INTERNATIONAL MONETARY FUND

Energy Security and The Green Transition

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WP/24/6

2024
JAN

WORKING PAPER

 WP/24/6

IMF Working Paper
Research Department

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Authorized for distribution by Florence Jaumotte
January 2024

ABSTRACT: The current energy crisis has raised important policy questions on how to strengthen short-term energy security while remaining firmly committed to the green transition, a challenge amplified by the recent consensus at COP28 to transition away from fossil fuels. This paper examines the historical determinants of the security of energy supply and analyzes the green transition implications for energy security. Looking back, we find that the diversification of energy trade partners, or the lack thereof, was the main factor that underpinned energy security dynamics within and across countries over the last two decades. Looking ahead, the green transition is expected to have a net positive effect on energy security provided investments are aligned to address new challenges posed by the increased reliance on renewables.

JEL Classification Numbers:	Q43, Q47, Q48, Q54, Q55, Q58, H20
Keywords:	Energy security; energy independence; green transition; climate mitigation; geo-political risks
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* The authors would like to thank Florence Jaumotte for helpful comments, and Sneha Thube and Hugo Rojas-Romagosa for model simulations.

WORKING PAPERS

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Introduction

The ongoing energy crisis amid Russia's invasion of Ukraine has exposed the longstanding vulnerabilities from fossil-fuel reliance and rekindled national energy security concerns. According to the International Energy Agency (IEA, 2023), energy security is the uninterrupted availability of energy sources at an affordable price. Despite the importance of other dimensions of energy security, especially affordability amid growing concerns about energy poverty, the focus in this paper is on the uninterrupted availability of energy supply. In such context, we examine key drivers of energy security—diversification of supply and political risk of suppliers—to understand the historical evolution of energy security and differences across countries. We also examine how the green transition—to which many countries have committed and reconfirmed at COP28 —could impact energy security going forward, considering both reduced reliance on fossil fuels and new challenges from renewable energy sources.

To this end, we proceed in three steps. First, looking back, we analyze how the diversification of energy trade partners and the political risks of those partners, the two main determinants of energy security, contributed to changing energy security dynamics over the last two decades. Using the Herfindahl–Hirschman Index (HHI) adjusted for the political risks and diversification of trade partners, we analyze energy security of coal, oil, and natural gas for the period 2000 to 2020 both at the global and the individual country levels. We account for political risks from two perspectives: risks of supply disruption due to political reasons in energy-exporting economies versus risks stemming from weak political alignment (measured as geo-political distance) between energy-exporting and importing economies. Second, taking a forward-looking perspective, we employ a model-based experiment to analyze how the green transition—underpinned by a globally coordinated carbon price floor arrangement— can be expected to affect energy security globally. Finally, we discuss new challenges to energy security that could arise from the use of renewables.

This paper contributes to the energy security literature in two ways. On the historical front, we decompose energy security risks into two main determinants: a diversification effect that shows how changing concentration of energy import sources affected energy security and a risk effect that quantifies the impact of political risks on energy security. From this decomposition, we then quantify the contribution of each of the two effects on energy security both at the global and national levels. A second contribution is a comprehensive analysis of energy security under the green transition. Specifically, we provide model-based evidence on how climate policy can be expected to weaken energy security for individual fossil fuels but strengthen energy independence and security on the aggregate through more domestic energy production.

Three core results are worth highlighting. First, we find that diversification of trade partners, or the lack thereof, was the main factor that underpinned global energy security over the last decade, although to different degrees for individual fossil fuels. This was particularly the case for coal and oil whose supply was largely concentrated amongst a few large producers. Increasing political risks and reduced diversification equally contributed to the relatively modest deterioration experienced in the security of natural gas supply. Across all fuels, concentration of energy trade among geopolitically aligned economies would weaken diversification and heighten energy insecurity.

Second, our model-based evidence suggests that the green transition is expected to have a net positive effect on energy security by reducing fossil fuel dependence. On the one hand, climate mitigation policies will reduce fossil fuel demand, forcing high-cost fossil-fuel producers to exit the energy market. The resulting increase in market concentration would weaken energy security. But on the other hand, increased renewable energy penetration amid climate policy will reduce energy import dependence and improve energy

security. Renewable energy does not require ongoing fuel imports or production, as energy generation with fossil fuels does. This means that current fuel importers can steadily reduce the share of fuels they import, a process that results from both the expansion of renewable energy in electricity production and electrification (i.e., the extension of electricity to additional uses). On net, the latter channel is expected to dominate.

Finally, the green transition brings new challenges to energy security which will require investments in infrastructure compatible with the renewable energy and electric mobility era. As countries expand their renewable energy production capacities, new risks to energy security would emerge, including potential import dependency for transition metals. Strengthening energy security in the renewable energy era will thus require a strategic support of production capacities in a variety of countries to facilitate import diversification. Furthermore, the intermittency of renewable energy, like solar and wind power, poses a challenge for uninterrupted energy supply. A wide range of solutions for this challenge exists, including energy storage and grid extensions. These solutions require investments in infrastructure as well. Given that the higher upfront costs of renewable energy are compensated by low operating cost, energy systems with renewable energy and supporting infrastructure are estimated to have a similar cost as energy systems built on fossil fuels.

The rest of the paper is organized as follows. The next section presents global aggregate trends in energy security while section 3 focuses on country-specific trends and their main drivers. The fourth section employs a global computable general equilibrium (CGE) model to examine the impact of climate mitigation policies on energy security. In section 5, new challenges amid the green transition, including increased dependence on green metal imports and intermittent energy supply, are discussed. Section 6 sums up the paper.

Trends in energy security

The goal in this section is twofold. First, we define energy security. Second, we present stylized facts on the historical global trends of its drivers, namely changing energy supply diversification on the one hand and the political risks of suppliers on the other.

What is energy security?

Energy security is determined by how diversified and politically secure a country's energy sources are. For our purpose, energy security is defined as the security of supply. That is, that all else equal, there is high energy security if there is a diversified portfolio of suppliers (Cohen, Joutz, and Loungani 2011) with low political risks (Le Coq and Paltseva 2009). Box 1 presents a summary of the relevant literature with several other dimensions that underpin energy security.

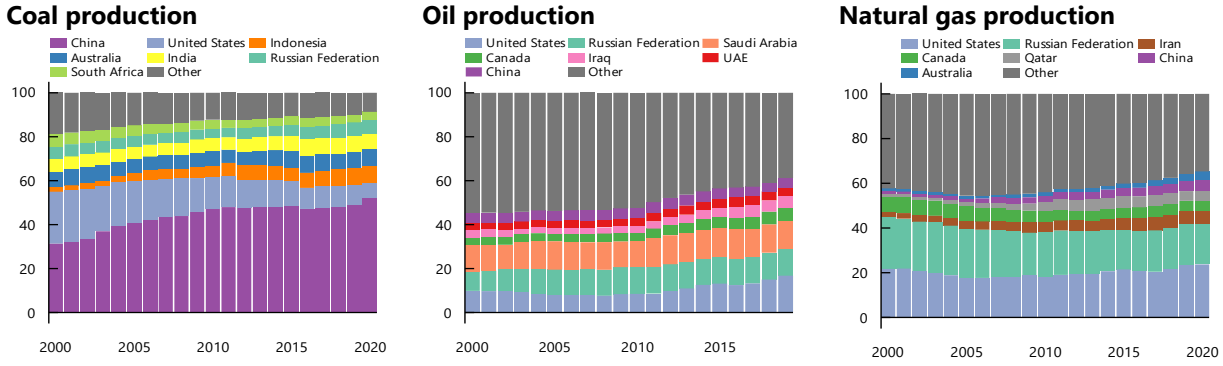
Historical trends in diversification and political risk indicators

Coal and oil productions have become more concentrated over the last two decades. Figure 1 shows the evolution of global production shares of top suppliers in the various fossil fuels. Together, the largest coal producers have captured an increasing share of the global coal market, driven by rising shares of China and, to a lesser extent, Indonesia (from 33% of global production in 2000 to 60% in 2020). For oil, there is also a noticeable shift toward more concentrated output markets during the last decade, with the United States, Canada and Iraq gaining market shares. But while the joint market share of the top 7 producers increased, it stayed below 60 percent. In contrast, the global natural gas market did not experience any material change in concentration over the last two decades, despite some modest shifts in market shares for a few natural gas

producers (e.g., Qatar, Iran, and China) matched by some decreases in Russia's and Canada's shares. The picture remains largely the same with respect to global export shares.

Figure 1: Composition of fossil fuel production by fuel and country

(Percent of global production)



Source: International Energy Agency, World Energy Balances; and IMF staff calculations.
Note: Production comprises the production of primary energy.

Indicators of political risks and democratic freedom have worsened in most fossil fuel producing economies during the last decade. Following the literature, we employ the Democracy Index compiled by the Economist Intelligence Unit as proxy for democratic freedom and two separate indicators for political risks: (i) the International Country Risk Guide (ICRG) index of the Political Risk Services Group (PRSG) and (ii) the Ideal Point Distance (IDP) measure constructed by Bailey, Strezhnev, and Voeten (2017). They complement each other by highlighting different aspects of risk. The Democracy Index is based on electoral process and pluralism, civil liberties, functioning of government, political participation and political culture (EIU 2022). Among the largest components of the ICRG index are government stability, socioeconomic conditions, as well as internal and external conflict (PRS 2018). Political risks appear to have increased for coal and natural gas, while the picture is more mixed for oil producers.

Box 1. What is Energy Security? A review of the relevant literature

Energy security is a broad concept that is difficult to define. Guaranteeing energy security remains at the heart of national security and energy policies in many economies. Yet, what constitutes energy security remains a matter of debate in the literature (Chester, 2010). According to Willrich (1976) and Luft and Korin (2009), energy security can be defined from two polar angles: for energy exporting and importing economies. From the standpoint of energy exporters, it is the security of demand—guaranteed access to diverse foreign markets—that matters. From the standpoint of energy importing economies, the reliability of energy supply is paramount. The International Energy Agency (IEA) defines energy security as the uninterrupted availability of energy sources at an affordable price (IEA 2014). Apart from the security of demand versus supply dichotomy, energy security is usually defined along several other dimensions, including the sustainability of supply (Blum and Legey, 2012).

Security of supply is the dominant theme in the energy security literature. The uninterrupted availability and affordability of energy supply is contingent upon several factors, notably the diversity and the political risks of supply sources (Le Coq and Paltseva 2009). Borrowed from portfolio theory in finance, the concept of energy supply diversity implies that all else equal, there is high energy security if there is a diversified portfolio of suppliers (Gupta 2008; Cohen, Joutz, and Loungani 2011; Månsson, Johansson, and Nilsson 2014). For fuels like natural gas, diversification goes beyond country of supply origin. The route of transport—pipeline or seaborne shipment—also matters. While there is more concentrated supply when infrastructural constraints limit natural gas imports via pipeline, liquefied natural gas (LNG) can strengthen energy security by broadening supply sources (Vivoda 2019). Such strategic importance of LNG has underpinned the increasing role of LNG in the energy security debate, with contracts for delivering LNG becoming more flexible and an increasing share of LNG traded in spot trading transactions instead of long-term contracts (IEA 2019).

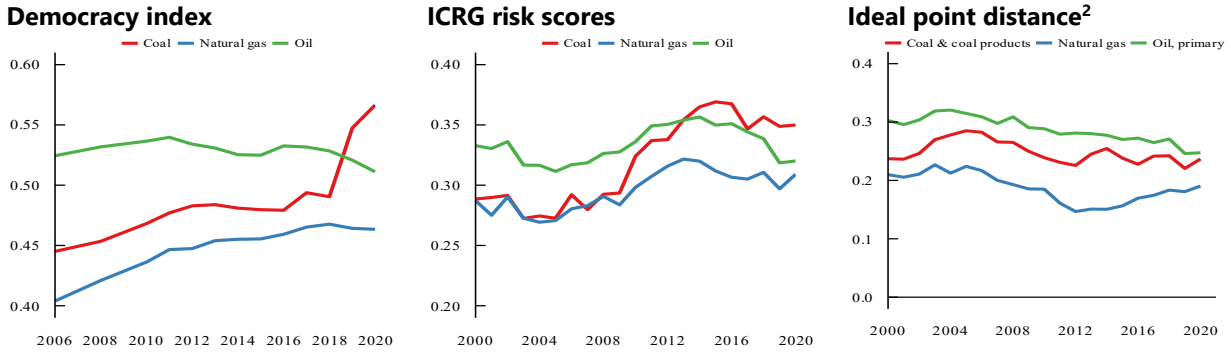
Renewable energy is gaining increasing importance in the analysis of energy security. Renewables are replacing energy imports (Gökgöz and Güvercin 2018). At the same time, renewables are creating new challenges for energy security. Renewables can decrease electricity price volatility in some countries, but increase it in others (Ketterer 2014; Rintamäki, Siddiqui, and Salo 2017). As energy security also depends on affordability, price volatility is a concern for energy security. However, there are examples for how price volatility can be handled in countries with a high share of renewables. Germany has already taken regulatory and policy measures to reduce price volatility caused by renewable energy and these are showing success (Ketterer 2014). Azzuni et al. (2020) show that an electricity system based entirely on renewable energy (as opposed to the current energy mix based mainly on oil and natural gas) would improve energy security in Jordan significantly along the dimensions of availability, cost, environment, and health and keep the level of diversity constant.

Energy security and energy independence are strongly inter-related, but the increase in domestic fossil fuel production to achieve energy independence delays the green transition. Cohen, Joutz, and Loungani (2011) distinguish between energy independence and energy security, with the former only focused on reducing the share of imported energy in the national energy mix. Increasing energy independence through investments into domestic fossil fuel production, however, conflicts with the Paris Agreement and efforts to reach net zero emissions. This means that energy security and sustainable investment can be achieved jointly only through investments into renewable energy capacity (Cevik 2022).

The political distance between fossil fuel producers and consumers has declined overall. The IDP measure is based on votes at the United Nations General Assembly via a Bayesian-based logit model over the three voting choices (yea, abstain, nay).[1] The higher the absolute value of the IDP between a country pair, the higher the political risks and potential for disruption to energy supply if one country is dependent on the other for its energy needs (see IMF 2023). However, due to the restricted availability of bilateral trade data by fuel, it is constructed only for OECD economies and their imports from fossil fuel suppliers. An interesting fact is that the geo-political distance between natural gas exporting and importing economies has increased since 2010, possibly reflecting the plateauing of globalization following the global financial crisis and the heightened trade and financial barriers (Aiyar et al. 2023) since then (Figure 2).

Figure 2: Political risk scores among major fossil fuel producers

(0-1, 1:highest, 0:lowest)



Source: International International Country Risk Guide, The PRS Group; Economist Intelligence Unit; Voeten, Strezhnev, and Bailey, 2009, United Nations General Assembly Voting Data; International Energy Agency, Coal, Natural Gas, and Oil Information Statistics; and IMF staff calculations.

Note: The first two charts display the weighted average of converted democracy index and ICRG. Conversion is made by $1 - \frac{Democracy\ index}{10}$ and $1 - \frac{ICRG}{100}$ respectively. The index is weighted by domestic production for each year. The third chart displays the weighted average of converted ideal point distance between selected OECD countries and their fossil fuel suppliers. Conversion is made by $1 - \frac{Ideal\ point\ distance}{6.58}$. Samples are limited to OECD countries due to the coverage of the data. Ideal point distance is weighted by importing values for each OECD country, then by GDP value for the average across OECD countries.

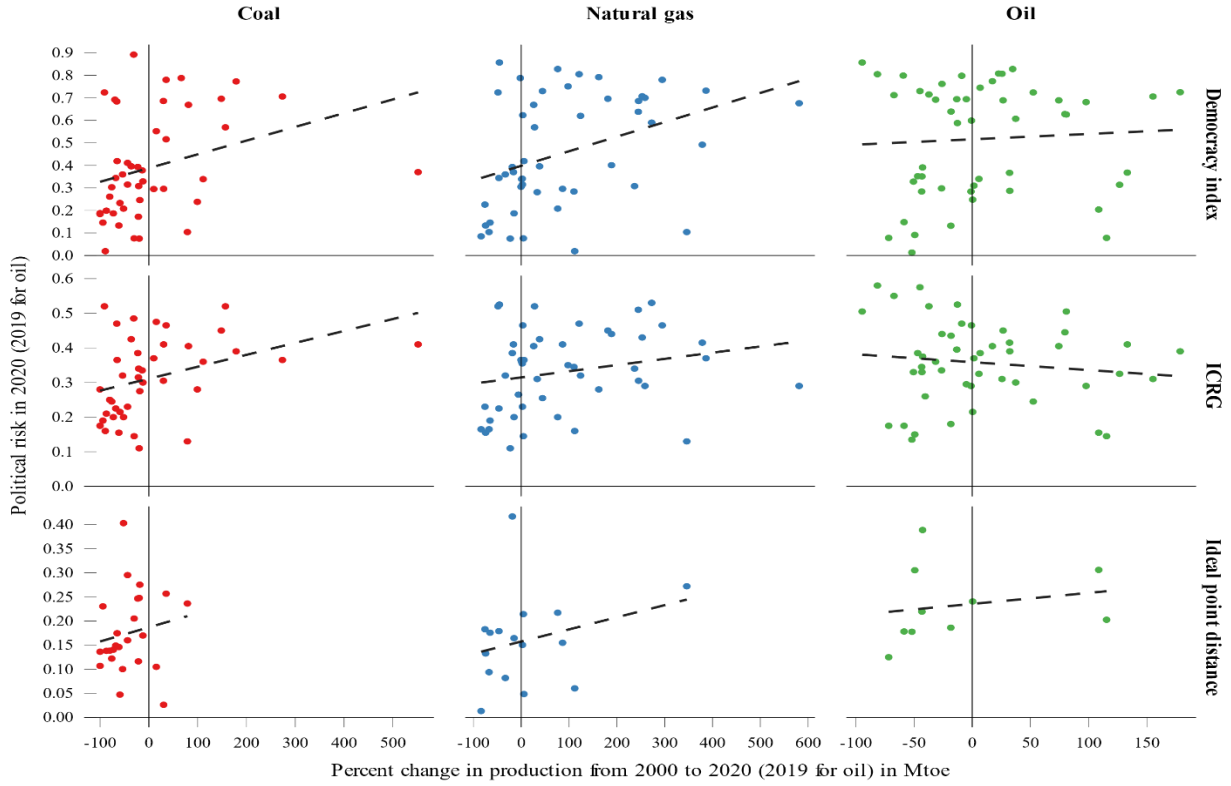
Energy security risks, amid concentrated production and heightened political risks, have varied across fuel types in recent years. While Figure 2 shows the political risks of major fossil fuel producers over time, Figure 3 examines if production has risen more in high or low political-risk producers across different dimensions. Overall, the magnitudes of the shifts in market shares towards (or away from) high-political risk producers (in 2019/2020 relative to 2000) have differed across fuels and dimensions of political risks. For example, coal and natural gas productions have shifted towards regions with lower scores on democratic freedom, higher risks of internal political instability and longer geo-political distance between producing and importing economies. However, the picture for oil is less clear. Production appears to have shifted toward countries with both low and high democratic freedom, and toward regions with lower political risk, the latter largely reflecting the increased market shares of the United States and Canada (Figure 1).

[1] The distance is not estimated but taken directly as available from this link: https://dataverse.harvard.edu/dataverse/Voeten which provides the most updated version of the distance for all the country pairs.

[2] The Ideal Point Distance risk trends are constructed for OECD countries due to the restricted availability of bilateral trade data by fuel.

Figure 3: Political risk and change in production in fossil fuels

(index: 0-1, 1=highest risk; Percent)

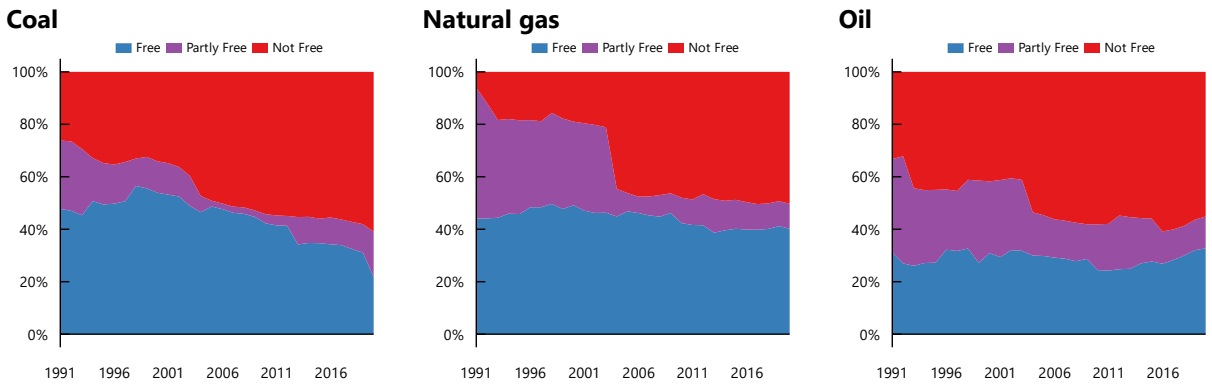


Source: PRS Group; International Energy Agency, World energy balances; Voeten, Strezhnev, and Bailey, 2009, United Nations General Assembly Voting Data; International Energy Agency, Coal, Natural Gas, and Oil Information Statistics; and IMF staff calculation.
Note: Production comprises the production of primary energy. The charts show top 50 producers based on 2000 production value for each type of fuel, excluding outliers.

Political risk influences energy security mainly through supply disruption. In addition to the other dimensions of political risks discussed above (Figure 2), we also assess the concentration of energy production across different systems of governance and cultures based on the widely used Freedom House Index (Freedom House 2022). The goal is not to draw any causal link between democratic freedom and political risks. To the extent that civil liberties and freedom matter for internal political stability (Aisen and Veiga, 2011), then their absence may potentially be manifested in energy security risks. Figure 4 shows the share of global production originating from countries classified as free, partly free, or not free. Coal production, like under the other risk indicators, has become increasingly concentrated in “not free” regions. Similar trends are observed for natural gas and oil.

Figure 4: Energy production by political freedom

(percent of global production)



Source: International Energy Agency, World Energy Balance; Freedom House; IMF staff calculation.
Note: Production comprises the production of primary energy. Dramatic change in Natural gas in early 2000 is due to the change in the status of RUS from “Partly Free” to “Not Free”.

Measurement of energy security

Having defined and identified the key determinants of energy security in the preceding section, this section is devoted to the measurement of energy security. We proceed in three steps. First, we measure energy security and quantify the contribution of the different drivers to its evolution at the global level. Second, we repeat the analysis at the country level to identify country-specific determinants of energy security. Finally, we test the predictive power of our index by illustrating how country-level measures correlate with recent macroeconomic developments in selected economies facing an acute energy crisis.

Energy security at the global level

There is a substantial variety of energy security indices used in the literature. A systematic review of the energy security literature by Gasser (2020) identifies 63 indices. These vary by scope, number of indicators considered, data treatment approach, multivariate analysis, normalization, weighting, and aggregation of the indicators (see literature review in Box 1). Index construction typically follows a standard procedure of calculating several indicators, normalizing them to make them comparable, weighting them and aggregating them. Broadly, energy security indices can be grouped into comprehensive and simple measures. The former employs arbitrary weights to condense multiple variables into an index while the latter uses single or fewer variables in a data-driven framework that avoids the use of arbitrary weights. Our measure of energy security risk is simple and avoids the use of arbitrary weights. Specifically, we focus on the security of supply for energy importers—which is the dominant theme in the literature—via the lens of energy market concentration and different dimensions of political risks. Our energy security risk index captures how vulnerable different countries are likely to be amid disruption of energy supply. While our indicator does not lend itself to easily incorporate a direct measure of affordability of energy, the security of supply—as defined above—is obviously a key determinant of affordability and energy price stability.

The Herfindahl–Hirschman index is the main measure of energy diversification. The basic Herfindahl–Hirschman Index (HHI), a standard measure of market concentration, is typically employed to measure energy security. It is based on portfolio theory in finance. This is the approach followed by Cohen, Joutz, and Loungani (2011) in defining a global diversification index (DI) as

$$DI(global) = \sum_i \left(\frac{X_i}{X}\right)^2 \times 100, \qquad (1)$$

where $\frac{X_i}{X}$ is country i's share in world production of a given (energy) resource.

The basic HHI is typically augmented with various indicators of idiosyncratic risks that affect the security of supply. This is consistent with the theme that energy security is basically the 'security of energy supply', including political risks of external energy sources, geo-political distance from suppliers and the size of a country's imported consumption relative to total global energy consumption. For example, the HHI can be adjusted for political risk as

$$DI_{pol}(global) = \sum_i \left[\left(\frac{X_i}{X}\right)^2 \times POL_i \times 100\right]. \qquad (2)$$

POL_i is political risk, where a higher value reflects higher risk. When using the ICRG index it is given as $POL_i = \left[1 - \frac{ICRG_i}{100}\right]$. When using the Democracy Index, it is given by $POL_i = \left[1 - \frac{DI_i}{10}\right]$.

The global index can be decomposed to assess the relative importance of the main drivers. Changes in the political-risk weighted HHI, DI_{pol}, can be decomposed into three components: 1) a diversification effect, which results from changes in unweighted diversification (first summand of equation 3); 2) a risk effect, which results from changes in the risk scores of individual countries (second summand) and 3) a covariance term (third summand). See Annex 1 for details of the derivation.

$$\begin{aligned} DI_{pol,2}(global) - DI_{pol,1}(global) \\ = \sum_i \left[\left(\left(\frac{X_{i,2}}{X_2}\right)^2 - \left(\frac{X_{i,1}}{X_1}\right)^2\right) \times POL_{i,1} \times 100\right] + \sum_i \left[\left(\frac{X_{i,1}}{X_1}\right)^2 \left(POL_{i,2} - POL_{i,1}\right) \times 100\right] \\ + \sum_i \left[\left(\left(\frac{X_{i,2}}{X_2}\right)^2 - \left(\frac{X_{i,1}}{X_1}\right)^2\right)\left(POL_{i,2} - POL_{i,1}\right) \times 100\right] \quad (3) \end{aligned}$$

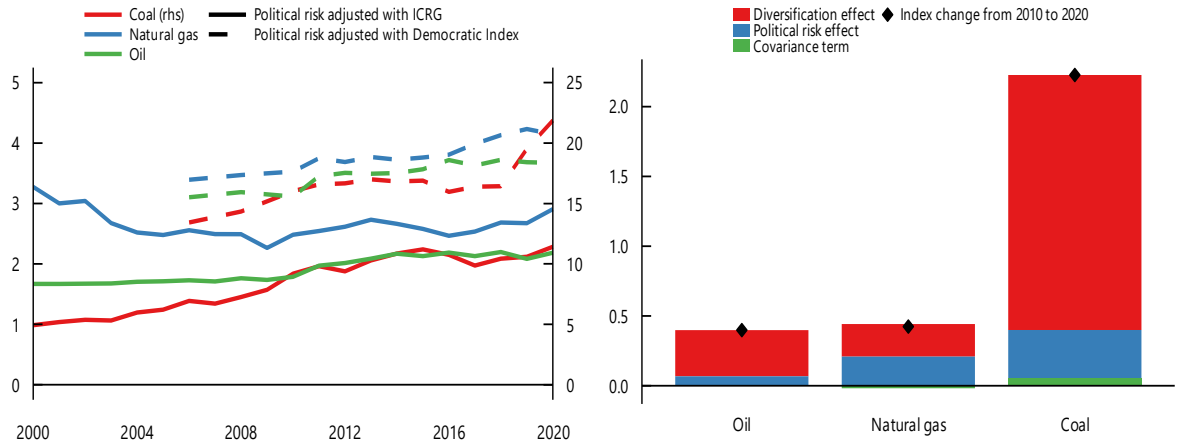
These effects are illustrated in the right panel of Figure 5.

Energy security risk has largely deteriorated in recent years, mostly driven by reduced diversification of supply. This is shown by the upward trend (since 2010) in the index value in the left panel of Figure 5. But the contribution of political risk varied across fuels and different dimensions (i.e., democratic freedom and internal instability). For example, the falling trend of diversification amid rising market shares of a few large producers, including the United States, Canada, and Iraq (see Figure 1), largely underpinned the heightening of oil supply risk. As shown below in Figure 5, political risks have had a marginal contribution since oil supply only shifted from one form of political risk (away from high-risk regions) to another (toward fossil-fuel producing regions with low democratic freedom scores). In the natural gas market, falling diversification and rising political risks have had equal significance on the security of gas supply. For coal, the diversification effect was even more dominant. Across all fuels, the shifts in supply across different political risk dimensions, as measured by the covariance term, have had varying impact on energy security.

Figure 5: Decomposition of global energy security risk index for productions of individual fuels

Energy security risk index

Decomposition with ICRG



Source: International Country Risk Guide, The PRS Group; Economist Intelligence Unit; International Energy Agency, World Energy Balance; and IMF staff calculations.
Note: An increase in the index value reflects a deterioration of energy security. The political risk adjusted with the ICRG (Democracy Index) aggregates 129 (145) countries due to availability of the indices. The Democracy Index is available only from 2006.

Trends in country-specific energy security

Having examined the global drivers of energy security, we now proceed with an assessment at the national level. Following the literature (Cohen, Joutz, and Loungani 2011), we define a country diversification index, weighted for political risks, (CDI_{pol}) as

$$CDI_{pol} = \sum_i \left[\left(\frac{NPI_i}{C} \right)^2 \times POL_i \times 100 \right] \qquad (4)$$

where NPI_i is the net positive imports from country i and C is the domestic country's total consumption of the fuel. Political risk POL_i is defined as before, depending on the indicator used. The index uses only net imports in the numerator and consumption in the denominator. The difference between total net imports and consumption is domestic production. The political risk of domestic production is hence effectively set to zero. A country which does not import a resource has a CDI of zero for that resource, the best possible score for energy security. Despite its name, the best possible score can be achieved by using energy from only a single source – domestic production. For non-domestic sources of energy supply, diversification is key to improve energy security.

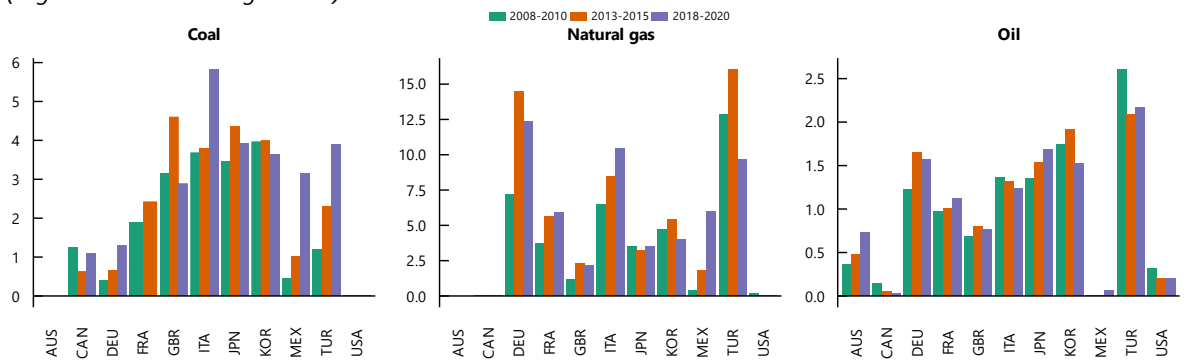
Energy security risks have varied over time across countries and individual fuels. Figure 6: Energy security as measured by ICRG political-risks weighted country diversification indices shows the trajectory of the index values for the period 2000 to 2020 by fuel for G20 countries with available data[3]. Three key insights can be drawn from this chart. First, on average and across countries, energy security risks appear highest for

[3] Calculating the CDI_{pol} requires data on both the exporter and the importer by fuel. Such data is available at yearly intervals only for OECD countries

natural gas importers and lowest for oil importers. This is further amplified by the reliance of natural gas on infrastructure, while global markets for oil and coal make it easier to switch suppliers. Second, energy security risks vary considerably across countries. The United States, for example, has a large domestic production of all three fuels, reducing its dependence on foreign sources and lowering its energy security risk. However, for other economies, high dependence on concentrated foreign supply of coal (e.g., Japan, Italy), natural gas (Türkiye and Germany) or oil (Japan and Türkiye) have worsened their energy security, although to varying degrees across the individual fuels. Third, energy security risks at the level of individual countries may be driven by transitory market developments, including temporary changes in production (or export) shares in a given year. This implies that our energy security risk index values for individual years need to be interpreted with caution. For example, given how quickly energy security can improve (or deteriorate) from year to year, a low level of energy security might be less alarming than a comparison of index values across countries at a given point in time might suggest. Multi-year averaging is the better approach in determining how energy security risks have evolved over time within countries.

Figure 6: Energy security as measured by ICRG political-risks weighted country diversification indices

(Higher index value=higher risk)

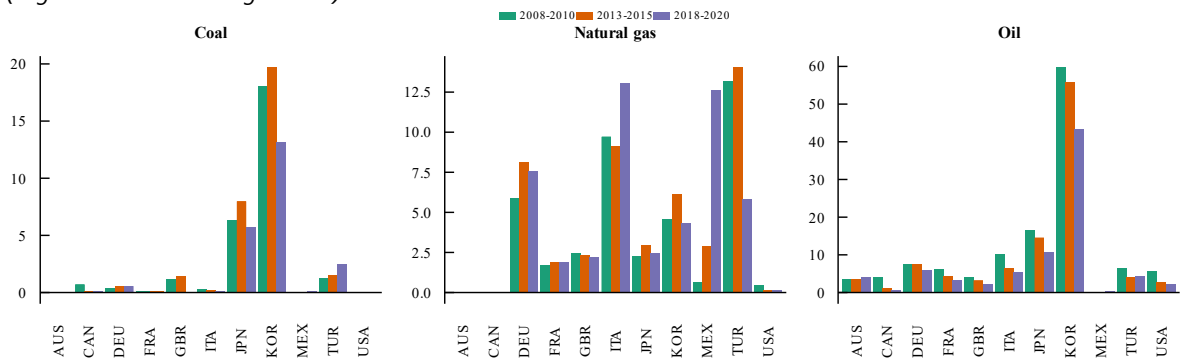


Source: PRS Group; International Energy Agency, Coal, Natural Gas, and Oil Information Statistics; and IMF staff calculations.
Note: Domestic consumption is computed as domestic production – net export. Domestic production and trade comprise primary energy and refined products.

The varying levels of energy security risks across countries can also be viewed from the context of energy intensity. A country's energy footprint per unit of output plays a crucial role in determining its energy security challenge. The lower the energy intensity of activity, the higher the possibility of maintaining a diversified energy supply portfolio, all else equal. This is clearly illustrated in Figure 7 below, with energy security risks for coal (e.g., Korea), natural gas (e.g., Italy), and oil (e.g., Korea) partly reflecting the intensive use of these fuels.

Figure 7: Energy Intensity as a magnifier of energy security risks

(Higher index value=higher risk)



Source: PRS Group; International Energy Agency, Coal, Natural Gas, and Oil Information Statistics; and IMF staff calculations.
Note: Domestic consumption is computed as domestic production – net export. Domestic production and trade comprise primary energy and refined products. This chart shows CDI_{pol} in equation (4) with the replacement of total consumption of the fuel with GDP.

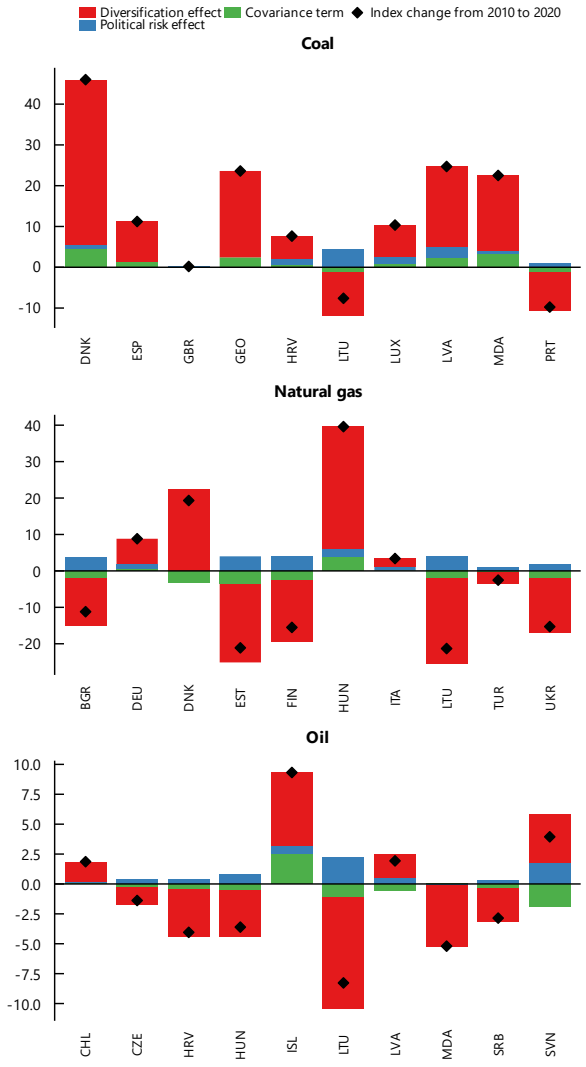
As for the global level, the diversification effect also dominates changes in energy security at the country level. We transfer the global decomposition in the preceding section (equation 3) to the country-specific context to analyze the individual contributions of the drivers. The results for selected economies[4] as shown in Figure 7, point to the dominant role of the diversification effect in the decade to 2020. While non-negligible, the political risk effects and covariance terms remain marginal for many countries. Like the picture painted by the global decomposition, coal and oil supplies have become more concentrated across countries, with the effect strongly evident in Denmark and Latvia (for coal) as well as Iceland and Slovenia (for oil). For natural gas, improvement in Lithuania's security of supply amid improved diversification is worth highlighting. Across all fuels, similar trends also emerge when democratic freedom and ideal point distance indicators are used as political risk proxies (Figure 16 in Annex 2).

Strong changes in diversification and energy security mostly reflect a move away from or towards a single dominant supplier. This is evident in the case of Lithuania that achieved a strong improvement in security of natural gas supply by moving from a 100 percent dependence on Russia in 2010 to a diversified portfolio with Russia (51 percent), Norway (45.8 percent) and the US (25.3 percent). The excess is used to supply neighboring countries. Similarly, large improvements in energy security for oil and coal are achieved by reducing dependence on a single supplier and vice versa. The opposite experience was at play in Hungary whose natural gas security strongly deteriorated amid increased import dependence on Russia, from 74.8 percent of consumption in 2010 to more than 100 percent of consumption in 2020. The excess imports were used for re-exports.

[4] Overall, the diversification effect dominates energy security trends across countries. We selected the indicated economies to capture the results on both sides—improvement or worsening—of the impact on energy security.

Figure 9 Decomposition of ICRG-political risk adjusted index, 2010-2020

(index difference from 2010 to 2020; positive for higher risk, negative for lower risk)



Source: PRS Group; International Energy Agency, Coal, Natural Gas, and Oil Information Statistics; and IMF staff calculations.
Note: Domestic consumption is computed as domestic production – net export. Domestic production and trade comprise primary energy and refined products.

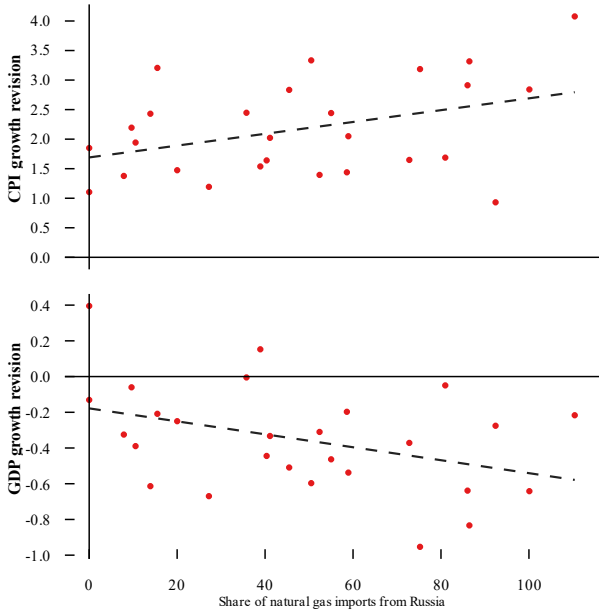
Energy security measures and recent macroeconomic developments

The current energy crisis, particularly in Europe, clearly demonstrates the importance of a diversified energy supply portfolio and the political risks of energy suppliers. As Di Bella and others (2022) and Lan, Sher, and Zhou (2022) highlighted, a complete shutdown of Russian gas supply to Europe would have weighed heavily on growth, especially amid existing supply infrastructure bottlenecks. While such a scenario has not (yet) materialized, the war in Ukraine continues to adversely affect growth prospects, largely reflected in recent IMF's growth downgrades for EU economies (Figure 8).

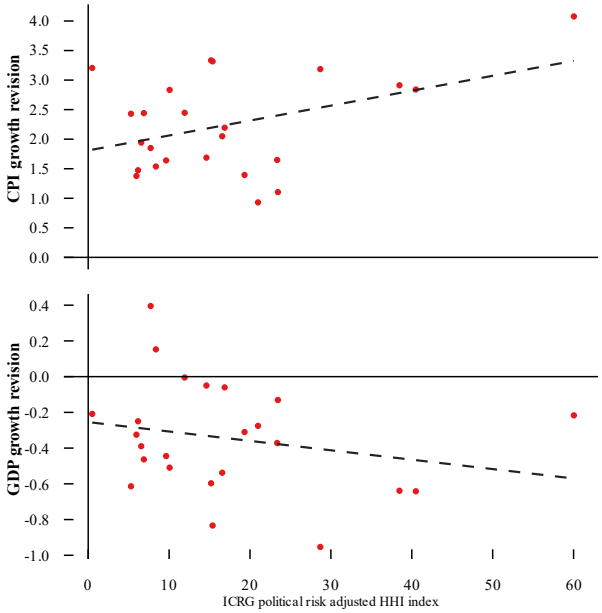
As documented earlier, the diversification of energy supply can help improve energy security. Apart from broadening supply sources across fuel types, diversification can also take the form of broadening energy transport routes, especially in the natural gas market where access to LNG supply can help reduce supply constraints posed by pipeline infrastructure. Figure 8 illustrates— using natural gas as an example—that the higher the dependence on Russian energy supply the greater the energy security risks and adverse growth outcomes, although responses in fiscal and monetary policy will also have impacted the final growth outcomes. Beyond growth, the recent surge in energy price pass-through to inflation—well documented elsewhere (Ari et al. 2022)—cannot be overemphasized.

Figure 10: Risks from Reliance on Russian Energy

Natural gas imports from Russia vs. WEO revision
(percent of total energy imports; percentage point difference)



Natural gas security risk index vs. WEO revision
(Higher index value=higher risk; percentage point difference)



Source: Eurostat; International Energy Agency; IMF, World Economic Outlook; and IMF staff calculations.
Note: Growth downgrades are computed as the change in projected average GDP growth from 2022 to 2027 between Jan 2022 WEO and Oct 2022 WEO. Negative values imply GDP growth downgrades.

The net zero transition: Out of existing challenges?

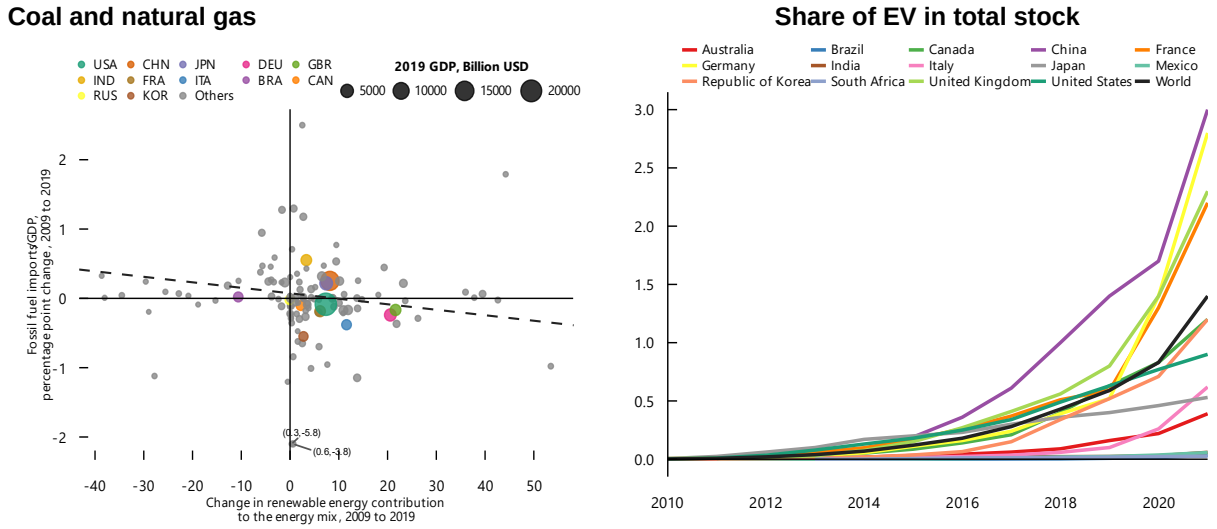
In this section, we use model-based evidence to project how the net-zero transition will affect energy security overall and across individual fuels. To set the stage for the model-based analysis, we first identify the key impact channels through which the green transition is likely to affect energy security.

Impact of climate policies on energy security: Channels

Decarbonizing the energy sector would have mixed effects on energy security via at least three main channels. First, the green transition will promote energy independence amid falling fossil-fuel import demand and increasing share of domestically produced renewable energy in the energy mix. This process is already at play (left panel of Figure 9Figure 11). While there is considerable variation, there is a negative correlation between the use of renewable energy and imports of coal and natural gas. However, natural gas may play a role as a 'transition fuel' in the form of backing up renewable electricity generation (IMF 2022, Chapter 3). Second, as fossil fuel demand falls, high marginal cost energy suppliers will exit the market, creating stronger market concentration and heightening energy security risk for economies still reliant on fossil fuels. Finally, the transition will spur an inter-fuel substitution away from coal—due to its higher emission intensity—toward natural gas, increasing the share and importance of the latter in the energy mix. The inter-fuel substitution means that the use of all types of fossil fuels falls in absolute terms (Kemfert et al. 2022), but coal is phased out faster. The effect of this inter-fuel substitution on energy security depends on the relative energy security of the two fuels.

How fast oil can be phased out depends on the pace of electrification in the transport sector. Coal and natural gas are increasingly replaced by renewables in electricity generation. Oil, by contrast, remains the dominant energy source for fueling the transport sector. While electrifying the transport sector would reduce oil reliance, electric vehicle penetration remains low in many economies and well below 2 percent globally at end-2021 (right panel of Figure 11), perpetuating oil demand. There may thus remain challenges to energy security from the oil sector, especially as the oil energy market gets more concentrated amid the climate transition. However, Figure 11 also shows how quickly the market for electric vehicles is developing. This development will be reinforced further by bans on internal combustion engines in California, Europe and China. This reduces the exposure of oil importers to oil supply disruptions.

Figure 11: Renewable energy use and fossil fuel imports



Source: International Energy Agency; UN Comtrade; World Economic Outlook; and IMF staff calculations.
Note: The renewable energy contribution to the energy mix is the share of solar, wind and hydro power in electricity generation in percent. Coal and natural gas imports comprise the imported value of "Coal; briquettes, ovoids and similar solid fuels manufactured from coal", "Lignite; whether or not agglomerated, excluding jet", and "Petroleum gases and other gaseous hydrocarbons".

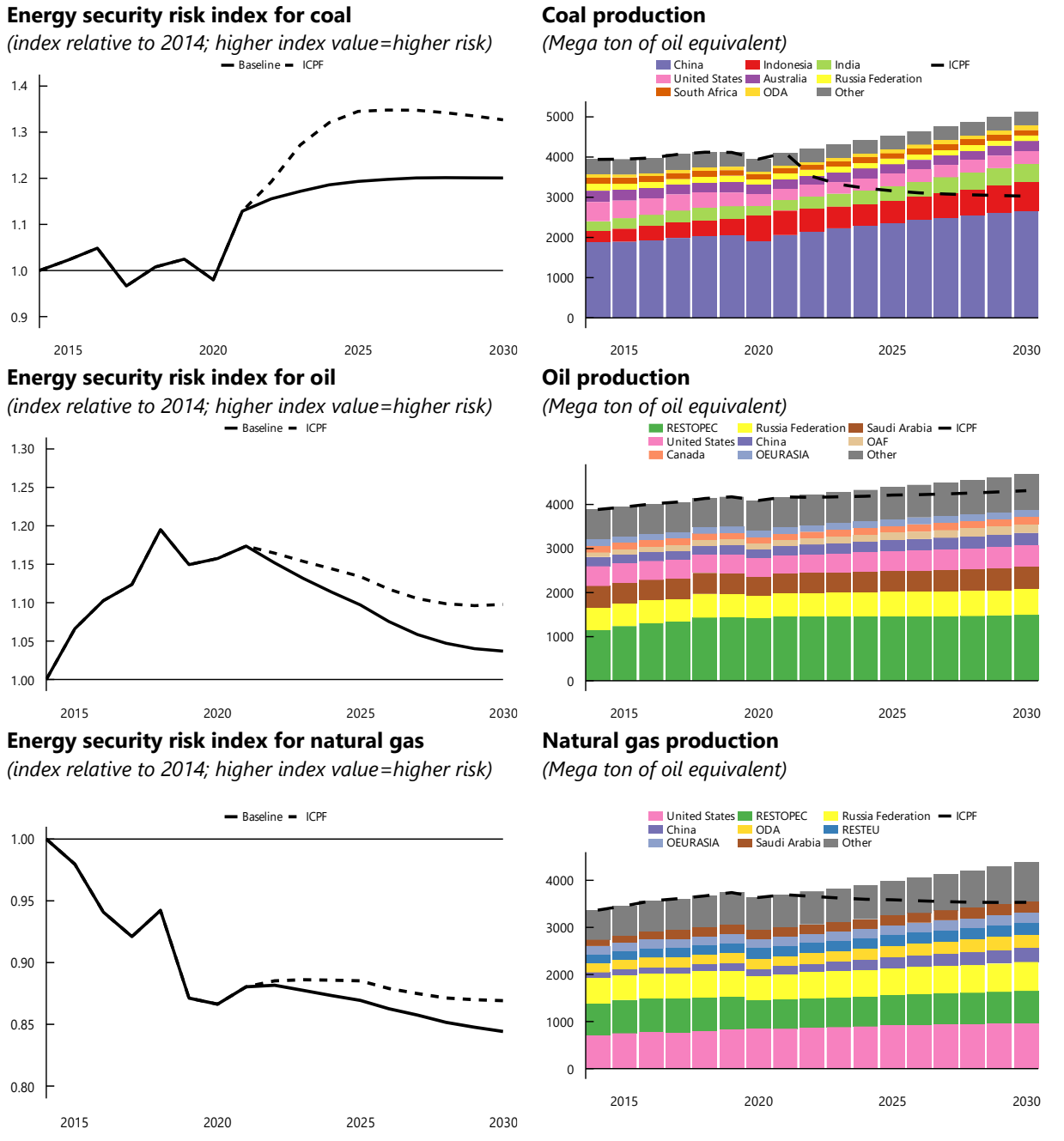
Impact of climate policies on energy security: a model-based experiment

The multiple-impact channels of the green transition on energy security requires model-based analysis. To this end, we employ IMF-ENV, a global computable general equilibrium model, to assess the energy security implications of the green transition underpinned by a globally coordinated *International Carbon Price Floor* (ICPF) scenario (see Chateau, Jaumotte, and Schwerhoff 2022). In this scenario, all countries introduce carbon prices, choosing the maximum of the level required to reach the country's NDC and a carbon price floor that is specific to the level of development of the country. This minimum carbon price is $US 75 for high-income countries, $US 50 for middle-income countries and $US 25 for low-income countries as suggested by Parry, Black, and Roaf (2021). The ICPF scenario is contrasted to a baseline scenario, where currently implemented climate policy (including existing carbon prices) is considered, but it is assumed that no new climate policies will be added.

At the individual fuel level, energy security deteriorates with the imposition of climate policy amid increased market concentration. Under the ICPF, energy security deteriorates for each fuel indicated by the rise in the index values relative to model baseline as shown by the dashed line in the right panels of Figure

11Figure 12. A reduction in fuel consumption is expected to reduce the diversity of fossil-fuel supply (for each individual fuel) as the highest cost producers leave the market faster than low-cost producers, consistent with historical trends. In contrast to this analysis at the level of individual fuels, energy security as whole increases (Figure 12), because the dependence on imported fossil fuels decreases.

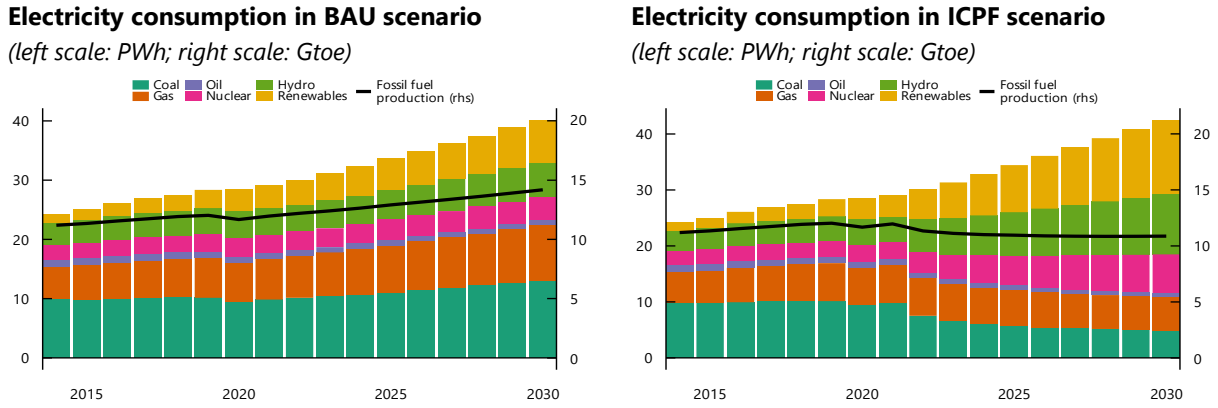
Figure 12: Global energy security in the baseline and International Carbon Price Floor (ICPF) scenarios



Source: PRS Group; IMF-ENV model
Note: The energy security risk index is calculated with the equation for DIpol(global). Oil production is calculated as the country's or region's oil demand less net exports.

A countervailing force is that climate policies can improve energy security by accelerating the replacement of fossil fuels with domestically produced renewable energy. Figure 12Figure 13: Global electricity generation (bar charts) and fossil fuel production (black line) compares two measures of energy consumption under the model baseline—business-as-usual (BAU)—and the ICPF scenario. The bar charts show the composition of electricity production over time. They show that in the ICPF scenario, the low-carbon energy sources (renewables, hydropower, and nuclear power) expand at the expense of fossil fuels. As electricity from the low-carbon sources is typically consumed close to the location of generation, this shift implies an improvement in overall energy independence and security. The black line shows the total production of fossil fuels. In the ICPF, this trajectory is much lower than in BAU, showing again a lower dependence on fossil fuels. However, a disorderly decarbonization transition could pose energy security risks in the short term, if investments in green energy sources is insufficient. To avoid this, it is important to have an internationally coordinated energy transition, with clear and credible policy signals that ensure sufficient investment in green energy sources to offset the needed decline in fossil fuel production. The resolution to phase out fossil fuels at COP28 is a first important step in this regard.

Figure 13: Global electricity generation (bar charts) and fossil fuel production (black line)



Source: IMF-ENV model

Note: The bar charts (measured on the left scale) show the composition of electricity generation in business as usual (BAU) on the left and in the ICPF scenario on the right. The black line (measured on the right scale) shows the production of all fossil fuels in gigatons of oil equivalent (Gtoe).

Climate policy can increase the share of renewable energy and thus improve energy security through increased energy independence. To show the bottom-line effect, we define a variant of the diversification index defined above as

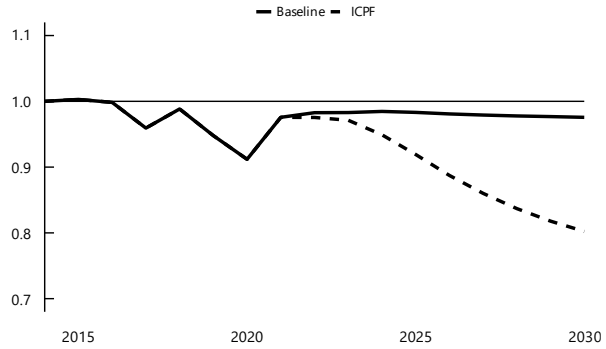
$$DI'_{pol}(global) = \sum_i \left[\left(\frac{F_i}{E} \right)^2 \times POL_i \times 100 \right] \qquad (5)$$

POL_i is the measure of political risk as defined before. F_i is the amount of fossil fuels produced by country i, measured in oil equivalent. E is total global energy produced, also measured in oil equivalent. The index captures both the diversity of supply and the option to source energy domestically, through renewable energy. It is thus a comprehensive measure of energy supply diversification. Note that it is possible to import renewable energy, for example from Norway's hydropower plants, though electricity. This possibility here is disregarded in the index due to a lack of data. The result is shown in Figure 12. The BAU scenario in the left panel of Figure 12Figure 13: Global electricity generation (bar charts) and fossil fuel production (black line) shows a slowly increasing share of renewable energy. As a result, the global reliance on fossil fuels decreases slowly, which reduces energy import dependence. See the black line of Figure 12.

In the ICPF scenario, by contrast, renewable energy expands more rapidly, and this causes a much faster improvement in energy security.

Figure 1415: Aggregate fossil security index

(percent)



Source: IMF-ENV model
Note: See equation 5 for the index shown in this chart.

The net zero transition: Into new challenges?

The net zero transition is expected to increase dependence on metal imports and generate the challenge of intermittency. As renewable energy takes on an increasing share of electricity production, new challenges to energy security arise. These challenges cause energy security concerns different from the supply diversification discussed in sections 2 to 4. In the first subsection, we discuss how an increased need for certain metals affects energy security. While the production of transition metals is more concentrated geographically than fossil fuels, there are also many options in the system to react flexibly to supply shortages. In the second subsection, we discuss the role of intermittency. Intermittency, or variability, refers to the weather-dependent fluctuations in the production of renewable energy. In most countries, intermittency will intensify as a challenge as it manifests more strongly when renewables reach a higher share in the electricity mix. There are several options to dampen the effect of intermittency. If they are used systematically, challenges from intermittency can be addressed effectively.

The supply of “transition metals”

Demand for “transition metals” is increasing rapidly, but these metals are only needed for *expanding* production, not maintaining it. Electric cars and renewable energy require several times as many metals as their conventional counterparts. Metals including copper, lithium, nickel, and zinc are thus sometimes termed “transition metals”. Electric cars, for example require more than five times as many metals than a conventional car (IEA 2021). As a result, demand for these metals is expected to increase strongly. Boer, Pescatori, and Stuermer (2021) estimate that prices for these metals will increase until 2030 when they will reach their historical record levels, before declining again in a Net-Zero emissions scenario. There is thus a concern that the supply of these metals could threaten energy security in similar ways as the supply of fossil fuels is currently. There is however a key difference: Transition metals are needed only to expand capacity. Once renewable capacity is built, it will generate electricity, even if metal supply is disrupted.

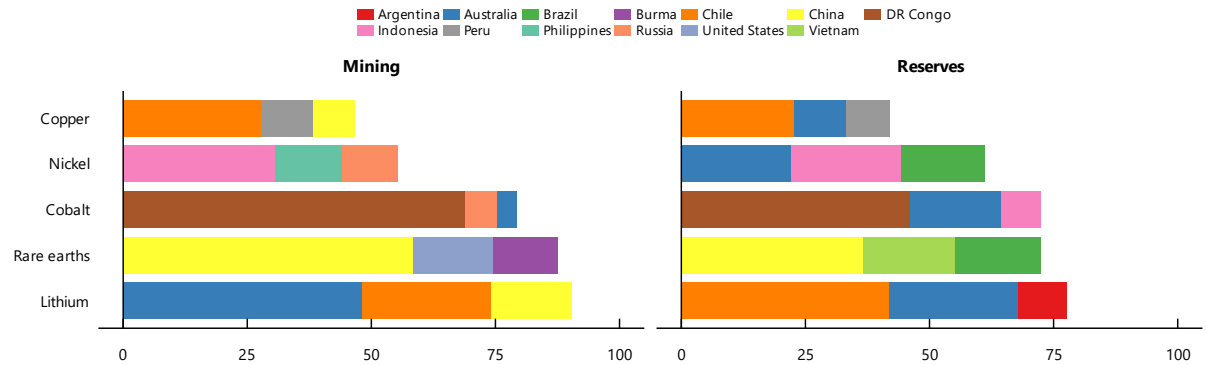
Reserves of transition metals are sufficient to meet projected demand. The geological availability of transition metals is illustrated for the example of lithium by (Greim, Solomon, and Breyer 2020). There are different deposits of lithium that will get increasingly expensive to extract. The metal will thus not be exhausted, but the cost of extraction will increase. For thirteen transition metals, current reserves are estimated to be sufficient to cover demand until 2060, except possibly for cobalt (Månberger and Johansson 2019). Given this, there is thus no risk of exhausting the geological supply of a metal. However, building a new mine to extract transition metals takes several years. As a result, it is meaningful to distinguish between short- and long-run supply elasticities (Boer, Pescatori, and Stuermer 2021). Short-run price increases are unlikely to be permanent as they incentivize investments into additional mining operations.

Demand of transition metals adjusts to higher prices. Supply responds to higher prices and the same applies to demand. There are three main channels which allow demand for transition metals to evade high prices. First, for each technology, there are different "sub-technologies", which need different amounts of metals. For solar energy, for example, there are currently three technology generations, each of which again has different options which rely on different metals. The different sub-technologies develop in parallel and their respective importance for production is determined by relative prices (Månberger and Stenqvist 2018). Second, unlike fossil fuels, transition metals are not destroyed by consumption, so higher prices are expected to increase recycling efforts (Hund et al. 2020). Third, there is technological progress which reduces the amount of metals used for a given application (Gielen 2021). Taken together, there is thus considerable flexibility in both demand and supply of transition metals to evade shortages in individual metals.

The production of transition metals is more concentrated than the production of oil and natural gas. Compared to the production of oil and natural gas seen in Figure 1, the production of transition metals is more concentrated. For copper, nickel, cobalt, rare earths and lithium, the largest producers have more than 25 percent market share (Figure 14Figure 16: The share of the production of top three producers to global total, 2021). Interestingly, though, in each case the largest producer is a different country. Processing for each of these five metals, by contrast, is done to more than 30 percent in each case by China (IEA 2021). Reserves are also concentrated in individual countries (Månberger and Johansson 2019). Reserves are distributed across countries similarly to production (Figure 14Figure 16: The share of the production of top three producers to global total, 2021). Tracing the concentration of metal production over time, however, reveals that it varies considerably, so that a concentration at one point in time can be reversed within short periods (Brown 2018).

Figure 16: The share of the production of top three producers to global total, 2021

(percent)



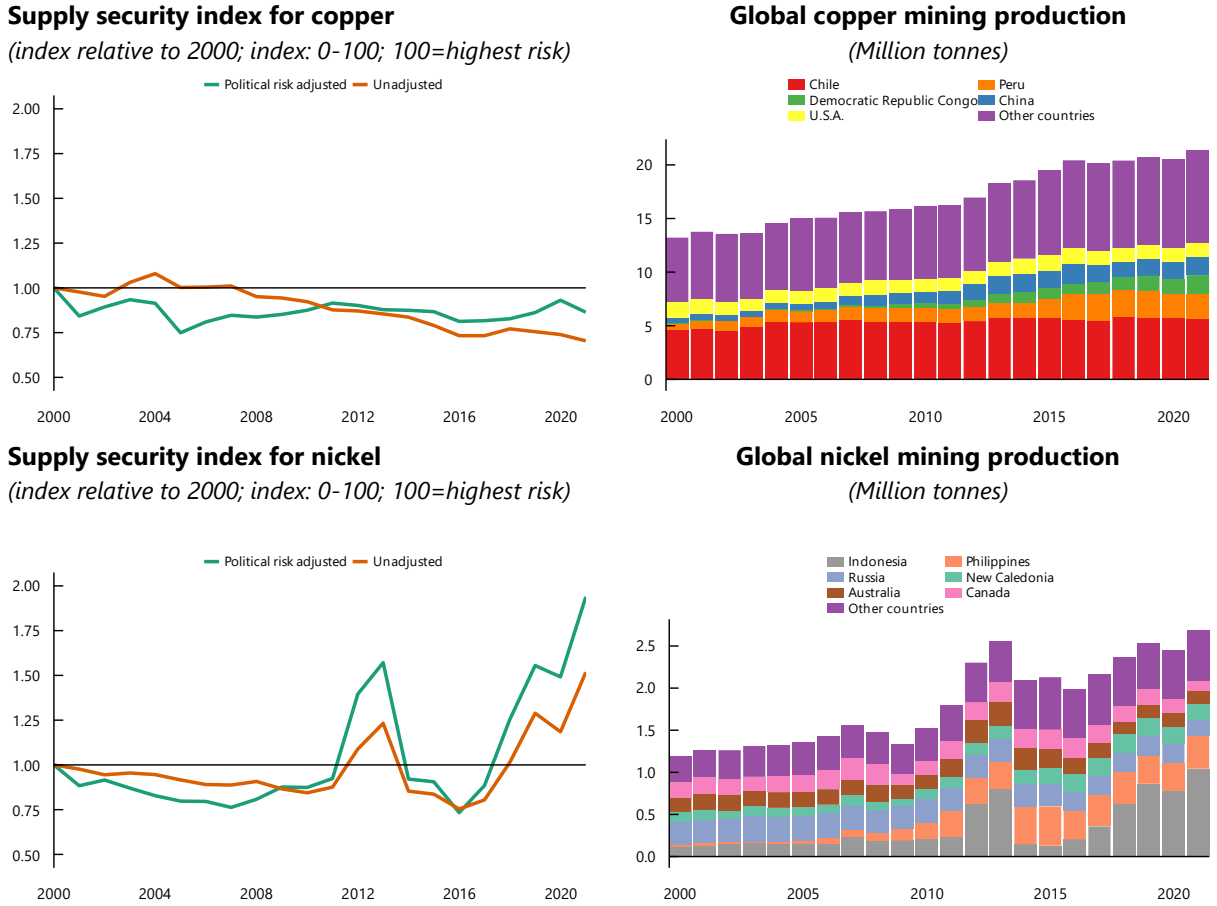
Source: U.S. Geological Survey, Mineral commodity summaries 2022; and IMF staff calculations.

As with fossil fuels, diversification of transition metal supply can improve energy security, especially amid high political risks in some transition metals-rich regions. For example, while political risks remain low in some top transition metals-producing regions, the opposite is true for other regions. Reducing the risk in metal supply as defined in the HHI will thus require diversifying metal imports as import volumes increase, especially for cobalt and rare earths, where mining is dominated by countries with high political uncertainty.

As we mentioned above, however, imports are needed only to increase capacity, not to maintain energy production and the metals are partial substitutes for each other. The HHI is thus a less useful measure for renewable energy than it is for fossil fuels.

There is no clear trend for the supply security of transition metals over time. Figure 17 Supply security index for copper and nickel over time shows the supply security for copper and nickel over time as well as a breakdown of production by country. While the security index is calculated as in equations 1 and 2, we describe them as "supply security" since these metals are not direct energy sources like fossil fuels. Further, we show the data only for copper and nickel because there are no comparable historical data for the other transition metals. For copper there is a slight trend towards more supply security (the two indices are below their 2000 values in 2021) because of the DR Congo and China gaining market shares. For nickel, supply security fluctuates strongly due to large variations in supply from Indonesia.

Figure 17 Supply security index for copper and nickel over time



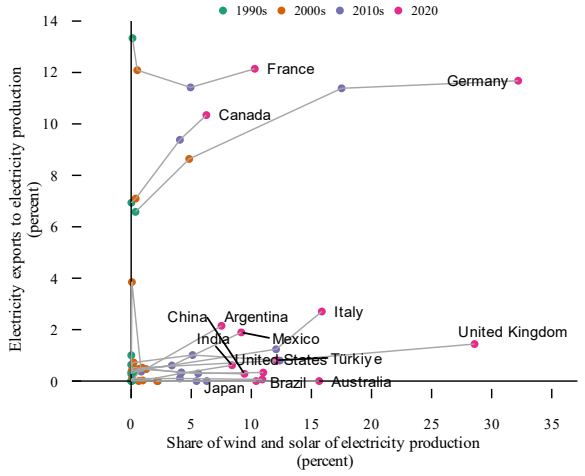
Source: World Bureau of Metal Statistics; PRS Group; and IMF staff calculations.
Note: Global supply security index for copper and nickel is created based on mining production (copper and nickel ores).

Electricity supply

As variable renewable energy advances, electricity networks require increasing use of "flexibility options". Wind and solar energy, which are the variable renewable energy (VRE) types, covered 54.7 percent of renewable energy capacity in 2021. The remaining renewable energy forms are geothermal energy, bioenergy, and hydropower. VRE are growing at a much faster rate than other forms of energy, so that the challenge of intermittency is becoming more important. Intermittency can be addressed by making the electricity system more flexible. Flexibility is needed to react quickly to a drop in electricity generation from a source to avoid a shortage of electricity and possible collapse of parts of the system. The risk of electricity shortage and system collapse makes intermittency a concern for energy security.

One flexibility option is investments in infrastructure, that is in grid extensions and energy storage. The availability of electricity from VRE varies by technology (wind or solar) and by geographic region. Steady supply can thus be achieved by connecting many VRE sources. This requires a large expansion of the transmission grid (Tröndle et al. 2020).

Figure 18: G-20 countries: electricity exports to production vs. share of wind and solar of electricity production
(percent)



Source: International Energy Agency, World Energy Balances; IMF staff calculations.
Note: The chart shows all G20 countries which achieved a share of wind and solar in electricity production in 2020 of at least 5%. The first three dots are decadal averages, while the

Independent regions, for example, would have much higher cost and less efficiency than interconnected regions (Child et al. 2019). But even a well-connected electricity grid will require some energy storage. Batteries are very useful for short-term storage and will lower the cost of generating electricity compared to a system without them (Yang et al. 2018). In the years 2013 to 2019, batteries have experienced a cost reduction of more than 50 percent and are already economically viable for storing electricity from renewable energy (Comello and Reichelstein 2019). Further efficiency gains can be obtained from long-term storage to balance demand and supply across seasons. Options for long-term storage are pumped hydro storage, where water is pumped into a hydro reservoir, and compressed air energy storage, which saves energy in compressed air (Dowling et al. 2020).

As part of the investments in grid infrastructure, international electricity trade expands. Expanding the electricity grid is done within countries, but international trade is another important option. Electricity trade is not an option for island economies like Australia and Japan. Very large economies, like the US and China, can achieve a lot of flexibility by extending the domestic grid. For all other countries, an expansion in VRE as a share of total electricity comes along with an increase in electricity trade. Figure 16 shows how the two variables co-evolved from the 1990s to the year 2020. As countries obtain gains

of trade in electricity, they also function mutually as insurance against strong price volatility or an undersupply of electricity. Bidirectional electricity trade puts country in a situation of mutual dependence: Any disruption of electricity trade would affect both countries in the same way.

This will disincentivize the use of energy trade for political purposes. The cost of renewable energy and supporting infrastructure is expected to be similar to the cost of fossil fuel based electricity generation (Way et al. 2022; Bogdanov et al. 2019).

A second flexibility option is demand and supply side flexibility. Power plants other than VRE can also be used to offset the variability and supply electricity whenever VRE is not producing enough. Existing natural gas capacity, for example, can be used as a complement to VRE (Baranes, Jacqmin, and Poudou 2017). Adding capacity in natural gas, by contrast, risks supplying too much (Gürsan and de Gooyert 2021) and risks turning into stranded assets (Kemfert et al. 2022). Hydropower can also take on the role of stepping up electricity production when supply from VRE is low (Dimanchev, Hodge, and Parsons 2021).

This is particularly important when electricity generation is reaching very low emission levels and the use of natural gas and coal is no longer desired. Demand response, the flexible use of electricity on the demand side, can contribute to balancing VRE and avoid the loss of excess energy. For example, large industrial facilities could manage their electricity by adjusting their electricity consumption to prices. However, this is mostly useful for short-term variation (Müller and Möst 2018).

A third flexibility option is using surplus electricity to produce zero-carbon fuels. An electricity system with a high share of VRE and few flexibility options will have to leave electricity from wind and solar unused when weather conditions are good for these two technologies, a measured described as “curtailment”. The excess electricity, however, could be used to produce green hydrogen with a technology called “power-to-gas”. A moderate carbon price and support for power-to-gas technology would allow economically feasible decarbonization (Yilmaz et al. 2022). Curtailment could be reduced by 87 percent and the need for wind and solar capacity could be reduced by 23 percent (Lyseng et al. 2018). While the technology itself would be loss-making, it would become viable through the more efficient use of wind and solar parks (Lynch, Devine, and Bertsch 2019). The gas could make use of the existing natural gas pipelines if the hydrogen is processed through a specific form of methanation (Romeo et al. 2022). Hydrogen can then be used again to generate electricity in retrofitted gas power plants but can also be used directly or after further processing for aviation (Dray et al. 2022) and shipping (Castelvecchi 2022).

Through the systematic use of flexibility options, challenges from the intermittency of wind and solar power for energy security can be overcome. This subsection has described which technologies are available to balance the intermittency from renewable energy. As the share of VRE in the electricity grid has been low so far, the main flexibility option used has been supply side flexibility from fossil fuel and hydropower plants. As the shares continue to increase and fossil fuels are phased out, the other options will have to be used increasingly. As Figure 16 indicates, grid extension is already following the extension of renewable energy. Supporting the other options will have to accompany policies for the decarbonization of the electricity sector. If done well, the entire electricity system can be operated with renewable energy without a threat for energy security (Haegel et al. 2019).

Conclusion

The current energy crisis has heightened the importance of striking a balance between meeting short-term energy needs and pursuing long-term energy security. This requires having a clear understanding of the key determinants of energy security—diversification and political risks—and how they interact with the green transition. On the one hand, high reliance on imported fossil fuels, especially from high political risk sources, exposes an economy to supply uncertainty. On the other hand, increasing domestic fossil fuels production by reneging on climate mitigation commitments may strengthen energy independence, but risks undermining the green transition and long-term energy security.

Increasing concentration of fossil fuel imports, amid growing export shares of key energy producers, has underpinned energy security trends in recent decades. To assess the relative importance of the main drivers of energy security, we decompose the politically weighted Herfindahl–Hirschmann index—the standard measure used in the literature—into two components: (i) a diversification effect, which results from changes in unweighted diversification and (ii) a political risk effect from two perspectives: risks due to political instability in energy-exporting economies versus risks stemming from increasing geo-political distance and fragmentation between energy-exporting and importing economies. Our results suggest that while political risk has had in some instances a material effect, diversification, or the lack thereof, is the main determinant of energy security.

Coal production has increased massively in China, but this is absorbed for domestic consumption, creating room for Indonesia and Australia to dominate the global coal export market. This has increased coal market concentration. Gas and oil markets are much more diversified but the strongly increasing shares by Australia, Qatar and the US have nevertheless caused energy security to deteriorate. Across all fuels, concentration of energy trade among geopolitically aligned economies may help reduce political risks but could weaken diversification and heighten energy insecurity.

There is a crucial interaction between climate policy and energy security. The model-based evidence illustrated in the paper suggests that several channels are at play. On the one hand, climate policy reduces demand for fossil fuels, causing the highest cost producers to leave the market. This increases market concentration. But on the other hand, the share of renewable energy increases amid climate policy, thus increasing the share of domestically produced energy. This decreases energy import dependence and improves energy security. Finally, the switch from highly concentrated coal supply to natural gas during the transition technically improves energy security at the global level because natural gas supply is more diversified than coal supply. On net, climate policies are expected to increase energy security.

The rapid increase in renewable energy deployment creates new challenges for energy security but solutions are already far advanced. One challenge is that the production of transition metals is more concentrated than the production of fossil fuels. However, the metals are needed only for the expansion of energy production capacity, not for ongoing energy generation. A hypothetical shortage of metal supply would thus not generate an immediate energy crisis as a collapse in fossil fuel exports does. In addition, the metals are not all concentrated in a single country, and they are mutually substitutable. The intermittency of renewable energy is also a challenge for energy security. However, there are several approaches to make the electricity system more flexible and hence robust to intermittency. Flexibility options are a more interconnected grid, energy storage, demand, and supply side flexibility as well as the production of zero-carbon fuels.

Beyond these main considerations, energy security is determined by many additional aspects. There are many aspects to energy security and many ways to measure it. One aspect of energy security which is difficult to measure in aggregate indicators is the dependence on infrastructure like pipelines and LNG

terminals. The role of infrastructure means that the diversification of energy sources does not fully reflect the dependence of a given country. Further, as renewable energy increases in importance, new measures of energy security might be needed. Two neighboring countries using large amounts of renewable energy might exchange electricity in both directions. Net imports would thus be close to zero, yet the countries are highly interdependent in their energy systems. This means they could stop the export of electricity to a neighboring country but would suffer from a disruption of trade as much as the trade partner.

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Annex 1: The decomposition of changes in energy security

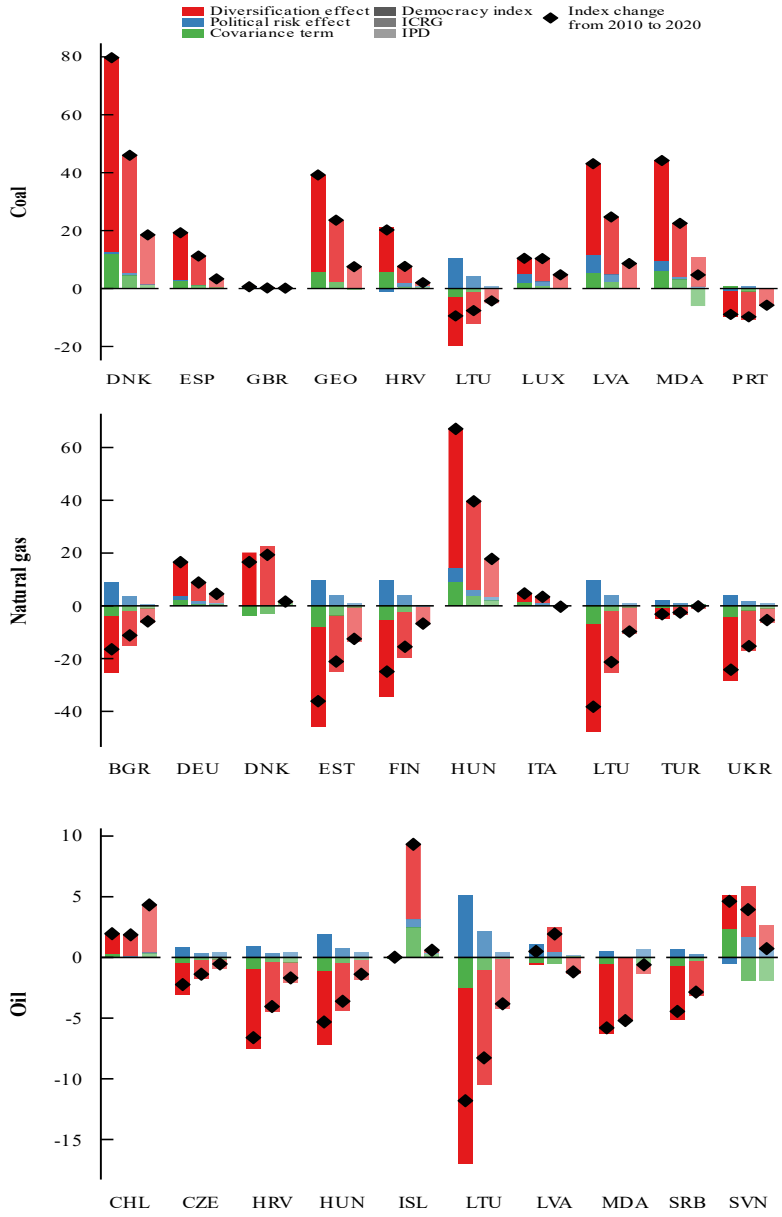
In this annex we show how changes in the energy security risk index can be decomposed into the three effects in Section 4.1. We take the DI_{pol} index in two points in time, noted as $DI_{pol,2}$ and $DI_{pol,1}$ and rewrite the difference. To facilitate the notation, we abbreviate $P_i = POL_i$:

$$
\begin{aligned}
&DI_{pol,2} - DI_{pol,1} \\
&= \sum_i \left[\left(\frac{X_{i,2}}{X_2} \right)^2 \times P_{i,2} \times 100 \right] - \sum_i \left[\left(\frac{X_{i,1}}{X_1} \right)^2 \times P_{i,1} \times 100 \right] \\
&= 100 \times \sum_i \left[\left(\frac{X_{i,2}}{X_2} \right)^2 \times P_{i,2} - \left(\frac{X_{i,1}}{X_1} \right)^2 \times P_{i,1} \right] \\
&= 100 \times \sum_i \left[\left(\left(\frac{X_{i,2}}{X_2} \right)^2 - \left(\frac{X_{i,1}}{X_1} \right)^2 \right) \times P_{i,1} + \left(\frac{X_{i,1}}{X_1} \right)^2 (P_{i,2} - P_{i,1}) + \left(\left(\frac{X_{i,2}}{X_2} \right)^2 - \left(\frac{X_{i,1}}{X_1} \right)^2 \right) (P_{i,2} - P_{i,1}) \right] \\
&= \sum_i \left[\left(\left(\frac{X_{i,2}}{X_2} \right)^2 - \left(\frac{X_{i,1}}{X_1} \right)^2 \right) \times P_{i,1} \times 100 \right] + \sum_i \left[\left(\frac{X_{i,1}}{X_1} \right)^2 (P_{i,2} - P_{i,1}) \times 100 \right] \\
&\qquad + \sum_i \left[\left(\left(\frac{X_{i,2}}{X_2} \right)^2 - \left(\frac{X_{i,1}}{X_1} \right)^2 \right) (P_{i,2} - P_{i,1}) \times 100 \right]
\end{aligned}
$$

Each of the summands corresponds to one of the effects. The first summand, $\sum_i \left[\left(\left(\frac{X_{i,2}}{X_2} \right)^2 - \left(\frac{X_{i,1}}{X_1} \right)^2 \right) \times P_{i,1} \times 100 \right]$, is the change in the global diversification index (DI), $DI(global)$, and reflects the diversification effect. The second summand, $\sum_i \left[\left(\frac{X_{i,1}}{X_1} \right)^2 (P_{i,2} - P_{i,1}) \times 100 \right]$, reflects the risk effect. The third summand, $\sum_i \left[\left(\left(\frac{X_{i,2}}{X_2} \right)^2 - \left(\frac{X_{i,1}}{X_1} \right)^2 \right) (P_{i,2} - P_{i,1}) \times 100 \right]$, is a covariance term.

Annex 2. Decomposition of energy security risk index with different political risk indicators

(index difference from 2010 to 2020; positive for higher risk, negative for lower risk)



Source: PRS Group; Economist Intelligence Unit; International Energy Agency, World Energy Balance; Voeten, Strezhnev, and Bailey, 2009, United Nations General Assembly Voting Data; International Energy Agency, Coal, Natural Gas, and Oil Information Statistics; and IMF staff calculations.
Note: Domestic consumption is computed as domestic production – net export. Domestic production and trade comprise primary energy and refined products.

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