the premise for the research objectives of the current study.

Additionally, while other empirical studies have provided evidence on the environmental effects of fossil fuel subsidies there are no attempts to scrutinize how these energy subsidies affect green trade. This lacuna in the literature thus provides the justification for the research objectives of the current study. The review begins with a general survey of the available evidence on green trade determinants before moving to the environmental effects of fossil fuel subsidies.

2.2.1. Evidence on determinants of green trade

A few factors have been identified as major determinants of green trade in empirical literature. These include institutional factors like environmental regulations, trade policies, economic factors like disparities in income levels, and other technological-related factors like R&D investments. The early study of Costantini and Crespi (2008) explores the channels by which environmental regulations influence green trade by focusing on trade in renewable technologies. The empirical results show that environmental regulations such as public and private sector environmental protection expenditures positively drive trade in renewable energy technologies. In another study, Costantini and Mazzanti (2012) explore whether environmental policies are apt for stimulating trade in green technologies or total trade. They discovered that environmental regulations that are channeled to support innovations positively boost green trade through increased exports of green products. Furthermore, Cantore and Cheng (2018) argue that domestic environmental taxes support domestic production of green products and lower import demand. Partly in contrast to Cantore and Cheng but in favor of the importance of environmental policies, Pienknagura (2024) shows that the introduction of new climate policies increases low-carbon technology imports. The empirical study conducted by Kang and Lee (2021) also emphasizes environmental policies as an important driver for green trade albeit with a focus on environmental taxes and energy intensity as main policy proxies. Their exploration divulges that the extent of green trade depends on the trading partner's energy intensity level as environmental taxes trigger growth in green exports mainly from developed wealthy economies. These outcomes lend credence to the possibility of harnessing green export advantage in line with the Porter hypothesis. While the approaches adopted are different across studies, the majority of extant work recognizes both environmental regulations and countries' affluence levels as essential determinants of green trade.

The existing research on international trade in waste partly points to similar conclusions. Kellenberg (2015) shows that waste imports increase in countries that loosen their environmental regulations in comparison to its' trading partner. However, Neves et al. (2024) argue that environmental taxes are not effective in controlling the exports of e-waste.

Other identified determinants for green technology diffusion through trade include trade policies as seen in the literature (De Melo and Solleder, 2020; Pienknagura, 2024). However, the evidence also points out that nontariff barriers to trade may be more important (Tamini and Sorgho, 2018). Environmental provisions in preferential trade agreements also support green exports while reducing dirty exports from developing countries (Brandi et al., 2020). Furthermore, Groba (2014) examined the green trade impacts of countries' renewable energy policies using the OECD sample. The investigation affirms that green exports are fostered by renewable energy policy adoption among the bloc's member countries. However, tariffs and environmental regulations play determinant roles in the levels of green trade among the importing countries. This suggests that environmental and other policies may also have heterogeneous effects. For example, Consoli et al. (2023) provide a more nuanced view that environmental policy stringency should be seen as relative to that of trading partners. Moreover, Kuik et al. (2019) show that renewable energy policies support exports of wind power technologies but give only temporary support to solar PV exports. Groba and Cao (2015) also report that some renewable energy support schemes increase import demand for solar PV, but some do not. There can also be heterogeneity across countries. Stronger intellectual property rights protection increases imports of low-carbon technologies but only among OECD countries (Dussaux et al., 2022).

Beyond these regulatory policies, a couple of studies have also emphasized the roles of other factors such as the infrastructural readiness of a green tech importer, and the general level of development among countries. For instance, technological-related factors like R&D investment levels and level of infrastructural capacity could influence green trade and technology diffusion among countries (Costantini and Crespi, 2008; Costantini and Mazzanti, 2012; Jin, 2016). The diffusion of energy innovations to areas with infrastructural deficits tends to require longer periods (Vaidyanathan et al., 2019). Infrastructural investments have also been identified as one of the major determinants of technological capabilities for stimulating technological diffusion alongside the development of people's skills in terms of the required level of technical know-how to utilize an imported technology (Dechezleprêtre et al., 2008). All these factors combined would impact a receiving country's level of absorptive capacity for not just green tech diffusion alone, but for total tech diffusion as a whole.

A major limitation of some of the reviewed studies is that they did not separate green energy technology diffusion but rather focused mainly on all green technologies. Furthermore, these studies have a common gap as they ignore the green trade impacts of fossil fuel subsidies despite integrating many other economic policy perspectives in their analyses. There is a clear reverse connection between environmental taxes and implicit fossil fuel subsidies because implicit subsidies are related to the negative externalities of fossil fuel use and environmental taxes are a policy to correct the externalities. Nevertheless, environmental taxes, as typically measured in the prior literature, also attempt to correct externalities related to water emissions, ozone depletion, waste management, biodiversity loss, and others. Moreover, explicit fossil fuel subsidies do not have a similar overlap with environmental taxes. Thus, there is only a partial overlap between implicit fossil fuel subsidies and environmental taxes and, thus, the existing empirical evidence on environmental taxes and regulations does not provide reliable evidence on the role of fossil fuel subsidies on international trade. In contrast, most extant studies on fossil fuel subsidies provide evidence of their environmental and overall welfare impacts. A review of this evidence is provided hereafter. However, since technology diffusion is essential for curbing environmental degradation according to existing literature, it is therefore paramount to investigate if fuel subsidies act as an impediment or otherwise to the diffusion of low-carbon energy technologies.

2.2.2. Review of studies on fossil fuel subsidies

Many studies have established empirical evidence of the environmental impacts of fossil fuel subsidies vis-à-vis fuel subsidies' impacts on energy-related carbon emissions levels. For instance, Mundaca (2017) studies the extent of the carbon mitigating effect of the removal of fossil fuel subsidies. The study focuses on emission data and the volume of subsidies granted for fossil fuels in the Middle East and North African countries. The article ascertains that a cut in subsidies for every liter of fuel (mainly diesel & petrol) could potentially cut down regional carbon emissions. In another study, Arzaghi and Squalli (2023) scrutinize the available subsidy figures in 139 economies to understand how subsidy policy impacts the environment. They also discover that emissions are much higher among economies that pay more subsidies. Many other studies have provided further evidence that fossil fuel subsidy removal would significantly enhance the reduction in energy-related emissions (Okorie and Wesseh, 2024; Parry et al., 2021; Schwanitz et al., 2014). However, Antimiani et al. (2023) note that the optimal outcome is reached when fossil fuel subsidy phase-out is combined with public support to clean energy technology development. Similarly, a study by Li and Sun (2018) concludes that adequate emission mitigation would not be attained in China simply by fuel subsidy removal. They argue that the fuel subsidy removal might as well create some substitution effect

Table 1
HS codes for low-carbon and conventional energy technologies.

Variable	Description	HS2017 code
LC	Low-carbon energy technologies = POWER + HEAT+ FUEL + TRANSPORT + EFF + STORAGE	
POWER	Low-carbon power technologies: hydropower, wind power, solar PV, nuclear power	8410, 850231, 854140, 8401
HEAT	Low-carbon heat technologies: solar hot water	841919
FUEL	Low-carbon fuels: ethanol, biodiesel, solid biomass	2207, 3826, 4401, 4402
TRANSPORT	Low-carbon transport technologies: hybrid and electric cars, busses and two-wheelers; locomotives powered by electric accumulators	870220, 870230, 870240, 870360, 870370, 870380, 871160, 860120
EFF	Energy efficiency technologies: energy efficient cement, insulation, heating and light; energy efficiency in heavy industries	252390, 680690, 700800, 701939, 841861, 841950, 903210, 853120, 853931, 840410
STORAGE	Energy storage technologies	850710, 850720, 850730, 850740, 850780, 850790, 853224
CONVENTIONAL	Conventional energy technologies: boilers and components, generators for producer gas, steam and gas turbines, furnace burners, gas-fired water heaters, electric generating sets, electric generators and components, internal combustion engines and components, vehicles and components	8402–8409, 8411, 8416, 8417, 841911, 8502, 8503, 850161–850164, 8701–8711, 8714

among alternative fossil resources. For example, energy consumers might be pushed to opt for even more carbon-intensive options like coal. A similar finding was confirmed for the case of Malaysia in the study of Babatunde et al. (2021). They also noted that phasing out the subsidy on natural gas would only aggravate a shift to more carbon-intensive fossil alternative via the substitution effect mechanism. As such, more policy reforms would be needed beyond removal of explicit subsidies to reach a desired low-carbon economy.

The economic impacts of fossil fuel subsidy removals have also been studied. While it is generally understood that complete subsidy removal would increase overall welfare (Coady et al., 2017), the impacts are unevenly distributed across households and firms (Cockburn et al., 2018; Rentschler et al., 2017; Timilsina and Curiel, 2023). The adverse effects among some groups are especially contributing to opposition towards unilateral policy reforms.

The subsidy policy reforms would also have dynamic effects through their impacts on structural and technological development. Steenblik and Mateo (2020) provide historical evidence how the removal of coal subsidies contributed, first, to coal imports substituting domestic production, but later to structural changes and decline in imports. The study of Li et al. (2024) confirms that the changes in energy-saving technologies can be essentially affected by fossil fuel subsidies based on their empirical assessments of the Chinese economy. They argued that in order to boost energy-saving technologies in China, important reforms to fossil subsidies would be necessary. Considering that most of these technologies originate from a couple of advanced economies, their accessibility and utilization would be dependent on the levels of green trade. This in turn brings into question the relevance of factors that drive green trade. On the other hand, subsidies granted to conventional energy potentially affect the relative rates of substituting these energy sources with green alternatives. Hence, fossil subsidies potentially pose some influence on levels of demand as well as diffusion of low-carbon energy technologies.

2.3. Contribution to the literature

Although the literature on green trade is substantial, to the best of our knowledge, the current study is the first to provide insights into the impacts of fossil fuel subsidies on low-carbon energy technology trade. Therefore, the current study provides novel empirical insights into how fossil fuel subsidies impact low-carbon technology diffusion. Thus, the present study fills this essential research gap to provide policy directives for fostering energy transition via the diffusion of low-carbon technologies.

3. Data and methodology

3.1. Data description

We rely on the International Monetary Fund's (IMF) data on fossil fuel subsidies (Black et al., 2023).[1] The fossil fuel subsidy data covers 170 countries from 2015 onwards. We aim to analyze international trade in low-carbon energy technologies. Thus, we need trade data, which we obtain from CEPII BACI database 202401b version (Gaulier and Zignago, 2010). BACI dataset provides data on bilateral trade flows at the product level, i.e., Harmonized System (HS) nomenclature 6-digit code level. We identify the low-carbon energy technologies using these HS codes. While prior empirical literature has used different lists of clean energy technologies, in our analysis, we follow the work of Glachant and Dechezleprêtre (2017) and Gosens (2020). The selected low-carbon and conventional energy technologies and associated HS codes are presented in Table 1. We utilize HS17 version, as it introduced new codes to identify trade in hybrid and electric vehicles. Thus, the trade data is available for 2017–2022. Finally, CEPII gravity dataset is used to obtain the control variables for the gravity model of trade (Conte et al., 2022). The CEPII data is available until 2021. We lose a few countries in the matching process and, thus, our estimation sample is an unbalanced panel that covers 167 countries[2] for the period 2017 to 2021.

We analyze low-carbon energy technologies, which include, e.g., wind, solar photovoltaic (PV) and other low-carbon power technologies, low-carbon heat and fuels, hybrid and electric vehicles, energy efficiency, and energy storage technologies. In the estimations, we also provide comparative results for conventional energy technologies, which are also presented at the end of Table 1.

[1] Data is available at https://climatedata.imf.org/

[2] Countries are: Afghanistan, Angola, Albania, United Arab Emirates, Argentina, Armenia, Australia, Austria, Azerbaijan, Burundi, Belgium, Benin, Burkina Faso, Bangladesh, Bulgaria, Bahrain, the Bahamas, Bosnia and Herzegovina, Belarus, Belize, Bolivia, Brazil, Barbados, Brunei Darussalam, Bhutan, Botswana, the Central African Republic, Canada, Switzerland, Chile, China, Côte d'Ivoire, Cameroon, the Democratic Republic of the Congo, the Congo, Colombia, the Comoros, Cabo Verde, Costa Rica, Cyprus, Czechia, Germany, Djibouti, Denmark, Dominican Republic, Algeria, Ecuador, Egypt, Spain, Estonia, Ethiopia, Finland, Fiji, France, Gabon, the UK, Georgia, Ghana, Guinea, Gambia, Guinea-Bissau, Equatorial Guinea, Greece, Guatemala, Guyana, Honduras, Croatia, Haiti, Hungary, Indonesia, India, Ireland, Iran, Iraq, Iceland, Israel, Italy, Jamaica, Jordania, Japan, Kazakhstan, Kenya, KyrgyzstanCambodia, Kiribati, the Republic of Korea, Kuwait, the Lao People's Democratic Republic, Lebanon, Liberia, Libya, Saint Lucia, Sri Lanka, Lesotho, Lithuania, Luxembourg, Latvia, Morocco, Moldova, Madagascar, Maldives, MexicoRepublic of North Macedonia, Mali, Malta, Myanmar, Mongolia, Mozambique, Mauritania, Mauritius, Malawi, Malaysia, Namibia, Niger, Nigeria, Nicaragua, the Netherlands, Norway, Nepal, New Zealand, Oman, Pakistan, Panama, Peru, the Philippines, Papua New Guinea, Poland, Portugal, Paraguay, Qatar, Romania, Russian FederationRwanda, Saudi Arabia, Sudan, Senegal, Singapore, Solomon Islands, Sierra Leone, El Salvador, Serbia, Sao Tome and Principe, Suriname, Slovakia, Slovenia, Sweden, Seychelles, Chad, Togo, Thailand, Tajikistan, Turkmenistan, Tonga, Trinidad and Tobago, Tunisia, Türkiye, Tanzania, Uganda, Ukraine, Uruguay, the US, Uzbekistan, Viet Nam, Yemen, South Africa, Zambia and Zimbabwe.

Descriptive statistics of our sample are presented in Table 2. Figs. 1, 2, and 3 present the development of fossil fuel subsidies (FFS), trade in low-carbon and conventional energy technologies, and trade in subclasses of low-carbon energy technologies over time. As seen in Table 2 and Fig. 1, the fossil fuel subsidies have been around 6 % of GDP in our sample. The explicit subsidies (EFFS) form a smaller proportion of this, and implicit subsidies related to air pollution, global warming, and other implicit subsidies (IFFS) form a larger proportion. The category of other implicit subsidies includes foregone consumption taxes and undercharging due to negative externalities related to accidents, congestion, and road damages. IFFS could also be categorized based on whether the subsidies target coal, gas, petroleum, or electricity. As seen in Table 2, explicit subsidies are larger for electricity and petroleum products and smaller for gas and coal. The three implicit subsidy types are quite similar in size.

As seen in Fig. 2, the international trade in energy technologies is nearing $2 trillion in current US dollars in our sample. However, a major proportion of this is attributable to conventional energy technologies. Yet, as is evident from Fig. 3, trade in low-carbon energy technologies has experienced accelerating growth with low-carbon power and low-carbon transport technologies as the two largest categories.

The impact of the COVID-19 pandemic is clearly visible in Figs. 1 and 2. However, we have estimated our results also excluding the year 2020 from the sample. Our findings remained robust and even somewhat stronger than when 2020 was included. Thus, we choose to use all the years in our baseline estimates.

3.2. Empirical procedures and model

The gravity model of international trade has been the workhorse of international trade literature since Tinbergen (1962). Yotov et al. (2016) review the theoretical foundations of the model. In the gravity model, the size of the economy in trading countries, Y_i and Y_j, proxy for the demand and supply of the exporter i and importer j and distance, D, creates resistance to trade. Once a disturbance term, η, is included this leads to the following model, where t refers to year:

$$E_{ijt} = \alpha_0 Y_{it}^{\beta_1} Y_{jt}^{\beta_2} D_{ij} \eta_{ijt} \quad (1)$$

In Eq. (1), E is the exports from country i to country j in year t. The model can be extended to include other factors that affect the trade costs: shared border, shared language, free trade agreements and other factors reflecting the trade costs between countries i and j. Following Anderson and Van Wincoop (2003), country and year fixed effects are commonly used to consider multilateral trade resistances that form a part of the trade costs. The literature on green trade has studied factors that influence the demand and supply of green goods, such as national environmental policies (Cantore and Cheng, 2018; Costantini and Mazzanti, 2012). The present investigation extends this analysis by exploring the role of fossil fuel subsidies. Thus, after log-linearization, Eq. (1) becomes:

$$\ln E_{ijt} = \ln\alpha_0 + \beta_1 \ln Y_{it} + \beta_2 \ln Y_{jt} + \beta_3 FFS_{it} + \beta_4 FFS_{jt} + \delta_{ij} + \tau_t + \ln\eta_{ijt} \quad (2)$$

In Eq. (2), Y is measured with GDP (in thousands current US dollars) for countries i and j and FFS is fossil fuel subsidies per GDP in countries i and j. We include exporter-importer pair fixed effects, δ, and time fixed effects, τ, as is suggested in the prior literature to address bilateral trade costs and endogeneity issues (Baier and Bergstrand, 2007; Yotov et al., 2016). Thus, distance and other common control variables that are constant over time for exporter-importer pairs are absorbed by the fixed effects.

The log-linear transformation of Eq. (2) leads to problems as the export flows equal zero for many observations. Instead, we estimate the equation using the level of trade (in thousands current US dollars) using a Poisson Pseudo-Maximum Likelihood (PPML) estimator. Santos Silva and Tenreyro (2006) show that the PPML method removes the bias that ordinary least squares estimation has in the presence of heteroskedasticity and, moreover, it provides a way to deal with the zero values of the dependent variable. Thus, we rely on the PPML estimator.

A limitation of the above model and our data is that they do not consider domestic trade (Borchert et al., 2021; Yotov, 2022). However, the existing datasets that also contain domestic trade are not disaggregated at the product level, which would be needed to study clean energy trade. Thus, the analysis focuses on international trade flows.

Table 2
Descriptive statistics.

Variable	Description	Mean	Median	St. Dev.
LC	Low-carbon energy technology imports	8361.2	0	101,742.6
CONVENTIONAL	Conventional energy technology imports	60,106.9	0	990,576.0
POWER	Low-carbon power technology imports	2215.9	0	44,143.8
HEAT	Low-carbon heat technology imports	70.4	0	2751.4
FUEL	Low-carbon fuel imports	1416.5	0	25,092.9
TRANSPORT	Low-carbon transport technology imports	2156.7	0	43,337.5
EFF	Energy efficiency technology imports	1213.7	0	14,658.0
STORAGE	Energy storage technology imports	1288.0	0	20,328.0
GDP	GDP (in million USD)	515,974.9	51,514.2	2,070,549.0
FFS_TOTAL	Total fossil fuel subsidies (% of GDP)	6.014	3.758	5.956
EFFS_TOTAL	Explicit fossil fuel subsidies (% of GDP)	1.413	0.627	2.095
IFFS_TOTAL	Implicit fossil fuel subsidies (% of GDP)	4.601	2.920	4.494
IFFS_POLLUTION	Implicit (air pollution) fossil fuel subsidies (% of GDP)	1.427	0.704	1.902
IFFS_WARMING	Implicit (global warming) fossil fuel subsidies (% of GDP)	1.655	0.964	1.871
IFFS_OTHER	Other implicit fossil fuel subsidies (% of GDP)	1.519	1.202	1.325
EFFS_COAL	Explicit coal subsidies (% of GDP)	0.005	0	0.035
EFFS_ELEC	Explicit electricity subsidies (% of GDP)	0.944	0.429	1.525
EFFS_GAS	Explicit gas subsidies (% of GDP)	0.171	0	0.673
EFFS_PETRO	Explicit petroleum subsidies (% of GDP)	0.268	0	0.847

Notes. 135,678 observations. Trade variables in current thousand USD.

4. Results

4.1. Impacts of fossil fuel subsidies on energy technology trade

We begin the discussion by examining the impacts of aggregate fossil fuel subsidies (FFS) on the trade in low-carbon energy technologies (LC) as seen in Table 3 model 1. In model 2, we separate between explicit subsidies (EFFS) and implicit subsidies (IFFS). Thereafter, we contrast

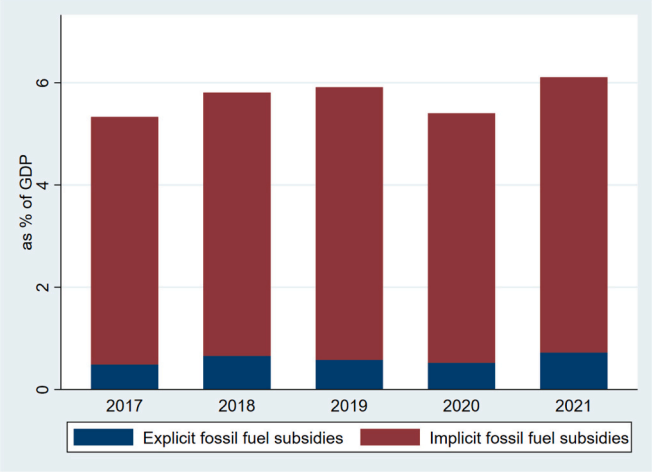

Fig. 1. Explicit and implicit fossil fuel subsidies as percentage of GDP.

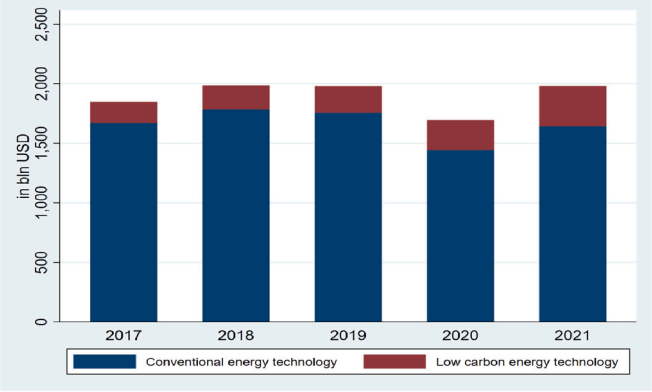

Fig. 2. Energy technology trade in billion USD.

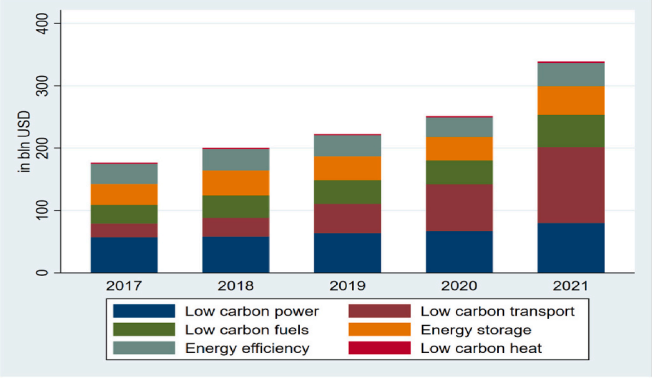

Fig. 3. International trade in low-carbon energy technologies.

the impacts of fossil fuel subsidies on LC with their impacts on trade in conventional energy technologies (models 3–4). It is also worth noting that the number of observations in Table 3 is lower than in Table 2, because the inclusion of importer-exporter fixed effects drops all country pairs that have no trade during the observation period.

The estimates in Table 3 show that importers' FFS significantly hamper the import demand for LC technologies. Similarly, exporters' FFS reduce the exports of clean energy technologies, although the magnitude and statistical significance of the coefficient is a bit lower. The coefficients imply that one percentage point reduction in fossil fuel subsidies per GDP would increase LC imports by 5.8 % and increase exports by 3.6 %. In line with the prior literature on trade impacts of environmental regulation (Costantini and Mazzanti, 2012; Kang and Lee, 2021), the results indicate that the subsidies on fossil fuels do not only discourage the adoption of clean energy technologies in the importing countries but also inherently acts as discouraging factor for domestic producers of these technologies. The implications of the findings are that if global subsidies on fossil fuel rise, the consumption of these particular fuel types becomes cheaper for the end users, thereby stimulating not just the demand for fossil fuels but also fossil fuel-related technological investments. Based on these findings, FFS act as significant impediments to the diffusion of low-carbon energy technologies. Considering that the adoption and adequate diffusion of these LC are apt for attaining global carbon neutrality, the current findings thus resonate with extant studies (Li et al., 2017; Monasterolo and Raberto, 2019; Rentschler and Bazilian, 2017) on the need to either phase out or reform fossil fuel subsidies.

Next, we comparatively look at the impacts of the aggregate FFS on trade in conventional energy technologies for both the exporting and importing countries as reported in Table 3. In both cases, one percentage point increase in the subsidies per GDP leads to approximately 2.5 % increase in conventional energy technology trade. The results further affirm that fossil fuel subsidies significantly trigger trade in conventional energy technologies both in the import demand side as well as in the export side. However, changes in the GDP of importers plays a larger role in the trade in conventional energy technology than in the LC technologies. While the exporters' economic size has a similar and significant effect on the exports of both LC and conventional energy technologies, importers' GDP does not have a significant effect on the demand of LC technologies but only on the demand of conventional energy technologies. However, we control for importer-exporter pair fixed effects and, thus, the coefficient of GDP reflects annual variation in GDP, i.e., business fluctuations. In line with the prior literature, it appears reasonable that business fluctuations influence the demand for conventional energy more strongly than the demand for LC technologies (Chen et al., 2019; Fedoseeva and Zeidan, 2018; Onifade et al., 2024; Zhao and Wu, 2007).

Comparing explicit subsidies (EFFS) and implicit subsidies (IFFS), we find that all categories of subsidies tend to undermine trade in LC technologies with coefficients in line with model 1. Yet, the coefficients

Table 3
Impacts of fossil fuel subsidies on energy technology trade.

	LC	LC	Conventional	Conventional
ln(GDPi)	0.681*	0.673*	0.627***	0.625***
	(0.359)	(0.358)	(0.128)	(0.128)
ln(GDPj)	0.256	0.255	0.760***	0.773***
	(0.288)	(0.285)	(0.096)	(0.094)
FFS_totali	−0.036*		0.024***	
	(0.021)		(0.007)	
FFS_totalj	−0.058***		0.017***	
	(0.017)		(0.006)	
EFFS_totali		−0.041		0.028**
		(0.033)		(0.011)
IFFS_totali		−0.033		0.023
		(0.038)		(0.015)
EFFS_totalj		−0.077***		−0.005
		(0.024)		(0.010)
IFFS_totalj		−0.040		0.039***
		(0.035)		(0.011)
Year FE	x	x	x	x
Importer-Exporter pair FE	x	x	x	x
Observations	65,691	65,691	86,739	86,739
Pseudo R2	0.976	0.976	0.995	0.995

Notes. PPML estimation. i refers to exporter. j refers to importer. Standard errors in parentheses. Standard errors are clustered at the importer-exporter pair level. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.

are non-significant except for the case of importing countries where explicit subsidies significantly reduce the demand for LC. This is an expected result considering that the demand for low-carbon technologies will plunge when there is a surge in demand for alternative good as induced by explicit subsidy. Meanwhile, an examination of the conventional technologies shows that the explicit subsidies significantly boost the exports of conventional energy technologies. Expectedly, the import demand for conventional energy technology is boosted by the implicit subsidies, but somewhat surprisingly is not affected by the explicit subsidies. These explicit subsidies are mostly concentrated in major fossil fuel producer countries (Black et al., 2023), and we suspect that our result may be related to domestic production and domestic trade that is unfortunately not included in our data.

4.2. Disaggregated fossil fuel subsidies and energy technology trade

The discussion continues with the analysis of the impacts of disaggregated fossil fuel subsidies on energy technology trade as seen in Table 4. Explicit fossil fuel subsidies are disaggregated into subsidies targeting coal, electricity, gas, and petroleum products. Moreover, the implicit subsidies are disaggregated into subsidies on air pollution, global warming, and other implicit fossil fuel subsidies.

Beyond the economic and aggregate effects of explicit and implicit subsidies, for which results are similar to the previous results in Table 3, we observe that increasing explicit coal and electricity subsidies significantly reduce the country's exports in LC. On the other hand, as explicit subsidies on gas and electricity increases, there is a significant negative impact on the import demand for LC. These are indications that coal, electricity and gas subsidies are significantly detrimental to the diffusion and adoption of low-carbon technologies. Similar to previous results, this evidence is further reinforced when we look at the trade in conventional energy technologies as higher subsidies on gas significantly boost export of conventional energy technologies and the coefficients on other explicit subsidies are also positive regarding exports. However, the importers' explicit subsidies on coal and petroleum have negative and significant coefficients indicating reduced imports of conventional energy technologies. As already argued above, this finding may reflect the situation in major fossil fuel producing countries, where these subsidies are the largest and they target domestic production that displaces imports. When we dropped the countries with the highest explicit subsidies on coal and petroleum, the coefficients became insignificant. With regard to our other estimation results, we did not find similar sensitivity to extreme observations.

Looking at the trade impacts of implicit fossil fuel subsidies in Table 4, we observe that implicit subsidies related to air pollution discourage both imports and exports of LC technologies, while implicit subsidies due to ignoring global warming impacts of fossil fuels have negative but insignificant impact on LC trade. However, in the case of conventional energy technologies the implicit subsidies on global warming significantly boost the trade in conventional energy technologies. This finding implies that a country that adopts or raises a carbon tax, i.e. lowers implicit subsidies related to global warming, would reduce both the imports and exports of conventional energy technologies. Moreover, subsidies related to air pollution reduce the trade in conventional energy technologies, which is a somewhat surprising finding. These varying results regarding subsidies related to pollution and global warming clearly support an argument that negative externalities related to pollution and global warming have distinct economic implications. Overall, the results suggest that including the costs of air pollution in the fuel prices leads to environmental and health benefits while also supporting domestic export competitiveness. Finally, other implicit fossil fuel subsidies appear to increase import demand for both LC and conventional technologies. It appears that these subsidies may not be necessarily strictly tied to either low-carbon energy technologies or technologies associated with conventional energy sources.

Table 4
Impacts of disaggregated fossil fuel subsidies on energy technology trade.

	LC	LC	Conventional	Conventional
ln(GDPi)	0.764**	0.714**	0.712***	0.629***
	(0.334)	(0.352)	(0.124)	(0.125)
ln(GDPj)	0.345	0.313	0.891***	0.780***
	(0.281)	(0.289)	(0.095)	(0.096)
EFFS_TOTALi	−0.041		0.017	
	(0.033)		(0.011)	
IFFS_TOTALi		−0.034		0.018
		(0.039)		(0.016)
EFFS_TOTALj	−0.085***		−0.013	
	(0.025)		(0.009)	
IFFS_TOTALj		−0.034		0.040***
		(0.035)		(0.011)
IFFS_POLLUTIONi	−0.117*		−0.080***	
	(0.067)		(0.026)	
IFFS_WARMINGi	−0.010		0.190***	
	(0.103)		(0.038)	
IFFS_OTHERi	0.117		−0.012	
	(0.112)		(0.058)	
IFFS_POLLUTIONj	−0.106**		−0.112***	
	(0.047)		(0.022)	
IFFS_WARMINGj	−0.172		0.099***	
	(0.107)		(0.025)	
IFFS_OTHERj	0.294***		0.241***	
	(0.071)		(0.028)	
EFFS_COALi		−1.577***		0.048
		(0.359)		(0.130)
EFFS_ELECi		−0.100**		0.002
		(0.043)		(0.011)
EFFS_GASi		0.050		0.065***
		(0.050)		(0.022)
EFFS_PETROi		0.090		0.017
		(0.106)		(0.057)
EFFS_COALj		−0.369		−0.436***
		(0.276)		(0.154)
EFFS_ELECj		−0.143***		0.020
		(0.037)		(0.020)
EFFS_GASj		−0.131***		−0.015
		(0.039)		(0.025)
EFFS_PETROj		0.202***		−0.059**
		(0.061)		(0.025)
Year FE	x	x	x	x
Importer-Exporter pair FE	x	x	x	x
Observations	65,691	65,691	86,739	86,739
Pseudo R2	0.977	0.977	0.995	0.995

Notes. PPML estimation. i refers to exporter. j refers to importer. Standard errors in parentheses. Standard errors are clustered at the importer-exporter pair level. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.

4.3. Fossil fuel subsidies and disaggregated low-carbon energy technologies

In Table 5, we investigate whether the results are sensitive to the type of low-carbon energy technology in question. We disaggregate the low-carbon energy technologies as follows: (1) power technologies including hydro power, wind power, solar PV and nuclear, (2) heat technologies (solar hot water), (3) low-carbon fuels including ethanol, bio-diesel and biomass, (4) low-carbon transport including hybrid vehicles, EVs and locomotives powered by electric accumulators, (5) energy efficiency technologies including energy efficient cement, insulation, lighting and energy efficiency in heavy industries and (6) energy storage technologies (e.g., electric accumulators). In Table 5, we report the results for each sub-category of low-carbon energy technologies.

Based on the results in Table 5, we note that domestic fossil fuel subsidies have a generally negative impact on imports of each of the LC technology sub-categories. The results regarding the impacts of exporting countries FFS policy is more mixed. From the results, fossil fuels subsidies appear to be clearly detrimental to the import demand for alternative fuels like ethanol, biodiesel and biomass. These fuels have

been identified as potential options in terms of the quest for carbon-neutral energy and energy security of supply (Abbasi and Abbasi, 2010; Govindhan et al., 2024). The exception in Table 5 is the export of low-carbon transport technologies, where FFS has a weakly positive significant impact. This finding could be related to the energy intensity of inputs used in the production of these products or the inclusion of hybrid vehicles in this category. As such, fuel subsidies may have continued to encourage the supply side of these technologies.

Moving on, while explicit fossil fuel subsidies are found exert insignificant impact on the exports of all examined technology categories, implicit fossil fuel subsidies on the other hand are found to significantly reduce the exports of all low-carbon technologies except technologies related to energy efficiency and storage. This further reaffirms that subsidies to fossil fuels are among the factors militating against sustainable innovations in power, heat, fuel and transport technologies. As for the import demand side of the trade impacts of fossil fuel subsidies, the results show that explicit subsidies appear to boost the imports of storage technologies while the implicit subsidies significantly reduce the demand of heat technologies and have negative coefficient in most of the technology categories. Overall, the results are preponderantly suggestive of the detrimental impacts of fossil fuel subsidies on the international trade and diffusion of low-carbon energy technologies.

4.4. Robustness tests

This section presents various robustness tests. In order to save space, we do not report the result tables but summarize the findings. All the results are available upon request.

In Tables 3–5, we have investigated the role of fossil fuel subsidies on energy technology trade using the whole sample of countries. Nevertheless, it could be that the structure and motives for energy technology trade is different in different countries. Thus, as robustness test, we explored this distinction. We classified countries as energy net importers and exporters based on their trade balance in the HS class 27 that includes conventional energy such as trade in coal, oil, gas and electricity products. We repeated the estimations in Tables 3 and 4 while allowing the effects of subsidies to differ for net importers and net exporters of energy. We found that the results in Table 3 regarding the role of explicit subsidies on LC technology trade mainly reflect the situation in energy net importer countries, which account for the majority of sample countries. In contrast, the sign of coefficients regarding aggregate subsidies and implicit subsidies were the same in both groups, although the results were not always statistically significant. With respect to trade in conventional energy technologies, the results for both net importers and net exporters of energy were in line with the aggregate results in Table 3. We also explored whether the results differ between EU and non-EU countries. While the impacts of fossil fuel subsidies on import demand were stronger among the EU countries, we found significant results in line with Table 3 in all countries.

Our baseline approach investigates how contemporaneous changes in fossil fuel subsidies affect trade in low carbon and conventional energy technologies. However, it is possible that such policy changes impact trade with some time lag. We investigated this issue by using both the current fossil fuel subsidies as well as the one-year-lagged fossil fuel subsidies as independent variables. These regressions showed that especially in the case of LC technology trade both the current and lagged subsidy have significant effects. Thus, a part of the effect of a change in fossil fuel subsidies may occur after a time lag. This indicates that the results in Table 3 may underestimate the full impact of fossil fuel subsidies and dynamic impacts may be even larger.

A related issue, which also concerns the potential causal interpretation of our results, is that countries endogenously decide on their fossil fuel subsidy policies. Controlling for importer-exporter pair fixed effects and year dummies is one attempt to control for this. However, it could be that different countries are on different time trends when it comes to LC trade and fossil fuel policies perhaps due to wider policy mixes or other reasons and the results would simply reflect these underlying trends. While we cannot include country specific year controls in our model, we can allow for country-specific linear time trends. When we include them and analyze LC trade in line with Tables 3 and 4, our results remain robust. Even though there may be other threats to the causal interpretation of our results, at least country specific linear time trends do not drive our results.

In Table 5, we examined the robustness of our results with respect to different categories of low-carbon energy technologies. As a further robustness test, we also used a broader definition of low-carbon technologies following Howell et al. (2023). This list of technologies is not restricted to energy related low-carbon technologies as in our baseline estimations. The empirical results with the alternative list were quantitatively similar, but statistically weaker. This indicates that the fossil fuel subsidies mainly affect trade in energy related technologies and less so for non-energy related clean technologies as could be expected.

We have also estimated the models in Table 3 using common control variables related to distance between countries, shared border, shared language and free trade agreement between countries. In these estimations, we did not include importer-exporter pair fixed effects but only importer and exporter dummies. The results were closely similar to baseline results in Table 3. Finally, we also re-estimated Table 3 while

Table 5
Impacts of fossil fuel subsidies on disaggregated low-carbon energy technologies.

	POWER	POWER	HEAT	HEAT	FUEL	FUEL	TRANSPORT	TRANPORT	EFF	EFF	STORAGE	STORAGE
FFS_TOTALi	−0.026		−0.012		0.031		0.100*		−0.020		0.008	
	(0.040)		(0.025)		(0.040)		(0.056)		(0.013)		(0.017)	
FFS_TOTALj	−0.037		−0.055***		−0.067*		−0.061		−0.000		−0.002	
	(0.040)		(0.019)		(0.035)		(0.047)		(0.011)		(0.011)	
EFFS_TOTALi		−0.082		−0.021		0.024		0.046		−0.010		−0.048
		(0.069)		(0.046)		(0.041)		(0.083)		(0.028)		(0.030)
IFFS_TOTALi		−0.088*		−0.052*		−0.120**		−0.104*		0.013		0.011
		(0.050)		(0.030)		(0.051)		(0.059)		(0.016)		(0.018)
EFFS_TOTALj		0.013		−0.007		0.036		0.165		−0.029		0.052**
		(0.083)		(0.035)		(0.050)		(0.131)		(0.031)		(0.023)
IFFS_TOTALj		0.010		−0.057*		−0.018		−0.016		−0.014		−0.013
		(0.082)		(0.034)		(0.052)		(0.097)		(0.018)		(0.022)
Year FE	x	x	x	x	x	x	x	x	x	x	x	x
Imp.-Exp. pair FE	x	x	x	x	x	x	x	x	x	x	x	x
Observations	42,325	42,325	22,127	22,127	32,617	32,617	22,122	22,122	52,169	52,169	48,556	48,556
Pseudo R2	0.961	0.961	0.980	0.980	0.969	0.969	0.952	0.952	0.981	0.981	0.985	0.986

Notes. PPML estimation. i refers to exporter. j refers to importer. Standard errors in parentheses. Standard errors are clustered at the importer-exporter pair level.* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$. Power = hydro, wind, solar PV and nuclear, Heat = solar hot water, Fuels = ethanol, biodiesel and biomass, Transport = hybrid vehicles, EVs and locomotives powered by electric accumulators, Energy efficiency = energy efficient cement, insulation, lighting and energy efficiency in heavy industries, Energy storage = Electric accumulators.

including the environmental taxes per GDP as a control variable as done in some previous studies.[3] As discussed in Section 2, there may be overlap between environmental taxes and fossil fuel subsidies. Unfortunately, the environmental tax data is available for fewer countries and our sample size drops significantly. Nevertheless, the additional estimations showed that explicit fossil fuel subsidies have a strong effect on LC trade, even stronger than in Table 3. The results regarding implicit fossil fuel subsidies were mostly statistically insignificant, which appears to be mostly due to a smaller sample size.

5. Conclusions and policy recommendations

By using a dataset for 167 countries in an unbalanced panel that covers period 2017 to 2021, we investigated the link between international trade in energy technologies and fossil fuel subsidies. We compared the disaggregated impacts of fossil fuel subsidies, i.e., impacts of explicit and implicit subsidies, in term of trade in low-carbon and conventional energy technologies and also included a disaggregate analysis of sub-categories of low-carbon energy technologies.

The result revealed that imports and exports of low-carbon energy technologies are significantly hampered by the countries' aggregate fossil fuel subsidies. This indicates that subsidizing fossil fuels discourages the diffusion of clean energy technologies as well as the domestic competitiveness in the production of these technology products in these countries. This evidence aligns with prior literature that has argued for the importance of environmental policies as determinant of green trade (Costantini and Mazzanti, 2012; Groba and Cao, 2015; Kang and Lee, 2021).

Specifically, we found that explicit fossil fuel subsidies significantly reduce the demand for low-carbon energy technologies in the importing countries, while also significantly boosting the exports of conventional energy technologies. The disaggregated results showed that an increase in coal and electricity subsidies significantly reduces the exports of low-carbon energy technologies. Similarly, an increase in subsidies on gas and electricity also yields a significant decline in the import demand for low-carbon energy technologies. Implicit fossil fuel subsidies reflect the fact that negative externalities of pollution, global warming, and others are not fully included in the fuel prices. Regarding these subsidies, we found that subsidies related to air pollution tend to discourage demand for all types of energy technologies. Moreover, implicit subsidies related to global warming were found to significantly boost exports and imports of conventional energy technologies, while not having a significant impact on low-carbon energy technology trade.

The results presented here suggest relevant policy advice. As argued in the prior literature, fossil fuel subsidies support the overconsumption of fossil fuels, accelerate climate change, worsen environmental problems and constitute a fiscal burden (Antimiani et al., 2023; Arzaghi and Squalli, 2023; Coady et al., 2017). Our results provide further evidence that they dissuade the diffusion of low-carbon energy technologies and thereby undermine climate change mitigation efforts. Furthermore, by lowering the global demand for low-carbon energy technologies, the fossil fuel subsidies also lower the incentives to invest in innovation and technological development in this field. Our findings provide yet another argument for the necessity of subsidy phase-out or major policy reform. Given that fossil fuel subsidy administration is far from over in many countries and difficult to reform in fossil fuel reliant countries, a range of structural approaches is essential and may include gradual subsidy removal plan, palliative measures to cushion the associated burden of the planned removal and scale up of clean energy financing and investments.

Given our disaggregated evidence, there appears to be some subsidies, which may be easier to cut than others. Especially, including the negative externalities of air pollution in the fuel prices was found to be beneficial both to clean technology diffusion as well as export competitiveness in all energy technologies. Similarly, explicit subsidies on coal and electricity were found to be detrimental for clean technology diffusion, while they did not contribute to domestic export competitiveness even in the case of conventional energy technologies. These could provide some examples of low hanging fruits for subsidy reform. Of course, while we have focused on international trade aspects, several other factors should also be considered when deciding how to reform or phase-out subsidies. Hence, more studies on other factors like welfare implications of total subsidy removal and how to reinvest fiscal savings to transfers to affected parties could provide complementary insights on policy implementation.

On the methodological side, one of the limitations of the present study is that we do not have access to domestic trade data in the examined technologies (Yotov, 2022). Future development of such datasets would allow a more reliable estimation and identification of country-specific effects of fossil fuel and other policies. Finally, implementing a more extensive and energy specific analysis, e.g., on solar technologies, wind technologies, hydro technologies, biofuel technologies, etc., could provide more specific policy insight to address the questions specific to each low-carbon technology.

CRediT authorship contribution statement

Jaana Rahko: Writing – original draft, Validation, Methodology, Formal analysis, Data curation, Conceptualization. **Stephen Taiwo Onifade:** Writing – original draft, Validation, Conceptualization, Writing – review & editing. **Andrew Adewale Alola:** Writing – original draft, Validation, Conceptualization.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.eneco.2025.108547.

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[3] Data is obtained from OECD database.

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