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The Energy Security Gains from Strengthening Europe's Climate Action

Prepared by Geoffroy Dolphin, Romain Duval, Hugo Rojas-Romagosa, and Galen Sher

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Executive Summary

Russia's invasion of Ukraine in 2022 sparked an energy crisis in Europe. As shown in this paper, this crisis came on the back of a broad-based deterioration in energy security in previous decades, as the continent came to rely increasingly on imported energy from ever fewer suppliers. Following the war, policymakers have taken an impressive array of individual and collective actions to strengthen energy security. The main question this paper addresses is whether strengthening efforts to mitigate climate change will also support Europe's energy security in the medium term. It examines two dimensions of energy security: security of supply, which improves as dependence on energy imports falls and/or imports become more diversified, and economic resilience to energy shocks, which is enhanced when the overall weight of energy spending in GDP declines.

The global general equilibrium model-based analysis in this paper finds that Europe's climate change mitigation and energy security goals are largely complementary. Greenhouse gas emissions reduction policies tend to lower the risk of foreign supply disruptions by reducing reliance on imported energy and diversifying the remaining imports among non-European suppliers. They also tend to improve European economies' resilience to energy shocks. This holds true particularly for those policies that directly curtail energy demand, such as sector-specific emissions and energy efficiency standards for cars and buildings. But even carbon pricing, which by its very nature raises energy prices, ends up lowering the amount spent on energy in most of Europe because energy demand is relatively elastic over the medium term.

However, Europe's energy security gains from climate change mitigation vary across policy tools and countries. If used as a standalone tool, carbon pricing cuts emissions at least economic cost but can weaken energy security for a while in some energy- and emissions-intensive economies in Eastern Europe, partly due to accelerated phasing out of domestic coal. Sector-specific regulations deliver larger energy security benefits and spread those more evenly across countries. Public investment in heat pumps enhances security of supply by reducing fossil fuel imports, but it needs to be combined with an expansion of carbon-neutral power generation as it could otherwise raise electricity and gas prices and thereby the weight of energy spending in GDP.

These findings strengthen the case for a broad climate policy package, which can both achieve Europe's emissions reduction goals at a low economic cost and yield sizable energy security co-benefits. Carbon pricing should remain at the forefront of this effort given its economic efficiency benefits, while sector-specific regulations and accelerated permitting procedures for green infrastructure will amplify the package's energy security benefits and spread them more evenly across different European countries. An illustrative package that would cut emissions in the European Union, the United Kingdom, and countries of the European Free Trade Association by 55 percent with respect to 1990 levels by 2030 could improve the continent's two energy security metrics studied in this paper by close to 8 percent by the same horizon.

The simulations also support the case for strong multilateral cooperation within Europe, given that countries differ in their degree of emissions or energy intensity, potential for renewable power generation, and financing costs. In particular, expanding common financial capacity for green investment at the EU level could accelerate the green transition by ensuring that its energy security co-benefits are more evenly shared across countries.

Further policies are needed. To boost investment in renewables and address their intermittency, European countries need to further improve electricity market design and support the deployment of technologies like batteries, green hydrogen, and those that enable demand-side flexibility. To avoid carbon lock-in, Europe needs to guard against overinvestment in fossil fuel infrastructure. Finally, deeper cooperation with other regions of the world can help secure supplies of minerals critical for the green transition.

1. Introduction

In 2022, Europe[1] suffered its worst energy crisis since the 1970s, triggered by Russia's war against Ukraine. Pipeline gas flows from Russia to Europe began dropping in the second half of 2021 and flows to many countries were suspended in 2022 (Di Bella and others 2022; Lan, Sher, and Zhou 2022). Prices of natural gas traded on the Dutch Title Transfer Facility increased over 20-fold between 2019 and August 2022, sending electricity prices up from €45 to €598 per megawatt hour in August 2022. Governments responded decisively, buying gas, providing financing to energy firms, requiring operators to fill gas storage facilities, leasing floating gas import terminals, and activating standby electricity generation capacity. Nevertheless, the energy crisis had first-order adverse economic impacts. Higher energy prices and calls for voluntary energy savings reduced consumption of gas by 15 to 20 percent, and that of electricity and coal by 5 to 10 percent (Figure 1, panel 1). Large industrial consumers bore most of the burden of gas demand reduction (IMF 2023a; Ruhnau and others 2023), which weighed on industrial production (Chiacchio and others 2023). The war and its associated trade restrictions led the IMF to revise down its forecasts for GDP growth by over 1 percent in 2022 and 2023, and ½ percent in 2024 (Figure 1, panel 2). These downward revisions were even larger for energy-insecure European economies.

Despite the impressive array of measures taken in response to the war, Europe's energy insecurity remains high, calling for further action. Indeed, markets expect energy prices in Europe to remain about 60 percent above prewar levels.[2] As the analysis in this paper shows, even before the war, Europe's energy security had deteriorated over several decades along two dimensions: (1) the continent became more exposed to foreign energy supply disruptions, as imports accounted for a growing share of overall energy consumption, and those imports became increasingly concentrated among fewer foreign suppliers; and (2) the European economy became slightly more sensitive to energy shocks in general, as the ratio of energy expenditures to GDP rose. Further, the projections presented in the following show that the war itself is likely to have ambiguous effects on Europe's energy security; on the one hand, it could reduce Europe's exposure to foreign energy supply disruptions, but on the other hand, it could make European economies more sensitive to any such disruptions due to the persistent rise in energy prices from the war.

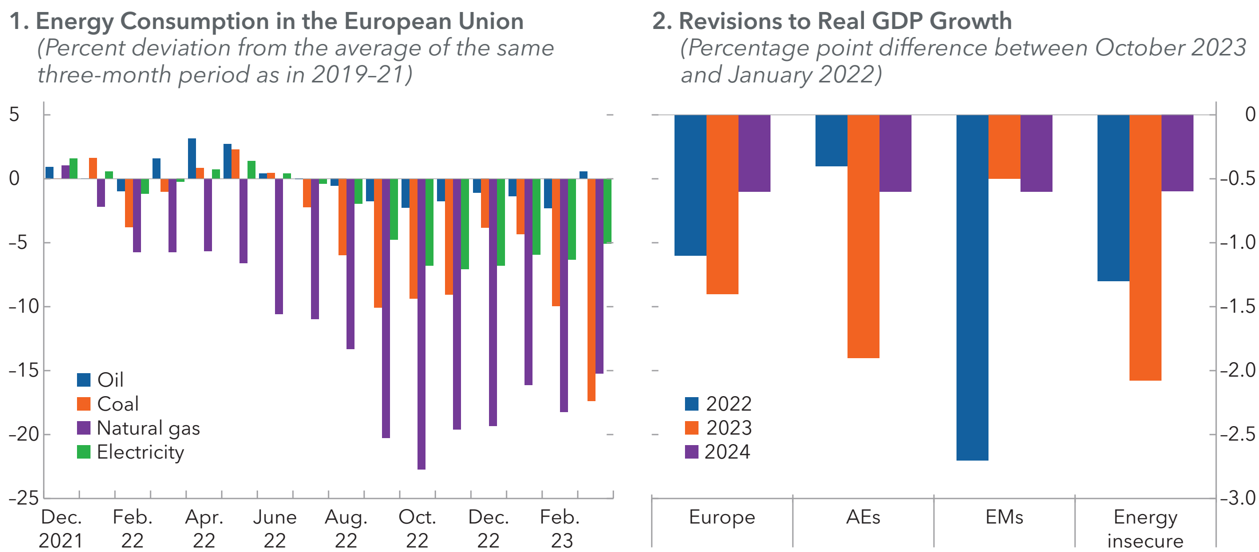
The key question this paper addresses is whether, and if so to what extent, greenhouse gas (GHG) emissions reduction policies could enhance Europe's energy security, over and above contributing to Europe's ambitious climate change mitigation agenda. The European Union's REPowerEU package, for example, proposed raising the European Union's 2030 renewable energy target from 32 to 45 percent and its energy efficiency target from 9 to 13 percent.[3] Most importantly, both the European Union and the United Kingdom have legally binding emission reduction targets, which involve cutting GHG emissions by 55 and 68 percent of 1990 levels by 2030, respectively, before reaching climate neutrality by 2050. At the EU level, the so-called Fit for 55 package of policy proposals shows which policy actions could be taken to achieve the 2030 targets. Fit for 55 includes carbon pricing, sector-specific regulations on energy efficiency, legal measures to speed up the deployment of renewable power generation, and financial support. There remains little comprehensive evidence regarding the energy security implications of Europe's emissions reduction policies, both individually and as a package; this paper aims to fill this gap.

1 In this paper, Europe means the European Union, the United Kingdom, and the European Free Trade Association. All areas have ambitious climate targets for 2030 that make them particularly suitable for analysis in this paper.

2 Calculated based on the change in a simple average of oil, gas, and electricity (futures) prices between 2019 and 2028 (2026 for electricity).

3 In 2023, the European Union ultimately revised up its renewable energy target to 42.5 percent and its energy efficiency target to 11.7 percent.

Figure 1. Europe's Energy Crisis Severely Affected Energy Consumption and the Economy



Sources: Eurostat; IMF, World Economic Outlook database; and authors' calculations.
Note: In panel 1, consumption each month is smoothed using three-month rolling averages, then the deviation is calculated from the average for the same three-month window over 2018–21. Energy-insecure economies include Austria, Czech Republic, Germany, Hungary, Italy, and Slovak Republic, as identified in Di Bella and others (2022). AEs = advanced European economies; EMs = European emerging market economies.

The impact of climate change mitigation policies on energy security is not straightforward a priori and likely to vary across European countries, calling for a quantitative assessment. On the one hand, promoting the deployment of renewable energy, which tends to be produced domestically, could reduce Europe's dependence on energy imports, including imports from unreliable suppliers (Jewell, Charp, and Riahi 2014; Kim, Panton, and Schwerhoff 2024). Likewise, enhancing energy efficiency (for cars and buildings, for example) should help energy security by reducing energy demand for a given level of domestic supply. On the other hand, various mitigation policies, especially carbon pricing, increase the cost of energy; thus, if energy demand is not responsive enough—more specifically, if its price elasticity is less than one, the overall weight of energy spending in GDP may rise, increasing the economy's exposure to energy shocks. Furthermore, higher carbon prices would be expected to speed up the phasing out of coal, a highly polluting yet rather safe source of energy for those European countries that still produce it. A related concern could be that many pathways to climate neutrality will rely for a while on natural gas, global production of which is concentrated in fewer global suppliers than other fuels (IEA 2007; Kim, Panton, and Schwerhoff 2024); there are also more infrastructure constraints associated with natural gas.

This paper assesses the impact of climate change mitigation policy actions on European countries' energy security by means of a global multicountry, multisector general equilibrium model. The model describes energy trade, consumption, and production patterns for each country over the medium term and how they relate to GHG emissions. The model is used here to simulate the impact of individual policy tools, such as higher carbon prices, tighter emission and performance standards for road transport and buildings, faster permitting procedures for renewables or public investment in heat pumps, as well as climate policy packages such as one that resembles the European Union's Fit for 55 agenda. Energy (in)security is analyzed here along the two dimensions mentioned earlier: (1) the risk of foreign energy supply disruptions and (2) the exposure of economic activity to any energy supply disruption.

The key findings from the simulations are the following:

- Climate change mitigation policies are expected to help Europe's energy security in the medium term. Higher carbon prices, tighter sector-specific energy efficiency regulations, and accelerated permitting would all improve Europe's energy security along the two dimensions considered in this paper.

- The energy security gains from climate change mitigation policies vary across policy tools and countries. If used as a standalone tool, carbon pricing cuts emissions at least cost but can weaken energy security for a while in some energy- and emission-intensive economies in Central and Eastern Europe, partly due to accelerated phasing out of domestically produced coal. Sector-specific energy efficiency regulations, while economically costlier than carbon pricing, deliver larger energy security co-benefits and spread those more evenly across countries. This is primarily because such regulations lower both the price and the consumption of energy, while carbon pricing only reduces the latter. Public investment in heat pumps enhances security of supply by reducing fossil fuel import dependence, but it needs to be combined with policies to decarbonize the power sector as it could otherwise raise gas and electricity prices and thereby the weight of energy spending in GDP.

- A broad package of measures can deliver sizable energy security gains for Europe. Such a package would combine both the economic efficiency of carbon pricing and the larger and more evenly shared energy security benefits of sector-specific regulations. Specifically, a package (1) lowers dependence on imported energy, because renewable energy is produced domestically while Europe's fossil fuel consumption tends to be imported; (2) diversifies energy imports away from non-European suppliers, as Norway's share rises while top non-European energy producers reallocate their exports away from Europe as its energy demand falls; (3) lowers energy expenditures, as energy efficiency investments reduce energy demand and accelerated renewables deployment raises energy supply, both of which help lower energy prices; and (iv) by decarbonizing the power sector, ensures that public investment in heat pumps—which could otherwise raise gas demand—enhances energy security.

- An illustrative package that would cut emissions by 55 percent vis-à-vis 1990 levels by 2030, and would be close in spirit to the envisaged climate policy mixes in the European Union, the United Kingdom, or countries of the European Free Trade Association (EFTA), is estimated to improve the two energy security metrics by close to 8 percent by 2030. This would reverse 13 years of deterioration in the European Union's economic resilience, and 8 years of deterioration in the European Union's security of supply.

The remainder of this paper proceeds as follows. The next section presents the energy security metrics used in this paper and shows their evolution for Europe before the war. The following section provides a brief overview of the model and discusses the calibration and results of baseline scenarios that investigate the effects of the war. The two subsequent sections present the simulation results for individual climate policy actions and a broad climate policy package, respectively. They are followed by a discussion of the policy implications from these model simulations. The annex goes beyond the policies analyzed in the model to explore, qualitatively, further policy actions Europe could take to achieve both its climate change mitigation and energy security goals. These include supporting technologies to address intermittency of renewables, making markets more efficient and attractive for renewables deployment, and securing the supply of minerals that are critical to the energy transition.

2. Europe's Deteriorating Energy Security Before the War

Energy security is a multifaceted concept that can be measured in many possible ways. For example, Sovacool and Mukherjee (2011) list 320 indicators of energy security along five broad dimensions. To keep things focused, this paper measures energy security along two main dimensions:[4]

- *Security of supply*, which is defined here in terms of the risk of foreign supply disruptions. The main metric used to capture this dimension is the composite energy supply insecurity index proposed by Cohen, Joutz, and Loungani (2011), defined for each country as

$$\sum_{\text{supplier country } i} \left(\frac{(\text{net positive energy imports})_i}{\text{energy consumption}} \right)^2$$

  where the sum runs across all *non-European* supplier countries. Whereas Cohen, Joutz, and Loungani (2011) assign countries risk weights based on a political risk score, this paper takes a more agnostic approach and treats all non-European countries identically. European energy suppliers like Norway effectively get a risk weight of zero, which reflects that they are deeply integrated democracies that are less likely to restrict energy exports to each other.[5] This metric summarizes both energy import dependence (that is, the ratio of net energy imports to consumption) and the geographic concentration of energy imports (that is, Herfindahl index with European countries getting zero weight), which are two other commonly used metrics in the literature. Annex 1 shows that the composite index is approximately equal to a weighted average of the two. This dimension of energy security captures the reliability of foreign energy supply.

- *Economic resilience*, which is defined here in terms of the sensitivity of economic activity to any energy shock. It is measured as the ratio of energy consumption expenditures of firms and households to GDP, both expressed in current prices. This ratio is closely related to the well-known ratio in economics called the Domar weight (Hulten 1978; Baqaee and Farhi 2019). It is also intuitive that economies with a high energy expenditure share be more vulnerable, all else equal. For example, upon impact, a 10 percent increase in energy prices would increase energy expenditures by 2 percentage points of GDP in an economy that starts out with an energy expenditure share of 20 percent of GDP, but only by 0.5 percentage point in an economy with an initial energy expenditure share of 5 percent.[6]

Along these two dimensions, Europe's energy security had deteriorated in the decades before Russia's invasion of Ukraine.[7] In the European Union, the composite energy supply insecurity index increased fivefold between 1990 and 2019 (Figure 2, panel 1), while energy expenditures increased slightly from 5.5 percent of GDP in 1970 to 6.6 percent in 2019 (Figure 2, panel 2). These increases were broad-based: the composite insecurity index increased between 1990 and 2019 for 25 of the 29 European countries, and

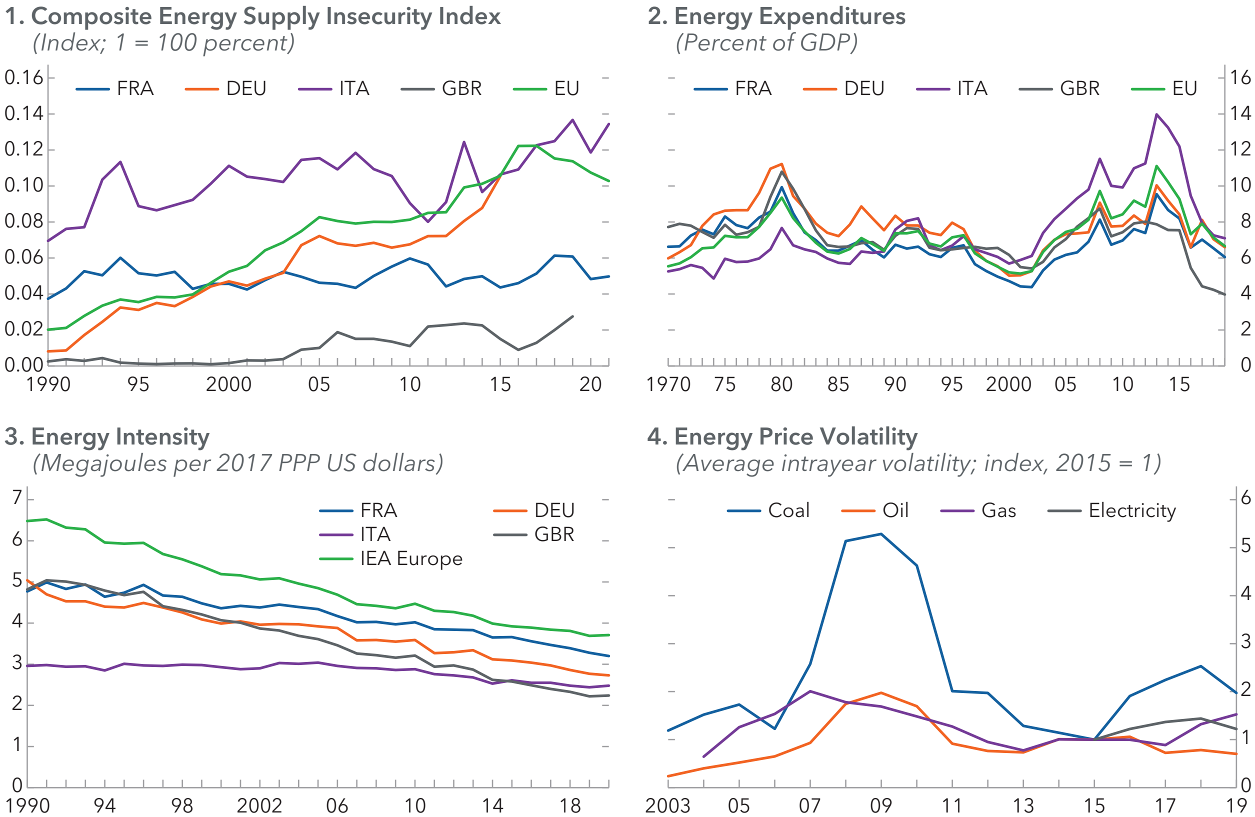
[4] This paper does not try to combine these two indicators into one energy security index, as in Le Coq and Paltseva (2009), because there are many possible ways of doing so, and any such effort would raise questions about the robustness of the results to the choice of index. Keeping the two indicators separate helps to emphasize that energy security is inherently an open concept.

[5] This definition also helps with consistency between country-level and Europe-level results, because Europe's imports cannot come from European countries.

[6] It is also worth noting that, in a competitive economy where firms produce according to a Cobb-Douglas production function with energy as one of the inputs, the energy expenditure share of GDP represents the elasticity of aggregate output to energy, that is, the percent change in GDP in response to a 1 percent change in the physical quantity of energy input. Therefore, it is the nominal energy expenditure share of GDP, rather than the physical energy intensity of GDP (that is, the ratio of real energy consumption to real GDP), that determines the sensitivity of the economy to changes in energy inputs. Unlike physical energy intensity, the ratio of nominal expenditures to nominal GDP depends on the relative price of energy, which determines how much energy firms use and hence the real marginal product of energy.

[7] This paper considers energy in the aggregate, effectively combining gas, oil, solid fuels (coal and coal products), biofuels, electricity, and heat in common units (joules). Similar patterns emerge for individual fuel types.

Figure 2. Europe's Energy Security Deteriorated in the Decades before Russia's War in Ukraine



Sources: Argus Media; EMBER; Eurostat; Grubb and others (2018); International Energy Agency (2023); and authors' calculations.
Note: Panel 1 shows the composite energy insecurity index of Cohen, Joutz, and Loungani (2011), assigning zero risk weights to European countries and unit risk weights to other countries. Panel 4 shows the three-year rolling average, indexed to 1 in 2015, of the standard deviation of daily fuel-specific energy prices within each year. Coal prices are Amsterdam/Rotterdam/Antwerp 6000 kcal/kg, oil prices are London Brent crude, gas prices are Dutch TTF, and electricity price volatility is averaged across European countries.
DEU = Germany; EU = European Union; FRA = France; GBR = United Kingdom; IEA Europe = Albania, Austria, Belarus, Belgium, Bosnia and Herzegovina, Bulgaria, Croatia, Czech Republic, Denmark, Finland, France, Germany, Greece, Hungary, Iceland, Ireland, Italy, Kosovo, Latvia, Lithuania, Luxembourg, Malta, Moldova, Montenegro, The Netherlands, North Macedonia, Norway, Poland, Portugal, Romania, Russia, Serbia, Slovak Republic, Spain, Sweden, Switzerland, Ukraine, United Kingdom; PPP = purchasing power parity.

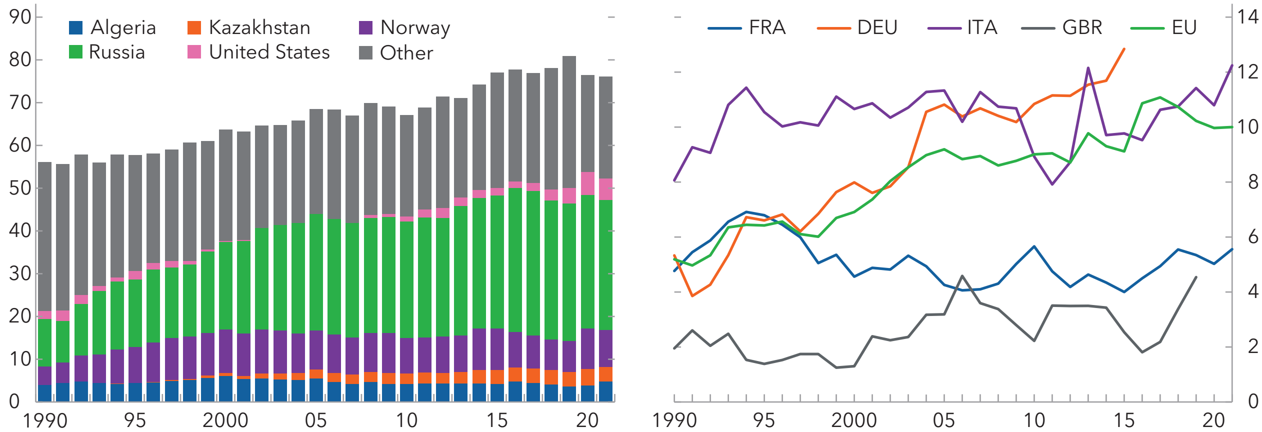
the energy expenditure shares increased in 17 out of 22 countries for which data are available. The large swings in energy expenditures were mostly driven by the evolution of international oil prices. The long-term downward trend in the United Kingdom reflects a 50 percent reduction in the economy's energy intensity (measured as the ratio of real energy consumption to real GDP) since 1990 (Figure 2, panel 3).

The main reason behind the deterioration of Europe's security of supply since 1990 is that the continent came to rely more on imported energy to meet its consumption needs and its energy imports became more geographically concentrated (Figure 3). The European Union's energy import dependence increased from about 56 percent in 1990 to 76 percent in 2021, pushed up by gas, oil, and coal imports from Russia. Further, the (weighted) geographic concentration of its energy imports doubled over that same period. The opening of Nord Stream 1 played an important role for Germany, as the replacement of Norwegian gas with Russian gas between 2010 and 2015 contributed toward a 20 percent increase in the geographic concentration of its overall energy imports, which reversed improvements made in the prior decade. Most European countries (including notably Germany, Italy, and the United Kingdom) increased the (weighted) geographic concentration of their energy imports between 1990 and 2015. In France, the geographic concentration of energy imports remained stable over this period as energy imports from Russia substituted those from Saudi Arabia.

Figure 3. Europe Came to Rely More on Imported Energy from Fewer Suppliers—Primarily Russia

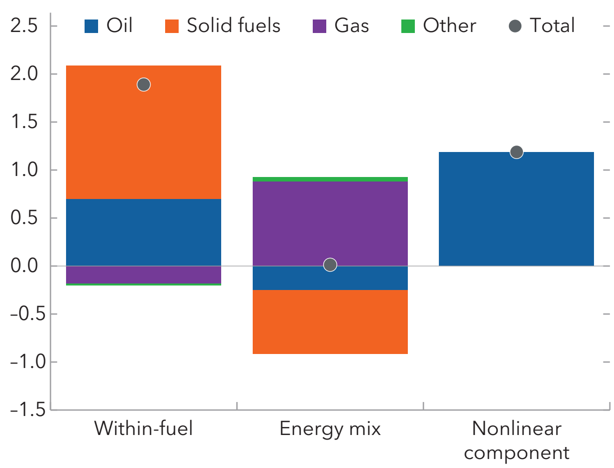
1. European Union: Energy Import Dependence
(Percent of energy consumption)

2. Geographic Energy Import Concentration
(Herfindahl index, percent, weighted)



Sources: Eurostat; and authors' calculations.
Note: Panel 1 shows the ratio of net (positive) energy imports over the European Union's energy consumption (gross available energy), broken down by supplier. The other supplier category is well-diversified across other supplier countries. Labels in the figure use International Organization for Standardization (ISO) country codes.

Figure 4. European Union: Contributions to Higher Concentration of Energy Imports in the Last Two Decades
(Percentage point change in Herfindahl index, 1999–2021)



Source: Authors' calculations.
Note: The figure shows a shift-share decomposition of the change between 2000 and 2021 in the weighted Herfindahl index of geographic concentration of the European Union's energy imports. European countries (European Union, European Free Trade Association, United Kingdom) get zero weight and other countries get unit weight. About 1.9 percentage points of the 3.1 percentage point change in energy import concentration can be explained by this decomposition. The nonlinearity reflects the fact that the actual index is above the linear, shift-share approximation at each point in time, and this difference grew over the period considered. The decomposition is done at the level of disaggregated energy sources. "Other" energy sources include electricity, heat, and biofuels.

The upward trend in the geographic concentration of energy imports in the European Union since 1999 is due to increasing concentrations of coal and oil imports (Figure 4). This finding emerges from a simple shift-share analysis, which decomposes the increase in concentration into the contributions of (1) changes in the import concentration of each energy source and (2) changes in the energy import mix. In contrast to coal and oil, imports of other energy sources, like gas, did not become more concentrated over this period for the European Union as a whole—with a few such important exceptions as Germany. Meanwhile, changes in the energy mix contributed negligibly to the increase in concentration due to offsetting forces: the energy import mix shifted toward natural gas, whose import sources are highly concentrated among few foreign producers, but it also shifted away from coal and oil, whose import sources also tend to be fairly concentrated. In Italy, by contrast, changes in the energy mix played a more decisive role, as the shift into natural gas drove up geographic concentrations of energy imports, and hence the insecurity of supply index, between 1999 and 2021.

These indicators capture the two most important dimensions of energy security, but they ignore potential amplification effects from physical infrastructure constraints and price instability. They treat the geographic concentration of and expenditure on imported pipeline gas and oil symmetrically to seaborne imports, even though pipeline imports can be harder to substitute in the event of a disruption in a specific trading partner. The modeling in the following attempts to capture such infrastructure constraints by calibrating so-called iceberg trade costs. Energy price instability in Europe had also been a concern, rising in the two decades before the pandemic (Figure 2, panel 4). However, the price stability dimension of energy security cannot be captured in the analysis of this paper due to the model's deterministic structure. Therefore, Annex 3 looks beyond the model, into the specific technologies (for example, hydrogen, batteries, and demand-side flexibility) Europe will need to maintain price stability as it adopts renewable energy, the supply of which varies intermittently with the weather.

3. The Mixed Effects of the War on Europe's Medium-Term Energy Security

The impact of the war on Europe's future energy security is not straightforward a priori. On the one hand, reduced energy dependence on Russia should help to reduce risks of potential future energy supply shocks. After the start of the war, the European Union phased out Russian coal and imposed sanctions on seaborne oil, which reduced its imports of Russian oil by 90 percent (European Commission 2023b). Russia's share in EU gas imports also fell dramatically from 41 percent in 2021 to 15 percent in the first 10 months of 2023 (European Commission 2023a). Further, the European Union committed to phasing out all remaining Russian fossil fuel imports before 2030.[8] On the other hand, the war could persistently increase energy prices in Europe, which would weaken energy security by raising the energy spending share in GDP and thereby making economic activity more sensitive to any energy disruptions, all else equal.

To simulate the effects of the Ukraine war and various climate mitigation policies on European energy security, this paper uses a global multicountry, multisector general equilibrium model (called "ENVISAGE"), developed by the World Bank and adapted at the IMF.[9] This recursive dynamic computational general equilibrium model describes economic activity, energy trade and use, and GHG emissions for 31 countries or country groups, including 10 in Europe.[10] The model captures production, consumption, and trade in 28 commodities, including crude oil, oil products, gas, and coal. It also describes electricity generation from each fossil fuel, renewable (wind, solar, hydro), and nuclear source. The model is yearly, but this paper focuses on results for the year 2030 (the "medium term"), for which the model is the most reliable.

The effects of the war are estimated by comparing energy security metrics under prewar and postwar baseline scenarios:

- The *prewar baseline* (Baseline 1) is calibrated using estimates of energy trade from the International Energy Agency and projections of the electricity mix, GHG emissions, and economic activity from the EU Reference Scenario 2020 and the IMF's January 2022 *World Economic Outlook* (IMF 2022a). The electricity mix in each country is calibrated by adjusting the productivities of each generation technology. The geographic concentration of Europe's energy imports in the model is about 12 percent in 2021 and its energy expenditures are 6 percent in 2019, similar to those for the European Union in Figure 3, panel 2, and Figure 2, panel 2, respectively. However, due to differences in definitions, the model's import dependence ratio is only about 54 percent in 2021, 22 percentage points below its level in the data.[11] This difference is taken into account when commenting on the results in the following.
- In the *postwar baseline* (Baseline 3), bilateral energy trade is adjusted to reflect the shutoff of Russian gas flows as observed in monthly data from Eurostat. For example, these data show that Germany reoriented its gas imports from 2021, when 65 percent of gas came from Russia, toward Norway, whose share of German gas imports increased from 19 percent to 60 percent, and such other countries as Belgium

[8] The commitment to phaseout appears in the Versailles Declaration of March 10–11, while the deadline of 2030 appears in the European Commission's press release of March 8.

[9] The ENVISAGE model is described in van der Mensbrugghe (2024). A model of comparable structure, called "IMF-ENV," was used recently by the IMF to examine the effects of the war on Europe's GDP and emissions in Rojas-Romagosa (forthcoming), which was written alongside this paper.

[10] The model features France, Germany, Italy, Norway, Poland, and the United Kingdom as individual countries, while other countries are grouped as follows: Bulgaria, Croatia, and Romania; Belgium and The Netherlands; Czech Republic, Hungary, and Slovakia; and rest of Europe, which includes the remaining EU and European Free Trade Association countries.

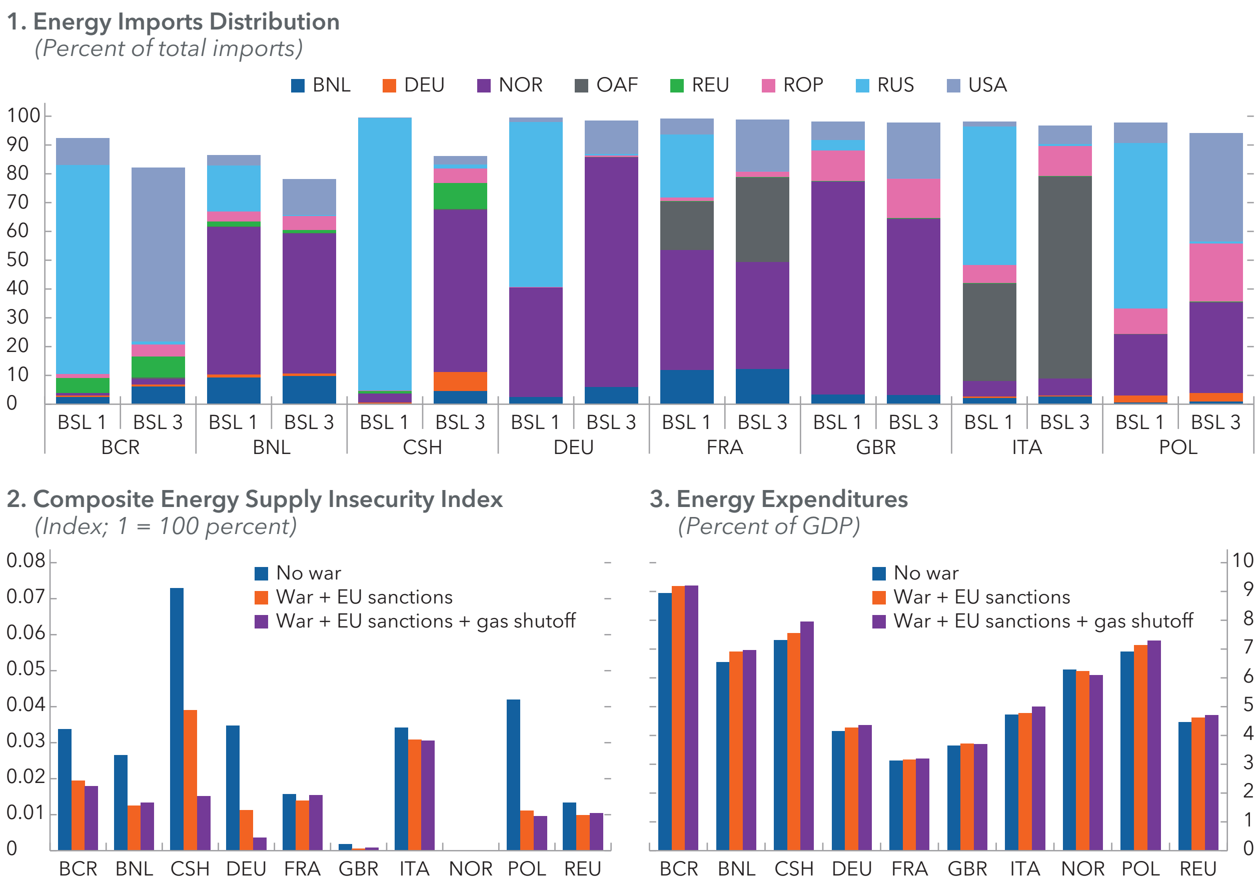
[11] About half of this discrepancy is due to a difference in the definition of energy consumption, which in the model double counts energy used in electricity generation. The other half is likely due to trade costs, which reduce imports in the model by creating a wedge between energy imports and exports.

and The Netherlands. Other countries that saw a decline of more than 15 percent in Russian gas imports include Croatia, Estonia, Finland, Latvia, The Netherlands, Poland, Portugal, and Sweden. In the postwar baseline, Europe is assumed to phase out all remaining Russian fossil fuels by 2030. Economic activity is assumed to follow the April 2023 *World Economic Outlook* (IMF 2023d), while emissions and the electricity mix are allowed to respond endogenously.

- Finally, a hypothetical intermediate scenario (Baseline 2—labeled as such because it falls between Baselines 1 and 3) is used to disentangle the impact of the gas shutoffs from that of the European Union's sanctions on Russia (and any other energy security effects of the war). In Baseline 2, gas imports are not adjusted, but European countries are assumed to continue phasing out Russian oil and coal.

The simulations suggest that Russia's war in Ukraine and the associated trade restrictions will have mixed effects on Europe's energy security in the medium term. The war is projected to cause Europe to import more of its energy from the United States (Figure 5, panel 1). France and Italy are projected to import more from Africa, while Germany, the Czech Republic/Slovak Republic/Hungary bloc, and Poland are projected to import more from Norway. The net effect is to reduce the geographic concentration of Europe's energy imports among non-European suppliers by about two-thirds (Annex Figure 2.1, panel 2). Europe is projected to respond to the war-induced increase in energy prices by producing more energy, which reduces its energy

Figure 5. Effects of the War on Europe's Energy Trade and Security in the Medium Term (2030)



Source: Authors' calculations.
Note: The figure shows the composite energy insecurity index of Cohen, Joutz, and Loungani (2011), modified to give European countries zero risk weight and other countries unit risk weight, where Europe includes the European Free Trade Association, the European Union, and the United Kingdom. Labels in the figure use International Organization for Standardization (ISO) country codes. BCR = Bulgaria, Croatia, and Romania; BNL = Belgium and The Netherlands; BSL = baseline scenario; CSH = Czech Republic, Slovak Republic, and Hungary; OAF = other African countries; REU = rest of Europe.

import dependence ratio by 1.2 percentage points (Annex Figure 2.1, panel 1). This reduction in import dependence is also found in Rojas-Romagosa (forthcoming). The decline in geographic concentration and import dependence together drive down the projected 2030 composite index of energy insecurity by some 8 percent in Europe as a whole (Figure 5, panel 2). However, despite rising European energy supply, energy prices remain higher in the postwar world (Baseline 3) than they would have been in a counterfactual no-war scenario (Baseline 1). As a result, and despite some reduction in energy consumption, European countries' energy expenditures are projected to rise by about 0.2 percent of GDP overall (Figure 5, panel 3).[12]

Looking into the drivers of Europe's enhanced security of supply, oil and coal sanctions on Russia appear to play a bigger role than the shutoffs of Russian gas, although both factors contribute positively. This can be inferred from the fact that the composite energy security index drops for most of Europe between Baseline 1 and Baseline 2, but does not change as much between Baseline 2 and Baseline 3. The model simulations suggest that oil and coal sanctions on Russia ultimately diversify Europe's energy imports more across non-European suppliers than shutoffs of Russian gas do.

[12] Norway is the exception, where a boom in economic activity (associated with higher energy exports) reduces its share of GDP spent on domestic energy use.

4. The Energy Security Effects of Different Climate Policy Tools

A. Calibration of Individual Instrument Scenarios

Having established that enhancing Europe's energy security will remain a key priority following Russia's war in Ukraine, this paper turns next to the question of whether climate policy tools could help enhance it. To this end, the following five illustrative individual policies are simulated one at a time, and their impacts on security of energy supply and economic resilience to energy shocks against the postwar baseline scenario (Baseline 3) are analyzed:

- *Higher carbon prices in the EU and UK emissions trading systems (ETS)*. These prices are assumed to rise more steeply over time, to end at €110 per ton in 2030 in the European Union instead of €33 as in the EU Reference Scenario (and these prices reach €118 in the United Kingdom). These higher prices reduce emissions by about 4 percent in 2030, compared to baseline. Further details on the calibration of each scenario are provided in Annex 3.
- *Tighter emissions and energy performance standards for road transport and buildings*. Energy efficiency in Europe's transport services sector is increased so that its consumption is reduced by 13 percent compared to the baseline. To capture tighter regulations on buildings, energy efficiency improves in the "other services" sector (which includes real estate activity, the main economic sector that operates buildings) to reduce its energy consumption by 5 percent. Households, which contribute to both transport and buildings emissions, adjust their preferences to reduce their energy consumption by 8 percent. These reductions in energy demand are sufficient to reduce overall emissions by 4 percent in 2030, which matches the emissions reduction achieved by higher carbon prices, in order to facilitate comparisons.
- *Accelerated renewables permitting processes*. These would increase total factor productivity of wind and solar power, which encourages investment and leads to 10 percent more such generation compared to baseline by 2030. This 10 percent improvement is consistent with a 40 percent improvement in the speed of renewables deployment, as would arise if the median European country's permitting times could match those of the country at the top quartile.
- *Public investment in heat pumps in residential buildings*. To simulate this policy, European households' preferences are shifted away from energy, reducing their overall demand by 6 percent in both the EU and EFTA region and the United Kingdom, while within energy, households' preferences shift away from coal and gas and toward electricity. These reductions in energy demand are sufficient to reduce emissions by 4 percent in 2030, which matches the emissions reduction achieved in the first two simulations listed above.
- *Removing fossil fuel subsidies*. Subsidies on fossil fuel production and consumption are phased out in this simulation, to varying degrees across countries and fuels depending on prewar estimates, drawing on data from Rademaekers and others (2020). By calibrating 2030 subsidies according to prewar data, this analysis assumes that the temporary energy subsidies introduced during the energy crisis will be fully phased out before 2030. Although fossil fuel subsidies are small relative to GDP in most of Europe, they can be large relative to the consumption of specific fuels. Subsidies for coal production in Germany, for example, make up only 0.1 percent of GDP (or €3.6 billion) but 1.3 euros per gigajoule of domestic coal use, which is about 25 percent of the retail price (Annex Figure 2.5, panels 1 and 2).

One feature should be borne in mind when comparing the individual policy simulation results. The carbon pricing, road and building regulations, and heat pumps scenarios reduce emissions by similar amounts, meaning that their energy security effects can be readily compared. However, accelerated permitting and a removal of fossil fuel subsidies can only be expected to reduce emissions by smaller amounts. For renewables, this is because of the limit on how much accelerated permitting could speed up deployment. For fossil fuel subsidies, this is because they are expected to be too small in the medium term—after returning to their prewar levels—for their removal to have a large impact on Europe's emissions.

In addition, the model simulations do not investigate two important related aspects of energy security. First, they do not explore the implications of the European Union's Carbon Border Adjustment Mechanism for energy security. The Carbon Border Adjustment Mechanism's direct effects are unlikely to be material, because the only energy products it covers are electricity, very little of which is imported,[13] and hydrogen, which is not included in the model due to uncertainty around how much of the energy mix it will contribute to in the future. Indeed, Makarov and others (2021) find negligible effects of the Carbon Border Adjustment Mechanism on the European Union's fossil fuel imports. Second, the model simulations do not investigate the potential energy security implications of supply chain risks associated with the green transition. These could potentially affect the flow, albeit much less the stock, of renewables. Specifically, while imports of solar panels or wind turbines could expose importers to supply chain disruptions originating abroad, these would not be expected to have acute implications for energy consumption because installed solar and wind plants could continue operating. Policies to address critical mineral dependencies are explored in Annex 3.

B. Effects of Individual Instrument Scenarios

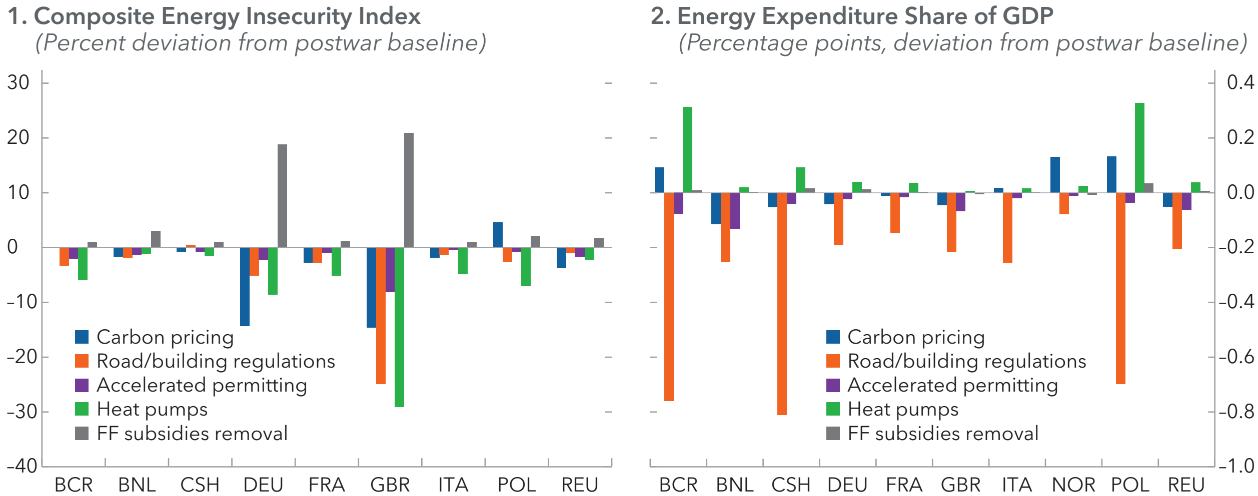
Climate change mitigation policies tend to enhance energy security in Europe along both the energy supply security and economic resilience dimensions. Figure 6 shows the effects of each policy instrument on the composite energy supply insecurity index (panel 1) and the energy expenditure share of GDP (panel 2). More detailed results on import dependence and geographic concentration are shown in Annex Figure 2.2. Specifically:

- *Higher carbon prices* tend to make supplies more secure and economies more resilient to energy disruptions, except for a few energy- and emissions-intensive economies in Central and Eastern Europe. Carbon pricing causes substitution away from dirtier toward cleaner energy sources, and since Europe's domestic energy production tends to be cleaner than its imported energy, its energy import dependence falls. In support of this intuition, economies where energy imports are dirtier than domestic production experience the largest reduction in import dependence in response to higher carbon prices (Annex Figure 2.3, panel 1). Poland and Czech Republic/Slovak Republic/Hungary as a group (which is a single bloc in the model) are the exceptions, where domestic energy production is more fossil-fuel-intensive than imports. At the same time, higher carbon prices reduce the geographic concentration of energy imports, mainly driven by lower shares of energy imports from the United States (and Africa, in the case of Italian imports), while the share of imports from Norway rises. Europe's energy suppliers, such as the United States and African countries, have relatively geographically diversified energy exports, meaning that they can easily reallocate these toward other destinations when Europe reduces its demand.[14] Overall, higher carbon pricing tends to improve the composite energy insecurity index in most of Europe (Figure 6, panel 1). Similarly, higher carbon prices tend to reduce the ratio of energy expenditures to GDP, because energy demand over the medium term is relatively responsive to prices, especially in Western Europe. Exceptions

[13] Over 99 percent of the European Union's electricity consumption is met through EU production.

[14] Indeed, countries whose energy suppliers are the least "locked in" to supplying Europe (in the sense of Europe accounting for a smaller share of their energy exports) experience the greatest improvement in geographic diversification of energy imports in response to higher carbon prices (Annex Figure 2.3, panel 2).

Figure 6. Effects of Illustrative Individual Climate Policy Instruments on Energy Security



Source: Authors' calculations.
Note: Panel 1 shows the deviation from baseline in the energy insecurity index of Cohen, Joutz, and Loungani (2011), modified to give European countries zero weight and other countries unit weight. Labels in the figure use International Organization for Standardization (ISO) country codes. BCR = Bulgaria, Croatia, and Romania; BNL = Belgium and The Netherlands; CSH = Czech Republic, Slovak Republic, and Hungary; FF = fossil fuels; REU = rest of Europe.

are again found mostly in the energy-intensive economies of Central and Eastern Europe (Annex Figure 2.3, panel 3). In Poland, energy expenditures rise relative to GDP because the coal-intensive electricity mix is rather rigid in the model, although in reality, it might prove more responsive to higher carbon prices.

- *Tighter regulations on energy efficiency* in road transport and buildings cause larger improvements in energy security compared to higher carbon prices, and they share them more evenly across European regions. As demand for natural gas for heating purposes falls for given domestic natural gas production, and as demand for (mostly imported) oil falls with more fuel-efficient road transport services, the dependence of energy consumption on imports falls. In this scenario, Europe also reduces the geographic concentration of its imports, including as imports from the United States fall. Because of this reduction in import dependence and geographic concentration, tighter regulations improve the composite energy supply insecurity index in all European regions (Figure 6, panel 1). Furthermore, lower energy demand means less energy spending, as less energy is used and energy prices fall (Figure 6, panel 2). By reducing both energy consumption and energy prices, tighter energy efficiency regulations reduce energy expenditures even more than do carbon prices.

- *Accelerated permitting for renewables* also improves energy security in all European regions, even though its effects are smaller. By increasing the supply of domestically produced energy, it brings down energy prices and expands economic activity, thereby improving economies' resilience to energy shocks (Figure 6, panel 2). Moreover, faster permitting reduces the risk of a disruption to foreign energy supplies, for two reasons. First, European energy importers replace their imports with domestically produced energy, particularly so in countries with greater wind and solar capacity to begin with (Annex Figure 2.4, panel 2). Second, faster permitting reduces the geographic concentration of energy imports, especially natural gas imports from the United States. Therefore, the composite energy supply insecurity index shows an improvement for all of Europe (Figure 6, panel 1).

- *Public investment in heat pumps* makes energy supply more secure but can raise energy costs if implemented in isolation. It leads to an expansion of electricity production, which replaces imported fossil fuels and hence reduces import dependency ratios. Demand for natural gas falls, especially from the United States, which tends to diversify energy imports in most of Europe. The latter effect is especially strong in the United Kingdom, because the United Kingdom is projected in 2030 both to import a high share of its energy from the United States and to have a high share of its gas consumption accounted for by households (44 percent). Therefore, the composite energy supply insecurity index improves for most European regions (Figure 6, panel 1). However, without a decarbonization of the power sector, energy expenditures rise relative to GDP (Figure 6, panel 2). This is because heat pumps increase demand for electricity, which in many countries drives up demand for gas from power plants. Since gas supply is rather inelastic, as evidenced by the challenges that Europe faced in increasing gas production during the 2022 energy crisis, this demand pushes up gas prices, and hence electricity prices. Rising energy costs are most noticeable in Poland, where the energy mix shifts from cheap gas (before heat pump investment) to more expensive electricity, and the Bulgaria/Croatia/Romania region, where the economy is relatively electricity-intensive and therefore energy expenditures are more sensitive to rising electricity prices.

- *Removing fossil fuel subsidies* has a negligible effect on energy security in most of Europe, given their small expected size by 2030, once the recent energy support measures taken in response to the war are fully phased out. The only two countries where they have a material impact are Germany and the United Kingdom, which tend to have the largest subsidies on fossil fuels relative to consumer expenditure thereon, reaching a tenth of the gas price in the United Kingdom and a quarter of the coal price in Germany (Annex Figure 2.5, panel 2). One important feature of European fossil fuel subsidies is that they tend to target production (50 percent of subsidies in the European Union) rather than consumption (35 percent), with the remainder targeting energy efficiency and research and development. As a result, while their removal slightly reduces GHG emissions (by 0.3 percent in the simulation) and benefits the economy, it causes domestic energy production to fall and energy import dependency to rise in Germany and the United Kingdom.[15] In addition, regardless of whether they are targeted at production or consumption, European fossil fuel subsidies tend to be skewed toward fuels that are produced domestically, like coal in Germany or gas in the United Kingdom. This means that, in the specific case of European economies, removing fossil fuel subsidies—even those to consumption—tends to raise the taxation of domestically produced energy even more than that of imported energy. Indeed, those European economies where fossil fuel subsidies are more skewed toward domestically produced energy products tend to experience a larger increase in import dependency when fossil fuel subsidies are removed (Annex Figure 2.5, panel 3).

[15] For a broader discussion of fossil fuel subsidies and the emission, GDP, and welfare benefits of their removal, see, for example, Burniaux and Chateau (2014) and Coady and others (2017). It is worth noting that removing fossil fuel subsidies has a different impact on import dependency from that of carbon taxation, for two reasons: (1) these subsidies are not equivalent to a negative carbon tax, because they are typically not based on the carbon content of each fuel; and (2) the peculiar design of key European economies' subsidies is such that they primarily benefit domestically produced fossil fuels. Indeed, import dependency ratios fall throughout Europe in a simple illustrative simulation under which countries impose a flat fossil fuel consumption tax (of 3 percent of the price of each fossil fuel), for example.

5. A Broad Policy Package

The varying emission reduction, economic efficiency, and energy security effects of different climate policy instruments strengthen the case for broad policy packages such as those currently being rolled out across Europe, including at the EU level. Carbon pricing is the economically efficient, least-cost way to meet ambitious GHG emission reduction goals. Sector-specific regulations, such as tighter emissions and energy efficiency standards for road transport and buildings, are not as cost-effective emission reduction tools, but they yield larger energy security gains that are also more widespread across countries. In particular, they also benefit energy- and emissions-intensive economies in Central and Eastern Europe. Finally, for investment in heat pumps to improve both dimensions of energy security, concomitant measures need to be taken to decarbonize the power sector, including accelerating permitting procedures for renewable power generation. Therefore, combining all these tools can simultaneously deliver on emission reduction, economic efficiency, and energy security objectives.

A. Calibrating a Broad Policy Package

To quantify the energy security effects of a broad set of climate change mitigation policies, an illustrative package is simulated. It is designed to capture the key features of climate change mitigation policies in the European Union, the United Kingdom, and EFTA, and targets an emissions reduction for Europe as a whole of 55 percent of 1990 levels by 2030. This level is in line with the emissions reduction targets in the European Union and Norway, but below the target in the United Kingdom and above that in Switzerland. The simulated package includes the following policies, which are in line with those examined in the preceding section, but typically set more ambitiously (see Annex 2 for details):

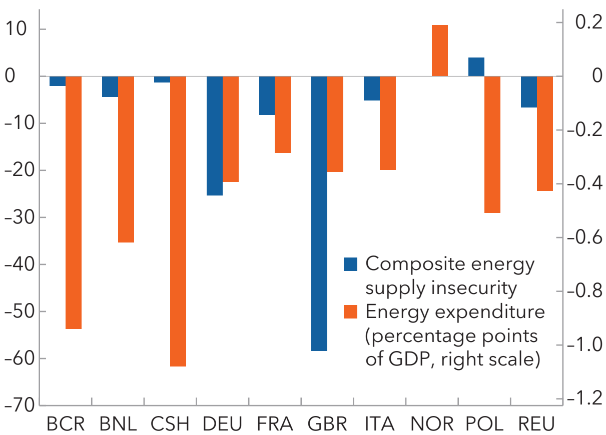
- *Higher carbon prices in electricity and manufacturing sectors*. Europe already has plans to increase its carbon prices over time, whether through the EU ETS, which also covers Norway and is linked to the Swiss ETS, or through the UK ETS, which covers similar sectors. Therefore, this component of the illustrative policy package assumes a steepening of these price paths. Carbon prices in the EU ETS, for example, are assumed to rise to €185 per ton in 2030 (rather than €33 in Baseline 1 and the EU Reference Scenario).
- *Tighter energy and emissions efficiency standards in road transport and buildings*. This element of the package captures Europe's tighter fuel-efficiency standards for new cars, vans, buildings, and heating systems, as well as target shares of electric vehicles, which vary across countries. These are calibrated to reduce energy demand in 2030, compared to baseline, by 13 percent in the transport services sector, 8 percent in the "other private services" sector (which includes real estate services), and 15 percent in households. It is assumed that firms improve their energy efficiency while households prefer less energy.
- *Accelerated permitting procedures for renewables*. This element of the package reflects efforts by many European countries to address this key bottleneck to the deployment of renewables. It is calibrated to result in 10 percent more wind and solar power generation in 2030 than in the baseline, as in the preceding section on individual policy scenarios.
- *Public investments in technologies like heat pumps that electrify households' energy consumption and enhance their energy efficiency*. Most national governments offer public support (for example, grants, tax rebates, or loans) for the purchase and installation of heat pumps and other renovations of residential buildings to enhance their energy efficiency. The European Union provides funding for residential building renovation too, in the form of coherence funds and the Recovery and Resilience Facility. The simulations approximate these policies through a further reduction in households' energy demand by 11 percent and an increase in their electricity demand.

B. Climate and Energy Security Impacts

The simulation results confirm that (1) the package would enhance energy security by reducing by at least 8 percent the risk of a disruption to Europe's foreign energy supply and the sensitivity of European economic activity to any energy disruptions, and (2) those gains would be widespread—even benefiting energy- and emission-intensive economies in Central and Eastern Europe, including the Bulgaria/Croatia/Romania and Czech Republic/Slovak Republic/Hungary regions. Specifically:

- *Security of supply*. The broad climate policy package reduces the composite energy supply insecurity index substantially for all European countries, except Poland, by 2030 (Figure 7, blue bars). The overall index for Europe drops by about 8 percent by 2030, reflecting underlying reductions in both import dependence and geographic concentration. As fossil fuel imports decline, dependence on imported energy falls in most of Europe, and by 0.6 percentage point overall (Annex Figure 2.6). The only exceptions are Poland and the Czech Republic/Slovak Republic/Hungary region, which substitute imports for their domestic production of fossil fuel–intensive oil products (covered by the EU ETS) and coal, respectively. Europe also reduces the share of its imports coming from the United States and increases that coming from Norway, which reduces energy import concentration by some 7 percent overall and by as much as 25 percent in Germany (Annex Figure 2.6). Italy lowers its concentration through reduced reliance on Africa, while the Czech Republic/Slovak Republic/Hungary group lowers it through cuts in imports coming from Eurasian and Middle Eastern regions.

Figure 7. A Broad Climate Policy Package Would Enhance Energy Security
(Percent deviation from postwar baseline, unless indicated otherwise)



Source: Authors' calculations.
Note: The composite index is from Cohen, Joutz, and Loungani (2011), but modified to give European countries zero weight and other countries unit weight. No composite energy supply insecurity index is shown for Norway because it is an energy exporter. Labels in the figure use International Organization for Standardization (ISO) country codes. BCR = Bulgaria, Croatia, and Romania; BNL = Belgium and The Netherlands; CSH = Czech Republic, Slovak Republic, and Hungary; REU = rest of Europe.

- *Economic resilience*. The broad climate policy package reduces Europe's ratio of energy expenditures to GDP by 10 percent of its baseline level (or by 0.4 percentage point, from 4.7 to 4.3 percent), with all European energy importers benefiting (Figure 7). The latter include energy- and emissions-intensive economies in Central and Eastern Europe, which gain from the energy efficiency investments driven by tighter road transport and buildings standards. In Norway, energy expenditures fall in nominal terms, but they rise relative to GDP because the economy becomes smaller as less energy needs to be produced domestically to export to the rest of Europe.

Poland stands out as the one country where the energy security benefits of a broad climate policy package are ambiguous: its energy spending share of GDP falls by 7 percent of its baseline level, but its composite energy supply insecurity index deteriorates by 5 percent. The latter reflects an increase in import dependence as domestically produced coal is phased out, with this effect outweighing the reduction in energy imports' geographic concentration in the Cohen-Joutz-Loungani index.[16] This deterioration would be

[16] It is worth noting here that alternative weighting schemes, which would assign greater weight to the geographic concentration component, could deliver a net improvement in Poland's security of supply.

modest, especially considering that Poland starts from a strong third place in Europe along this (security of supply) dimension in the postwar baseline and would remain a solid fourth under the broad policy package. Nonetheless, these results emphasize the importance of ramping up domestic electricity generation as coal is phased out. For example, the government's plan to increase the supply of renewables and/or nuclear energy could be helpful in this regard, as it would help replace domestically produced coal without increasing import dependence (IMF 2023c; Krogulski 2023). Poland's energy security could also be enhanced by expanding electricity interconnections with neighboring countries, which would increase imports of renewable electricity from safe European suppliers and thereby reduce risks from import dependence (European countries receive zero weight under the Cohen-Joutz-Loungani index used in this paper, unlike non-European countries; see Annex 1). For example, Poland could raise its 2030 interconnection target to 15 percent of electricity production, in line with the European Union's target. More broadly, deeper integration of electricity markets would improve energy security throughout Europe, as suggested by further model simulations (Box 1).

These simulation results complement those of Kim, Panton, and Schwerhoff (2024), who find that the world could enhance its energy security by raising carbon prices. In their analysis, higher global—rather than just European—carbon prices could increase the geographic concentration of energy exports and imports by lowering global fossil fuel prices and thereby driving high-cost producers out of the market, but this effect would be dominated by reduced reliance on imported energy (an effect also found in Jewell, Charp, and Riahi 2014). The broad European policy package simulated here does not affect global fossil fuel demand enough to affect materially global fossil fuel prices, implying that high-cost suppliers are not driven out of the market and thereby amplifying the energy security gains from Europe's climate action.

C. Overinvestment in Fossil Fuels

As it ramps up its climate policy action, Europe must guard against persistent overinvestment in public fossil fuel infrastructure along the green transition path—a material risk, according to the analysis in this paper. For example, simulations of the climate policy package in this paper suggest that Europe is broadly on track regarding its investments in climate-neutral power generation but is overinvesting in fossil fuels. Specifically, Europe's fossil fuel capital stock in 2030 is projected to be almost 20 percent larger than implied by the broad climate policy scenario that achieves a 55 percent emission cut. This cumulative overinvestment even reaches almost 40 percent for fossil fuel power generation (versus 15 percent in fossil fuel extraction). New investments in natural gas infrastructure can help maintain adequate supply of a bridging source of energy that will be phased out gradually by 2050 and provides a buffer against unforeseen disruptions. However, the 20 percent overinvestment figure coming out of the simulations points to the need for reexamining some of these projects.

To alleviate such risks of "carbon lock-in," Europe needs to exercise close regulatory oversight of fossil fuel investment plans, which are developed by industry associations with an informational advantage and an incentive to overstate investment needs. To date, this oversight seems inadequate—for example, most countries' national energy plans as of 2023 did not assess whether there could be overinvestment in oil infrastructure (European Commission 2023a). It is thus welcome that the Agency for the Cooperation of Energy Regulators (2023a) noted that the European Network of Transmission System Operators for Gas' proposed investments in gas infrastructure, at €110 billion in its plans from 2022, were "likely to exceed reasonable needs for such infrastructure, considering the expected reduction in gas demand in Europe from 2030." To combat overinvestment in natural gas infrastructure, policymakers could require that new gas infrastructure be "hydrogen-ready" (as in Germany) and provide appropriate definitions and regulations that govern the certification of this term. It is also essential to ensure that any government tax incentives for investment in coal or oil production or distribution be rapidly phased out.

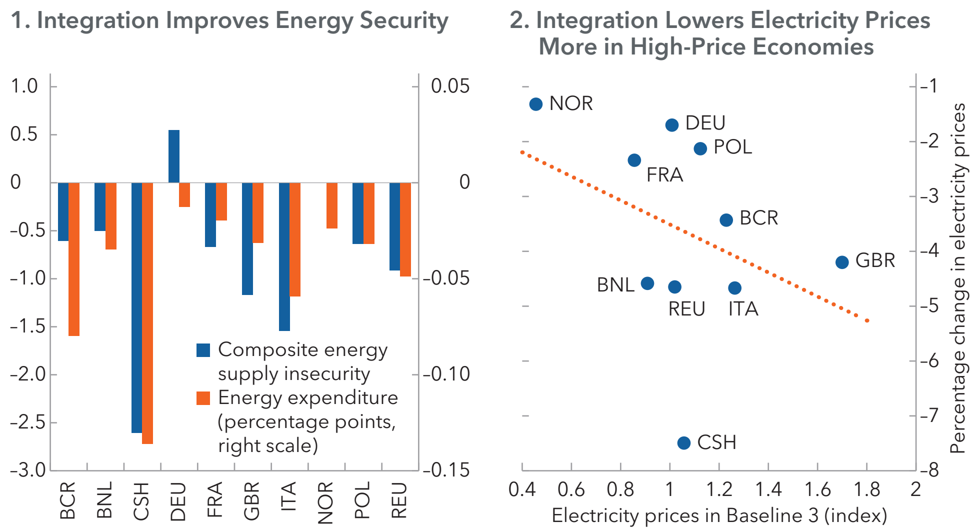
Box 1. Simulating a Closer Energy Union through Electricity Market Integration

Deeper integration of electricity markets in Europe, captured in the model by reduced trade costs, would increase electricity trade between European countries. The illustrative simulations, under which cross-border electricity trade increases by 50 percent, suggest that this integration would improve energy security along the two dimensions (security of supply and economic resilience) considered in this paper:

- *Security of supply*. Even though more electricity trade would increase import dependence, it would reduce the geographic concentration of energy imports among non-European suppliers. The net effect would be to reduce exposure to foreign supply disruptions in most of Europe, as measured by the composite energy supply insecurity index (Box Figure 1.1, panel 1).
- *Economic resilience*. Economies become less sensitive to energy supply disruptions because energy prices and hence energy expenditures fall (Box Figure 1.1, panel 1). The fall in electricity prices tends to be greater in economies that have higher electricity prices in the baseline (Italy, United Kingdom), because these have the most to gain from cheaper electricity imports as electricity market integration equalizes electricity prices across Europe (Box Figure 1.1, panel 2).

While a closer energy union enhances Europe's energy security, the simulations suggest that it has negligible effects on its greenhouse gas emissions, as would be expected. With electricity production shifting to more competitive economies like Germany and the Belgium/The Netherlands region, where electricity prices are lower in the baseline, emissions increase there by 0.3 percent, but fall symmetrically in other economies such as Italy (by 0.4 percent).

Box Figure 1.1. The Energy Security Impacts of Deeper Electricity Market Integration
(Deviation from baseline, percent unless indicated otherwise)



Source: Authors' calculations.
Note: In panel 1, the composite index is from Cohen, Joutz, and Loungani (2011), modified to give European countries getting zero weight and other countries unit weight. No composite energy supply insecurity index is shown for Norway because it is an energy exporter. The composite index is shown in percent deviation from the postwar baseline (Baseline 3), while the energy expenditure share of GDP is shown in percentage point deviation. Labels in the figure use International Organization for Standardization (ISO) country codes. BCR = Bulgaria, Croatia, and Romania; BNL = Belgium and The Netherlands; CSH = Czech Republic, Slovak Republic, and Hungary; REU = rest of Europe.

6. Conclusions and Policy Implications

The green transition requires a transformation of Europe's energy system. As this paper shows, this transition also provides a unique opportunity to enhance Europe's energy security after the recent energy crisis and decades of neglect. Ambitious climate policy action across Europe mitigates two fundamental sources of energy insecurity: the risk of foreign supply disruptions, by reducing reliance on imported energy and by diversifying energy supplies geographically among non-European suppliers; and the overall weight of energy expenditures in the economy, by curtailing energy demand. A broad policy package that would cut emissions by 55 percent vis-à-vis 1990 levels at the 2030 horizon by combining multiple instruments, including carbon pricing and sector-specific regulations, could enhance Europe's energy security along these two metrics by some 8 percent. It would also spread those gains widely across the continent.

In combining different instruments to meet their emission reduction objectives, European policymakers will face some partial trade-off between minimizing the economic costs and maximizing the energy security gains from their climate policy packages. In some cases, the choice will be straightforward; for example, the very small energy security gains from some fossil fuel subsidies cannot justify their adverse emission, economic, and distributive effects, all of which call for their removal. But in general, for a given reduction in GHG emissions, policymakers who put more weight on economic efficiency would make heavier use of carbon pricing, while those who are relatively more concerned about energy security would rely comparatively more on sector-specific emission and energy efficiency regulations. Such a trade-off also provides a rationale for the coexistence of multiple instruments and targets, over and above an overall emission reduction objective. For example, the European Union's 2030 renewables and energy efficiency targets, and any future revisions of these as new emission reduction goals are set for 2040, can help the European Union achieve its preferred combination of economic efficiency and energy security along its decarbonization path.[17]

The heterogenous energy security gains from climate action across countries also highlights the need for greater multilateral cooperation on energy in Europe. In particular, deeper integration of European electricity markets would improve energy security across the continent by diversifying energy imports from non-European suppliers and reducing energy prices (Box 1). In the European Union, this means pursuing the Energy Union. The European Union has achieved some successes in electricity market integration, especially in the coupling of the day-ahead electricity markets—by allowing prices in every market and cross-border trades to be simultaneously determined, it ensures that more interconnection capacity is used to send electricity from low- to high-price zones, reducing cross-country differentials in wholesale electricity prices. However, further progress is needed to connect electricity grids between EU member states. For example, seven of them do not yet meet the European Union's target of having sufficient cross-border capacity to export 15 percent of their electricity production to neighboring countries (European Commission 2023b).

More broadly, energy policies, which remain a predominantly national rather than EU-level competency, could be better coordinated. Most member states, for example, still need to set targets to measure progress toward the European Union's energy import diversification objectives. Furthermore, power capacity mechanisms—which provide financial compensation for power plants to be available for generating electricity when needed—differ from country to country (Roques 2021). Steps toward harmonizing and integrating these mechanisms across countries would help minimize the associated market distortions. Such steps could include standardizing the reliability criteria—which gauge the ability of the power system to deliver as

[17] The finding that multiple policy instruments are needed to achieve multiple policy objectives—here, energy security, emissions reduction, and economic efficiency—echoes a general principle in economics called the Tinbergen Rule.

needed through foreseeable and unforeseeable events—across countries, developing common methodologies for "resource adequacy assessments," and establishing rules for dealing with electricity shortages in two neighboring countries.

Multilateral cooperation could also be strengthened through joint financing arrangements, which could abate European emissions at minimum cost while spreading the economic and energy security gains from climate policy action more evenly. An EU-level fund for energy security and climate could help fund projects to decarbonize private capital, like buildings, and develop new technology, both of which are key yet might otherwise remain underfunded due to low domestic returns or allocated inefficiently across member states. Such a fund has been proposed, for example, by Arnold and others (2022) and Abraham, O'Connell, and Arruga Oleaga (2023). The model simulations in this paper suggest that energy- and emissions-intensive economies in Central and Eastern Europe enjoy smaller energy security co-benefits from climate change mitigation action, and also happen to have lower marginal abatement costs of GHG emissions in many cases. By supporting investments in these economies, an EU-level fund could enhance their energy security and economic gains from climate action while accelerating Europe's green transition at low cost, thereby also benefiting the Western European countries that might be net contributors to such a fund.

Annex 1. The Composite Energy Insecurity Index

This annex shows that the composite energy insecurity index of Cohen, Joutz, and Loungani (2011) is approximately equal to the weighted average of two other commonly used energy insecurity indicators: energy import dependence and the geographic concentration of energy imports.

The composite energy insecurity index is defined for a given importing country in a given year as

$$\sum_{\text{supplier country } i} \left(\frac{(\text{net positive energy imports})_i}{\text{energy consumption}} \right)^2,$$

where the summation runs across each *non-European* energy supplier *i*, and net positive energy imports denotes imports net of exports if these are positive, otherwise zero. This definition is equivalent to that proposed in Cohen, Joutz, and Loungani (2011), except that, while those authors use a political risk index taken from the International Country Risk Guide, the definition here assigns zero risk to European countries and equal (unit) risk weight to all non-European supplier countries. The rationale for this choice of weighting scheme is explained in the main text.

The reason that this index can be considered as a combination of import dependence and geographic concentration is that it can be written equivalently as

$$\left(\frac{\text{total net positive energy imports}}{\text{energy consumption}} \right)^2 \left[\sum_{\text{supplier country } i} \left(\frac{(\text{net positive energy imports})_i}{\text{total net positive energy imports}} \right)^2 \right],$$

where total net positive energy imports is defined as the sum (across *non-European* supplier countries *i*) of net positive energy imports. The first ratio within the round brackets is similar to import dependence (although imports from European countries get zero weight), which is then squared, and the term in square brackets is similar to the (risk-weighted) Herfindahl index of geographic import concentration (assigning European countries zero risk and non-European countries an equal unit risk weight). One key distinction should be highlighted here: the first term in round brackets gives zero weight to imports from European countries, whereas the rest of this paper shows the standard import dependence ratio, which does not differentiate between European and non-European imports.

In other words, the composite index is approximately equal to

$$(\text{import dependence})^2 \, [\text{geographic import concentration}].$$

Therefore, the cube root of the composite index is approximately equal to

$$(\text{import dependence})^{2/3} \, [\text{geographic import concentration}]^{1/3},$$

which shows that the (cube root of the) composite index is approximately equal to a weighted (geometric) average of import dependence and geographic import concentration, with a weight of two-thirds placed on import dependence and one-third on geographic import concentration.

The approximation will be better for countries that are net energy importers (because then net positive energy imports are similar to net energy imports), especially those who are net energy importers with respect to each trading partner. Conversely, the approximation might be worse for energy exporters or for countries that are heavily engaged in energy re-export activity (that is, importing energy from one supplier country and then re-exporting it to other consumer countries).

Annex 2. Further Calibration Details and Simulation Results

This annex provides further details on the calibration of each scenario and their simulated energy security impacts. To save space, it is not self-contained and should be read jointly with the main text.

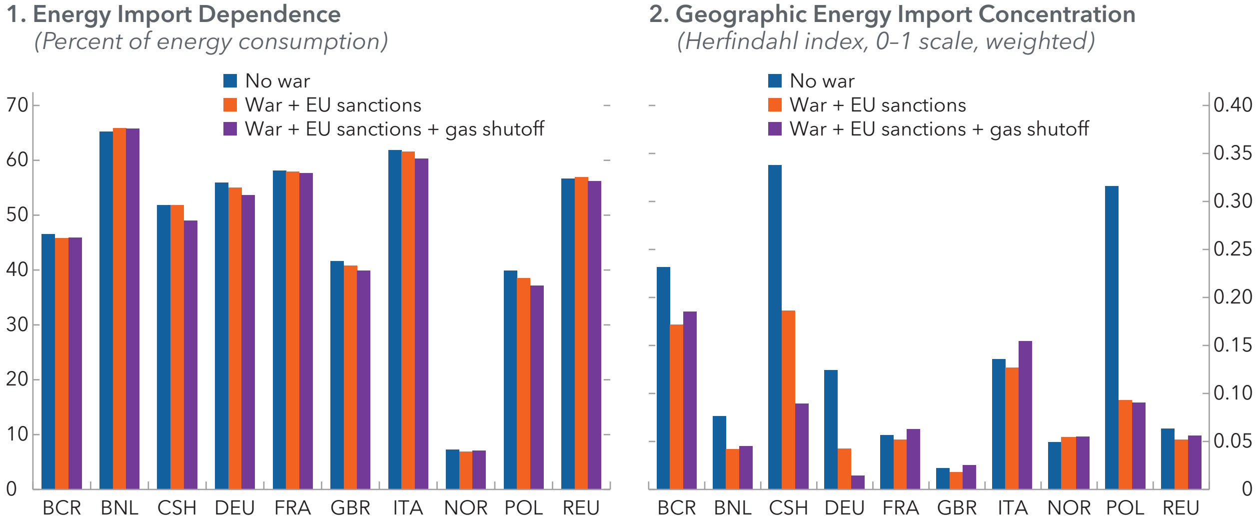
A. Calibrating the Effects of the War

Three baseline scenarios are used in this analysis, as defined in the main text. Energy intensity and productivity of power generation technologies are the same in all baseline scenarios. All electricity and non-energy trade in the prewar baseline (Baseline 1) is calibrated to match the Global Trade Analysis Project database version 11. All historical and projected economic variables have been averaged to the regional country groupings in the model using purchasing-power-parity GDP-weighted averages. The economy is assumed to be on a steady state growth path after 2027, meaning that GDP continues growing at its 2027 rate and current account balances are maintained at 2027 levels. The second baseline scenario (Baseline 2) assumes no change to natural gas trade, but European countries phase out Russian oil and coal by 2030. Economic variables follow their projections in the IMF's April 2022 *World Economic Outlook* (IMF 2022b), which reflect the impact of the war and European sanctions on Russia but do not assume any shutoff of Russian gas supplies to Europe.

The postwar baseline scenario (Baseline 3) adds the Russian gas shutoff to Europe to Baseline 2, which therefore accounts for all developments so far associated with the war. Given that Eurostat's annual bilateral energy trade data for 2022 and 2023 were not yet available at the time of this analysis, the geographic distribution of natural gas imports (that is, "import shares") after the Russian gas shutoffs had to be estimated using the available monthly bilateral gas trade data up to June 2023. The annual gas import shares in 2022 were assumed to match those in 2021 for most countries, except for those where the available monthly data show a significant change in Russian gas imports. A significant change was defined here to be a 15 percent reduction in Russian gas imports between 2022:Q4 and the average for the fourth quarters of 2017–21. According to this definition, the following countries saw material declines in their Russian gas imports in the monthly data: Croatia, Estonia, Finland, Germany, Latvia, The Netherlands, North Macedonia, Poland, Portugal, and Sweden, as well as the European Union as a whole. For these affected countries, the immediate postwar gas imports from Russia are estimated by adjusting down the imports from 2021 (from the annual data) by the percentage change in the bilateral gas imports from Russia between 2022:Q4 and the average for the fourth quarters of 2017–21. In Baseline 3, economic variables follow their projections in the IMF's April 2023 *World Economic Outlook* (IMF 2023d), which account for Russian gas shutoffs. Furthermore, GHG emissions and electricity mix in Baseline 3 are allowed to vary endogenously in response to the shocks of the war, which means that they are not calibrated and therefore differ from those assumed in Baseline 1.

The evolution of energy security under these different baseline scenarios is discussed in the main text. Annex Figure 2.1 shows the model's simulated effects of the war on energy import dependence and geographic import energy import concentration under the three baseline scenarios in 2030. The war leads to a reduction of energy import dependence in all of Europe, compared to the prewar baseline, whereas it reduces the geographic concentration for all European regions except Italy and France.

Annex Figure 2.1. The War Tended to Reduce the Risk from Abroad of Disruptions to Europe's Energy Supply in the Medium Term



Source: Authors' calculations.
Note: Panel 2 shows the weighted Herfindahl index where European supplier countries get zero weight and other countries get unit weight. Labels in the figure use International Organization for Standardization (ISO) country codes. BCR = Bulgaria, Croatia, and Romania; BNL = Belgium and The Netherlands; CSH = Czech Republic, Slovak Republic, and Hungary; REU = rest of Europe.

B. Calibrating Different Climate Policies

This subsection provides further calibration details and impacts on energy import dependence and geographic energy import concentration of the individual climate policy scenarios.

Higher Carbon Prices on Current ETS Sectors

This scenario simulates the impact of higher carbon prices on power generation and industry, which are the main sectors currently included in the EU and UK ETS. Carbon prices are raised so that the EU/EFTA region and the United Kingdom each achieve emissions reductions of 4 percent. Carbon pricing revenue is assumed to be returned to households in the form of labor tax reductions, so the carbon pricing schemes are fiscally neutral.

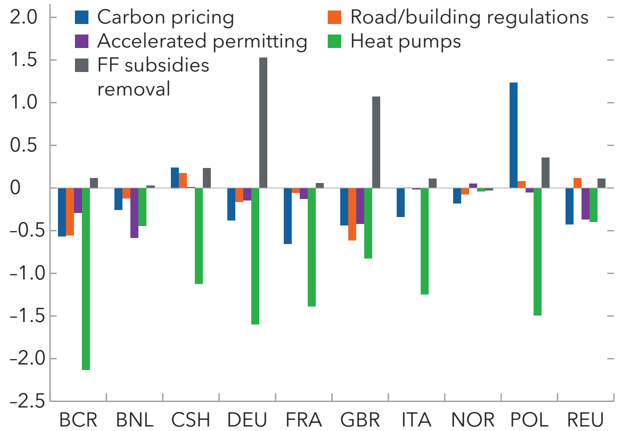
The results of this scenario simulation are discussed in the main text, but Annex Figure 2.2 shows the impacts on import dependence and geographic concentration. Energy import dependence tends to fall because Europe's domestic energy production tends to be cleaner than its imported energy, meaning that higher carbon prices cause substitution toward domestic energy sources. These effects are stronger in countries with dirtier energy imports relative to domestic energy production (Annex Figure 2.3, panel 1). At the same time, higher carbon prices diversify Europe's energy imports geographically across non-European suppliers (Annex Figure 2.2, panel 2), mainly driven by lower shares of energy imports from the United States (and Africa, in the case of Italian imports). These diversification effects are stronger for countries whose suppliers are less locked in to supplying Europe (Annex Figure 2.3, panel 2).

Tightened Energy and Emissions Efficiency Standards for Road Transport and Buildings

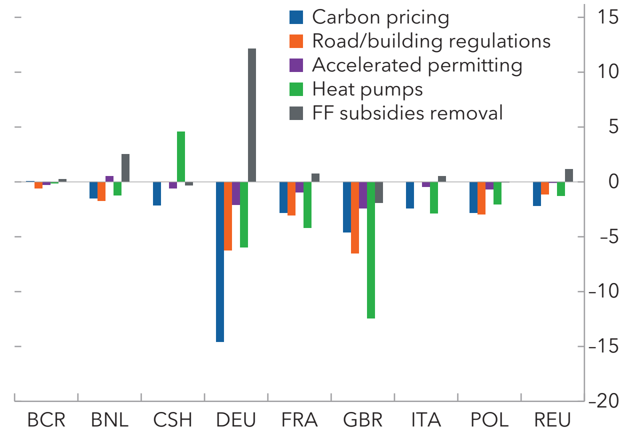
Emission reductions resulting from tighter standards are modeled as a technological improvement in energy efficiency, which is associated with an annual cost in the form of forced investment that does not add to the production potential of the economy. To calibrate the overall cost, which ends up being 2.8 percent of gross fixed investment per year between 2023 and 2030, the key assumption is that transport emissions fall by

Annex Figure 2.2. Effects of Individual Climate Policy Instruments on Europe's Security of Supply

1. Energy Import Dependence
(Percent of energy consumption)



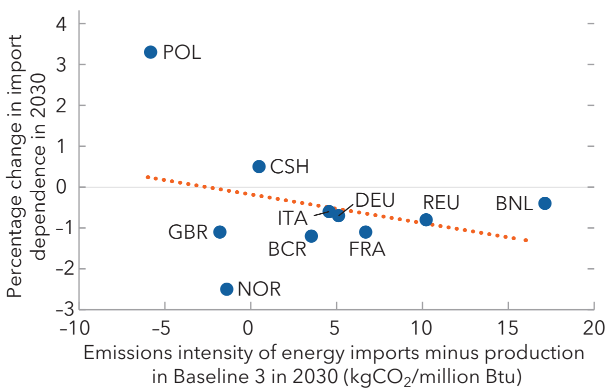
2. Geographic Energy Import Concentration
(Percent deviation from baseline, weighted)



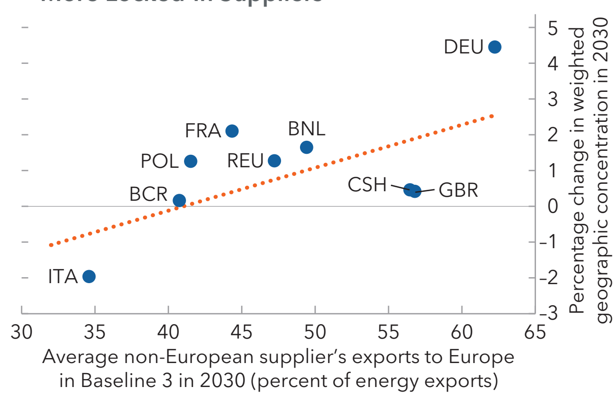
Source: Authors' calculations.
Note: In panel 2, European supplier countries get zero weight and other countries get unit weight. Labels in the figure use International Organization for Standardization (ISO) country codes. BCR = Bulgaria, Croatia, and Romania; BNL = Belgium and The Netherlands; CSH = Czech Republic, Slovak Republic, and Hungary; FF = fossil fuels; REU = rest of Europe.

Annex Figure 2.3. Determinants of the Effect of Carbon Pricing on Energy Security

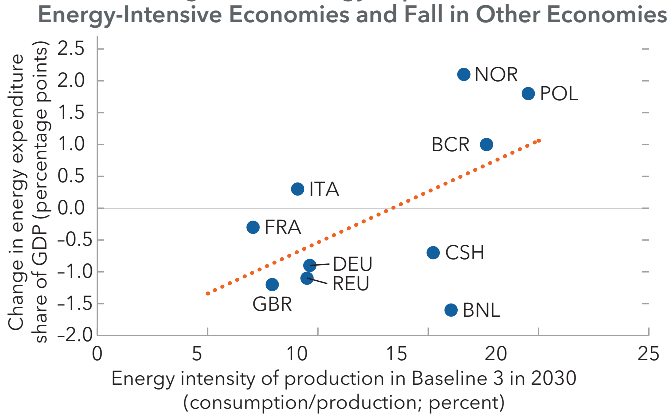
1. Carbon Prices Cause Import Dependence to Fall More in Countries with Dirtier Imports



2. Carbon Prices Cause Geographic Concentration of Energy Imports to Fall by Less in Countries with More Locked-In Suppliers



3. Carbon Pricing Causes Energy Expenditure to Increase in Energy-Intensive Economies and Fall in Other Economies



Source: Authors' calculations.
Note: Variables on the horizontal axes are from Baseline 3 in 2030. The vertical axes show the change, in percent or percentage points in 2030, between Baseline 3 and the individual policy scenario with higher carbon prices. Labels in the figure use International Organization for Standardization (ISO) country codes. BCR = Bulgaria, Croatia, and Romania; BNL = Belgium and The Netherlands; Btu = British thermal unit; CSH = Czech Republic, Slovak Republic, and Hungary; kgCO$_2$ = kilogram of carbon dioxide equivalent per kilogram; REU = rest of Europe.

8 percent relative to baseline and buildings emissions fall by 5 percent, in both the EU/EFTA region and the United Kingdom. (Together, these are sufficient to add up to a 4 percent reduction of overall emissions in both the EU/EFTA region and the United Kingdom.) In turn, these emissions reductions are calibrated to cost 0.6 percent of gross fixed investment in the case of road transport and 2.2 percent in the case of buildings, which add up to the 2.8 percent total cost. The costs for each sector are estimated as follows:

- *Road transport energy efficiency investments that reduce the sector's emissions by 8 percent are assumed to cost about 0.6 percent of European fixed investment*. Tighter regulations on road transport, which produce emissions reductions of 4 to 11 percent, would cost vehicle manufacturers €400 to €2,700 per vehicle (European Commission 2017a). Averaging across these ranges suggests that an emissions reduction of around 8 percent corresponds to an average cost to manufacturers of €1,550 per vehicle. This cost estimate is multiplied by an estimate of the number of newly registered vehicles in the European Union, the United Kingdom, and EFTA countries between 2023 and 2030. There were 14.5 million newly registered vehicles (12.7 million cars and 1.9 million trucks) in 2021, at which rate there would be 116 million newly registered vehicles between 2023 and 2030, yielding a cumulative cost of €180 billion, or 0.6 percent of the €3.5 trillion in gross fixed investment per year. The costs to consumers are assumed to be zero as the higher cost of more fuel-efficient vehicles is offset by the lower running costs associated with fuel efficiency.

- *Buildings energy efficiency investments that reduce the sector's emissions by 5 percent are assumed to cost about 2.2 percent of European fixed investment*. Energy renovation projects in the European Union and United Kingdom between 2012 and 2016 reduced annual buildings emissions by 12 percent at a cumulative cost of €1,365 billion (European Commission 2019). Therefore, scaling these numbers down linearly, a reduction of buildings emissions by 5 percent would require cumulative energy renovation investments (over the 2023–30 period) of about €570 billion in the European Union and United Kingdom, or about €610 billion in the European Union, the United Kingdom, and EFTA combined (scaling up by GDP), which is 2.2 percent of fixed investment per year. The large cost estimate here reflects the implicit assumption that no energy renovations would have taken place in the absence of a need for decarbonization, which is required due to a lack of data on counterfactual buildings investments. Therefore, the GDP impacts of this scenario are likely to be lower than simulated here.

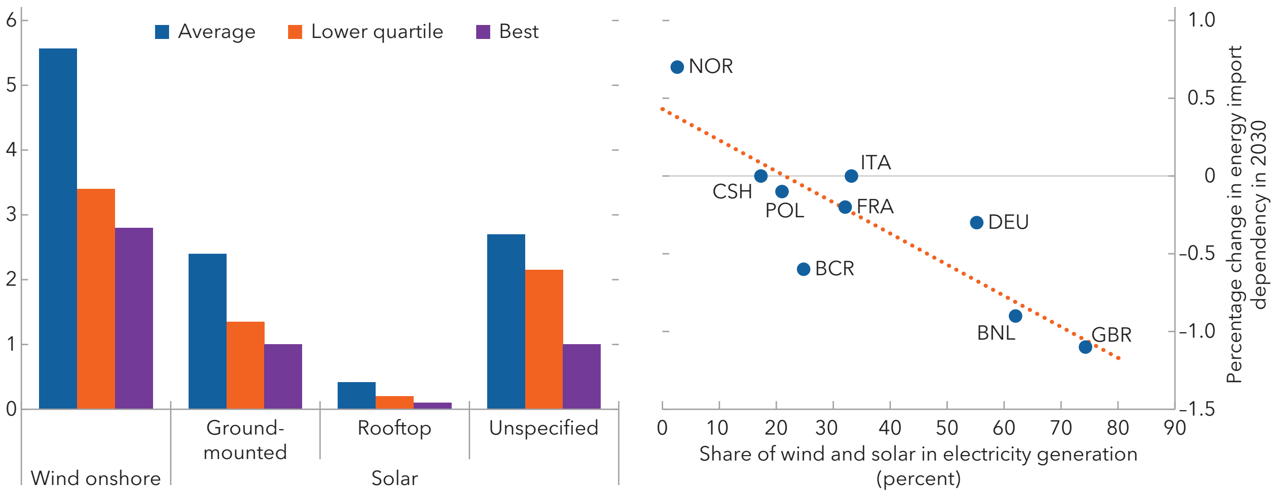
To meet these emissions reduction goals, it is assumed that energy demand falls in road transport and buildings by 8 and 5 percent, respectively, relative to baseline, thus matching one-for-one the percentage decline in emissions. This one-for-one response of energy demand is supported by the simulations for vehicles in European Commission (2017b). Furthermore, it is assumed that the "other private services" sector accounts for buildings emissions in the model, which means that this sector is calibrated to reduce its emissions and energy demand by 5 percent. (This assumption is supported by the fact that the services sector, including real estate services, owns the vast majority of the building capital stock, according to Organisation for Economic Co-operation and Development [OECD] data.) In the model, road transport emissions are generated by both the transport services sector and by households. In turn, it is assumed that energy demand and emissions fall by 13 percent relative to baseline in the transport services sector and by 8 percent in households. These reductions in energy demand are assumed in both the EU/EFTA region and the United Kingdom.

The simulation results suggest that tighter energy and emissions efficiency standards produce energy security co-benefits that are more evenly shared across European regions than in the case of carbon pricing. Specifically, as demand for natural gas for heating purposes falls, with no reduction in natural gas production, the dependence of energy consumption on imports falls (Annex Figure 2.2, panel 1). Geographic concentration of energy imports falls, driven by lower European energy imports from the United States (Annex Figure 2.2, panel 2).

Annex Figure 2.4. Permitting Procedures Duration and Effects of Accelerating Them

1. Permitting Procedures Duration
(Years)

2. Faster Permitting Causes Energy Import Dependence to Fall More in Countries with More Existing Installed Wind and Solar Capacity



Sources: Tallat-Kelpšaitė and others (2022); and authors' calculations.
Note: In panel 2, the share of wind and solar generation is from Baseline 3 in 2030. The percentage change in import dependency is between Baseline 3 and the scenario with accelerated permitting procedures. Labels in the figure use International Organization for Standardization (ISO) country codes. BCR = Bulgaria, Croatia, and Romania; BNL = Belgium and The Netherlands; CSH = Czech Republic, Slovak Republic, and Hungary; REU = rest of Europe.

Accelerated Permitting Procedures

This scenario assumes that permitting procedures for renewables are sped up by 40 percent in Europe, which means that the baseline path of development of renewable power generation capacity is achieved 40 percent sooner. The 40 percent potential speed-up is calculated as the average, across different renewable energy technologies (onshore wind, ground-mounted solar, and unspecified solar), of the percentage difference between the average European permitting duration and that of the country at the fastest 25th percentile of the sample, as shown in Annex Figure 2.4, panel 1. For onshore wind for example, the average European country takes 5.6 years to process permitting applications, whereas Spain, the country at the fastest 25th percentile of the sample, takes just 3.4 years, which is 39 percent faster.

The simulations indicate that faster permitting reduces the risk of a disruption to foreign energy supplies, for two reasons. First, European energy importers replace their imports with domestically produced energy (Annex Figure 2.2, panel 1), with stronger effects in countries with more wind and solar capacity to begin with (Annex Figure 2.4, panel 2). Second, faster permitting reduces the geographic concentration of energy imports among non-European suppliers (Annex Figure 2.2, panel 2), driven especially by lower natural gas imports from the United States.

Public Investment in Residential Heat Pumps

This policy assumes that about 22 million heat pumps are installed in residential buildings in Europe. These heat pumps are calibrated to reduce households' energy demand by 6 percent overall. This 6 percent reduction comes from assuming that about 8 percent of residential dwellings receive a heat pump, which cuts their gas consumption to zero and increases their electricity consumption by 20 percent of the energy that they were previously using in the form of gas. To achieve this 6 percent energy demand reduction, EU and EFTA households reduce their demand for coal and gas by 50 percent and increase their electricity demand by 15 percent, while UK households reduce their demand for coal and gas by 16 percent and increase their electricity demand by 7 percent. The cost for the whole of Europe is calibrated at €126 billion, or 0.4 percent of gross fixed investment per year between 2023 and 2030. This implies a cost per heat pump of €5,645. In turn, this number is the product of the average cost of space and water heating heat pumps from the EU Reference Scenario Technology Assumptions (De Vita and others 2021), €784 per kilowatt, and the average capacity of a heat pump, 3.6 kilowatts, and then doubled to reflect the labor costs of installation.

The simulation results suggest that investment in heat pumps reduces the risk of a disruption to foreign energy supplies. To meet the higher demand for electricity, Europe expands its electricity production, which replaces imported fossil fuels and reduces import dependency ratios (Annex Figure 2.2, panel 1). Geographic concentrations of energy imports fall in most of Europe (Annex Figure 2.2, panel 2), driven by lower imports from the United States. The one exception here is the Czech Republic/Slovak Republic/Hungary region, where household income gains cause oil imports to increase, and these imports are highly geographically concentrated (in other Eurasian countries).

Removal of Fossil Fuel Subsidies

One challenge faced by this study was the lack of timely and comprehensive data on fossil fuel subsidies (including tax exemptions) by European countries. The approach taken here was to calibrate fossil fuel subsidies for each country and fuel, and to distinguish between production and consumption subsidies, according to the data in Rademaekers and others (2020), and for the United Kingdom, using data published by the OECD. The fossil fuel subsidies data apply to the year 2018, which means that this study assumes that these 2018-level subsidies are maintained in the baseline until 2030.

The OECD fossil fuel subsidies for France, Germany, and Italy do not differ systematically from the European Commission data. For example, the OECD data show higher fossil fuel subsidies than the European Commission data for Italy, but lower subsidies for Germany and France. This pattern suggests that the OECD data for the United Kingdom are sufficiently comparable with the European Commission data for other European countries.

These data provide nominal fossil fuel subsidies (that is, subsidies in euros) according to two different classifications. The first is by fossil fuel, breaking down subsidies into those directed at oil, gas, and coal. The second breakdown is by beneficiary, breaking down subsidies into those targeting energy consumption and those targeting energy production. Since the data do not provide a joint breakdown along these two dimensions, the two distributions are assumed to be independent of each other.

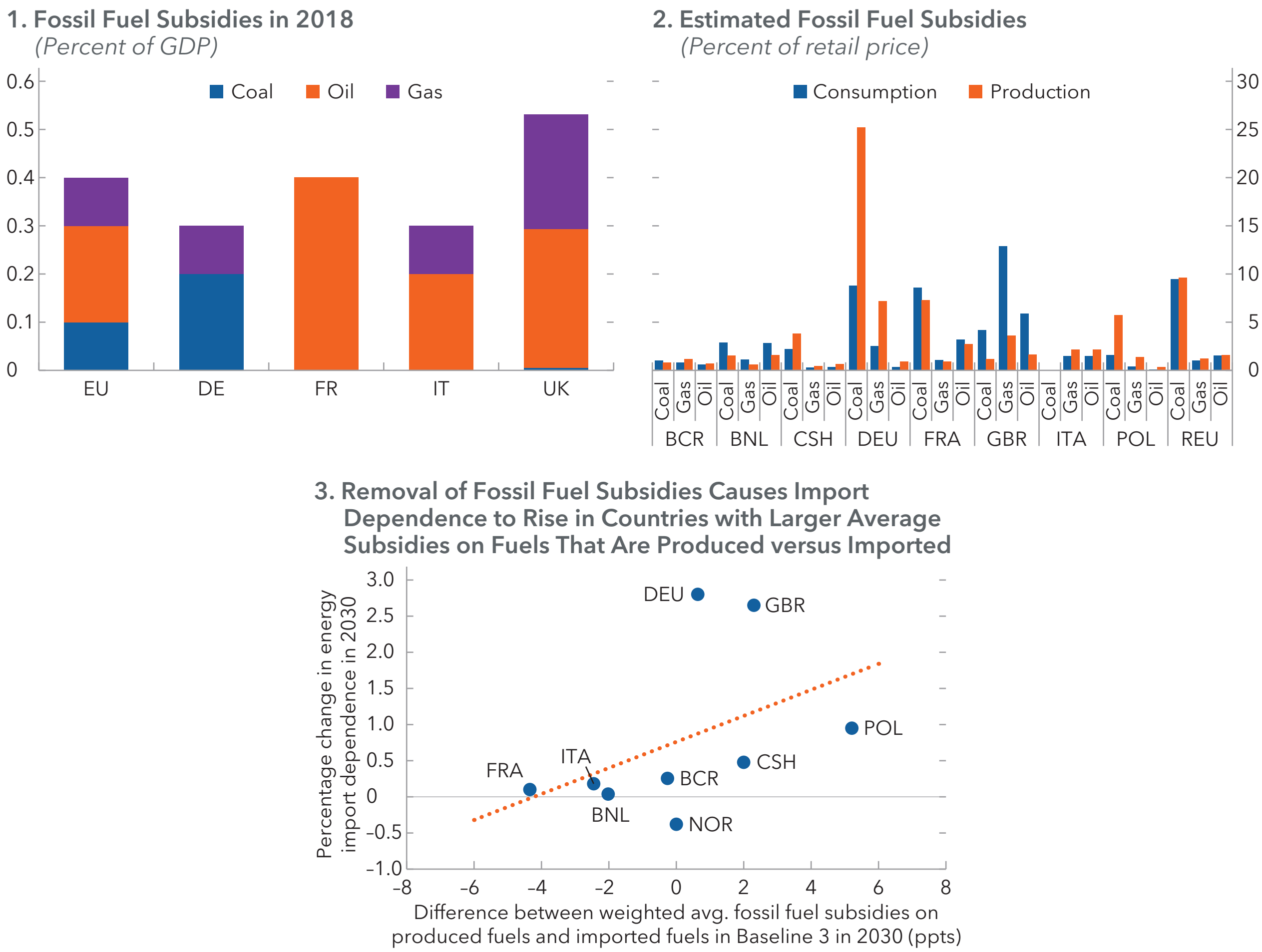
To express these subsidies in percent of each country's retail price, which are needed for the model, the value of each category of subsidy (in euros) is divided by the consumption (in joules) of that fossil fuel, where consumption data are taken from the IMF's Climate Policy Assessment Tool. Then, the resulting subsidy (in euros per joule) is divided by the retail price of that fuel, also taken from the Climate Policy Assessment Tool (in euros per joule). Finally, the resulting subsidies in percent of the retail price are split into consumption and production subsidies in proportion to the split in the data for energy subsidies (in euros). The resulting subsidies are shown in Annex Figure 2.5, panels 1 and 2.

For example, following this method, the United Kingdom's subsidies for gas consumption were about €4.5 billion (0.2 percent of GDP) in 2018. This amounts to some 1.7 euros per gigajoule of domestic gas use, or 13 percent of the retail price.

C. Calibrating a Broad Policy Package

This section provides further detail on the calibration of the broad climate policy package scenario, which is described in the main text. This package includes four of the individual policies presented earlier: higher carbon prices in ETS sectors, tighter emissions and energy efficiency standards for road transport and buildings, accelerated permitting procedures for renewables, and public investment in residential heat

Annex Figure 2.5. Fossil Fuel Subsidy Levels and Effects of Removing Them



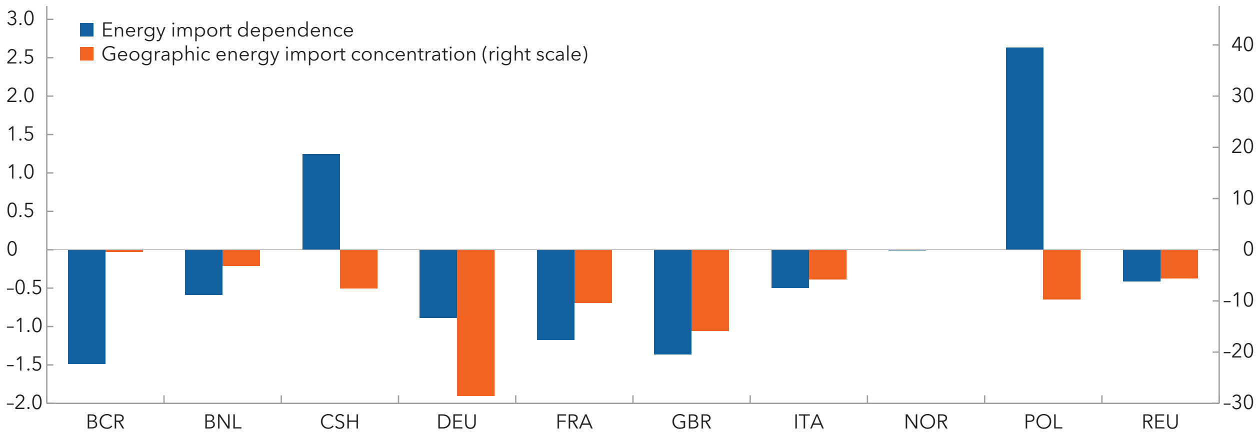
Sources: European Commission; International Institute for Sustainable Development; and authors' calculations.
Note: In panel 2, fossil fuel subsidies include subsidies on both production and consumption. The horizontal axis shows the difference between two weighted averages of these total fossil fuel subsidies: (1) weighted by the domestically produced fuel mix and (2) weighted by the imported fuel mix. Labels in the figure use International Organization for Standardization (ISO) country codes. BCR = Bulgaria, Croatia, and Romania; BNL = Belgium and The Netherlands; CSH = Czech Republic, Slovak Republic, and Hungary; ppts = percentage points; REU = rest of Europe.

pumps. These policies are combined to form a policy package that captures the key features of climate change mitigation policies in the European Union, the United Kingdom, and EFTA, and targets an emissions reduction for Europe as a whole of 55 percent of 1990 levels by 2030.

The individual policy instruments in the package are calibrated with reference to the magnitudes in the Fit for 55 proposals, which tend to be larger than the individual policy scenarios discussed previously. The key magnitudes are provided in the main text; this section provides further detail.

- Carbon prices in the ETS are 1.5 times higher than in the individual policy scenario (€185 versus €110 in the European Union). This reflects that the impact assessment for the European Union's ETS Directive (European Commission 2021) found EU-wide emissions reductions of about 7 percent, which are about 1.7 times higher than the (4 percent) emissions reductions in the individual policy carbon pricing scenario discussed earlier.

Annex Figure 2.6. A Broad Climate Policy Package Improves Europe's Security of Energy Supply
(Percent deviation from baseline)



Source: Authors' calculations.
Note: The figure shows the deviation from baseline in energy import dependence (in percentage points) and weighted geographic energy import concentration (in percent). The latter gives European countries zero weight and other countries unit weight. No geographic import concentration is shown for Norway because it is an energy exporter. Labels in the figure use International Organization for Standardization (ISO) country codes. BCR = Bulgaria, Croatia, and Romania; BNL = Belgium and The Netherlands; CSH = Czech Republic, Slovak Republic, and Hungary; REU = rest of Europe.

- Energy and emissions efficiency regulations on road transport and buildings are calibrated to reduce energy demand by about 1.8 times as much as in the individual policy scenario for road transport and buildings (that is, by 15 percent versus 8 percent for households and by 8 percent versus 5 percent in the "other services" sector). The impact assessment for the European Union's ETS Directive (European Commission 2021) found that when the European Union extends its carbon pricing to road transport and buildings, it would achieve an EU-wide emissions reduction of 10 percent relative to the EU Reference Scenario; 10 percent is about 2.5 times the (4 percent) emissions reduction in the individual policy scenario for road transport and buildings regulations discussed earlier. In the simulations here, a factor of only 1.8, rather than 2.5, is needed to achieve the overall 55 percent emissions reduction objective. The cost of the sector-specific regulations is calibrated to be 5.8 percent of gross annual fixed investment, which is about 1.8 times the cost in the individual policy scenario for road transport and buildings regulations.
- Public investment in residential energy efficiency programs is calibrated to reduce household energy demand by 11 percent, which would be broadly similar to the 11.7 percent energy saving objective in the European Union's Energy Efficiency Directive. This 11 percent energy savings is approximately 1.5 times the energy savings in the individual policy heat pumps scenario. Similarly, costs are assumed to be 1.5 times higher than in the individual policy heat pumps scenario, or 0.6 percent of gross annual fixed investment.

The simulation results suggest that this broad policy package reduces the dependence on imported energy in most of Europe (Annex Figure 2.6, blue bars), given that emissions-producing fossil fuels tend to be imported. Europe's imports fall by 0.6 percentage point of consumption, from 51.8 to 51.2 percent. Europe tends to reduce its US energy imports and partially replace them with Norwegian imports, which greatly reduces geographic concentrations of imports among non-European suppliers (Annex Figure 2.6, yellow bars). Europe's energy imports become 7 percent less concentrated, with the weighted Herfindahl index falling from 0.042 to 0.039.

Annex 3. Wider Policy Needs for the Green Transition

For both climate change mitigation and energy security purposes, Europe needs a broader set of policies than examined in the previous modeling exercises. At a broad conceptual level, the case for further government intervention rests upon the need to address various unpriced externalities (not only with respect to climate and energy security, but also network effects in electricity, learning-by-doing in renewables) and market imperfections (information asymmetries regarding the energy efficiency gains from certain investments; financial constraints to massive green infrastructure scaling-up; weak market competition in electricity, transport, and some critical minerals for the green transition; imperfect credibility of future climate policy). In practice, key issues for policymakers include how to encourage the vast quantities of private investment needed to transform energy systems and how to address the intermittency of renewables. To address these challenges, policies will have to support the adoption of new technologies like green hydrogen, design markets that encourage appropriate private sector investment, and enhance the security of critical mineral supplies. This annex briefly reviews key challenges and suggests specific reforms in each of these three areas.

A. Supporting Technologies to Address Intermittency

To achieve its goals of climate neutrality, Europe will need to electrify much of its energy consumption and meet its baseload electricity demand with renewables and nuclear. However, electricity demand at peak times will increase even as fossil-fuel-powered electricity plants are phased out. This means that Europe will need to find large quantities of "flexibility" in the form of zero carbon dispatchable power or demand-reduction measures. The following technologies are expected to be critical for energy security and climate change mitigation:

- *Batteries*. Grid-scale battery storage will be needed to manage intraday and daily balancing, due for example to the intermittency of renewable electricity production. In Europe, 41 gigawatts of new battery capacity are estimated to be needed by 2040, in addition to the 126 gigawatts estimated to be installed by 2030 (ENTSO-E 2023a). Support mechanisms for pumped hydro and battery storage, like capacity auctions, could provide the revenue predictability needed to expand investment (IEA 2023b). Regulatory frameworks should improve incentives for investment in batteries by ensuring a level playing field between batteries and power producers. For example, they can be allowed to offer ancillary services[18] (like maintaining stable voltage levels) and, like power producers, they can have taxes or fees (like network fees) levied only once when electricity is supplied to the grid instead of levying them also when the batteries are drawing electricity from the grid. In March 2023, the European Commission adopted these recommendations for action by member states (European Commission 2023d).

- *Hydrogen*. Green hydrogen will be needed to store energy between seasons (for example, to provide electricity in winter when heating demand is higher), to import energy by sea from faraway countries, and for hard-to-electrify production activities like steelmaking or aviation transport. Some 4–5 terawatts of hydrogen might need to be produced in the world annually by 2050, with Africa, the Americas, the Middle East, and Oceania having the highest potential of becoming exporters, and Europe and Asia becoming likely importers (IRENA 2022). The European Commission (2024) estimates the European Union's annual

[18] The European Union defines ancillary services in Directive (EU) 2019/944 to include balancing power supply and demand, steady state voltage control, fast reactive current injections, inertia for local grid stability, short-circuit current, black start capability, and island operation capability.

production of some 2,150 terawatt-hours of hydrogen by 2050. European governments have actively supported investments in hydrogen-related infrastructure and issued regulations to support the certification of producers of green hydrogen (that is, hydrogen produced with renewables). As was the case in the past with solar power, government intervention can help create a market, bring down costs through learning-by-doing, and facilitate the emergence of the best technological options, for example the best chemical form in which to transport hydrogen. Europe's publicly funded intermediation mechanism (H2Global), which auctions long-term contracts to purchase green hydrogen in the world market and then re-sells the hydrogen to the highest bidder in the European Union, can help accelerate the development of this market in a cost-efficient way. Such mechanisms could be expanded by, for example, having more countries participate in their funding (Federal Ministry for Economic Affairs and Climate Action 2022).

- *Demand-side technologies*. In addition to supply-side curtailment (that is, turning off wind and solar power plants) and electricity storage, it would help to balance electricity markets if electricity demand could be more responsive to prevailing electricity market conditions. This could be achieved by requiring electricity suppliers to offer customers the option of a contract with flexible prices, as in California, for example. On its own, the market may underprovide this option, because utilities do not fully internalize the network benefits of such contracts (IEA 2023c). Public programs could also auction demand-side response contracts (as in France and the United Kingdom) that pay large end-users to reduce their consumption at peak times, because of the large social gain from avoiding blackouts. Similarly, the Agency for the Cooperation of Energy Regulators has recommended that the European Union introduce a regulation to remove barriers to consumers' participation in wholesale electricity markets (ACER 2022). National authorities could devote more attention to demand-side policies in their long-term planning (European Commission 2023a).

B. Making Markets More Efficient and Attractive for Renewables Deployment

Market design could also provide stronger incentives for investment in renewables. Investment would benefit from more predictability in future prices at which electricity will be sold. In principle, such hedges could be purchased on forward electricity markets, but in practice these are illiquid in Europe beyond three years' maturity (ACER 2023b). Therefore, the reforms agreed between the European Parliament and Council in December 2023, which allow governments to offer two-way contracts for difference to zero emission power producers and make it easier to enter into power purchase agreements, are a welcome step toward greater predictability.

Further technical improvements to market design would also enhance incentives to invest in renewables and reduce the impact on the network of their intermittency. For example, renewables could be allowed to compete in balancing markets, which they can do by offering to curtail power production when there is a short-term oversupply (IEA 2023a). Finally, electricity market settlement periods need to be shortened (for example, from 60 minutes to 15 minutes, as Germany did with its intraday market in 2011) and electricity trading needs to be allowed closer to the time of physical delivery (for example, from 60 minutes in the intraday market in most of Europe to 30 minutes as tested on the Estonian-Finnish border or even 5 minutes as in parts of Austria, Belgium, and Germany/Luxembourg) (IRENA 2019; IEA 2023b).

C. Securing Critical Minerals

Europe will also need to secure its supply chain of critical minerals for the green transition, including aluminum, cobalt, copper, graphite, lithium, nickel, and rare earths. These minerals are used in electric vehicles, batteries, and wiring, as well as in renewable electricity technologies such as solar panels and wind turbines. Importing these minerals can expose Europe to geographic concentration risks, given that, for most of them, around 70 percent of global production is concentrated in the three largest producing countries (IMF 2023b). This concentration is higher than in fossil fuel commodity markets, in which the top three producers account for about 50 percent of global production, and private agents might not internalize the systemic risk arising from such collective dependence on similar suppliers.

The most effective approach would involve reducing barriers to trade and production of critical minerals. Yet trade restrictions on these materials have proliferated, with export restrictions in particular growing fivefold between 2009 and 2020 (Kowalski and Legendre 2023). Instead, new trade agreements could be struck to prevent other countries from restricting exports to Europe, which they might otherwise consider in response to supply shortages. Similarly, strategic partnerships could reduce barriers to cross-border investments in extraction and refining projects. Since 2021, the European Union has signed strategic partnership agreements with nine countries (Argentina, Canada, Chile, Democratic Republic of the Congo, Greenland, Kazakhstan, Namibia, Ukraine, Zambia). Finally, faster permitting for European extraction, refining, and recycling projects would encourage domestic production.

The European Commission's March 2023 proposal (European Commission 2023c) of a regulation on critical raw materials includes these elements but could be further improved. It would also helpfully coordinate strategic stocks of critical raw materials between member states and enhance the assessment of security of critical minerals supply by requiring stress tests. However, the impacts of domestic content benchmarks (10 percent of consumption for extraction activity, 40 percent for processing, and 15 percent for recycling) should be carefully assessed, given their potential to impose economic costs and delay the green transition. In particular, the target for processing is relatively high and could trigger responses by source countries.

References

Abraham, Laurent, Marguerite O'Connell, and Iñigo Arruga Oleaga. 2023. "The Legal and Institutional Feasibility of an EU Climate and Energy Security Fund." ECB Occasional Paper 2023/313, European Central Bank, Frankfurt.

Agency for the Cooperation of Energy Regulators (ACER). 2022. "Framework Guideline on Demand Response." Ljubljana, Slovenia.

Agency for the Cooperation of Energy Regulators (ACER). 2023a. "Opinion on the ENTSOG Draft Ten-Year Network Development Plan 2022." Opinion 06/2023, Ljubljana, Slovenia.

Agency for the Cooperation of Energy Regulators (ACER). 2023b. "Further Development of the EU Electricity Forward Market." Policy Paper, Ljubljana, Slovenia.

Arnold, Nathaniel, Ravi Balakrishnan, Bergljot Barkbu, Hamid Davoodi, Andresa Lagerborg, Waikei Lam, Paulo Medas, and others. 2022. "Reforming the EU Fiscal Framework: Strengthening the Fiscal Rules and Institutions." IMF Departmental Paper 2022/014, International Monetary Fund, Washington, DC.

Baqaee, David, and Emmanuel Farhi. 2019. "Networks, Barriers, and Trade." NBER Working Paper 26108, National Bureau of Economic Research, Cambridge, MA.

Burniaux, Jean-Marc, and Jean Chateau. 2014. "Greenhouse Gases Mitigation Potential and Economic Efficiency of Phasing-Out Fossil Fuel Subsidies." *International Economics* 140: 71–88.

Chiacchio, Francesco, Roberto De Santis, Vanessa Gunnella, and Laura Lebastard. 2023. "How Have Higher Energy Prices Affected Industrial Production and Imports?" *ECB Economic Bulletin* 1/2023.

Coady, David, Ian Parry, Louis Sears, and Baoping Shang. 2017. "How Large Are Global Fossil Fuel Subsidies?" *World Development* 91: 11–27.

Cohen, Gail, Frederick Joutz, and Prakash Loungani. 2011. "Measuring Energy Security: Trends in the Diversification of Oil and Natural Gas Supplies." *Energy Policy* 39 (9): 4860–69.

De Vita, A, P. Capros, L. Paroussos, K. Fragkiadakis, P. Karkatsoulis, Lena Höglund-Isaksson, Wilfried Winiwarter, and others. 2021. "EU Reference Scenario 2020 – Energy, Transport and GHG Emissions – Trends to 2050." Directorate-General for Climate Action, Directorate-General for Energy, and Directorate-General for Mobility and Transport, Publications Office of the European Union, Luxembourg.

Di Bella, Gabriel, Mark J. Flanagan, Karim Foda, Svitlana Maslova, Alex Pienkowski, Martin Stuermer, and Frederik G. Toscani. 2022. "Natural Gas in Europe: The Potential Impact of Disruptions to Supply." IMF Working Paper 2022/145, International Monetary Fund, Washington, DC.

European Commission. 2017a. "Executive Summary of the Impact Assessment Accompanying the Document: Proposal for a Regulation of the European Parliament and of the Council Setting Emission Performance Standards for New Passenger Cars and for the New Light Commercial Vehicles as Part of the Union's Integrated Approach to Reduce CO2 Emissions from Light-Duty Vehicles and Amending Regulation (EC) No 715/2007 (recast)." Staff Working Document SWD(2017) 651, Brussels.

European Commission. 2017b. "Impact Assessment Accompanying the Document: Proposal for a Regulation of the European Parliament and of the Council Setting Emission Performance Standards for New Passenger Cars and for the New Light Commercial Vehicles as Part of the Union's Integrated Approach to Reduce CO2 Emissions from Light-Duty Vehicles and Amending Regulation (EC) No 715/2007 (recast)." Staff Working Document SWD(2017) 650, Brussels.

European Commission. 2019. "Comprehensive Study of Building Energy Renovation Activities and the Uptake of Nearly Zero-Energy Buildings in the EU – Final Report." Directorate-General for Energy, Brussels.

European Commission. 2021. "Impact Assessment Report Accompanying the Document: Directive of the European Parliament and of the Council Amending Directive 2003/87/EC, Establishing a System for Greenhouse Gas Emission Allowance Trading within the Union, Decision (EU) 2015/1814 Concerning the Establishment and Operation of a Market Stability Reserve for the Union Greenhouse Gas Emission Trading Scheme and Regulation (EU) 2015/757." Staff Working Document SWD(2021) 601, Brussels.

European Commission. 2023a. "EU Wide Assessment of the Draft Updated National Energy and Climate Plans: An Important Step Towards the More Ambitious 2030 Energy and Climate Objectives Under the European Green Deal and RePowerEU." COM(2023) 796, Brussels.

European Commission. 2023b. "State of the Energy Union 2023." Staff Working Document SWD(2023) 646, Brussels.

European Commission. 2023c. "Regulation of the European Parliament and of the Council Establishing a Framework for Ensuring a Secure and Sustainable Supply of Critical Raw Materials and Amending Regulations (EU) 168/2013, (EU) 2018/858, 2018/1724 and (EU) 2019/1020." COM/2023/160 Final, Brussels.

European Commission. 2023d. "Commission Recommendations on How to Exploit the Potential of Energy Storage." News Announcement, Directorate-General for Energy, March 14, Brussels.

European Commission. 2024. "Impact Assessment Report Accompanying the Document: Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions. Securing our Future – Europe's 2040 Climate Target And Path To Climate Neutrality by 2050 Building A Sustainable, Just and Prosperous Society." Staff Working Document SWD(2024) 63, part 1/5, Strasbourg.

European Network of Transmission System Operators for Electricity (ENTSO-E). 2023a. "Ten-Year Network Development Plan 2022 – System Needs Study: Opportunities for a More Efficient European Power System in 2030 and 2040." Brussels.

Federal Ministry for Economic Affairs and Climate Action. 2022. "Federal Ministry for Economic Affairs and Climate Action Launches First Auction Procedure for H2Global – €900 Million for the Purchase of Green Hydrogen Derivatives." Press release, August 12. https://www.bmwk.de/Redaktion/EN/Pressemitteilungen/2022/12/20221208-federal-ministry-for-economic-affairs-and-climate-action-launches-first-auction-procedure-for-h2global.html.

Grubb, Michael, Igor Bashmakov, Paul Drummond, Anna Myshak, Nick Hughes, Andrea Biancardi, Paolo Agnolucci, and others. 2018. "An Exploration of Energy Cost, Ranges, Limits and Adjustment Process." Institute for Sustainable Resources, University College London, London.

Hulten, Charles. 1978. "Growth Accounting with Intermediate Inputs." *The Review of Economic Studies* 45 (3): 511–18.

International Energy Agency (IEA). 2007. *Energy Security and Climate Policy: Assessing Interactions*. Paris: OECD Publishing.

International Energy Agency (IEA). 2023a. *Renewable Energy Market Update: Outlook for 2023 and 2024*. Paris.

International Energy Agency (IEA). 2023b. "Grid-scale Storage." https://www.iea.org/energy-system/electricity/grid-scale-storage.

International Energy Agency (IEA). 2023c. "Demand Response." https://www.iea.org/energy-system/energy-efficiency-and-demand/demand-response.

International Energy Agency (IEA). 2023d. *SDG7: Data and Projections*. IEA, Paris https://www.iea.org/reports/sdg7-data-and-projections, License: CC BY 4.0

International Monetary Fund (IMF). 2022a. *World Economic Outlook Update: Rising Caseloads, A Disrupted Recovery, and Higher Inflation*. Washington, DC, January.

International Monetary Fund (IMF). 2022b. *World Economic Outlook: War Sets Back the Global Recovery*. Washington, DC, April.

International Monetary Fund (IMF). 2023a. "Germany: Staff Report for the 2023 Article IV Consultation." IMF Country Report 2023/258, Washington, DC.

International Monetary Fund (IMF). 2023b. "Fragmentation and Commodity Markets: Vulnerabilities and Risks." In *World Economic Outlook: Navigating Global Divergence*. Washington, DC, October.

International Monetary Fund (IMF). 2023c. "Poland: Staff Report for the 2023 Article IV Consultation." IMF Country Report 23/189, Washington, DC.

International Monetary Fund (IMF). 2023d. *World Economic Outlook: A Rocky Recovery*. Washington, DC, April.

International Renewable Energy Agency (IRENA). 2019. "Increasing Time Granularity in Electricity Markets." Innovation Landscape Brief, Abu Dhabi.

International Renewable Energy Agency (IRENA). 2022. "Geopolitics of the Energy Transformation: The Hydrogen Factor." Abu Dhabi.

Jewell, Jessica, Aleh Charp, and Keywan Riahi. 2014. "Energy Security Under De-carbonization Scenarios: An Assessment Framework and Evaluation Under Different Technology and Policy Choices." *Energy Policy* 65: 743–60.

Kim, Jaden, Augustus Panton, and Gregor Schwerhoff. 2024. "Energy Security and the Green Transition." IMF Working Paper 24/6, International Monetary Fund, Washington, DC.

Kowalski, Przemyslaw, and Clarisse Legendre. 2023. "Raw Materials Critical for the Green Transition: Production, International Trade and Export Restrictions." OECD Trade Policy Paper 269, Organisation for Economic Co-operation and Development, Paris.

Krogulski, Krzysztof. 2023. "Balancing Decarbonization with Energy Security in Poland." IMF Country Report 23/190, International Monetary Fund, Washington, DC.

Lan, Ting, Galen Sher, and Jing Zhou. 2022. "The Economic Impacts on Germany of a Potential Russian Gas Shutoff." IMF Working Paper 2022/144, International Monetary Fund, Washington, DC.

Le Coq, Chloe, and Elena Paltseva. 2009. "Measuring the Security of External Energy Supply in the European Union." *Energy Policy* 37 (11): 4474–81.

Makarov, Igor, Daniel Besley, Hasan Dudu, Jakub Boratyński, Maksym Chepeliev, Elena Golub, Vladislava Nemova, and others. 2021. "Russia and Global Green Transition: Risks and Opportunities." World Bank, Washington, DC.

Rademaekers, Koen, Matthew Smith, João Gorenstein Dedecca, Liliana Guevara Opinska, Onne Hoogland, Joris Moerenhout, Thierry Badouard, and others. 2020. "Energy Subsidies – Energy Costs, Taxes and the Impact of Government Interventions on Investments – Final Report." Publications Office, European Commission, Luxembourg.

Rojas-Romagosa, Hugo. Forthcoming. "Medium-term Macroeconomic Effects of Russia's War in Ukraine and How it Affects Energy Security and Global Emission Targets." IMF Working Paper, International Monetary Fund, Washington, DC.

Roques, Fabien. 2021. "The Evolution of the European Model for Electricity Markets." In *Handbook on Electricity Markets*, edited by Jean-Michel Glachant, Paul Joskow, and Michael Pollitt, 308–30. Cheltenham, UK: Edward Elgar Publishing.

Ruhnau, Oliver, Clemens Stiewe, Jarusch Muessel, and Lion Hirth. 2023. "Natural Gas Savings in Germany During the 2022 Energy Crisis." *Nature Energy* 8: 621–28.

Sovacool, Benjamin, and Ishani Mukherjee. 2011. "Conceptualizing and Measuring Energy Security: A Synthesized Approach." *Energy* 36(8): 5343-55.

Tallat-Kelpšaitė, Jurga, Robert Brückmann, Jörn Banasiak, Sunna Kokkonen, John Szabo, Dierk Bauknecht, Dominik Seebach, and others. 2022. "Technical Support for RES Policy Development and Implementation – Simplification of Permission and Administrative Procedures for RES Installations (RES Simplify) – Interim Report." Directorate-General for Energy, Publications Office of the European Union, Luxembourg.

Van der Mensbrugghe, Dominique. 2024. "The Environmental Impact and Sustainability Applied General Equilibrium (ENVISAGE) Model. Version 10.4." Center for Global Trade Analysis, Purdue University, West Lafayette, IN.

PUBLICATIONS

The Energy Security Gains from Strengthening Europe's Climate Action

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