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## RESEARCH ARTICLE OPEN ACCESS

# Impact of Gasoline and Diesel Subsidy Reforms on Global Biofuel Mandates

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## ABSTRACT

Fossil fuel subsidy reform(s) support the deployment of low-carbon technologies, yet fossil fuel subsidies remain stubbornly high, while money allocated by governments to renewable energy continues to grow. In the transport sector, this tension is observed between biofuels that still rely on national policies and gasoline/diesel subsidies. Using a global Computable General Equilibrium (CGE) model, we study how phasing out gasoline and diesel subsidies would impact global biofuel mandates. We find that where they are implemented, Fossil Fuel Subsidy Reforms increase biofuel competitiveness and lower the cost of achieving the mandates. The fiscal benefit is therefore twofold with savings on fossil and bio-based energy subsidies. In a multilateral reform scenario, we simulate the rise in fiscal revenue from phasing out the fossil fuel subsidies to be 25% higher when the avoided spending on biofuels' support is accounted for. In the rest of the world, however, the biofuel targets become costlier to achieve as the price of fossil fuels drops. Considering that global biofuel 2030 targets are achieved, governments' support for biofuel falls by \$6 billion in regions phasing gasoline and diesel subsidies but increases by \$600 million in the rest of the world.

## 1 | Introduction

Fossil fuel subsidies broke an all-time high in 2022 (International Energy Agency 2023b), while money allocated by governments to renewable energy continued to grow (International Energy Agency 2023a). Yet, Fossil Fuel Subsidy Reforms (FFSR) are known to support the deployment of low-carbon technologies (Bridle and Kitson 2014; International Energy Agency 2014). This tension between support/subsidy programs is evident in the transport sector. It is the largest single-sector recipient of fossil fuel subsidies (Black et al. 2023), while biofuels can be one of the most successful ways of decarbonizing the transport sector (Ebadian et al. 2020) still relying on national support policies to penetrate the market (OECD/FAO 2021).

Several countries refer to a fossil fuel subsidy phase-out in their Nationally Determined Contributions, and 50 undertook

various degrees of reforms between 2015 and 2018 (Global Subsidies Initiative 2019). The results of past reforms were mixed (UNDP 2021). In Indonesia, for example, subsidies for fossil fuels used in the transport sector dropped from \$15 billion to almost zero following a successful fuel-pricing reform in 2015–2017 (OECD 2019b). These, however, bounced back with gasoline and diesel subsidies in 2022 estimated there at \$6.7 billion and \$12.1 billion, respectively (International Monetary Fund 2023). Simultaneously, the Indonesian government continues to promote biodiesel for a clean energy transition (Dermawan et al. 2022), while low oil prices impede biofuels' competitiveness (Winchester and Ledvina 2017).

A large body of literature exists on the impact of FFSRs and biofuel mandates on the environment and welfare. Food security has been a concern for biofuels (Mitchell 2008; Zhang et al. 2013; Zilberman et al. 2013), while their greenhouse

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gas (GHG) emission balance is ambiguous and depends on, among other things, land-use changes (Searchinger et al. 2008; Timilsina and Mevel 2013) and feedstock composition (Laborde and Valin 2012; Britz and Delzeit 2013), where they are produced (Mareike 2011), and by-product considerations (Taheripour et al. 2010). FFSRs on the other hand were found to lower GHG emissions (Burniaux and Chateau 2014; Chepeliev and Mensbrughe 2020; Black et al. 2023) but to be regressive if not complemented by revenue recycling mechanisms (Siddig et al. 2014; Wesseh, Lin, and Atsagli 2016).

To the best of our knowledge, fossil fuel subsidy reforms' impact on biofuel markets and mandates remains undetermined. This study does not aim to provide an evaluation of either policy but rather investigate the interaction between gasoline and diesel FFSR and existing global biofuel mandates. The focus is not on the combined environmental or distributional impact of the policies. Instead, we provide a detailed evaluation of the impact of gasoline and diesel FFSRs on fossil and biofuel sectors in a world where existing global biofuel mandates are achieved. The goal is to explore how the consumption and competitiveness of transport fuel changes and how this, in turn, impacts the governments' fiscal revenue and the overall economy to provide an evaluation of FFSRs that account for interactions with biofuel mandates.

Considering that fossil and biofuel commodities are part of a complex global value chain and our focus on how these interact, we employ the DART-BIO model, a global recursive dynamic Computable General Equilibrium (CGE) model (Calzadilla, Delzeit, and Klepper 2017; Delzeit, Winkler, and Söder 2018). CGE models that account for the linkage and feedback effects between markets are particularly well suited for the study of biofuel policies (Kretschmer and Peterson 2010). Similarly, they capture the significant general equilibrium effect of FFSR (Saunders and Schneider 2000) and linkages between all markets including those that require energy as an input (Ellis 2010).

We integrate to the DART-BIO model pre- and post-tax estimates from the IMF for gasoline and diesel subsidies. Pre-tax subsidies measure support mechanisms that directly impact end-user prices. These are relatively less complex than other forms of government support and are generally well-accepted to fit the definition of a subsidy by different stakeholders (UNEP, OECD, IISD 2019). This is helpful in view of the fact that governments like the UK treasury are reported to have denied providing subsidies at all "on the grounds that any support it offers doesn't artificially lower prices paid by consumers" (Mehta 2022). Post-tax subsidies on the other hand account for the cost of externalities indirectly paid by society and therefore fall outside the definition of subsidies from the Agreement on Subsidies and Countervailing Measures (ASCM). Still, not paying the cost of damages to the environment from production can legitimately be understood as a subsidy (Stiglitz 2006). Post-tax subsidies also provide an opportunity to investigate efficient pricing policies which is key to informing the discussion on fuel pricing reforms (Coady et al. 2019).

We find that the subsidy reforms reinforce biofuel mandates. Where they are implemented, FFSRs increase biofuel competitiveness and lower the cost of achieving the mandates. The fiscal

benefit of the reforms is therefore twofold with savings on both fossil fuel and biofuel subsidies. Accounting for the decrease in biofuel support from a multilateral pre-tax gasoline and diesel subsidies reform, we simulate the overall rise in fiscal revenue to be 25% higher. In the rest of the world, however, the biofuel targets become costlier to achieve as the international price of fossil fuels drops. Considering that biofuel 2030 targets are achieved in all regions, we find that biofuel subsidies fall by \$6 billion in regions phasing out their subsidies but that this is partially offset by a \$600 million increase in the rest of the world. We conclude that aligning policy objectives is a low-hanging fruit given the cumulative benefits it generates at a relatively low economic cost.

The rest of the article is structured as follows: Section 2 introduces the DART-BIO model, the data used, and the definition of scenarios; Section 3 presents the results of the simulations; Section 4 discusses the results; Section 5 presents some of the limitations of the study. Finally, Section 6 concludes and explores policy implications.

## 2 | Materials and Methods

Fossil Fuel Subsidy Reforms (FFSRs) and biofuel policies provoke simultaneous adjustment in the fossil fuel and biofuel market. At the same time, biofuels are embedded in a highly integrated agricultural market that relies on energy inputs to sustain production. Capturing these interactions is essential to understanding the impact of each policy on one another. Partial equilibrium models that struggle to represent the link between sectors are not well suited to address questions relating to international competitiveness effects (Ellis 2010). Instead, CGE models have been recognized to be particularly well-equipped to capture these complex interactions because their sectors represent the full economy (Kretschmer and Peterson 2010).

### 2.1 | Model

We use the DART-BIO model, which is a version of the Dynamic Applied Regional Trade (DART) model designed to represent in detail the agricultural sector, land use, and conventional biofuels. The DART model is a global multisectoral, multiregional recursive-dynamic CGE model that was developed in the 1990s at the Kiel Institute for the World Economy (Springer 1998). It has since then been widely applied to analyze international climate policies (e.g., Klepper and Peterson 2006a), environmental policies (e.g., Weitzel et al. 2012), energy policies (e.g., Klepper and Peterson 2006b), and biofuel policies (e.g., Kretschmer, Narita, and Peterson 2009; Calzadilla, Delzeit, and Klepper 2017; Delzeit, Winkler, and Söder 2018; Schuenemann and Delzeit 2022).

The DART-BIO is the bio-economy and land-use version of the DART model. Fundamentally, both share the same structure. The bio-economy extension however includes land heterogeneity using the agro-ecological zones classification as well as the complex production process chains of biofuels. The model is largely calibrated on the GTAP9 database (Aguiar, Narayanan, and McDougall 2016). Its current aggregation includes 23

regions, 51 sectors, and 21 factors of production. Noticeably, as per Table 1, the OPEC countries and Qatar have been aggregated based on their similarities with respect to energy subsidies. For the same reason, countries that have signed the Declaration of Cooperation (DoC) have been aggregated into the PPEC region. Russia and Malaysia are not included in the PPEC region although they have signed the declaration. Instead, Russia is modeled as a single region while Malaysia is aggregated with Indonesia due to its important role in worldwide biofuel production and consumption.

As detailed by Delzeit et al. (2021), to enable the modeling of the relationship between bio-based and fossil fuel-based fuel for transport, several key sectors were disaggregated from the original GTAP database. Concerning biofuels, biodiesel and bioethanol from different sources (i.e., oilseeds and grains) were included as well as their corresponding processing sectors and by-products. The adapted database also includes dedicated sectors for motor gasoline and motor diesel. Sectors were split using data from the meó Consulting Team, a company providing consulting services with a special focus on renewables' sustainability and climate change (F.O. Licht 2015), and FAOSTAT on production, price, and bilateral trade data. Production volumes were converted in dollars before the trade shares were used to distribute production assuming trade costs, tariffs, and export

taxes/subsidies remained unchanged from the original GTAP sector (Schuenemann and Delzeit 2019).

The DART-BIO model is a classical Walrasian general equilibrium model where the economy in each region is modeled as a competitive economy with flexible price and market clearing conditions. A single agent simultaneously represents utility-maximizing consumers, profit-maximizing producers, and the regional government. The economies evolve through a sequence of single-period static equilibrium connected through capital accumulation and changes in labor supply for periods from 2011 until 2030. Changes in the labor force, the rate of labor productivity growth, and human capital accumulation determine labor supply and productivity changes. Labor productivity and human capital growth are assumed to be constant but regionally differentiated.

Production exhibits a constant return to scale and is modeled using multilevel nested constant elasticity of substitution (CES) production functions. Crucially, in the case of motor gasoline and diesel, crude oil enters feed oil in production with no substitution possibilities with labor and capital. Biodiesel on the other hand can be produced using various oil seeds that can be substituted for one another, while bioethanol is a composite of various grain-specific bioethanol products, each of which with its own

**TABLE 1** | List of regions in DART-BIO.

Central and South America			Europe	
BRA	Brazil	FSU	Rest of the former Soviet Union	
PAC	Paraguay, Argentina, Uruguay, Chile	CEU	Central European Union with Belgium, France, Luxembourg, Netherlands	
LAM	Rest of Latin America	DEU	Germany	
Middle East and Northern Africa		MED	Mediterranean with Cyprus, Greece, Italy, Malta, Portugal, Spain	
MEA	Rest of the Middle East and Africa	MEE	Eastern EU with Austria, Czech Republic, Estonia, Hungary, Latvia, Lithuania, Poland, Slovakia, Slovenia, Romania, Bulgaria, Croatia	
Asia		NEW	North-Western EU with Denmark, Finland, Ireland, Sweden, United Kingdom	
CHN	China, Hong Kong	NOR	Norway	
IND	India	RNE	Rest of Northern Europe. Switzerland, Iceland, Liechtenstein	
EAS	Eastern Asia. Japan, South Korea, Taiwan, Singapore	North America		
MAI	Malaysia, Indonesia	CAN	Canada	
ROA	Rest of Asia	USA	United States of America	
RUS	Russia	OPEC and partner		
Oceania		OPEC	Algeria, Angola, Congo, Ecuador, Iran, Iraq, Kuwait, Libya, Nigeria, Gabon, Saudi Arabia, United Arab Emirates, Venezuela, Qatar	
ANZ	Australia, New Zealand, Rest of Oceania	PPEC	Azerbaijan, Bahrain, Brunei Darussalam, Kazakhstan, Mexico, Oman, South Sudan	

nesting and production function. Final consumption in turn is modeled with nonunitary income elasticities using the linear expenditure system (LES) approach and is composed of both a fixed subsistence level and a supernumerary consumption. Only the latter reacts to changes in price/income and therefore allows substitution between biodiesel and diesel or bioethanol and gasoline, as well as, to a lesser extent, between each other. For a full technical description of the model, see Delzeit et al. (2021).

## 2.2 | Subsidies and Calibration

The current study complements the model with the 2022 IMF's publicly available data on fossil fuel subsidies published in 2015 and 2021. The estimates cover 150 and 192 countries in the respective databases and the 2003–2025 period. Specific gasoline and diesel estimates are included, allowing the integration of the subsidies into the model with no additional commodity disaggregation. The IMF derives pre-tax fossil fuel subsidies using the price-gap approach by comparing average end-user prices with free-market reference prices reflecting the full cost of supply (Coady et al. 2019). Support measures that do not influence end-user prices are not captured, but the method benefits from being relatively low data-intensive and measuring a well-accepted category of subsidies (UNEP, OECD, IISD 2019).

The database also contains post-tax subsidies, which are defined as the exemption from the corrective Pigouvian tax reflecting the cost of externalities (Coady et al. 2019). These include the cost of local air pollution mortality, broader costs associated with the use of fuels in road vehicles, and global warming (Parry, Black, and Vernon 2021). Post-tax subsidies stray away from the WTO 1994 definition of a subsidy ratified in the Agreement on Subsidies and Countervailing Measures (ASCM). Considering the duality of the topic and the link to climate mitigation, post-tax subsidies, however, offer an opportunity to investigate efficient pricing policies.

To match the model specification, the fossil fuels subsidy and consumption values provided by the IMF are summed between countries to match the regions in Table 1. Diving the resulting subsidies and consumption values by each other allows us to derive the ad-valorem subsidy rate corresponding to the model regional aggregation. To integrate these ad-valorem rates into the model, a new (negative) sales tax variable is applied to the model's Armington aggregate of imports and domestic consumption. This means that all agents face the same rates, as well as industries consuming the same intermediates.

The model's base year values are recalculated following the integration of the subsidies to minimize the deviation from the benchmark values which implicitly reflects the distortions of the market. The model is then calibrated using labor productivity to match the regional GDP growth projections of the OECD (2019a). To simulate a robust baseline, we simultaneously calibrated the production of motor gasoline, diesel, and crude oil. Between 2011 and 2020, the global cumulative growth of gasoline and diesel production as well as the share of each region in global production is calibrated to replicate figures reported by the United Nations Statistics Division. After 2020, we

calibrated the regional production share of crude oil based on the Joint Research Center (JRC) data (Wojtowicz et al. 2021).

### 2.2.1 | Baseline Simulation (“Ref”)

In the baseline, fossil fuel subsidies are kept constant after 2021. Biofuel mandates' targets for biodiesel and bioethanol are gradually and linearly reached in all regions by 2030. Biofuel targets are expressed as percent of consumption and based on the projections used in the FAO/OECD 2022 agricultural outlook (OECD/FAO 2021). The EU mandate sets maximum consumption shares instead of a minimum blending rate or consumption target. Considering that the EU 2030 target of 14% share of renewables in total transport fuel consumption cannot be met without a sufficiently large amount of biofuels, we assume that member states meet the renewable energy in transport target with the Directive (2018) maximum allowable share of biofuels. As per the EU Renewable Energy Directive RED, palm oil-based biodiesel is phased out in the EU due to its “high-iluc risk” classification.

### 2.2.2 | Pre-Tax Fossil Fuel Subsidy Reform (“PreT\_FFSR”)

In the first policy scenario (“PreT\_FFSR”), a reform starting in 2023 is introduced under which gasoline and diesel pre-tax subsidies are linearly phased out in the regions with biofuel mandates (regions in *italic* in Table 2). This reflects a situation where countries motivate a reform with the ambition to support their renewable transport fuel mandates/targets or more broadly a renewable energy transition. We disregard Ukraine, part of the FSU region, and RUS who despite having a biofuel mandate cannot be expected to implement a fossil fuel subsidy reform given the current geopolitical context of the war in Ukraine. As in the baseline, global biofuel mandates are included in the simulation to understand the interaction between the two policies. Regions not listed in the table did not have pre-tax subsidies in 2021 based on the IMF database.

**TABLE 2** | Motor diesel and gasoline pre-tax subsidies in 2021.

Regions	Motor gasoline	Motor diesel
OPEC	35.2%	85.7%
Former Soviet Union		0.3%
Russia		1.5%
<i>PPEC (Partners of OPEC)</i>	2.4%	9.3%
<i>Oceania</i>		0.03%
<i>Rest of the Middle East and Africa</i>	1.9%	8.4%
<i>Rest of Asia</i>	0.02%	0.2%
<i>Malaysia and Indonesia</i>	3.8%	23.9%
<i>Latin America</i>	0.6%	2.1%



### 2.2.3 | Post-Tax Subsidy Phase-Out in the EU (“PosT\_FFSR”)

Biofuels are not free from the externalities included in the IMF post-tax subsidies estimates. Only applying a policy internalizing the costs of these externalities to fossil fuels could therefore be considered inconsistent. The difference in local air pollution and global warming (largest sources of subsidies in the database) between fossil- and bio-based transport fuels is however subject to uncertainty. GHG emissions not being explicitly depicted in the model, instead of only applying the post-tax subsidies to fossil fuels we rely on the EU RED’s sustainability criteria to explore a “single region” phase-out scenario.

The EU RED’s sustainability criteria state that food and feed crop biofuels’ GHG intensity should be at least 50% lower than their fossil fuel alternative to count toward the mandate’s target (Directive 2018). We accordingly assume that half of the post-tax subsidy rates on gasoline and diesel apply to bioethanol and biodiesel produced using these feedstocks in the region and in the second policy scenario (“PosT\_FFSR”), a phase out of post-tax subsidies on all four fuels is implemented in the EU starting in 2023. This complements the first multilateral phase-out scenario with one where the countries implementing the reform face a common biofuel mandate target (EU level) but differentiated fossil fuel subsidies (country level). Double counting is avoided as motor gasoline and diesel do not enter the production of biofuels as intermediate.

## 3 | Results

### 3.1 | Governmental Spending on FFS

Pre-tax fossil fuel subsidies tend to be concentrated in net crude oil exporting countries, and in 2020 were made up of about 31% of gasoline and diesel subsidies. We simulate, in 2020, that global pre-tax gasoline and diesel subsidies amount to 120 billion dollars and reach \$135 billion in 2030. Solely considering regions with biofuel mandates, the overall value of gasoline and diesel pre-tax subsidies in the baseline scenario falls to \$24.7 billion in 2030. The relative size of the subsidies in value being consistent with the ad-valorem rates (see Table 2), Malaysia and Indonesia (MAI) turn out to be the regions with the largest pre-tax subsidies and a biofuel mandate, followed by the Middle East and Northern Africa and PPEC. Diesel with its higher ad-valorem rate is found to make up around 82% of total pre-tax gasoline and diesel subsidies between 2023 and 2030.

Post-tax subsidies on gasoline and diesel are larger and more widespread than pre-tax subsidies. In the EU where they are phased out in the second policy scenario (“PosT\_FFSR”), we simulate that they amount to \$92 billion in 2030. The regional and fuel variations, depicted in Table 3, are the result of both the relative size of the ad-valorem subsidies (see Data S1) and the value of consumption. As for pre-tax subsidies, diesel post-tax subsidies are found to be higher than those on gasoline, and the same can be said when comparing biodiesel to bioethanol. In the whole EU region in 2030, diesel makes up about 77% of total post-tax subsidies. This share is relatively constant across all EU regions except for Germany where the share reaches 87% and North-Western EU where it drops to 56%.

### 3.2 | Fossil Fuels for Transport

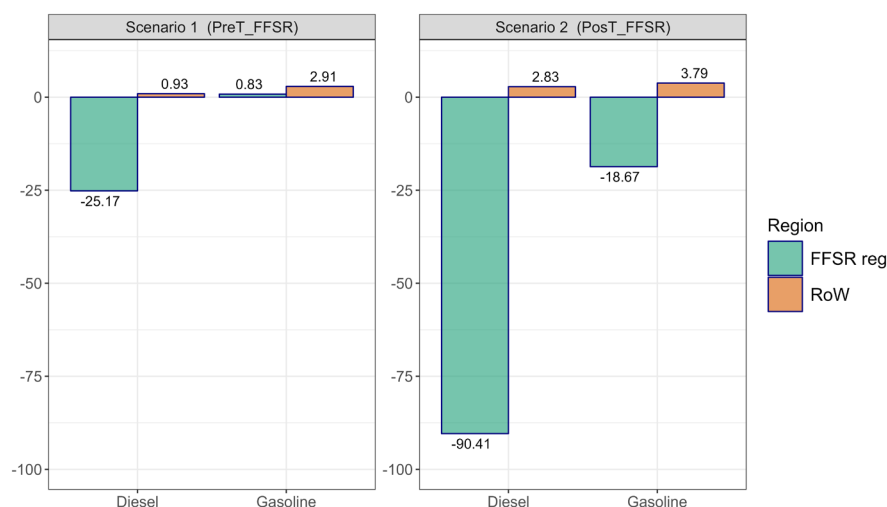
The simulation results show that, in regions that remove pre or post-tax fossil fuel subsidies, prices for gasoline and diesel rise relative to the reference scenario. This leads to a reduction in consumption largely proportional to the value of the subsidies that were phased out. In the first policy scenario (“PreT\_FFSR”), regions phasing out pre-tax subsidies experience a \$24 billion (5%) decline in the overall consumption of fossil fuels for transport by 2030 compared to the baseline (summing up values for gasoline and diesel, see Figure 1). In the second policy scenario (“PosT\_FFSR”), following the removal of post-tax subsidy, the EU consumption of fossil fuel for transport drops by \$109 billion (18%).

In the rest of the world, however, the total consumption of gasoline and diesel increases by \$3.8 billion and \$6.6 billion in scenarios 1 and 2, respectively. For diesel, this type of consumption leakage, caused by what is sometimes referred to as the “fossil-fuel-price” leakage channel (Böhringer, Rosendahl, and Schneider 2014), is best explained by considering bilateral trade. As displayed in Table 4, regions phasing out fossil fuel subsidies exports and imports of diesel to/from the rest of the world shrink following the pre-tax FFSR. This suggests that the growing diesel consumption outside of the reform area is not the result of a diversion of domestic consumption to the export market from the regions phasing out their subsidies. Rather it is triggered by these regions’ decreasing import demand. In other words, the rest of the world absorbs on its home market some of the exports it no longer makes to regions implementing the reform.

The same trade effects cannot be the only source of the growing gasoline consumption since, as per Table 4, the trade of this fuel increases between regions inside and outside the reform area.

**TABLE 3** | EU baseline post-tax subsidies in 2030, in \$ billion.

	Central EU	Germany	Eastern EU	Mediterranean	North-Western EU	Total
Bioethanol	0.2	0.1	0.1	0.2	0.2	0.7
Biodiesel	1.0	1.1	0.2	1.1	0.3	3.7
Gasoline	4.4	1.8	1.7	4.6	4.2	16.7
Diesel	19.1	20.2	4.9	21.2	5.9	71.3
Total	24.6	23.2	6.9	27.1	10.5	92.3



**FIGURE 1** | Gasoline and diesel 2030 consumption changes relative to the baseline, in \$ billion.

**TABLE 4** | Scenario 1 (“Pre\_FFSR”) 2030 changes in trade relative to the baseline, in \$ billion.

		Motor gasoline		Motor diesel	
		FFSR	RoW	FFSR	RoW
FFSR	Imports	0.1	0.3	(−2.9)	(−10.7)
	Exports		0.0		(−0.9)
Row	Imports	0.0	0.1	(−0.9)	3.2
	Exports	0.3		(−10.7)	

Rather than trade, we find that an expansion in gasoline production of \$2.5 billion in the rest of the world is largely responsible for the growing consumption there. This is especially evident in the US and China, the largest producers and consumers of gasoline who together make up about half of this change. As reflected in decreasing production costs of gasoline, this is the result of the decrease in demand for crude oil to produce diesel. The production of diesel, which is more heavily subsidized than gasoline, declines everywhere following the reform, either directly because of the domestic reform or due to the lower demand caused by reforms abroad. This puts downward pressure on the price of crude oil, the largest input in the production of both diesel and gasoline. In turn, this leads gasoline to become relatively more attractive, as its production costs drop, and consumption grows outside of the reform area.

The same mechanics apply to the consumption leakage of gasoline and diesel in scenario 2. Diesel consumption outside the EU increases mostly from trade between regions outside the EU while gasoline consumption grows due to an expansion in production. Again, we find that the US and China together make up half of the change in gasoline consumption outside of the reform area and that the share of gasoline in their overall transport fuel mix expands. Interestingly, gasoline exports from the rest of the world to regions phasing out their subsidies increase in scenario 1 while they decrease in scenario 2. This helps to explain the \$0.8 billion rise in gasoline consumption where the pre-tax

subsidies are phased out in scenario 1 (see Figure 1). Not only is gasoline benefiting from lower production costs, but gasoline is also becoming relatively cheaper than diesel as its subsidies are not as large. In the MEA, for example, following the pre-tax FFSR, gasoline's own prices rise by 1.8%, while relative to diesel, it drops by 7%. This together with the lower production costs at home and abroad leads to an increase in production, imports, and consumption where the pre-tax subsidies are removed. In scenario 2, the same effect is observed in Germany where diesel subsidies are relatively larger than gasoline. Gasoline production, imports, and consumption rise there, but this is offset at the overall EU level by a drop in the rest of the EU regions.

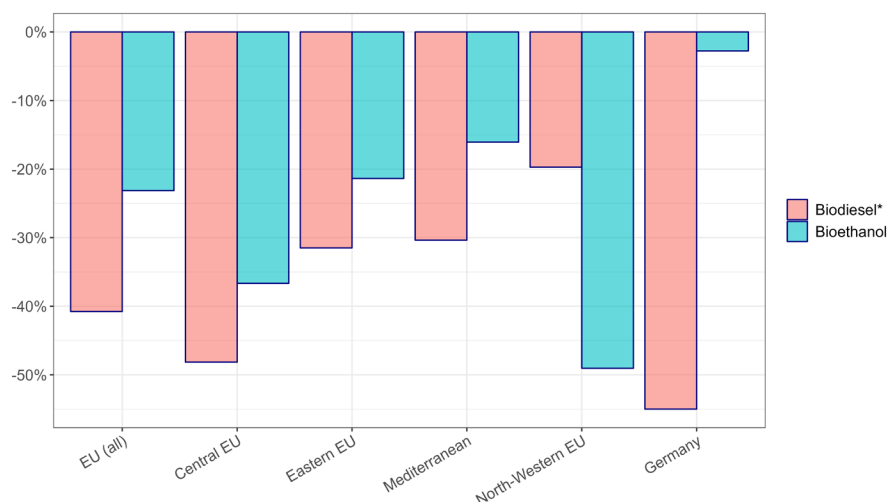
### 3.3 | Biofuels

Biofuels are directly impacted by the changes in the fossil transport fuel sector. Since biofuel mandates' targets are calibrated as a share of transport fuel consumption, an increase/decrease in the demand for gasoline or diesel implies an increase/decrease in the amount of biofuels needed for governments to reach their targets. In regions implementing the reform, this means that typically while the price of biofuels rises, their consumption drops together with the government support needed to achieve the mandate. Outside of these regions, biofuel prices contract, but increased fossil fuel consumption leads to more biofuel consumption to meet the mandates and government spending on biofuel subsidies to increase.

In the first policy scenario (“PreT\_FFSR”), we find that by 2030, the support from regions implementing a pre-tax FFSR to biofuels decrease by about \$6.2 billion (27%) compared to the baseline, while a \$0.6 billion increase is observed in the rest of the world (Table 5). In regions implementing the pre-tax FFSR, this translates into a 25-cent saving on biofuel support for each dollar not spent on gasoline and diesel subsidy. The Malaysia and Indonesia region with the largest subsidies on both fossil and biofuels experiences the most change in consumption and subsidy level. In the Rest of the Middle East and Africa the need for biofuel support following the reform completely disappears. While growing its share of biofuels in total transport fuel by a

**TABLE 5** | 2030 Change in biofuel subsidies relative to baseline, in \$ billion.

	Policy scenario 1 (PreT_FFSR)			Policy scenario 2 (PostT_FFSR)		
	FFSR reg	RoW	World	EU	Non-EU	World
Biodiesel	(−6.2)	0.2	(−6.1)	(−5.4)	0.2	(−5.2)
Bioethanol	0.01	0.4	0.4	(−1.3)	0.4	(−1.0)
Total	(−6.2)	0.6	(−5.6)	(−6.8)	0.6	(−6.2)

**FIGURE 2** | Scenario 2 (“PostT\_FFSR”) 2030 changes in EU biofuels subsidies relative to baseline, in \$. \*Biodiesel from all sources.

modest 0.2%, this represents a 90% expansion in biofuel consumption and is enough for the region to reach its target by 2030 without the need for government interventions.

In the second policy scenario (“PostT\_FFSR”), by 2030, the support from EU governments to biofuels decrease by about \$6.8 billion (35%) compared to the baseline, while a \$0.6 billion increase is observed outside the EU. In regions implementing the post-tax FFSR, this translates into a 7-cent saving on biofuel support for each dollar of gasoline and diesel subsidy phased out. We find that the percentage change in biofuel support depicted in Figure 2, is larger than the post-tax ad-valorem subsidy phased out on the corresponding fuel. This is the result of the combined drop in biofuel consumption needed to achieve the target and a competitive effect making biofuels relatively more attractive. In the central EU region, overall biofuel support declined by 45%, which is more than twice the size of the subsidies on diesel and gasoline phased out in the region. This is explained by the fact that while consumption shrinks at a rate comparable to the post-tax subsidy removed, the price of biofuels like biodiesel also fell by 1.2% relative to their fossil fuel alternative (i.e., diesel).

We find that this is also what explains the decrease in bioethanol subsidy in Germany. In scenario 2 (“PostT\_FFSR”), the German consumption of bioethanol increases by 5% because the subsidy on gasoline is many times lower than the one on diesel, and also lower than in any other EU region. Yet, the government's support for bioethanol falls by 4% following the phase-out, suggesting that the competitive effect between fossil and biofuels dominates over the induced consumption one. Indeed, not only

does the relative price of bioethanol drops by 0.3%, but the subsidy per unit of bioethanol consumed decreases as well. More broadly the same is true of all regions that phase out the subsidies on fossil fuels. Biofuels become relatively more competitive as their relative price decreases, leading to a lower subsidy per unit of biofuel to reach the mandates.

Outside of the reform area, the effect is reversed. While in absolute terms biofuel prices contract, they do so by less than fossil fuel prices. As the price gap between biofuels and fossil fuels increases, the government must expand support per unit of biofuel consumed to reach the mandates' targets. As a result, while the EU biofuel market benefits when the region implements a post-tax FFSR, it suffers from fossil fuel subsidy reforms in other regions of the world. Similarly, countries like China, that do not implement a subsidy reform in either scenario, experience an increase in biofuel subsidies and relative price in both simulations.

### 3.4 | Rest of the Economy

Phasing-out subsidies on gasoline and diesel triggers a reduction in the demand and price for crude oil, the main input for their production. Summing over all regions phasing out subsidies, we find that in 2030 crude oil consumption shrinks by \$15 billion (3%) in the first scenario and \$32 billion (8%) in the second scenario. Some of this is offset by a rise in consumption in the rest of the world of \$0.7 billion and \$7 billion in the two scenarios, respectively, leading to a global reduction in crude oil consumption of \$14 billion (0.4%) and \$25 billion (0.7%), respectively. In



turn, consumption of petroleum and coke products, which are produced using the now cheaper crude oil, increases in and out of the reform area. This forward linkage is simulated in 2030 at \$20 billion (0.8%) globally in the first scenario and at \$54 billion (2.3%) in the second. In comparison, driven by COVID-19 restrictions, the final consumption of oil and petroleum products for energy purposes in the EU fell by 10% in 2020 (Eurostat 2022).

Backward and forward linkages are also observed in the agricultural sector where the price and demand for biofuel feedstocks tend to decline together with the consumption of the biofuels. In scenario 1, this is especially evident for the palm oil sector whose consumption drops by \$1.6 billion in the Malaysia and Indonesia region. In scenario 2, the EU region notably decreases its demand for rapeseed oil and wheat/corn which in the region are the main feedstocks in the production of biodiesel and bioethanol. As consumption of oil seeds and grain for biofuel production shrinks, the supply of by-products contracts, and their prices increase by up to 8% in 2030 in the EU regions which puts upward pressure on the price of the livestock sectors (Table 6).

These linkages have a bearing on the reforms' overall impact on fiscal revenue. Not only does the decreasing consumption of gasoline and diesel erode fiscal revenue from the pre-existing taxes but changes in the consumption of other energy commodities as well as of commodities in other sectors impact government revenues. Considering all changes in pre-existing tax revenues

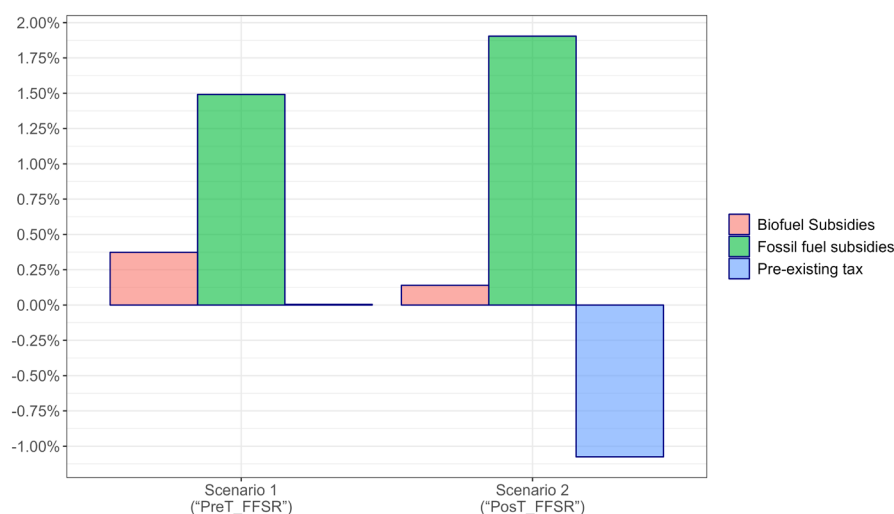
and avoided spending on subsidies, we simulate overall fiscal revenue to increase in both scenarios where the subsidies are phased out as well as in the rest of the world. Where the FFSRs are implemented we find that government revenue increases by 1.9% and 1.2% in scenarios 1 and 2, respectively. Figure 3 breaks down the source of the increase in fiscal revenue where the subsidies are phased out.

Most of the increase in fiscal revenue in regions implementing the reforms is found to be the result of avoided spending on fossil fuel subsidies. Overall, however, government revenue in these regions also increases by 0.37% and 0.14% from avoided spending on biofuel support in scenarios 1 and 2, respectively. This corresponds to the increase in government revenue being 25% and 17% higher when the impact of fossil fuel subsidy reform on biofuel supports is considered as part of the changing government budget. We note that while revenue from pre-existing tax shrinks in scenario 2, it does not do so in a visible manner in scenario 1. This is the result of pre-existing taxes on gasoline and diesel in regions with pre-tax fossil fuel subsidies being relatively small, especially compared to the ones in the EU.

Change to 2030 GDP remains below 1% in all scenarios and regions (Table 7). That being said, regions phasing out subsidies tend to experience a drop in their GDP. The effect is especially pronounced in scenario 2 for the EU which phases out relatively

**TABLE 6** | Scenario 2 ("PosT\_FFSR") 2030 rapeseed (oil) and by-products consumption change in the EU relative to the baseline.

		Central EU	Germany	Eastern EU	Mediterranean	North-Western EU
Rapeseed	Price	(−0.1%)	(−0.3%)	(−0.3%)	(−0.1%)	(−0.2%)
	Quantity	(−9.8%)	(−7.8%)	(−5.7%)	(−6.0%)	(−6.5%)
Rapeseed oil	Price	(−1.7%)	(−3.4%)	(−1.1%)	(−2.2%)	(−1.6%)
	Quantity	(−9.0%)	(−23.0%)	(−1.9%)	(−5.1%)	(−1.1%)
Rapeseed meal	Price	8.4%	6.7%	4.8%	4.9%	4.8%
	Quantity	(−13.0%)	(−10.9%)	(−8.1%)	(−7.8%)	(−7.3%)



**FIGURE 3** | Composition of the change in fiscal revenue where the subsidies are phased out, in 2030.

**TABLE 7** | Change in real GDP in 2030 following the phase-out, in \$ billion.

	Policy Sc1 (PreT_FFSR)			Policy Sc2 (PosT_FFSR)		
	FFSR reg	RoW	Total	EU	Non-EU	Total
Real GDP \$ billion	(−2)	17.8	15.8	(−72.2)	(−8.7)	(−80.9)
Real GDP %	(−0.01%)	0.02%	0.01%	(−0.4%)	(−0.01%)	(−0.1%)

larger subsidies than the regions in scenario 1. By the end of the reform, we simulate the EU real GDP contracts by 0.4% or \$72 billion. This should be contrasted with the cost of the externalities captured by the post-tax subsidies phased out in the simulation which amount to \$92 billion. With this in mind, the results suggest a possible welfare improvement effect, even in regions where real GDP fell because of the reform as this would be more than compensated by the avoided damages to the economy from externalities. Given the lack of explicit damage function in the model however, no definitive answer to the overall welfare effect can be reached for regions whose GDP dropped.

Scenario 1, clearly indicates a positive welfare effect of FFSR at the global scale as aggregated world real GDP increases. Comparing this to the decrease in global real GDP in scenario 2, we find that it is due to the composition of countries outside of the reform area. Net energy importers real GDP rise as they benefit from countries abroad implementing a reform as they can now access energy commodities at a cheaper price on the world market. Large energy exporters on the other hand tend to suffer from the shrinking demand on the international market regardless of whether they phase out their fossil fuel subsidies. The real GDP of Russia and OPEC, for example, decrease by about \$2 billion to \$10 billion in scenarios 1 and 2 which is roughly equivalent to the drop in their net exports.

## 4 | Discussion

Aligned with the results that fossil fuel subsidies weaken the cost-competitiveness of renewable energies (Bridle and Kitson 2014), we find that biofuel mandates become cheaper to achieve following the reforms. This complements the result from Ebadian et al. (2020) that relatively low petroleum and fossil fuel prices hindered the effectiveness of biofuel policies and emphasizes that part of that is due to subsidies in the fossil fuel sector and therefore not the direct effect of the market. Addressing distortions in the fossil fuel sector can thus also be part of the enabling factors to boost the bioenergy sector growth listed by studies like the one by Ebadian et al. (2020).

Looking closer at the biofuel sector, variations are observed in the impact of the reforms. As a result of the difference in the size of the subsidies, the share of gasoline in the transport fuel mix tends to increase. Subsidies to biodiesel thereby decline by more than gasoline where the subsidies are removed, while they increased by more in the rest of the world. The composition of individual biofuels like biodiesel not only changes as a result of targeted policies like the palm and/or soy-based biodiesel bans implemented in the EU (Heimann et al. 2023) but the overall composition of the biofuel sector is sensitive to policies on alternative fossil fuels. This nicely complements the findings of

studies on the impact of biodiesel policies on crop supply expansion like the one by Britz and Hertel (2011) and stresses that the development of the broader policy context can have an important impact on biofuels supply chains.

The sensitivity of biofuel supply chains also hints at the reorientation of trade patterns following the reforms toward and between regions without or with relatively low subsidies as well as between substitutes like gasoline and diesel. As highlighted by Table 8, several studies have taken a multiregional approach and were able to capture shifting trade patterns. Studies with a single country focus like Siddig et al. (2014) on the other hand stressed the potential substitution between energy commodities in consumption bundles. Neither, however, accounted for both changes on top of the substitution within the transport sector. Most strikingly we find that the gasoline sector benefits at least relative to the diesel sector both in and out of the reform area. As noted in the result section, outside the reform area this is especially evident for the US whose transport fuel mix already favors gasoline. This is also true for regions like Malaysia and Indonesia whose mix remains dominated by diesel following the reform but still shift part of its consumption mix in favor of gasoline. This stress both the impact of reforms on countries' future energy mix and the importance of the initial energy mix for the impact of reforms.

Isolated policy impact assessments will produce a biased estimate of the benefit–cost of Fossil Fuel Subsidy Reforms and biofuel mandates when these take place simultaneously. Even global multi-sectoral studies like Black et al. (2023), which include both gasoline and diesel have undervalued the fiscal benefit of a global FFSR by neglecting its impact on governments' spending on renewable energy subsidies. We also note that they fail to capture supply and demand interactions as well as feedback effects between sectors and regions. We simulate that the fiscal revenue increase in the FFSR area by 25% and 17% in scenarios 1 and 2, respectively when the saving on biofuels subsidies is accounted for. This supports the finding from Antimiani, Costantini, and Paglialunga (2023) that reusing the revenue from an FFSR to finance a clean energy transition is a win-win solution for decarbonization. Antimiani, Costantini, and Paglialunga (2023) and Fouré et al. (2023) both capture part of this interaction effect by combining carbon pricing and fossil fuel subsidy reforms with other policies. They however do not explicitly estimate the fiscal saving feedback between policies. Instead, as per Table 8, they focus on the trade-offs between various policies and the overall cost of achieving net zero by the mid-century. Like Black et al. (2023) and Fouré et al. (2023), we note that as fossil fuel consumption declines following the reform the fiscal revenue from pre-existing fuel taxes may erode. Still, overall fiscal revenue rises in both scenarios inside and outside the reform area.

**TABLE 8** | Comparison of selected studies on fossil fuel subsidy reforms.

Author(s)	Scenario	Modeling setup
Antimiani, Costantini, and Paglialunga 2023	Combinations of a carbon pricing mechanism and the phase-out of fossil fuels subsidies between 2020 and 2025	Time horizon: 2050 Subsidy data source: GTAP10, based on IMF estimates Reforms regions: EU Commodities covered: coal, gas, crude oil, electricity. No biofuels, gasoline, diesel Demand system: Constant Difference of Elasticities (CDE) Relevant assumption: At least part of the revenue saved is recycled to finance investment in clean technologies
Black et al. 2023	Global phase-out of pre and post-tax subsidies on all fossil fuels.	Time horizon: 2030 Subsidy data source: IMF Reforms regions: Global Commodities covered: coal, gas, electricity, petroleum, diesel, gasoline. No biofuels Demand system: No clear modeling of demand Relevant assumption: No visible general equilibrium or feedback effects
Burniaux and Chateau 2014	Full removal of fossil fuel subsidies between 2013 and 2020	Time horizon: 2050 Subsidy data source: IEA Reforms regions: mostly non-OECD countries Commodities covered: Coal, gas, refined oil, electricity. No biofuels, gasoline, diesel Demand system: Extended Linear Expenditure System (ELES) Relevant modeling assumption: Higher coal and gas but lower crude oil supply elasticities than in present studies
Chepeliev and Mensbrugghe 2020	Removal of fossil fuel consumption subsidies between 2020 and 2025	Time horizon: 2030 Subsidy data source: GTAP10 (based on IMF estimates) Reforms regions: Focus on countries with fossil fuel subsidies more than 3% of GDP or larger than \$5 billion in 2011 Commodities covered: Coal, petroleum products, gas, electricity. No biofuels, gasoline, diesel Demand system: Constant Difference of Elasticities (CDE) Relevant modeling assumption: Considers alternative oil price development and assumes a 1% annual GDP carbon intensity improvement
Fouré et al. 2023	Net-zero emission by mid-century. Combines various instruments, including carbon pricing, the removal of fossil fuel support, regulations in the power sector, and the stimulation of low-carbon investments	Time horizon: 2050 Subsidy data source: OECD and IEA Reforms regions: Global Energy commodities covered: Coal, crude oil, gas, refined/power oil, electricity. No biofuels, gasoline, diesel Demand system: Extended Linear Expenditure System (ELES) Relevant modeling assumption: assumes a cap on emissions for all periods to ensure no carbon leakage
Saunders and Schneider 2000	Removal of fossil fuel consumption subsidies from 2001 to 2005	Time horizon: 2010 Subsidy data source: World Bank Reforms regions: developing and transition economies Commodities covered: Coal, gas, petroleum products. No biofuels, gasoline, diesel Demand system: Unspecified utility function Relevant modeling assumption: Baseline GDP per capita in all economies is assumed to converge toward that of the US in the very long run

(Continues)

TABLE 8 | (Continued)

Author(s)	Scenario	Modeling setup
Siddig et al. 2014	Complete or partial removal of subsidies on imported petroleum products	Time horizon: Static at 2006 benchmark Subsidy data source: Nigerian Petroleum Products Pricing Regulatory Agency Reforms regions: Nigerian Commodities covered: Petroleum products Demand system: Demand system: Constant Difference of Elasticities (CDE) Relevant modeling assumption: Alternative scenarios with government transfers

Single-country/region studies will overestimate GHG emission reduction due to the increase in consumption outside of the reform area. Compared to the no reform baseline, we simulate in the policy scenarios an increase of gasoline, diesel, and crude oil consumption outside of the reform area equivalent to 11% and 10% of the drop where the subsidies are phased out. Saunders and Schneider (2000), who as per Table 8 focus on developing countries, found the increase in consumption outside of the reform area to be at least in part driven by a diversion of production where the subsidies are removed to world markets. We instead find that it is due to a decline in demand for the fuels on the world market triggering an increase in trade between regions that did not implement a reform. We also note that the drop-in demand results in a lower price for the fuels' inputs like crude oil which lowers their prices. Both of these put downward pressure on world prices and trigger government spending for biofuels outside of the reform area to expand. In both scenarios, we find support for biofuels must increase by \$600 million in the rest of the world so that targets are achieved in all regions.

Our results expand on the direct linkage presented by the literature between fossil fuel subsidies and energy-intensive sectors (Rentschler, Kornejew, and Bazilian 2017), to backward and forward linkages within the fossil fuel energy sector, as well as from biofuels to and from their value chain. As diesel and gasoline subsidies are removed, consumption of products produced from crude oil expands in all regions while the price of livestock for example increases in regions implementing the reforms. Considering all sectoral and general equilibrium effects, our results match Antimiani, Costantini, and Paglialunga (2023) and the impact of FFSR on GDP in the reform area is relatively small at below 1% but negative. This however contrasts with Chepeliev and Mensbrugghe (2020) who find that FFSR tends to increase GDP by 0.02% to 0.1% depending on the assumption made for the price of oil. The finding that oil exporting countries may suffer from terms-of-trade losses as world energy prices fall when multilateral reforms are implemented (Burniaux and Chateau 2014) may be an explanation for this diversion. Alternative assumptions (see Table 8) on how much can energy supply react to changes in price for example have also been found to impact the result of the reform and could be another reason for the differences in results (ibid).

## 5 | Limitations

The data used and the modeling approach might be sources for differences in results with the literature. On the data side, not all

forms of government support are captured by the IMF estimates. The transfer of risks via favorable interest rates on loans is for example omitted here. We also note the lack of differentiation between intermediate and final consumption subsidies, as well as across activities. As already argued by Chepeliev et al. (2018), available knowledge on global energy subsidies do not contain enough information to represent the differentiation accurately.

The EU post-tax subsidies on biofuels used in the present study rely on an approximation based on the sustainability criteria of the biofuel mandate. We note that the most conservative estimate available was used and that many vegetable-based biofuels have been reported to lead to greater emission savings (Directive 2023). Still, the results would benefit from endogenously determining post-tax subsidies on biofuels to allow a more accurate analysis of the changes in the composition of biofuels. Explicitly modeling GHG emissions would be a good first step in this direction and allow an environmental impact assessment of FFSRs.

On the modeling side still, in every iteration, each regional producer extracts a given fixed stock of natural resources. Prices then clear the market in a micro-type closure fashion. This has several implications. For one, the lack of a dynamic supply function does not allow for updating stocks and therefore resource depletion. There is also no intertemporal optimization which is relevant considering the green paradox. The impact producer expectations would have on FFSR depends on how the reform is implemented (i.e., gradual/complete, immediate/delayed) but would likely lower the drop in the initial quantity consumed. To mitigate this drawback, the present study focuses on changes in the consumption of commodities rather than resources and compares results at the end of the simulations' period only.

Expanding the model to include additional alternatives to diesel and gasoline (e.g., electric cars) would widen the scope of possible substitutions in consumption and improve the accuracy of the results. Biofuel mandates being widespread, the fact that they are available at scale, and the assumptions that would have been required to integrate and calibrate electric cars to the model motivated our choice of focus. Still, more sectors could have been added to the model to increase the scope of our results. For example, including renewable energy generation would have permit to investigate the impact of the policies on power generation. The transport sector being the largest single-sector recipient of fossil fuel subsidies (Black et al. 2023) and data/computational limitation informed our choice to narrow down our investigation to this sector.



Rather than increasing the dimension of the model, the transport sector itself could be modeled to a greater degree of realism. Diesel and gasoline have their own substitution possibilities in the consumption nesting and some level of nonhomotheticity is allowed for by the LES approach but traveling is modeled like any other commodity. Travel is however a “derived demand.” Most travels happen for a purpose and are not an end in themselves. We therefore acknowledge that the simulated drop in transport fuel consumption may be overestimated but emphasize that more substitution possibilities are available to consumers than modeled here.

## 6 | Conclusions

Fossil fuel subsidy reforms are an effective way to increase the competitiveness of biofuels and reduce the consumption of gasoline and diesel. They do not lead to a large substitution between the two fuel types since biofuel targets are most commonly specified as a percent of total transport fuel consumption. Instead, the consumption of both fuels drops as prices rise and the size of the transport sector shrinks. This suggests that consumers reduce the number/length of trips they undertake using internal combustion engine-powered vehicles and are incentivized by the reforms to switch to other fuels/engines or modes of transport (i.e., non-motorized, public, electric).

Governments benefit from savings on both fossil and biomass-based energy subsidies as less support is needed for biofuels to reach their target. The fiscal saving of FFSRs is thereby greater than previously estimated by isolated policy evaluations. This complements the existing literature on the regressive impact of phasing out fossil fuel subsidies by highlighting that more funds may be available for revenue recycling if this saving on renewable energies is considered a part of the available budget.

While reforms and their impact on biofuels lower the cost of an energy transition, they are not without drawbacks. For one, they lower the price of fossil fuel on the world market and while this benefits economies that do not implement a reform, it also means that their opportunity cost of a transition rises. This also leads to a drop in the real GDP of large net energy exporters and countries that implement the reforms. Accounting for the avoided cost of the damages from externalities to the economies is likely to more than offset this effect and result in a positive welfare effect in all regions. Still, relative winners/losers can nevertheless be identified purely on the grounds of changing economic levels.

This is especially true for regions like OPEC, who despite not implementing any policy still experience a loss as global demand declines. This points to the possible use of reforms as a geopolitical instrument by large players on the world market. Fossil fuel subsidies do not necessarily discriminate imports by regions of origin and reforms would therefore be a rather blunt tool for any single country. Still, they would reorient global energy supply chains and as such may be valuable for countries aiming to influence international trade dynamics. Countries can find additional benefits in forming coalitions to gain weight on the world market as a way to strengthen their position in favor of or against a reform. While OPEC can resist a reform, other groups

of countries like the Friends of Fossil Fuel Subsidy Reform have been promoting a policy shift since 2010 (Gerasimchuk et al. 2017).

We highlight the positive impact fossil fuel subsidy reforms have on biofuel mandates which work to enhance the overall support reforms provide to the energy transition. Future work could seek to strengthen this conclusion by expanding our results to other energy sectors or modes of transport. A model with a disaggregated power generation sector would for example capture additional effects through substitution between energy sources in that sector. We expect the mechanisms driving our results to apply, but the size of these impacts remains to be quantified.

## Author Contributions

**Robin Argueyrolles:** conceptualization, data curation, formal analysis, methodology, software, visualization, writing – original draft, writing – review and editing. **Tobias Heimann:** data curation, methodology, software, writing – original draft. **Ruth Delzeit:** conceptualization, data curation, methodology, supervision, writing – original draft.

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## Conflicts of Interest

The authors declare no conflicts of interest.

## Data Availability Statement

The data that support the results of this study are available from <https://doi.org/10.5281/zenodo.14524748>. The study is based on data from GTAP. Restrictions apply to the availability of these data, which were used under license for this study.

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## Supporting Information

Additional supporting information can be found online in the Supporting Information section.