Medium-term macroeconomic effects of Russia's War in Ukraine and how it affects energy security and global emission targets

Hugo Rojas-Romagosa

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Abstract

Russia's War in Ukraine has disrupted the supply of natural gas for many European countries triggering an energy crisis and affecting energy security. We simulate the medium-term effects of these trade disruptions and find that Russia's real GDP losses are severe, while those European countries more dependent on Russian natural gas are also affected but to a lesser extent. Even though fossil fuel consumption and emissions are reduced as a consequence, these reductions are relatively small compared to the required mitigation efforts under Europe's nationally determined contributions (NDCs). Moreover, achieving these NDCs has become costlier after Russia's War in Ukraine following the real GDP reductions in Europe and lost access to relatively cheap Russian pipeline natural gas imports. We also find that constructing a new Russian pipeline to China does not provide significant macroeconomic benefits for either country.

1 Introduction

The Russian invasion and current war in Ukraine was met by economic sanctions from several countries and countermeasures by the Russian authorities. As a result Russian trade flows to Europe have been severely disrupted, in particular, Russian natural gas exports. This presents both a risk and an opportunity for EU countries. On the one hand, the EU faces a short-term gas shortage that has resulted in an energy crisis, with large price increases and the threat of rationing in some countries in the 2022-2023 winter and beyond. On the other hand, unwinding itself from the heavy reliance on Russian energy imports, the EU has the opportunity to increase its energy security and accelerate its transformation into a green economy reliant mostly on renewable generation.

The short term implications of the Russian gas shutoff have been extensively analyzed (see for example, Albrizio et al., 2022; Di Bella et al., 2022; Bachmann et al., 2022; Baqaee et al., 2022; Lan et al., 2022). As a complement to these papers, in this study we focus on the medium- and long-term impacts of Russia's War in Ukraine on EU energy markets and its economic implications for the EU and Russia. In addition, we also analyze the macroeconomic and global emission changes that would result from a reshaping of the international natural gas markets through the redirection of Russian energy to other non-European markets and the expected expansion in liquefied natural gas (LNG) trade. Finally, we analyze how the Russia's War in Ukraine will affect the economic costs of countries implementing the emission reductions agreed in their national determined contributions (NDCs).

For this quantitative analysis we employ the IMF-ENV model, which is a global recursive dynamic computable general equilibrium (CGE) model that provides rich sectoral detail and includes modeling features for energy and climate issues. The model is well suited to analyze the macroeconomic effects and structural change that result from energy shocks and climate policy changes. It allows simulating impacts on energy demand and supply, changes in the electricity generation mix, greenhouse gas (GHG) emissions, macroeconomic variables, sectoral outcomes and trade.[1] For this study, we focus our analysis on how the trade disruptions from the Russia's War in Ukraine affect the electricity generation mix and energy security in the three major EU economies (Germany, Italy, France), the rest of the EU, the UK, as well as China and India, and how this will affect national and global emission levels as well as real GDP.

We run five main scenarios. First, as a reference point, we assume a full embargo of Russian imports by the EU and selected OECD countries (Australia, Canada, Japan, Korea and the US). In reality, however, only specific products have been banned and hence, in our second scenario we implement the current sanctions, which excludes some important commodities (i.e. pipeline imports of natural gas and oil), but include the shutoff of natural gas applied by the Russian government.[2] Third, we simulate a scenario that allows the possibility of Russia diverting gas exports to China –through an additional pipeline that is assumed to be completed by 2030, and increased Russian LNG exports to non-EU countries. US and other countries increase their LNG exports to the EU. These new trade flows reshape the international natural gas markets to partially compensate for the shutdown of the gas pipelines connecting Russia and the EU. Fourth, in addition to Russia's War in Ukraine trade sanctions and reshaping of the natural gas markets, we analyze the macroeconomic, energy and climate effects when countries implement their current NDC emission targets. In our fifth and final scenario, we do not account for Russia's War in Ukraine and its related trade disruptions, and only assume that countries achieve their NDCs using a generalized carbon tax on all GHG emissions. This allows us to estimate how the costs of implementing these NDCs change with Russia's War in Ukraine.

We find that the trade disruptions associated with Russia's War in Ukraine result in substantial real GDP losses to Russia, and to a lesser extent, the EU and UK. These losses for Russia are larger when a full embargo is simulated in Scenario 1 (with a real GDP reduction of almost 11% in 2030 compared to baseline values), but are still sizable when we only implement the current applied and announced sanctions in Scenario 2 (8%). EU GDP losses by 2030 are below 1%, and higher for the countries that are more dependent on Russian gas –i.e. Italy, Germany and the Rest EU region. As a reaction to the natural gas shutoff, most EU countries increase their natural gas imports from other suppliers (mainly Norway, US, Qatar and Algeria), but they also reshuffle their electricity generation mix to rely more on renewable generation. These shifts reduce overall GHG emissions in the EU by around 5% in 2030 when compared with the baseline values, with large reductions in Italy (15%), Germany and the Rest of EU region (both by around 6%). In addition, the ratio of imports to domestic energy consumption is also declining in most EU countries. Both these indicators point to an increase in energy security in Europe, although they would be more

[1] The current version of the model includes all G20 countries (Argentina, Australia, Brazil, Canada, China, France, Germany, India, Indonesia, Italy, Japan, Korea, Mexico, Russia, Saudi Arabia, South Africa, Turkey, the United Kingdom, and the United States) and regional aggregations (Africa, East Asia, Eurasia, EU, Latin America and oil-producers) that include all other countries to make the model global.

[2] However, we do not model other non-trade sanctions that have been imposed by the EU and other OECD countries, such as, individual restrictive measures, sanctions targeted at the financial sector and the closure of EU airspace and ports to Russian vessels. See for example: `https://www.consilium.europa.eu/en/policies/sanctions/restrictive-measures-against-russia-over-ukraine/`.

dependent on other natural gas suppliers, and international natural gas prices are expected to be on average 25% higher by 2030.

Given that around 95% of Russian natural gas exports go through pipelines, the shutoff of trade with the EU drastically decreases these exports. Even if Russia increases LNG exports and constructs a new pipeline to link its Western Siberian gas fields to China, exports would still decrease by 80% compared to the baseline pre-war volumes. Moreover, the economic and environmental benefits to China of getting access to cheaper Russian natural gas are also expected to be relatively muted, as China relies heavily on coal and renewable electricity generation and the new import volumes of Russian natural gas are relatively low compared to China's overall energy imports.

Finally, we interact Russia's War in Ukraine trade disruptions and rerouting of natural gas exports with NDC emission mitigation policies. We find that Russia's War in Ukraine shock does increase the overall economic costs (reflected in the reductions in real GDP) for most European countries of reaching their NDCs emission targets. On the other hand, renewable generation is increased and emissions are reduced by around 4% (with respect to baseline levels in 2030) as a reaction to the disruption of natural gas imports from Russia. However, the necessary emission reduction policies required to reach the NDCs are much higher (around 40% with respect to baseline levels in 2030)and hence, ambitious mitigation policies will still be required to reach the NDC targets. The associated GDP losses for most European countries, in conjunction with the loss of access to the relatively cheap natural gas that is pipe-lined from Russia and its substitution for more expensive LNG imports makes achieving the emission targets more costly.

2 Review of studies analyzing the short-term effects of a Russian natural gas shutoff

Several recent papers analyze the short-term (2022-2023) effects of the disruption of Russian natural gas imports to Germany (Bachmann et al., 2022; Lan et al., 2022) and Europe (Albrizio et al., 2022; Baqaee et al., 2022; Di Bella et al., 2022). They analyze the differential impact of gas shortages for European countries and the potential GDP effects. [3] All papers use several (technical) assumptions to estimate the gas shortages for 2022 and 2023 (i.e., LNG imports, gas consumption, inventory changes, infrastructure expansion, gas to coal switching, renewable and nuclear power expansion). For the GDP effects they use different IO and production function models, which require an additional set of assumptions regarding different elasticities of substitution (mainly between gas an other energy sources) and how the shortages are dealt with (price adjustments or rationing). Some studies also add demand side effects (through changes in trade) and uncertainty effects.

Albrizio et al. (2022), Bachmann et al. (2022) and Baqaee et al. (2022) use the trade model from Baqaee and Farhi (2019) to estimate the GDP effects of the gas shortages.[4] However, it is important to remark that these papers are running a partial-equilibrium version of the Baqaee and Farhi (2019) model using a "sufficient statistic" approach. This

[3] Lan et al. (2022) also summarizes other papers that have done short-term assessments for Germany, including Bachmann et al. (2022).

[4] The model is part of the new quantitative trade (NQT) framework, which are highly stylized general equilibrium models (static, one factor, few sectors, simple production and demand functions, no government) used mainly in academia. These models are more parsimonious and rely on fewer elasticities (or assume CD functions) and are easier to describe and analyze than CGE models. On the other hand, they lack most of the sectoral, factor and public finance details that policy research requires.

however, is an inadequate numerical instrument for the exercise, as it is based on a second-order approximation that in general only holds for marginal shocks to the model, and by keeping other variables fixed. For instance, this approximation assumes that total exports are unchanged by the gas supply shock, which fails to account for the trade-related general equilibrium effects of lower aggregate demand in a highly integrated region as the EU.

Di Bella et al. (2022) has the advantage that it deals with most European countries and it presents a very detailed analysis on the country-specific Russian gas dependence and substitution possibilities. They identify two main groups of countries that will experience the largest short-term disruptions: i. Germany and Austria (with a gas shortage in winter of 18%); ii. Czechia, Slovakia and Hungary (with a shortage in winter of 91%). Importantly, all other countries are expected to be able to substitute to alternative gas supply sources (mainly LNG) and are not expected to have gas shortages, but will be indirectly affected by gas price increases. To estimate the short-term macroeconomic effects of these shortages they use a combination of two models: the estimations from Albrizio et al. (2022) (using the second-order approximation from the model by Baqaee and Farhi, 2019) and a multi-sector model with demand spillovers. They calibrate the second model to the regional gas shortage that they have previously estimated. Their results show that losses are conditional on the country-specific reliance on Russian gas and the overall gas-intensity of each economy, while gas-intensive sectors (electricity, chemicals) are the most affected. They also estimate a "solidarity" scenario where gas is re-exported to the hardest hit countries, which spreads the GDP losses to reduce the large negative impacts for the most affected countries. Finally, they also estimate a scenario where households are protected from the shock –by keeping their gas consumption fixed– and find that GDP losses are increased by around 50% on average, with GDP losses reaching up to 6% in the most affected countries.[5]

For Germany, the studies have a wide range of GDP effects (from 0.2 to 5% of GDP for 2022/23). But when using more realistic short-term elasticities and gas substitution constraints, the effects are between (2 and 5%). For other EU countries, the results are country-specific depending on the extent that each country is expected to have a gas shortage. For those countries that will, the results can be substantial.

As highlighted by Albrizio et al. (2022), there is an important indirect effect of Russia's War in Ukraine: the higher demand of LNG by Europe will increase international LNG prices, and Korea and Japan will also be negatively affected by higher international LNG prices. In addition, this paper also mentions that redirecting Russian natural gas exports from Europe to China will only become viable at least until 2030. The pipeline that currently connects Russia to China sources its gas from fields in Far East Russia and the volumes are relatively small (around 5% of total Russian gas exports). China and Russia have agreed to build a second pipeline that would connect the natural gas fields in Western Siberia, but the timeline for full construction is 2030 and its capacity will only cover one-third of the current Russian exports to Europe.

Al-Karablieh (2022), on the other hand, analyses the short-term impacts of Russia's War in Ukraine effects of a European ban on imports of crude and refined oil from Russia. This study finds that the effects can also be significant for some specific European countries, but given the easier substitution possibilities to alternative oil suppliers, the effects are smaller than the natural gas disruption from the war.

A related IMF study by Ari et al. (2022) emphasizes the trade-offs between short term energy price and security issues with the medium-term EU climate goals. The main pol-

[5] Di Bella et al. (2022) compare their results to other studies at the EU-level: ECB (using DSGE and NiGEM models), ECFIN (DSGE), and OECD (using NiGEM and a partial equilibrium IO model). Their results are on the lower end of the output losses when compared to the other papers in the literature.

icy recommendation balances these trade-offs by proposing short-term income support for low-income households (with limited and targeted support to vulnerable firms), while not distorting prices to keep the incentives for both firms and households to reduce energy consumption, increase energy efficiency investments and switch to renewable sources. The paper also highlights that substituting away from gas could have positive climate implications, but there are also dangers: short-term gas-to-oil and gas-to-coal substitution, and the global effects of larger EU LNG demand on prices for countries that currently rely on it (Bangladesh, Pakistan, India, and Indonesia), moving to coal.

Finally, our study is closest to Chepeliev et al. (2022) who also employ a CGE model, but assess both the short and medium-run effects of trade sanctions to Russian fossil fuel exports. They employ the ENVISAGE model calibrated until 2030 and apply a gradual tariff increase by mostly OECD countries to Russian exports of natural gas, crude oil, coal, and petroleum products. This generates a gradual reduction in Russian exports to the EU (50% in 2022 and 80% in 2030). They find moderate medium term GDP effects for the EU (real income drops by 0.4% in 2030), but substantial environmental co-benefits: CO2 emissions drop by 3.1% in 2022 and the reduction reaches 7% in 2030 compared to the baseline. According to this study, such emission reductions can ease the EU mitigation targets outlined in the Green Deal[6] and it will also reduce the implicit carbon price to achieve their emission targets by around 40 EUR per tonne of CO2. By contrast the Russian economic impacts will be substantial. They estimated that Russian real income is reduced by 6% (relative to baseline values) already in 2022 and reaches 8% losses by 2030. They also present short-term effects for EU countries, which are in the lower bound of other related studies (-0.7 to -1.7%). This study, however, was designed before the EU sanctions were defined, and hence, they assume that the trade sanctions are imposed using import tariffs. The actual trade sanctions, however, are a combination of trade bans on specific products that do not generate tariff revenue for the imposing countries, and hence, their estimated impact on OECD countries is likely underestimated. Moreover, they do not account for the non-fungibility of natural gas trade: Russian imports to the EU are mainly done through existing pipelines, with a very low share imported as LNG. This severely restricts the capacity of Russia to redirect natural gas exports to other countries, but also the import capacity of the EU to substitute Russian natural gas from other suppliers.

3 Methodology and data

In this section we provide an overview of the IMF-ENV model that we employ and of the main characteristics of the baseline, where we update both the overall Russian trade to Europe and European energy imports from different sources.

3.1 Model

IMF-ENV is a global recursive dynamic computable general equilibrium (CGE) model developed by the IMF research department.[7] Dynamic CGE models are well suited for the analysis of structural change and sectoral impacts that result from energy and climate shocks and policies. The model allows simulating impacts on energy demand and supply, greenhouse gas

[6] `https://ec.europa.eu/info/strategy/priorities-2019-2024/european-green-deal_en`.

[7] The model documentation is still being drafted. Meanwhile readers interested in the model can consult the documentations of the twin-models on which IMF-ENV is built on: the ENVISAGE model (van der Mensbrugghe, 2019) and the OECD's ENV-Linkages Model (Château et al., 2014).

(GHG), macroeconomic variables, sectoral outcomes and trade. The model is based on a neoclassical framework, which optimizes consumption and production decisions by households and firms, but deals mainly with real values and with almost perfect markets for commodities and production factors (labor, capital, land).

The model is based on the activities of the key actors: firms, households, and markets. Firms purchase inputs and primary factors to produce goods and services. Households receive the factor incomes and in turn demand the goods and services produced by firms. Markets determine equilibrium prices for factors, goods, and services. Finally, countries exchange goods on international markets. Factors of production are almost perfectly mobile across sectors (real rigidities make adjustments sluggish in short run) but not across countries. However, an important feature of IMF-ENV is that capital stocks have vintages such that firms' production and behavior are different in the short and long run. This allows a more realistic adjustment of the capital stock in the short- and medium-run, as it increases the capital costs for expanding activities and reduces the productivity of capital that is tied to declining economic activities.

The model is recursive dynamic: it is solved as a sequence of comparative static equilibria. The factors of production are taken exogenously at each point in time and linked between time periods with accumulation expressions, like the dynamics of a Solow growth model. Production follows a series of nested constant-elasticity-of-substitution (CES) functions to capture the different substitutability across all inputs. International trade is modeled using the so-called Armington specification that posits that demand for goods is differentiated by region of origin. This specification uses a full set of bilateral flows and prices by traded commodity. The model also links economic activity to environmental outcomes, specifically to the emission of greenhouses gases and other pollutants.

The model describes how economic activities and agents are inter-linked across economic sectors and world countries or regions. The model can be used for scenario analysis and quantitative policy assessments. For scenario analysis, the model projects up to 2050 and contains an internally consistent set of trends of all economic, sectoral, trade-related, and environmental variables. In this context, the model can be used to analyze economic impacts of various drivers of structural changes like technical progress, increases in living standards, changes in preferences and in production. A second use for the model is quantitative economic and environmental policy assessment for the coming decades, including scenarios of a transition to a low carbon economy. In this case the model assesses the costs and benefits of different sets of policy instruments for reaching given targets like GHGs emission reduction. However, the model's projections for the very long-run are especially uncertain since disruptive technology innovations could materialize at longer horizons.

3.2 Data and baseline values

The model is built primarily on a database of input-output tables, combined with national accounts and bilateral trade flows. The central input of the model is the GTAP 10 Power database (Aguiar et al., 2019; Chepeliev, 2020b). The database contains country-specific input-output tables for 141 countries and 65 commodities and real macro flows.[8] The database also represents world trade flows comprehensively for a given starting year. To allow a detailed modeling of energy supply, the database includes eight electricity generation technologies, as well as an electricity transmission and distribution activity. Finally, the database also includes all main greenhouse gases: carbon dioxide (CO_2), methane (CH_4),

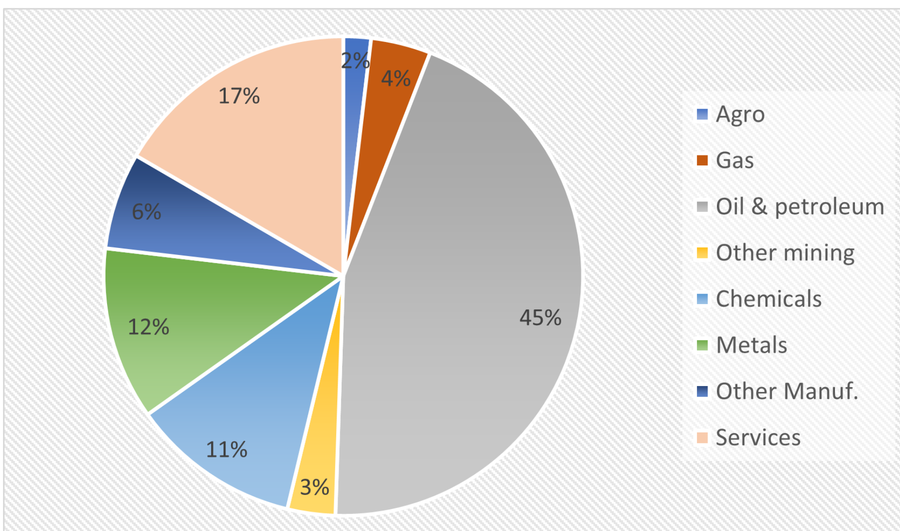
[8]This version of the model employs 36 activities, 28 commodities sectors and 25 country/regions, which are detailed in Tables 1-3 in the Appendix.

nitrous oxide (N_2O) and fluorinated gases –hydrofluorocarbons (HFCs), Per-fluorocarbons (PFCs) and Sulphur hexafluoride (SF_6)[9]

In our baseline we use electricity generation and total GHG emission projections from the Climate Policy Assessment Tool (CPAT) from the IMF's Fiscal Affairs Department (FAD). The electricity generation projections incorporate the expected increase in renewable generation and we assume an annual overall energy efficiency growth of 1.5%. Emission projections include technological advances that reduce the emission intensity of economic activities, but it does not include emission reductions associated with new mitigation policies. The baseline only includes already implemented carbon pricing policies, such as the EU's emissions trading system (ETS).

For this study, we include two major adjustments to the GTAP database. First, we updated the natural gas bilateral Russian exports data; and second, we updated the EU and the United Kingdom (UK) bilateral natural gas imports to reflect the latest 2021. For this update we use a combination of UN-COMTRADE data and the IEA Natural Gas Information Statistics for 2021.[10] The first adjustment is reflected in the updated Russian natural gas export values in Figures 1 and 2. This also implies that total Russian energy exports are also updated (see Figures 3 and 4).

Figure 1: Russian exports by product in 2021 (baseline shares)



[9]Cf. Chepeliev (2020a).

[10]https://doi-org.libproxy-imf.imf.org/10.1787/naturgas-data-en.

Figure 2: Russian exports by destination in 2021 (baseline shares)

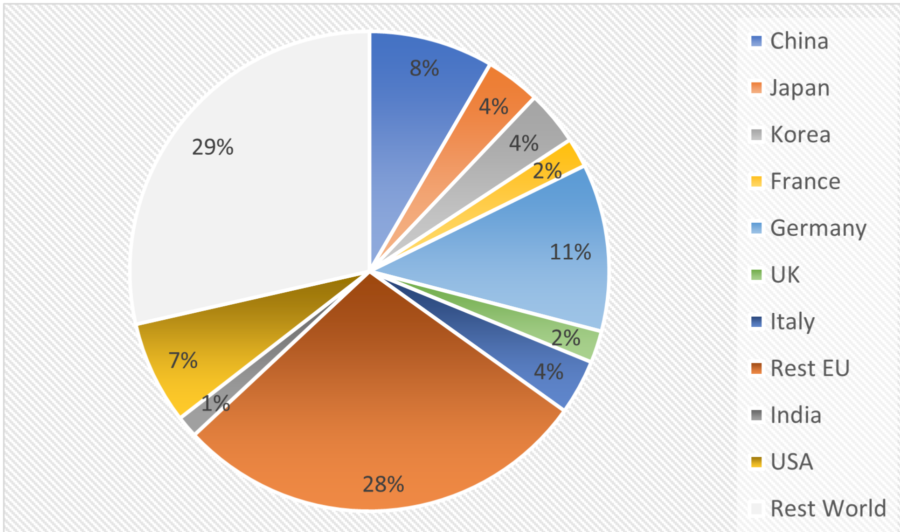


Figure 3: Russian natural gas exports by destination in 2021 (baseline shares)

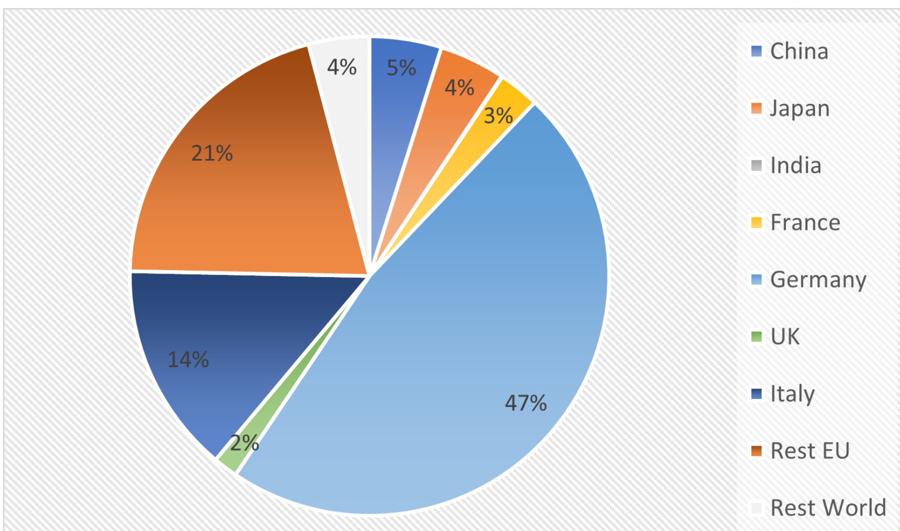
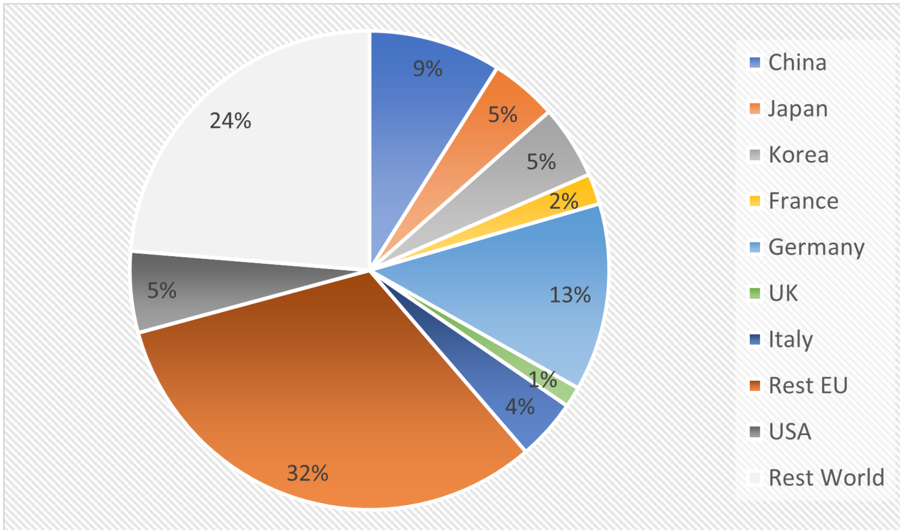


Figure 4: Russian crude and refined oil exports by destination in 2021 (baseline shares)



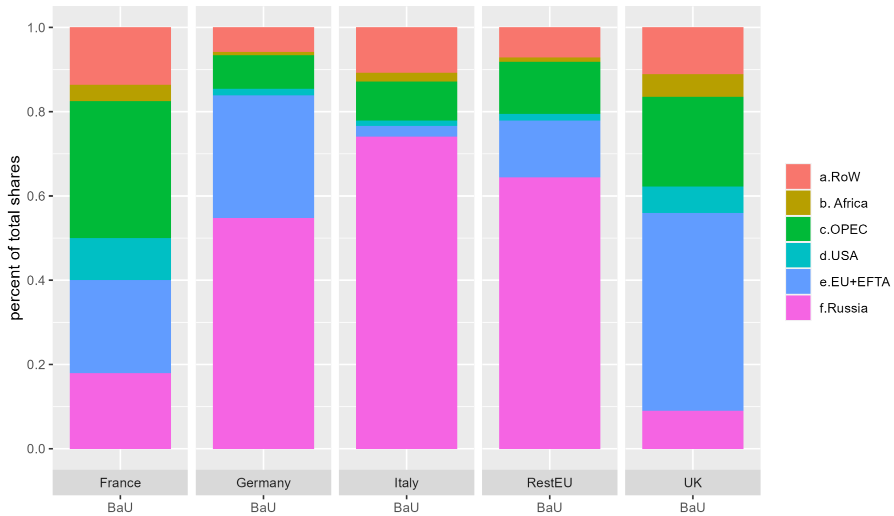
We observe that Russian crude and refined oil is the main Russian export, while gas only represents 3% of total exports. But almost half of all Russian exports, including energy, go to other European countries. Russian gas exports by large go to EU countries (around 80%), but more importantly they represent the bulk of gas imports for some central European countries. For instance, it accounts for around 60% of German natural gas imports, but more than 90% for other countries like Bulgaria, Hungary, Czechia and Slovakia (cf. Di Bella et al., 2022). Given that these natural gas exports are done mainly through pipelines, this makes natural gas trade non-fungible and very difficult to substitute, both for importers and exporters. Conversely, even though Russian oil exports are also going mainly to the EU, they can be more easily redirected to other markets.

The second major trade data adjustment provides updated values on natural gas import sources for the EU and UK. For this adjustment we used a combination of IEA Natural Gas Information Statistics[11] and EuroStat natural gas consumption and supply statistics.[12] Figure 5 shows the initial (2021) energy import dependence of EU countries. We observe that Germany, Italy and the Rest EU region rely heavily on Russian energy imports, while France and the UK do not. When focusing only on natural gas Figure 6 shows that the import dependence ratios increase for Germany, Italy and the Rest EU region. Italy, for instance, has almost 95% of natural gas imports coming from Russia, while the RestEU region presents the average import dependence, but this is hiding large dependence in Central European countries (e.g. Austria, Czechia, Slovakia and Hungary) and very low dependencies of Western Europe (i.e. Spain and The Netherlands).

[11] IEA data are provided by OECD (`https://www.oecd-ilibrary.org/energy/data/iea-natural-gas-information-statistics_naturgas-data-en`.

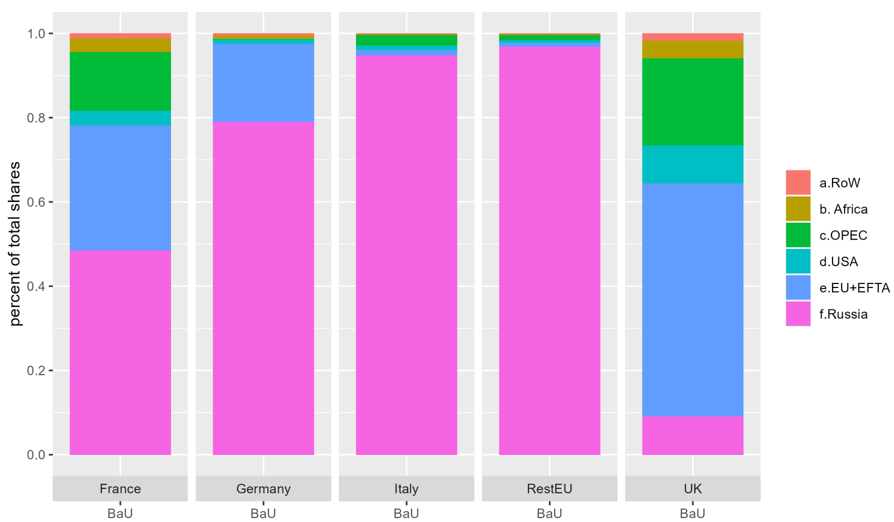
[12] `https://ec.europa.eu/eurostat/web/energy/data`.

Figure 5: Energy import shares for European countries by supplier in 2021 (baseline shares)



Note: Energy commodities are coal, crude and refined oil, and natural gas. The OPEC region includes Saudi Arabia and other oil-exporting countries (see Table 1).

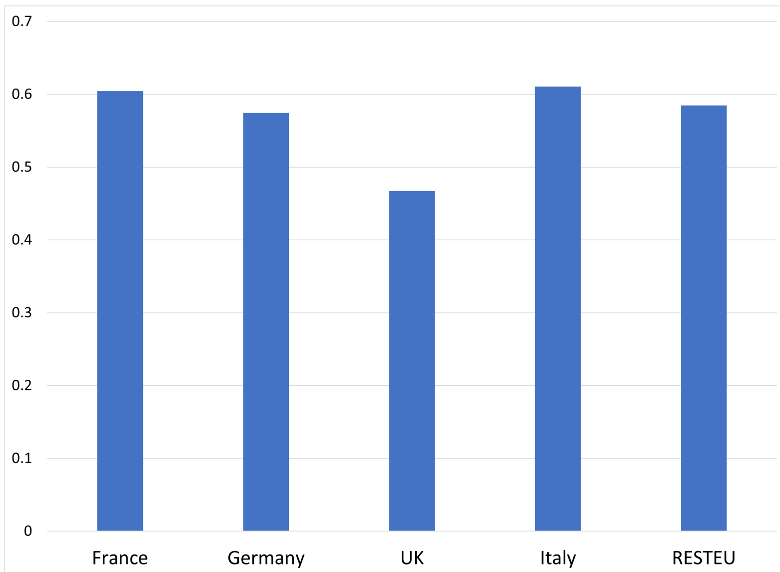
Figure 6: Natural gas import shares by supplier in 2021 (baseline shares)



Note: The OPEC region includes Saudi Arabia and other oil-exporting countries (see Table 1).

Finally, Figure 7 presents the share of total energy imports relative to domestic energy consumption. Here we find that most European countries have dependency ratios of around 60%, with the UK having a lower share. This means that more than half of energy demand is linked to imports. This measure is directly linked to energy security, as high energy import dependency ratios indicate larger risks. This indicator is inversely correlated with the share of renewable energy in total electricity generation and domestic fossil fuel production. Larger renewable generation shares implies that less fossil fuels are needed in total energy consumption, while higher domestic fossil fuel production also reduces the need for energy imports.

Figure 7: Energy imports as a share of total energy domestic consumption in 2021 (baseline shares)



4 Scenario construction

In this section we explain in detail how we construct each of our scenarios, which are divided into two main groups: trade disruptions and interactions with countries' mitigation policies as stated in their NDCs.

4.1 Trade sanctions from Russia's War in Ukraine

In a first scenario, we make the simplistic assumption of a total trade embargo from all EU countries and some OECD countries (i.e. Australia, Canada, Japan, Korea and the United States). Although this has not been the case so far, this scenario will provide a reference for the upper limit effects of the trade sanctions.

Scenario 2, on the other hand, constructs the trade sanctions based on the EU sanctions imposed by the European Council.[13] Hence, we assume a full import ban for all products, with the exception of agricultural products and food, fertilizer, pharmaceutical and medical products. Although there was initial discussion on banning Russian crude and refined oil imports, this has been switched to an import price cap. However, it is still not clear how this will exactly impact Russian oil exports. It is likely that Russian increases its exports to countries that did not impose the price cap, and consequently the EU countries will increase

[13]For simplicity, we also assume that the other OECD countries imposing sanctions follow the EU-specific bans.

imports from alternative suppliers. Under these conditions, we do not assume that overall Russian oil exports to the EU are reduced by 25%.[14]

On the other hand, the EU did not ban Russian natural gas imports (at least until 2024), but Russia has already stopped most of its gas exports to most EU countries. Thus, we also assume that there are no more imports of Russian natural gas by the EU in the medium term. There are no explicit bans on electricity imports from Russia, so we assume that electricity trade continues (i.e. Baltic countries continue to import electricity from Russia). The EU also imposed export bans for EU firms to export to Russia iron and steel, cement, wood and seafood.

An important consideration in our scenarios, is that natural gas exported through pipelines cannot be redirected to other countries not connected to the pipeline. The non-fungibility of natural gas trade is crucial to understand the energy security and economic implications of Russia's War in Ukraine. For instance, Gustafson (2020) explains in detail the economic, legal and geopolitical conditions required to build these pipelines, which take many years to negotiate and build. LNG, on the other hand, while making natural gas more tradable, still requires large investments for both exporting and importing countries, which can only be slowly expanded. Hence, it can take several years to fully be able to substitute for natural gas traded through existing pipelines. Therefore, we assume in both Scenarios 1 and 2 that Russian natural gas that was exported to Europe before the sanctions cannot be redirected to other countries. In addition, to reflect the limitations of expanding natural gas exports in the short term, we also constrain the natural gas exports of other (non-Russian) suppliers to Europe to be the same as in the baseline projections.

In Scenario 3, we relax these natural gas constrains to allow for an expansion of Russian LNG and pipeline exports. According to the expert opinion of Thane Gustafson, there is currently only one major gas project producing LNG in Russia (Sakhalin II) and Russia relied on foreign technologies and expertise for this project. Given the current sanctions, this implies that LNG expansion is largely constrained in Russia. Therefore, we assume that future expansion of LNG exports will increase total Russian natural gas exports by 5% annually. Regarding new pipelines to redirect Russian natural gas exports to Europe, the only major alternative is a new pipeline to China. The pipeline connecting Russia to China (Power of Siberia I) is currently running close to full capacity and it is constrained by the size of the natural gas fields in East Siberia. Therefore, a new pipeline (Power of Siberia II) needs to connect the fields in West Siberia to China, which will make this pipeline more costly. According to Thane Gustafson, it can take many years to negotiate this new pipeline –as it took around 10 years for Power of Siberia I– and therefore, 2030 is an optimistic assumption on when the pipeline can become operational.[15] Under this conditions, we assume that Russia constructs a new pipeline to China by 2030, which increases current exports to this country by 300%.

Moreover, in Scenario 3 we also expand the LNG exports of the US, Qatar and Algeria to Europe in response to higher prices and the supply vacuum after the shutoff of Russian natural gas imports.[16] The US started exporting LNG to the EU in 2018 and volumes have

[14]It is expected that the price cap will have an impact on the bilateral oil trade between Russia and the EU, but overall export and import levels by both parties, as well as international prices, will probably not be substantially changed given the relatively large number of oil suppliers and the ease to trade oil in international markets.

[15]Moreover, there is no reliable information on the costs associated with Power of Siberia 2, so these are not accounted in our simulations at the moment.

[16]Qatar and Algeria are not separate regions in our model and are include din the Rest OPEC and the Other African (OAF) regions, respectively. However, natural gas exports from these aggregate regions to the EU represent the exports of these two countries only.

been increasing rapidly, from 14.2 billion cubic meters (bcm) in 2019 to 34 bcm in 2021, and 2022 has seen an even larger increase with an expected 79 bcm by years end.[17] This represents an average yearly increase of around 80%. In Scenario 3 we simulate additional growth of LNG exports from these non-Russian suppliers, while in previous scenarios these exports where fixed at the baseline values.

Technically, these trade disruptions are modeled using the so-called iceberg trade costs, which create a price wedge between exporting producers and importing consumers. To ban certain trade flows we arbitrarily increase these trade costs to effectively make the trade flows zero. This methodology has the advantage that it does not require import tariffs to reduce the trade flows, which would create tariff revenues that in reality are not being received by the countries imposing the import bans.[18]

4.2 Interaction with climate policies

First, in Scenario 4 we only assume that the climate policies consistent with the NDCs are implemented. This scenario, therefore, will be used as a reference for the economic costs of achieving the NDCs without the direct and indirect effects of Russia's War in Ukraine on trade. Hence, Scenario 5 includes the trade disruptions from Russia's War in Ukraine (from Scenario 2) and the reshaping of the international natural gas markets (from Scenario 3), but we now add climate policies that are consistent with national determined contributions (NDCs). In this case, we estimate the carbon price that will be consistent with the emission reductions required for the EU and other countries to reach their NDCs by 2030.

These NDC scenarios, which are based solely on carbon taxation, do not reflect the most recently announced climate policies. In general, all countries will likely employ a combination of different climate policy instruments. For example, many countries, including the US, are not planning to use carbon pricing as their main climate policy to decrease GHG emissions. In the case of the EU and as a reaction to Russia cutting their gas exports to the EU, the European Commission has proposed the REPowerEU package,[19] which aims to achieve full independence from Russian energy imports well before 2030. This is planned to be achieved through four inter-related dimensions: (i) reducing energy consumption; (ii) diversifying supplies; (iii) accelerating the green transition; and (iv) improving connectivity within Europe. On the other hand, this proposal does not include the temporary use of coal plants to avoid gas shortages in 2022/23. While Europe is initially replacing Russian gas with cargoes of seaborne LNG from countries including the US and Qatar, the longer-term part of the project focuses on cutting reliance on imported fossil fuels. Under the plan, the EU wants to have 17.5 gigawatts of hydrogen capacity within three years and has increased the renewable generation target from 40 to 45% of total electricity generation by 2030.[20] Analyzing these more detailed climate policies are beyond the scope of this study, but the policies in the REPowerEU package and the EU Green Deal (Fit for 55), will be analyzed in an upcoming joint paper with the IMF's European Department (EUR).

4.3 Scenario summary

Based on the considerations and assumptions explained above, we construct the following scenarios, which are divided into two main groups:

[17] According to the European Commission (EU-US LNG Trade bulletin) and Reuters.
[18] As explained in Section 2 this is a limitation of the study by Chepeliev et al. (2022).
[19] `https://ec.europa.eu/commission/presscorner/detail/en/IP_22_3131`.
[20] Financial Times, Special Report on Energy Transition, September 2022.

1. Russian trade disruption:
   - Scenario 1 (Sce1): Russian sanctions from the EU, Australia, Canada, Japan, Korea and the US. We first assume the extreme case of a total embargo on all Russian imports. This includes Russian exports of gas (which Russia unilaterally stopped). In addition, we assume that Russia cannot divert its pipeline natural gas exports that currently go to the EU to other regions, while the EU cannot increase (for 2022 and 2023) their natural gas imports from other non-EU regions.
   - Scenario 2 (Sce2): Same as Scenario 1, but we exclude sectors with no import bans in the EU (agriculture, food and electricity), plus we assume that there are no effective restrictions on Russian crude and refined oil exports. The EU also imposes export bans on iron, steel, wood, cement and seafood.
   - Scenario 3 (Sce3): Same as Scenario 2, but we adjust the international market for natural gas. Russia increases its natural gas exports by 5% annually (through expanding LNG exports) to all countries, except those who imposed sanctions. Russia constructs new pipelines to China (with an increase of 300% on current exports there).
2. Interaction with climate commitments:
   - Scenario 4 (Sce4): All countries achieve their NDC emission targets, but we do not assume the international trade shock from Russia's War in Ukraine (as a way to compare the NDC costs with and without the war).
   - Scenario 5 (Sce5): Same as Scenario 3 but now all countries achieve their NDC emission targets through an increase in the carbon tax rate.

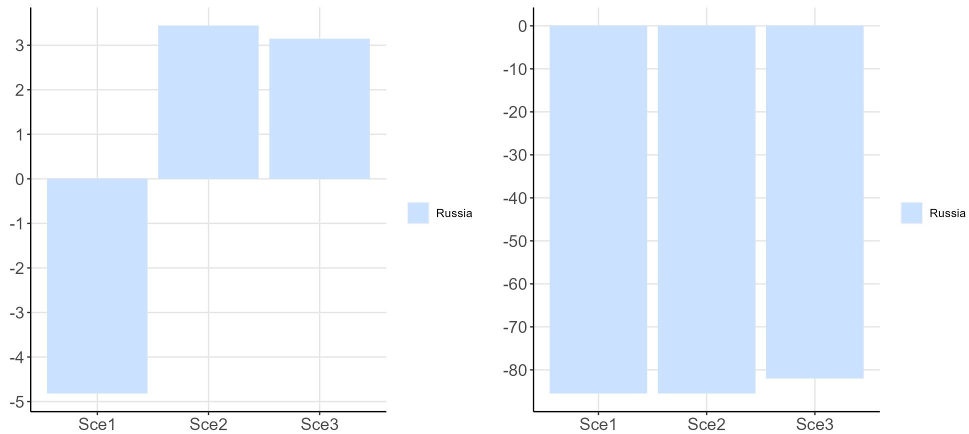
5 Main results

5.1 Russian trade disruption

First, we analyze the effects of the Ukraine war sanctions and countermeasures on Russian trade flows. The initial impact of a full embargo from the EU and other OECD countries (Scenario 1) is a substantial reduction of Russian crude and refined oil exports by almost 5% (see Figure 20). Moreover, there is a 85% decrease of Russian natural gas exports to Europe as pipelines are shut down. However, when the current sanctions, which only partially restrict Russian oil exports, are simulated we find that oil exports are actually increasing with respect to baseline values. Russia increases oil production and exports to non-European destinations to partially compensate for the closure of the European markets. In this way lost foreign income from previous export to Europe is less critical as Russia increases foreign revenue from oil as the current sanctions are not expected to seriously limit this income source.[21] Conversely, allowing Russia to increase LNG exports and including additional natural gas exports through a new pipeline to China do not improve natural gas exports significantly, and these are still declining by more than 80% in Scenario 3. Note that we assume that by 2030 the new pipeline from Russia to China is fully operational and the full effects are therefore accounted for in Scenario 3. Hence, for Russian natural gas exports to regain pre-war levels will require much larger volumes of exports to China and/or exporting to India or other large markets.

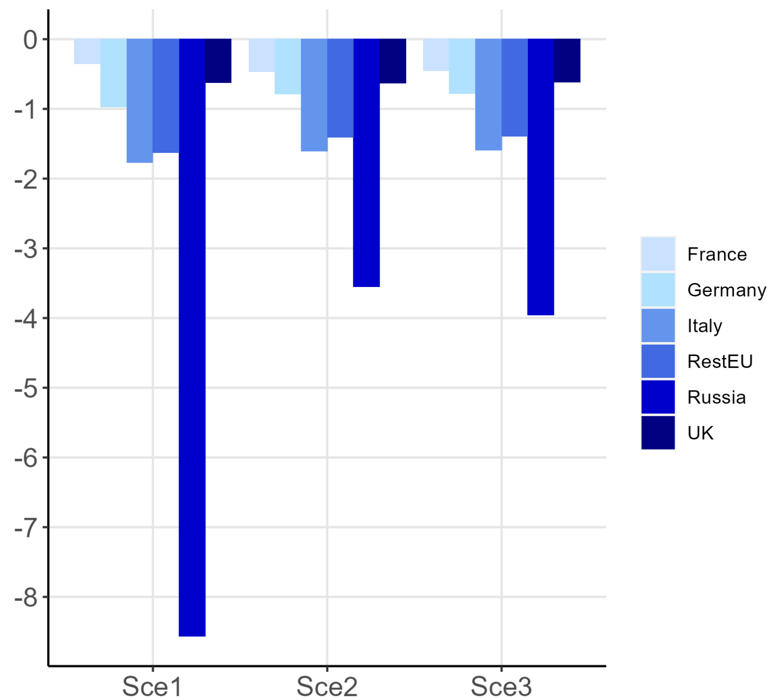
[21] Already in the short run the oil sanctions have not created any significant reduction in Russian oil exports, as these have been redirected from Europe to China and India as reported by The Economist (2023).

Figure 8: Russian exports of crude and refined oil (left-hand graph) and natural gas (right-hand graph) for different scenarios in 2030 (% change w.r.t. baseline)



With a full embargo overall Russian exports are decreasing by around 8.5% (see Figure 9) and this also triggers a smaller export reduction for the EU (around 1%). When we simulate the current sanctions, the export decrease is halved to around 3.5%. This is explained by the current oil sanctions not being expected to substantially reduce Russian oil exports. However, allowing a part of Russian natural gas to be redirected to China, together with larger LNG trade, does not mitigate the decline of Russian exports. Recall that crude and refined oil represent almost half of total Russian exports, and total exports are mainly driving by the changes in oil exports. This explains why, even when allowing for larger natural gas exports, total exports even decline slightly more, which is driven by oil exports increasing less in Scenario 3 than in Scenario 2 (see Figure 20 above). In other words, redirecting Russian natural gas exports has very limited effects on Russian exports, but the possibility to redirect oil exports is very important for the Russian economy.

Figure 9: Total exports for different scenarios in 2030 (% change w.r.t. baseline)



These reductions in trade have severe macroeconomic implications for Russia. Figure 10 shows the real GDP changes in 2030 when compared to baseline values. As expected, Russia has the highest GDP losses and these are more severe in the case where there is a total embargo from countries imposing sanctions (Scenario 1). These losses are less pronounced with the current partial trade sanctions (Scenario 2) and when Russia can redirect its natural gas exports to China and increase its LNG exports to other regions. On the other hand, these GDP losses can be considered a lower bound, as we do not include potential productivity losses associated with lower trade levels, such as technological transfers imbedded in imports and other dynamic benefits associated with closer integration to international markets.

For EU countries the GDP costs are less than 1% and do not vary much between scenarios. China and the US have very small negative effects, which are driven by the indirect effect on their exports as European demand decreases. For China, the option to import cheaper Russian natural gas does not have a substantial overall economic effect.

Figure 10: Real GDP for different scenarios in 2030 (% change w.r.t. baseline)

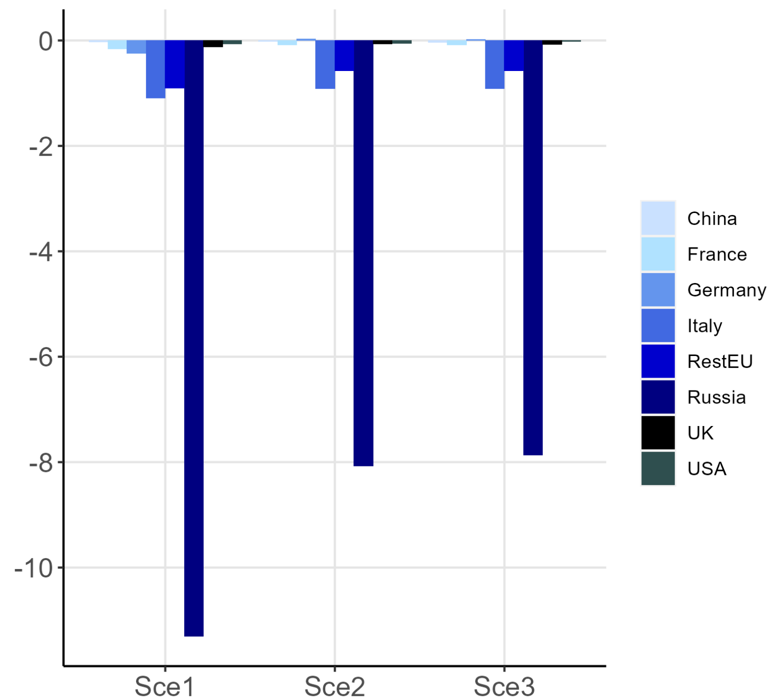
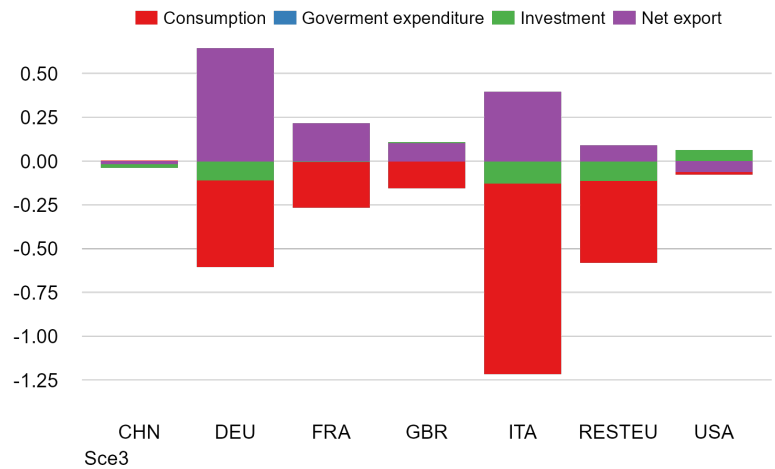


Figure 11 breaks down the real GDP changes by components. For most European countries private consumption is declining significantly, and this is partially compensated by an increase in net exports. In the case of Germany, the relatively large net export increase almost compensates for losses in consumption and investment. However, the overall reductions in private consumption are correlated with consumer welfare losses. These are specially pronounced for Italy, which is one of the European countries most negatively affected by the war.

Figure 11: Decomposition of real GDP effects in Scenario 3 in 2030 (% change w.r.t. baseline)



From Figure 12 we observe that the Russian shutoff of natural gas exports triggers changes in the electricity generation mix in all EU regions. In particular, there is a substantial reduction in gas generation. Italy has the highest decrease in gas, but this is also significant for Germany and the other EU countries (Rest EU). The reduction in gas generation is substituted mostly by renewable sources, as coal and oil generation remain very close to their baseline (BaU) values. Recall that these are medium-term effects and in the short-term European countries might need to revert to coal and nuclear powered electricity generation to avoid gas shortages in 2022 and 2023.

Figure 12: Electricity generation mix for EU countries for different scenarios in 2030 (shares)

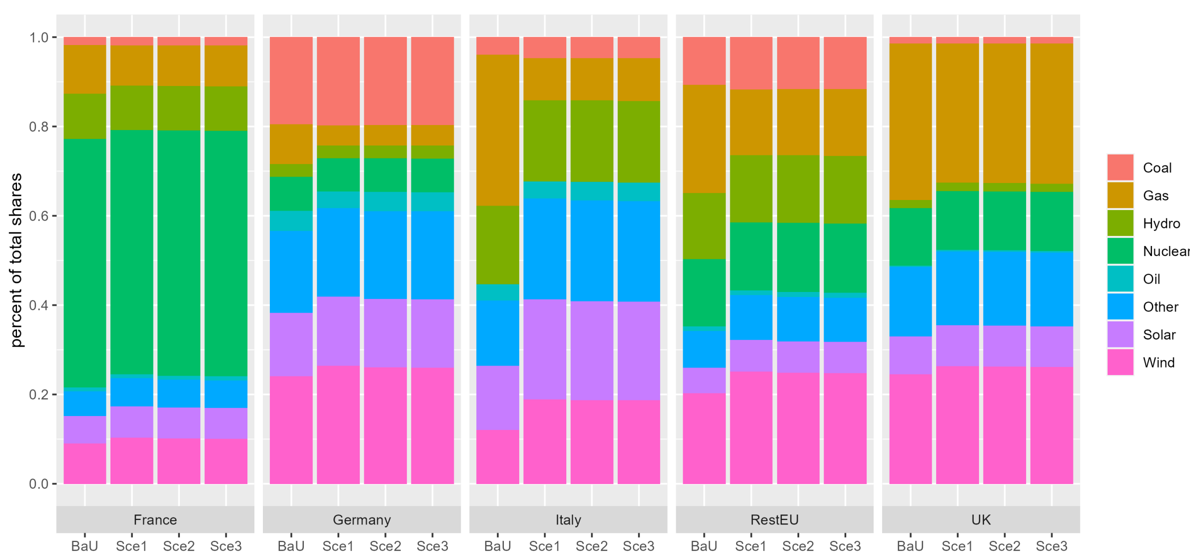


Figure 13 shows the electricity generation mix for China. This is dominated by coal and renewable generation, with natural gas being the least important power source. Hence, the new Russia-China pipeline, which is expected to generate a 300% expansion in current Russian natural gas exports to China does not have a significant effect on electricity generation and the resulting export volumes are still relatively small compared to overall Chinese energy demand. Figure 14 shows the energy import shares of China by main supplier. The bottom graphs shows that Russia was already the largest supplier of natural gas to China, and with the new pipeline it is expected to provide almost 90% of total imports. Nonetheless, the upper graph in Figure 14 shows that Russia provides less than 10% of total energy imports from China, which also include oil and coal imports. Russia's War in Ukraine increases this share to 20%, but this also includes a sharp increase in crude and refined oil imports from Russia, and not only the additional natural gas. Hence the new gas pipeline will represent only a fraction of increased energy imports to China. This explains why China does not benefit much from the new pipeline, even though this will reduce the price it pays for natural gas imports.

Figure 13: Electricity generation mix for China for different scenarios in 2030 (shares)

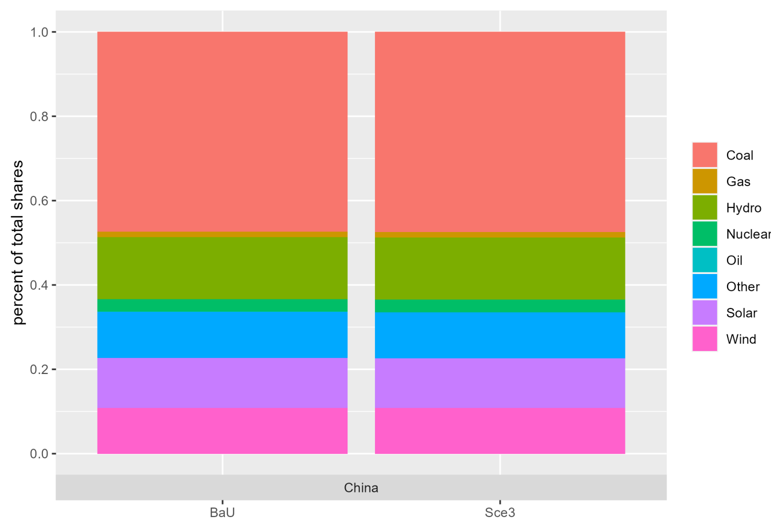
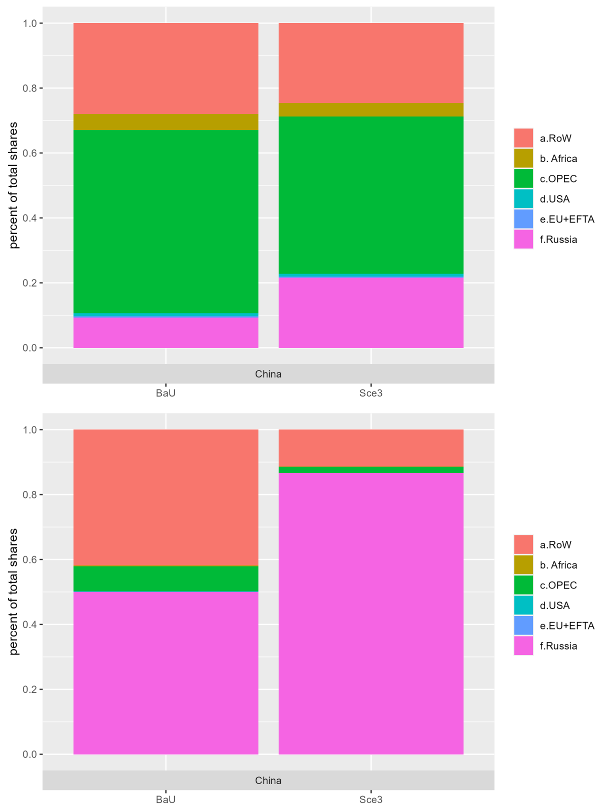


Figure 14: China: Total energy (top graph) and natural gas (bottom graph) import shares by supplier in 2021 (% change w.r.t. baseline)



Overall, the shutoff of Russian natural gas exports to the EU has a positive impact on GHG emissions in European countries through a substitution away from gas to renewable generation. Figure 15 shows the percentage changes in total emissions with respect to the baseline and here we observe that Italy has the largest decrease. This is explained by the relatively large substitution from gas to renewable electricity generation, and hence, the largest relative reductions in emissions. But other European countries have relatively large reductions as well. On the other hand, Chinese emissions increase with the inflow of cheaper Russian natural gas.

Figure 15: Overall GHG emissions for different scenarios in 2030 (% change w.r.t. baseline)

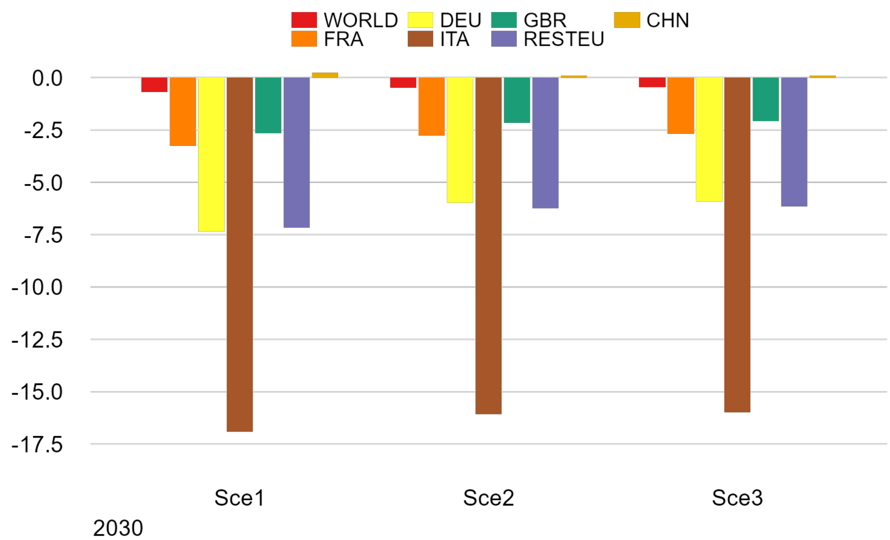
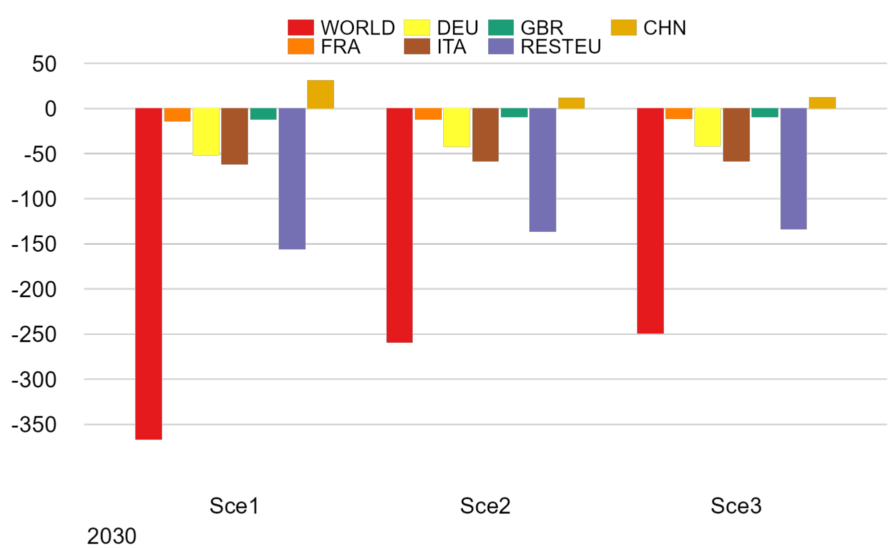


Figure 16) shows how these relative increases are translated into absolute emission reductions in MTCO2eq levels. Global emission are being reduced by around 250 metric tones and the largest contributor is the Rest of EU region and to a lesser extent the other European countries.

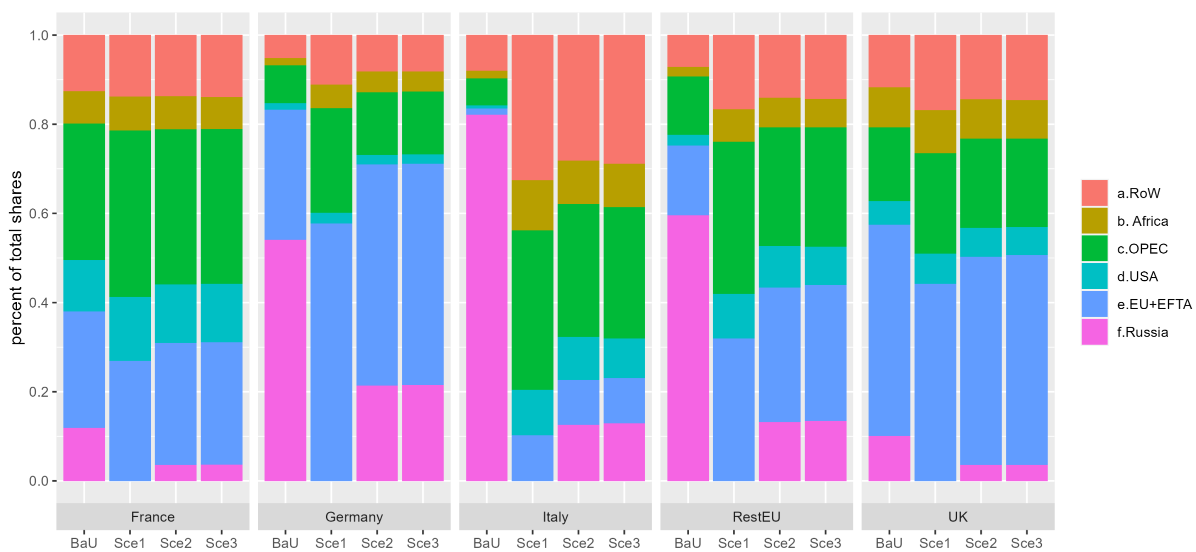
Figure 16: Overall GHG emissions for different scenarios in 2030 (changes in MTCO2eq levels w.r.t baseline)



To assess how Russia's War in Ukraine can potentially change energy security in Europe, we employ two main indicators. The first is the share of imported energy from Russia and other suppliers. Figure 17 shows the overall energy imports (coal, crude and refined oil and natural gas), while Figure 18 shows the imports shares only for natural gas. As expected from the shutoff of natural gas imports from Russia and the partial ban on oil imports, we observe that the EU dependency on Russian energy imports is substantially reduced by 2030. These sharp reductions are compensated mainly by more energy (and natural gas) imports from Norway (EU+EFTA), Qatar (OPEC), Algeria (Africa) and the US.[22] Note that the increase in natural gas imports from non-Russian suppliers is based on the updated 2021 natural gas import data. However, the model does not account for the large investments in LNG terminals undertaken in Europe, in particular in Germany, and hence the shares of LNG imports into Europe from the US and Qatar will be larger than predicted by the model.

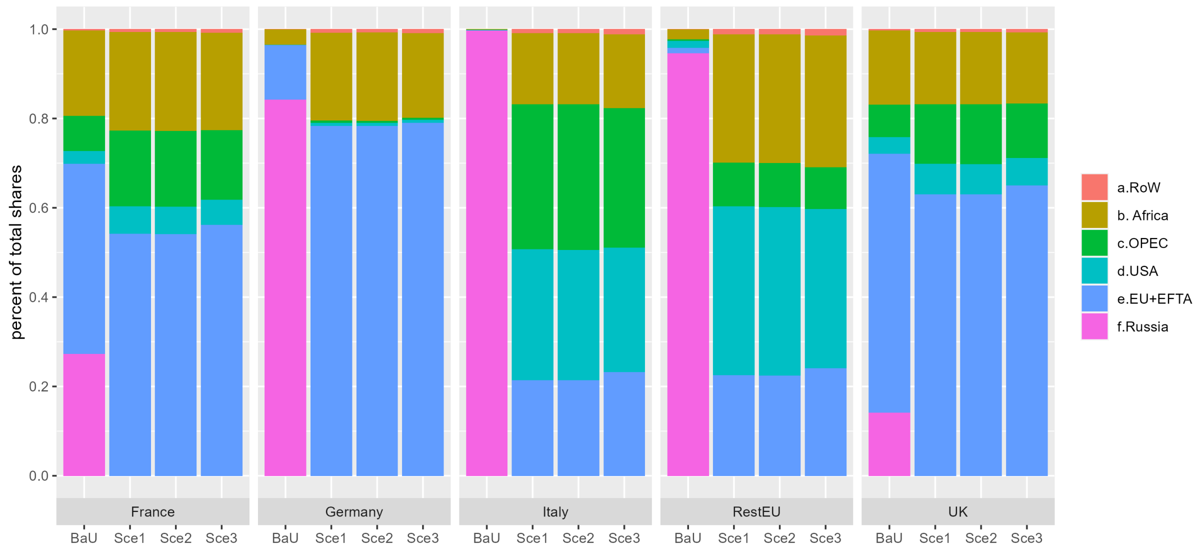
The increased dependency on non-Russian exports, however, can create future security issues if these countries become less reliable energy sources. It is also important to note that Norway will need to expand their current natural gas production and exports in this scenario, as they have lower trade costs (through existing pipelines) to supply European markets. Nevertheless, this will require that Norway invests heavily in new gas fields and possibly in new pipelines to Europe.

Figure 17: Imported energy shares by source for different scenarios in 2030



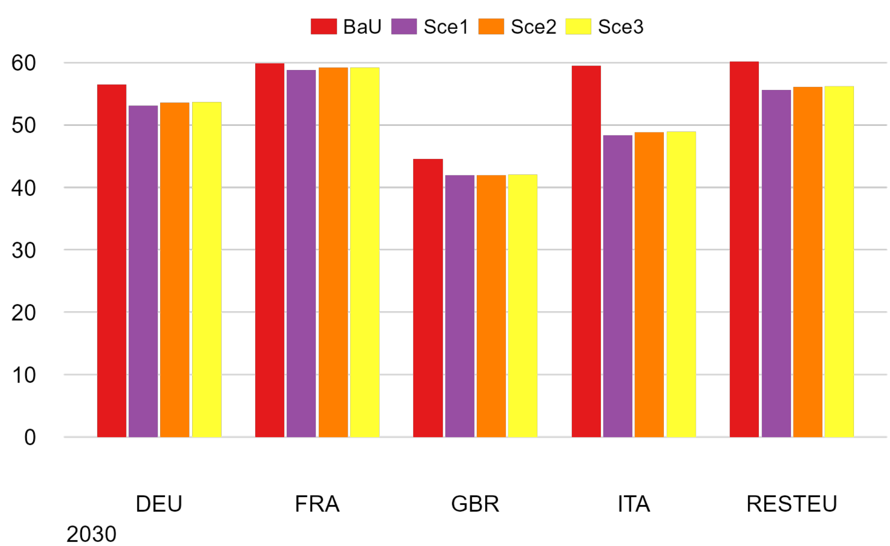
[22] These results are consistent with the recent study by EWI (2022), which finds that the current shutoff of Russian gas export to the EU can be substituted in the medium term by LNG imports, in particular from the US. They also estimate that under most of their scenarios, international gas prices go to their pre-crisis values.

Figure 18: Imported natural gas shares by source for different scenarios in 2030



The second indicator is the share of energy (and natural gas) imports to domestic energy consumption. Figure 19 shows that Italy has the sharpest decline in the share of imported energy relative to their energy demand from 60% to less than 50%. This is explained by their large dependency on Russian natural gas imports and the stark reduction of gas in their electricity mix. All other European countries have a decline in their imported shares, but less pronounced.

Figure 19: Share of imported energy relative to domestic energy demand for different scenarios in 2030



Therefore both indicators point to an improvement in energy security, even though the increased share of energy imports from non-OECD countries (i.e. Qatar and Algeria) could be concerning. Another measure of energy security are energy prices and we find that in the medium-term, the international price of natural gas increases by 25% relative to baseline prices. This reflects the removal from international markets of most Russian natural gas imports that was relatively cheap for European markets. Despite the very high current international gas prices, it is expected that in the medium-term the increase in natural gas exports from non-Russian countries will fill the supply gap left by Russian pipeline gas. Figure 20 shows that the sharp decrease in Russian exports, is more than compensated by production and export increases in the EU+EFTA (mainly Norway), the US, Rest OPEC (mainly Qatar) and Africa (mainly Algeria). Total (World) natural exports are increasing by almost 8%. This is a response to the higher current prices and the associated larger investments in LNG terminals and carrier ships. On the other hand, the disruption of the cheaper Russian pipeline gas and the overall higher natural gas prices are reducing global demand for gas by around 3% (see Figure 21). As expected, the reduction is sharpest in the EU and UK (20%), but it is a trend for developed countries. Russia and India, conversely have an increase in natural gas demand. In the NDC scenario (Sce4) the reduction is larger given the requirements to reduce emissions, and Russia's War in Ukraine is accelerating this trend of reduced global gas demand. Therefore, the combination of both higher supply through exports and lower global demand dampen in the medium-term the current very high natural gas prices, with a resulting increase of 25% by 2030.

Figure 20: Natural gas exports by main suppliers for different scenarios in 2030 (billion cubic meters)

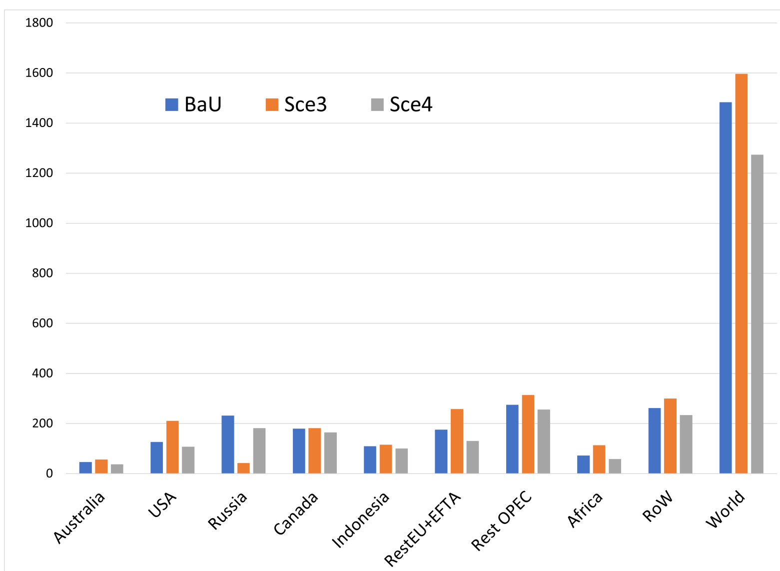
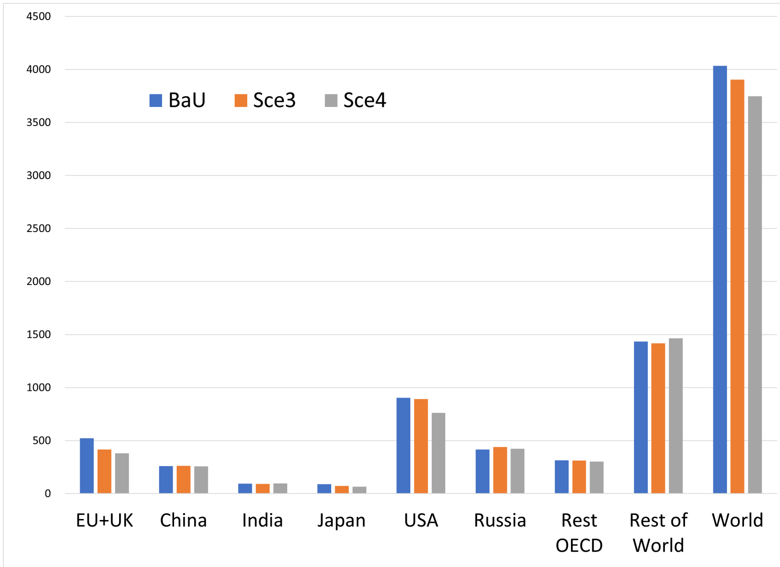
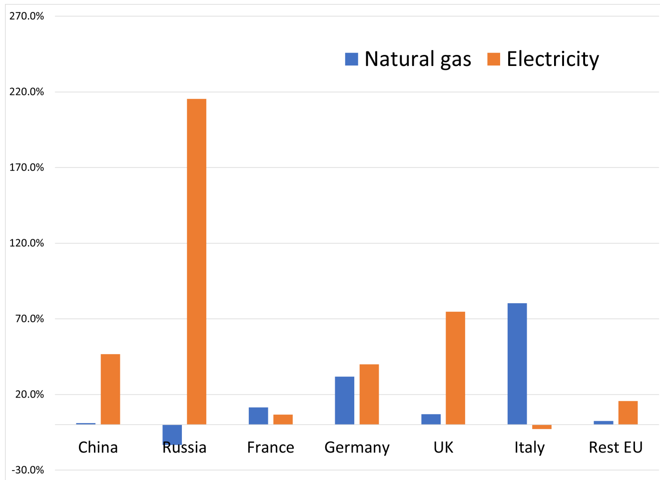


Figure 21: Demand of natural gas exports by main regions for different scenarios in 2030 (billion cubic meters)



In turn, larger international prices are translated into higher domestic consumer prices for natural gas (see Figure 22). Electricity prices are also increasing, but the values are not directly correlated with natural gas prices. This reflects the dual use of natural gas for electricity generation, but also for heating and industrial activities. On the other hand, electricity prices reflect changes in the costs of the different generation sources and their relative importance in the electricity mix. This can create some contrasting price changes. For instance, consumer natural gas prices are declining in Russia, but electricity prices are increasing by more than 200%, while the inverse pattern is observed in Italy. Nevertheless, it is expected that the current spike in energy prices will ease in the medium-term, as alternative suppliers of natural gas fill in the void left by Russian imports and the economy moves towards renewable generation.

Figure 22: Consumer price for natural gas and electricity in Scenario 3 in 2030 (% change w.r.t. baseline prices)



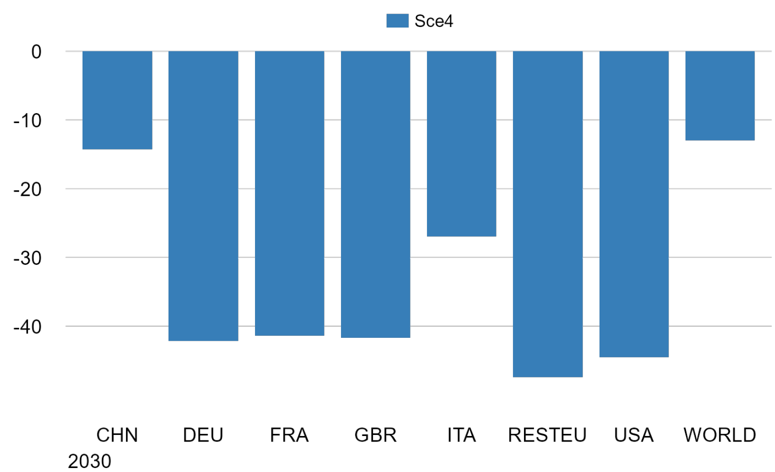
5.2 Interaction of the war with climate commitments

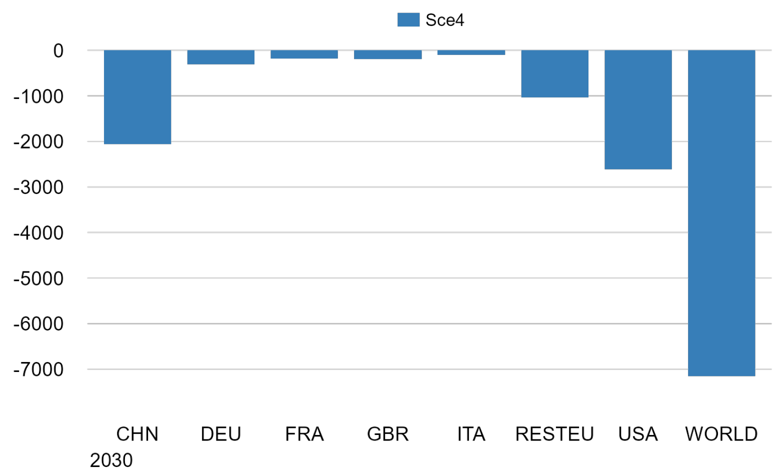
In this section we model a global commitment to reducing emissions through the implementation of the NDCs in G20 countries (Sce4). We then interact this global NDC scenario with Russia's War in Ukraine trade shocks (Sce4) to assess how the war affects the implementation of the NDCs.

Achieving the NDC commitments requires drastic GHG emissions by 2030. For example, the EU's Green Deal envisages a reduction of 55% with respect to 2005 emission values for all sources of GHG.[23] Figure 23 shows the percentage reduction with respect to baseline values and the level decrease in total GHG emissions. The NDC commitments, which are relative to a historical emission value (2005 for the EU), result in emission changes with respect to our emission projections of around 40% for most European countries, with the exception of Italy that requires a lower emission reduction. The implementation of these NDC targets results in global emissions reductions of around 12% or 7000 MTCO2eq with respect to baseline projections in 2030. Most emissions reductions by volume are in China and the US, even though EU countries have similar percentage reductions as the US.

[23]Including $C0_2$ emissions from land use and land-use change and forestry (LULUCF). The NDC 2030 emission levels where taken from the IMF's Climate Policy Assessment Tool (CPAT).

Figure 23: Overall GHG emissions for NDC scenario (Sce4) in 2030, as % change w.r.t. baseline values (top graph) and changes in MTCO2eq w.r.t baseline levels (bottom graph)





For simplicity, we model the NDC emission reductions through a general carbon tax levied on all GHGs and polluting activities.[24] Figure 24 shows that to achieve their NDCs countries require substantial increases in carbon tax rates. The level of these tax rates is related to the carbon-intensity of each country. For example, Germany and the Rest of EU region have relatively large shares of coal electricity generation and energy-intensive industries. Including the Ukrainian shock (Scenario t), which shifts the electricity mix towards a larger share of renewable generation and reduces the domestic consumption of imported fossil fuels, means that the carbon tax rate is lower on average by around US$25 per ton of CO_2eq for EU countries, with the largest decreases in Germany and the Rest of EU region.

[24]In reality, most countries are planning to reduce emissions through a combination of different mitigation policies, many of which include some type of carbon pricing.

Figure 24: Carbon tax rates for scenarios including NDCs in 2030 (US$ by ton of CO_2eq)

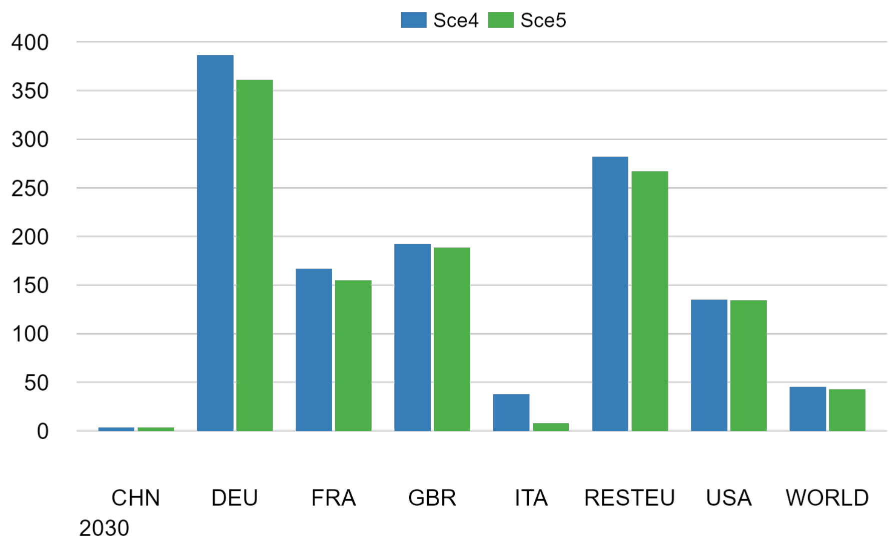


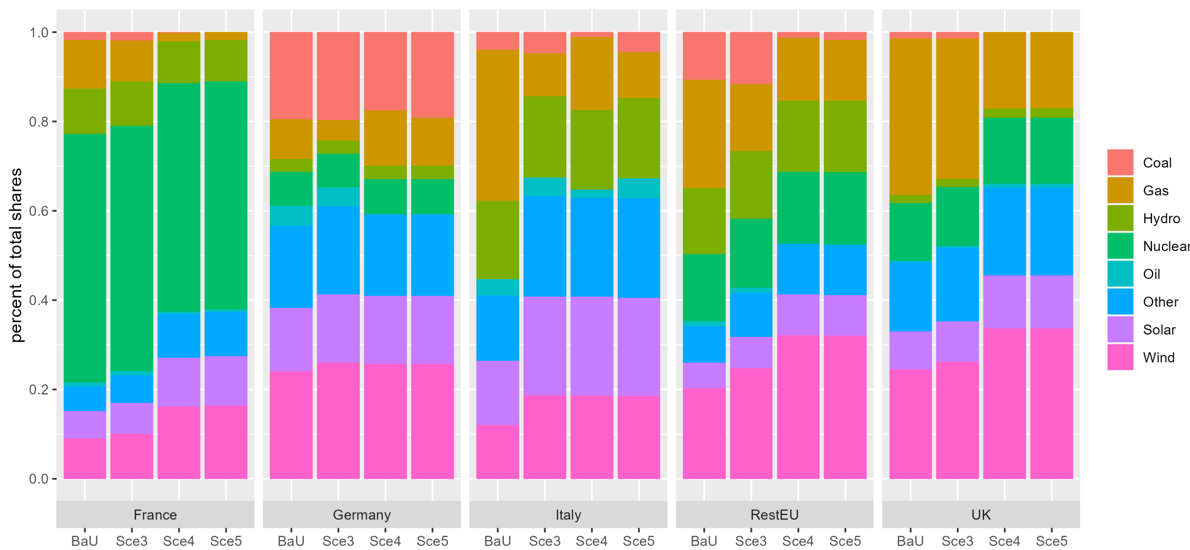
Figure 25 presents the changes in the electricity generation mix in all EU regions and the UK. The electricity mix for 2030 under the NDC is calibrated to match the values from the PRIMES energy model from the European Commission's Joint Research Center (JRC-Seville)[25] The calibration to the PRIMES values is done exactly to match the shares of fossil fuel and renewable generation, while the shares of different fossil fuels (coal, gas and oil) and different renewables (solar, hydro, wind and others) can be different than in PRIMES.[26] Therefore, by construction the NDC values for both Scenario 4 and 5 are similar. However, the figure shows that for the UK, France and the Rest of EU region, Russia's War in Ukraine produces an intermediate step between the baseline values and the NDC targets. In Italy the large changes associated with the war bring them already to the NDC targets. In the case of Germany, the war shocks move the share of renewable generation beyond the NDC targets.[27]

[25]Energy models provide richer technical details than CGE models regarding the interaction of different generation technologies, the specification of the country grid and the potential (and costs) of increasing each power source in each country.

[26]We keep the volumes of nuclear generation fixed to the baseline values.

[27]In other words, when we let the CGE model endogenously determine the electricity mix, it provides values that are different than those from the PRIMES energy model. This reflects the inaccuracies of the CGE model to properly measure generation changes without constraints based on the technical details of energy models.

Figure 25: Electricity generation mix for EU countries for scenarios including NDCs in 2030 (shares)



Russia's War in Ukraine shock, nevertheless, does increase the overall economic costs (reflected in the reductions in real GDP) of reaching the NDCs. From Figure 26 we observe that real GDP losses are larger in the scenarios with Russia's War in Ukraine shock (Scenario 5) than in the scenario without (Scenario 4) in all European countries. Italy and the Rest of EU region have the largest differences, while GDP losses in Germany are very similar. This is also the case for China and the US, which experience very limited GDP changes from Russia's War in Ukraine trade shocks. The most pronounced difference, however, if for Russia (not shown), where the GDP costs of implementing their NDC move from around -1% to -8%.

Interestingly, the NDC costs for China are slightly higher with the Ukrainian shock, even though they initially benefit from access to cheaper Russian natural gas imports that are less polluting than their coal generation. But as explained above, gas generation represents a very small fraction of electricity generation in China and the larger imports of natural gas from Russia are relatively small when compared to their overall energy imports.

Figure 26: Real GDP for scenarios including NDCs in 2030 (% change w.r.t. baseline)

Finally, when we look at energy security indicators, from Figures 27 and 28 we observe that the Russian share of imports for total energy and gas are substantially lower after Russia's War in Ukraine shock (Scenarios 3 and 5) than when the NDCs are implemented without those trade shocks (Scenario 4). France and the UK, which did not have a large share of Russian imports to start with, experience relatively small changes.

Figure 27: Imported energy shares by source for different scenarios in 2030

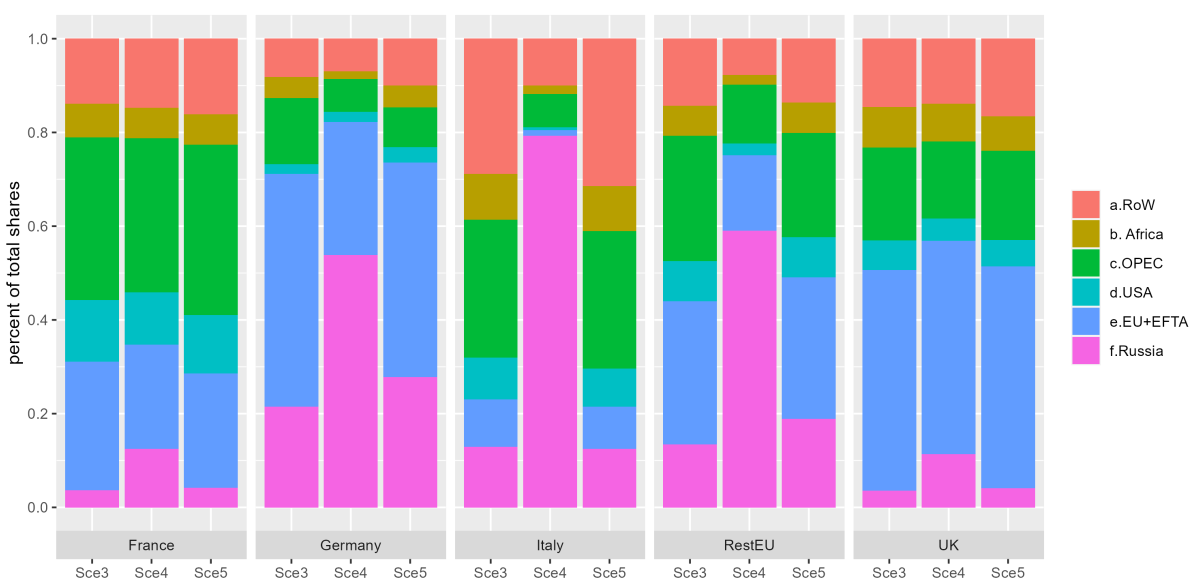


Figure 28: Imported natural gas shares by source for different scenarios in 2030

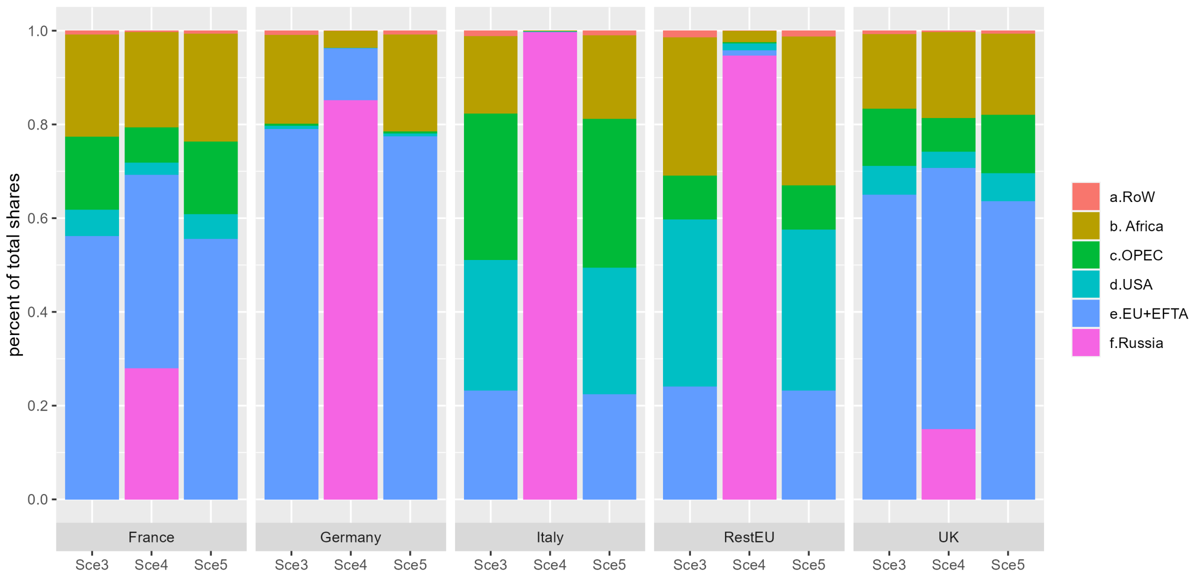


Figure 29 shows that total energy imports relative to total energy domestic demand is also lower with the Ukrainian trade shocks; mainly for Italy, but also for Germany and the Rest EU region. Figure 30 shows that electricity prices in Scenario 4 are increasing with carbon taxation, even though the price of natural gas is declining. The interaction of the NDC policies with Russia's War in Ukraine shock (Scenario 5) make natural gas prices higher, but electricity prices are not changing much, as the shutoff of Russian natural gas imports forces countries to move more aggressively towards renewable generation.

Figure 29: Share of imported energy relative to domestic energy demand for different scenarios in 2030

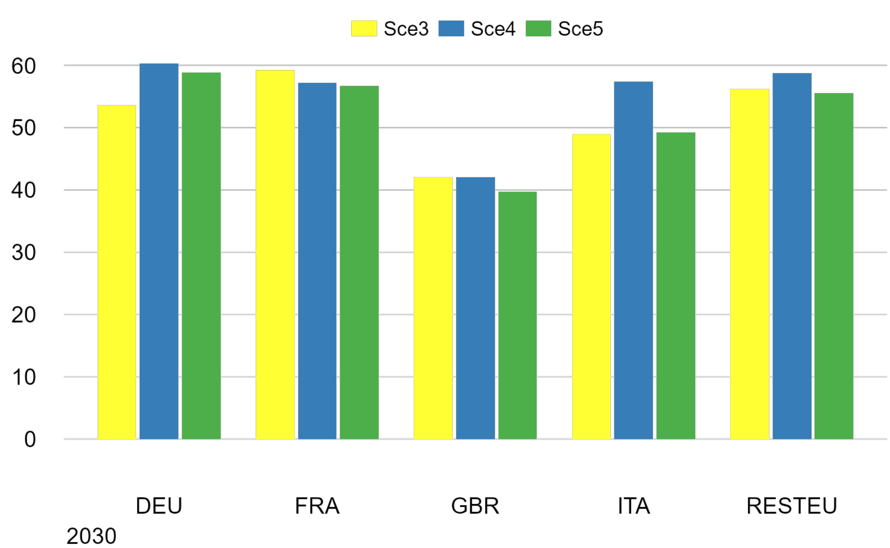
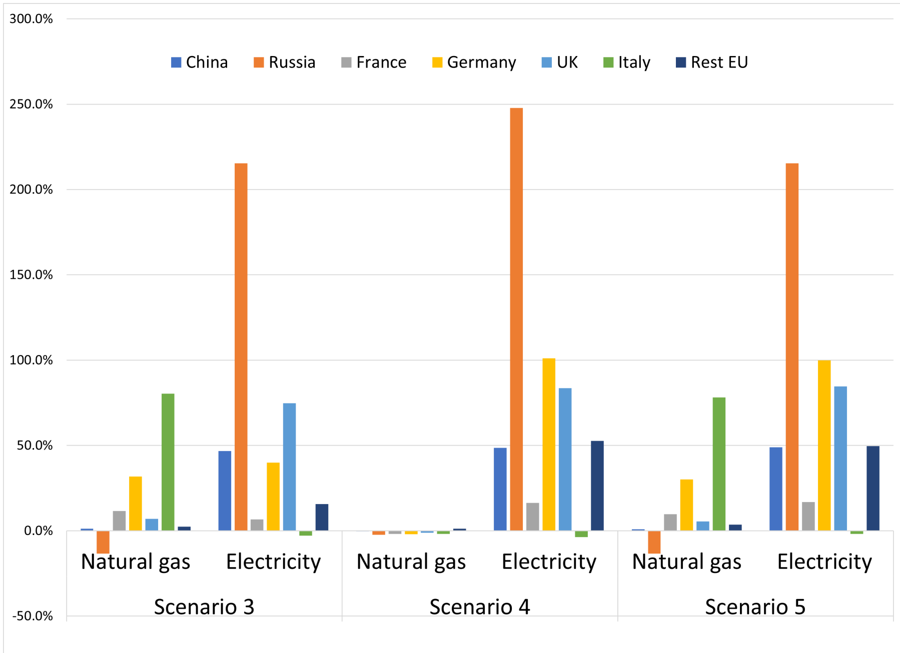


Figure 30: Consumer price for electricity in different scenarios in 2030 (% change w.r.t. baseline prices)



6 Summary

The trade sanctions imposed as a consequence of the Russian invasion of Ukraine are expected the generate substantial economic losses for Russia in the medium term, but it will also affect European countries. In particular, the Russian shutoff of gas exports to the EU has already resulted in very high energy price and significant economic losses for the European countries that are most dependent on Russian natural gas imports. In the medium term the real GDP losses associated with the war are expected to be relatively high for Russia (around 8%), but moderate for other European countries (less than 1%) and negligible for other G20 countries. On the other hand, switching away from these energy imports from Russia is expected to create a greener electricity generation mix and reduce EU overall emissions between 2 to 5%.

In general, from the countries in our model Italy is the most affected by Russia's War in Ukraine, with the largest GDP losses, consumption reductions and higher natural gas consumer prices; but it is also the country that increases renewable generation and reduces emissions the most. This is a result of their initial high dependency on Russian natural gas imports and their relatively large share of electricity generation using natural gas. However, other European countries can be also severely affected by the war, in particular Central and Eastern European countries that also depend heavily on Russian energy imports, such as Austria, Czechia, Slovakia, Hungary and Bulgaria. In our model these countries are aggregated in the Rest of EU region, which also includes countries that are not expected to be as affected by the war.

The switch of EU countries from less gas to more renewable generation could also increase energy security for these countries, at least if measured by the import share of fossil fuels from Russia or the share of total energy imports relative to domestic energy consumption.

However, natural gas prices are expected to be higher in the medium-term and EU countries will still import substantial amounts of natural gas, but the main suppliers will be Norway, the US, Qatar and Algeria, instead of Russia. We also find that if a new pipeline between Russia and China is constructed, it will have relatively small economic and environmental implications for both countries. Natural gas exports of Russia will still decrease by almost 80% of pre-war levels and the increased trade volumes are not substantial enough for China, both as a share of total energy imports or to propitiate a shift from coal to gas electricity generation.

When countries implement their NDCs the overall costs of implementing the NDCs increases for European countries as a consequence of the negative GDP effects of the war and loosing access to cheap Russian natural gas. The required shadow price of carbon to reach the NDCs, however, is slightly lower after Russia's War in Ukraine, as countries move faster toward renewable generation and rely less on imported fossil fuel energy.

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Appendix

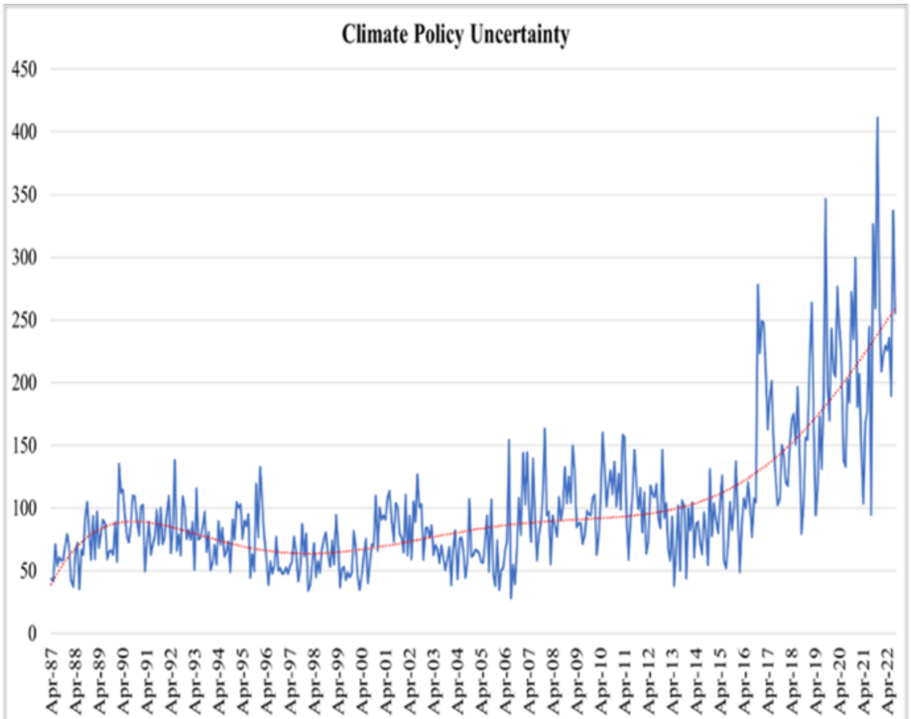
A Investment requirements and uncertainty

While there is increased pressure for countries to decarbonize and transform to a cleaner and greener economy, the green transition is subject to uncertainty. There are two main sources of uncertainty around the green transition: 1) environmental deregulation and general uncertainty about the implementation of environmental policies, 2) soaring prices of metals necessary for renewable energy projects driven by demand-supply mismatches. On the former, and building on the methodology of the economic policy uncertainty index by Baker et al. (2016),[28] Gavriilidis (2021) constructs the climate policy uncertainty index.[29] Figure 1 shows that while the climate index is quite volatile, it has been on a trend increase especially in the last few years. This increase in environmental policy uncertainty deters firms' investments in green energy and green innovation more broadly (Kyaw, 2022), which in turn slows down the green transition.

[28]The index is constructed by Baker et al. (2016) and reflects the frequency of articles in 10 leading newspapers in the U.S. that contain the terms: "economic" or "economy"; "uncertain" or "uncertainty"; and one or more of "Congress", "deficit", "Federal Reserve", "legislation", "regulation", or "White House" and is available at `policyuncertainty.com`.

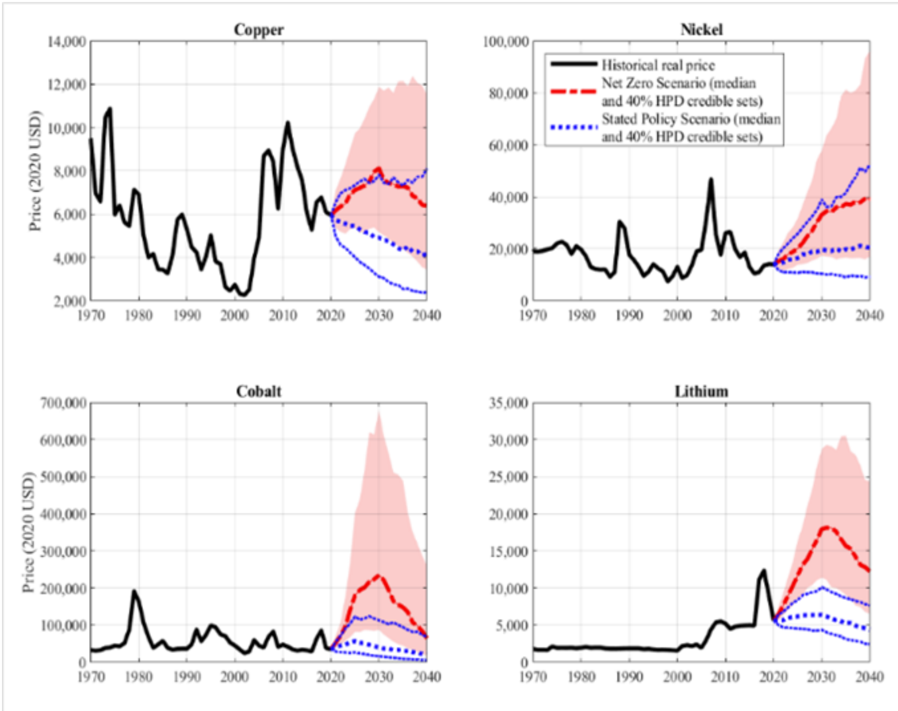
[29]Gavriilidis constructs the Climate Policy Uncertainty index by searching for articles in eight leading US newspapers containing the terms "uncertainty" or "uncertain" and "carbon dioxide" or "climate" or "climate risk" or "greenhouse gas emissions" or "greenhouse" or "CO2" or "emissions" or "global warming" or "climate change" or "green energy" or "renewable energy" or "environmental" and ("regulation" or "legislation" or "White House" or "Congress" or "EPA" or "law" or "policy" (including variants such as "uncertainties", "regulatory", "policies", etc.) from January 2000 till March 2021. The eight newspapers are: Boston Globe, Chicago Tribune, Los Angeles Times, Miami Herald, New York Times, Tampa Bay Times, USA Today and the Wall Street Journal. For each newspaper, he scales the number of relevant articles per month with the total number of articles during the same month. Next, these eight series are standardized to have a unit standard deviation and then averaged across newspapers by month. Finally, the averaged series are normalized to have a mean value of 100 for the period 2000:M1-2021:M3.

Figure 31: Climate policy uncertainty index



Source: Gavriilidis (2021).

Figure 32: Prices of the four metals are expected to rise significantly in the IEA net zero scenario



Source: Boer et al. (2021).

The energy transition might be subject to derailment if demand for metals continues to exceed supply. A fast-paced transition that is consistent with the 'net zero' scenario of the International Energy Agency (IEA), implies soaring demand over the next decade for copper, nickel, cobalt and lithium –metals used in low carbon technologies.[30] This is met with inelastic supply given capital intensive (extractive) production methods. An IMF study finds that prices for copper, nickel, cobalt, and lithium could reach historical peaks for an unprecedented, sustained period in the IEA's net zero emissions scenario (**?**). The real prices of nickel, cobalt and lithium would rise several hundred percent from 2020 levels, while the copper price would increase by more than 60 percent. It is noteworthy that there is sufficient uncertainty about the demand and prices of metals driven by uncertainty about the pace of technological progress and policy implementation. Therefore, the four metals might be potential bottlenecks for the energy transition.

[30] Electric vehicles, for example, use over six times more minerals than their conventional counterparts. An offshore wind plant requires over seven times the amount of copper compared with a gas-fired plant (IEA, 2021).

B Aggregation tables

Table 1: Regional concordance between IMF-ENV and the GTAP database

1	Australia (AUS)	Australia (AUS)
2	China (CHN)	China (CHN)
3	Japan (JPN)	Japan (JPN)
4	India (IND)	India (IND)
5	United States (USA)	United States of America (USA)
6	Russia (RUS)	Russian Federation (RUS)
7	Argentina (Argentina)	Argentina (ARG)
8	Brazil (Brazil)	Brazil (BRA)
9	Canada (Canada)	Canada (CAN)
10	Indonesia (Indonesia)	Indonesia (IDN)
11	Korea (Korea)	Korea, Republic of (KOR)
12	Mexico (Mexico)	Mexico (MEX)
13	Saudi Arabia (Saudi)	Saudi Arabia (SAU)
14	South Africa (SouthAfrica)	South Africa (ZAF)
15	Turkey (Turkey)	Turkey (TUR)
16	France (France)	France (FRA)
17	Germany (Germany)	Germany (DEU)
18	United Kingdom (UK)	United Kingdom (GBR)
19	Italy (Italy)	Italy (ITA)
20	Rest of EU & EFTA (RESTEU)	Austria (AUT), Belgium (BEL), Cyprus (CYP), Czech Republic (CZE), Denmark (DNK), Estonia (EST), Finland (FIN), Greece (GRC), Hungary (HUN), Ireland (IRL), Latvia (LVA), Lithuania (LTU), Luxembourg (LUX), Malta (MLT), Netherlands (NLD), Poland (POL), Portugal (PRT), Slovakia (SVK), Slovenia (SVN), Spain (ESP), Sweden (SWE), Switzerland (CHE), Norway (NOR), Rest of EFTA (XEF), Bulgaria (BGR), Croatia (HRV), Romania (ROU)
21	Other Oil-Exporting countries (RESTOPEC)	Ecuador (ECU), Venezuela (VEN), Bahrain (BHR), Islamic Republic of Iran (IRN), Israel (ISR), Kuwait (KWT), Oman (OMN), Qatar (QAT), United Arab Emirates (ARE), Rest of Western Asia (XWS), Jordan (JOR), Rest of North Africa (XNF), Nigeria (NGA), South Central Africa (XAC)
22	Other developing and emerging East Asia & New Zealand (ODA)	New Zealand (NZL), Rest of Oceania (XOC), Hong Kong (HKG), Mongolia (MNG), Chinese Taipei (TWN), Rest of East Asia (XEA), Cambodia (KHM), Lao People s Democratic Republic (LAO), Malaysia (MYS), Philippines (PHL), Singapore (SGP), Thailand (THA), Viet Nam (VNM), Rest of Southeast Asia (XSE), Brunei Darussalam (BRN), Bangladesh (BGD), Nepal (NPL), Pakistan (PAK), Sri Lanka (LKA), Rest of South Asia (XSA), Rest of South African Customs Union (XSC)
23	Other developing and emerging Africa (OAF)	Egypt (EGY), Morocco (MAR), Tunisia (TUN), Cameroon (CMR), Cote d Ivoire (CIV), Ghana (GHA), Senegal (SEN), Benin (BEN), Burkina Faso (BFA), Guinea (GIN), Togo (TGO), Rest of Western Africa (XWF), Central Africa (XCF), Ethiopia (ETH), Kenya (KEN), Madagascar (MDG), Malawi (MWI), Mauritius (MUS), Mozambique (MOZ), United Republic of Tanzania (TZA), Uganda (UGA), Zambia (ZMB), Zimbabwe (ZWE), Rwanda (RWA), Rest of Eastern Africa (XEC), Botswana (BWA), Namibia (NAM)
24	Other developing and emerging Eurasia (OEURASIA)	Albania (ALB), Belarus (BLR), Ukraine (UKR), Rest of Eastern Europe (XEE), Rest of Europe (XER), Kazakhstan (KAZ), Kyrgyzstan (KGZ), Rest of Former Soviet Union (XSU), Tajikistan (TJK), Armenia (ARM), Azerbaijan (AZE), Georgia (GEO)
25	Other developing and emerging Latin America (OLA)	Rest of North America (XNA), Plurinational Republic of Bolivia (BOL), Chile (CHL), Colombia (COL), Paraguay (PRY), Peru (PER), Uruguay (URY), Rest of South America (XSM), Costa Rica (CRI), Guatemala (GTM), Honduras (HND), Nicaragua (NIC), Panama (PAN), El Salvador (SLV), Rest of Central America (XCA), Caribbean (XCB), Dominican Republic (DOM), Jamaica (JAM), Puerto Rico (PRI), Trinidad and Tobago (TTO), Rest of the World (XTW)

Table 2: Concordance for activities between IMF-ENV and the GTAP database

1	All Crops (cro)	Paddy Rice (pdr), Wheat (wht), Other Grains (maize, barley, rye, oats, other cereals) (gro), Vegetables and fruits (v_f), Oil Seeds (osd), Sugar cane and sugar beet (c_b), Plant Fibres (cotton, flax, hemp, sisal and other raw vegetable materials used in textiles) (pfb), Other Crops (ocr)
2	Livestock (lvs)	Bovine cattle, sheep and goats, horses (ctl), Animal products n.e.s. (oap), Raw milk (rmk), Wool, silk-worm cocoons (wol)
3	Forestry (frs)	Forestry (frs)
4	Fisheries (fsh)	Fishing (fsh)
5	Construction (cns)	Construction (cns)
6	Minerals n.e.s. (OMN)	Minerals n.e.s. (oxt)
7	Water services (wts)	Water supply; sewerage, waste management and remediation activities (wtr)
8	Coal extraction (coa)	Coal (coa)
9	Crude Oil extraction (oil)	Oil (oil)
10	Petroleum and coal products (p_c)	Manufacture of coke and refined petroleum products (p_c)
11	Natural gas: extraction, manufacture & distribution (gas)	Gas (gas), Gas manufacture, distribution (gdt)
12	Coal powered electricity (clp)	Coal power baseload (CoalBL), Coal-based CCS (colccs)
13	Oil powered electricity (olp)	Oil power baseload (OilBL), Oil power peakload (OilP)
14	Gas Powered electricity (gsp)	Gas power baseload (GasBL), Gas power peakload (GasP), Gas-based CCS (gasccs)
15	Nuclear power (nuc)	Nuclear power (NuclearBL), Advanced nuclear (advnuc)
16	Hydro power (hyd)	Hydro power baseload (HydroBL), Hydro power peakload (HydroP)
17	Wind power (wnd)	Wind power (WindBL)
18	Solar power (sol)	Solar power (SolarP)
19	Other power (xel)	Other baseload includes biofuels, waste, geothermal, and tidal technologies (OtherBL)
20	Electricity transmission and distribution (etd)	Electricity transmission and distribution (TnD)
21	Paper & Paper Products (ppp)	Paper products, publishing (ppp)
22	Non-metallic minerals (nmm)	Mineral products n.e.s. (nmm)
23	Iron and Steel (i_s)	Iron and steel (i_s)
24	Chemical products (crp)	Chemical products (chm)
25	Non-ferrous metals (nfm)	Non-ferrous Metals (nfm)
26	Electronics (ele)	Electronic equipment (ele)
27	Food Products (fdp)	Bovine cattle, sheep and goat, horse meat products (cmt), Meat products n.e.s. (omt), Vegetable oils and fats (vol), Dairy products (mil), Processed rice (pcr), Sugar (sgr), Food products n.e.s. (ofd), Beverages and tobacco products (b_t)
28	Textiles (txt)	Textiles (tex), Wearing apparel (wap), Leather products (lea)
29	Transport Equipment (mvh)	Motor vehicles and parts (mvh), Transport equipment n.e.s. (otn)
30	Fabricated metal products (fmp)	Metal products (fmp)
31	Other manufacturing (includes recycling) (oma)	Wood products (lum), Machinery and equipment n.e.s. (ome), Electrical equipment (eeq), Basic pharmaceuticals (bph), Rubber and plastic products (rpp), Manufactures n.e.s. (omf)
32	Water Transport (wtp)	Sea transport (wtp)
33	Air Transport (atp)	Air transport (atp)
34	Land transport (otp)	Transport n.e.s.: Land transport and transport via pipelines (otp)
35	Other collective services (osg)	Public administration and defense (osg), Education (edu), Human health and social work (hht)
36	Other Business services (osc)	Communication (cmn), Financial services n.e.s. (ofi), Insurance (ins), Recreation and other services (ros), Dwellings (dwe), Trade (trd), Accommodation and food service activities (afs), Warehousing and support activities (whs), Business services n.e.s. (obs), Real estate activities (rsa)

Table 3: Concordance for commodities between IMF-ENV and the GTAP database

1	All Crops (cro)	Paddy Rice (pdr), Wheat (wht), Other Grains (maize, barley, rye, oats, other cereals) (gro), Vegetables and fruits (v_f), Oil Seeds (osd), Sugar cane and sugar beet (c_b), Plant Fibres (cotton, flax, hemp, sisal and other raw vegetable materials used in textiles) (pfb), Other Crops (ocr)
2	Livestock (lvs)	Bovine cattle, sheep and goats, horses (ctl), Animal products n.e.s. (oap), Raw milk (rmk), Wool, silk-worm cocoons (wol)
3	Forestry (frs)	Forestry (frs)
4	Fisheries (fsh)	Fishing (fsh)
5	Construction (cns)	Construction (cns)
6	Minerals n.e.s. (OMN)	Minerals n.e.s. (oxt)
7	Water services (wts)	Water supply; sewerage, waste management and remediation activities (wtr)
8	Coal extraction (coa)	Coal (coa)
9	Crude Oil extraction (oil)	Oil (oil)
10	Petroleum and coal products (p_c)	Manufacture of coke and refined petroleum products (p_c)
11	Natural gas (gas)	Natural gas extraction (gas), Gas manufacture and distribution (gdt)
12	Electricity (ELY)	Coal power baseload (CoalBL), Coal-based CCS (colccs), Oil power baseload (OilBL), Oil power peakload (OilP), Gas power baseload (GasBL), Gas power peakload (GasP), Gas-based CCS (gasccs), Nuclear power (NuclearBL), Advanced nuclear (advnuc), Hydro power baseload (HydroBL), Hydro power peakload (HydroP), Wind power (WindBL), Solar power (SolarP), Other baseload includes biofuels, waste, geothermal, and tidal technologies (OtherBL), Electricity transmission and distribution (TnD)
13	Paper & Paper Products (ppp)	Paper products, publishing (ppp)
14	Non-metallic minerals (nmm)	Mineral products n.e.s. (nmm)
15	Iron and Steel (i_s)	Iron and steel (i_s)
16	Chemical products (crp)	Chemical products (chm)
17	Non-ferrous metals (nfm)	Non-ferrous Metals (nfm)
18	Electronics (ele)	Electronic equipment (ele)
19	Food Products (fdp)	Bovine cattle, sheep and goat, horse meat products (cmt), Meat products n.e.s. (omt), Vegetable oils and fats (vol), Dairy products (mil), Processed rice (pcr), Sugar (sgr), Food products n.e.s. (ofd), Beverages and tobacco products (b_t)
20	Textiles (txt)	Textiles (tex), Wearing apparel (wap), Leather products (lea)
21	Transport Equipment (mvh)	Motor vehicles and parts (mvh), Transport equipment n.e.s. (otn)
22	Fabricated metal products (fmp)	Metal products (fmp)
23	Other manufacturing (includes recycling) (oma)	Wood products (lum), Machinery and equipment n.e.s. (ome), Electrical equipment (eeq), Basic pharmaceuticals (bph), Rubber and plastic products (rpp), Manufactures n.e.s. (omf)
24	Water Transport (wtp)	Sea transport (wtp)
25	Air Transport (atp)	Air transport (atp)
26	Land transport (otp)	Transport n.e.s.: Land transport and transport via pipelines (otp)
27	Other collective services (osg)	Public administration and defense (osg), Education (edu), Human health and social work (hht)
28	Other Business services (osc)	Communication (cmn), Financial services n.e.s. (ofi), Insurance (ins), Recreation and other services (ros), Dwellings (dwe), Trade (trd), Accommodation and food service activities (afs), Warehousing and support activities (whs), Business services n.e.s. (obs), Real estate activities (rsa)