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What if? The macroeconomic and distributional effects for Germany of a stop of energy imports from Russia

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Abstract

This paper discusses the economic effects of a potential cut-off of the German economy from Russian energy imports. We use a multi-sector open-economy model and a simplified approach based on an aggregate production function to estimate the effects of a shock to energy inputs. We show that the effects are likely to be substantial but manageable because of substitution of energy imports and reallocation along the production chain. In the short run, a stop of Russian energy imports would lead to an output loss relative to the baseline situation, without the energy cut-off, in the range 0.5% to 3% of GDP.

1 | INTRODUCTION

On 24 February 2022, Russia invaded Ukraine, thus continuing and escalating the war between the two countries that began in 2014. After an initial state of shock, European countries began to consider import boycotts of Russian fossil fuels, particularly oil, coal and natural gas. Perhaps interestingly, Zachmann *et al.* (2024) had gamed out such a scenario one month before the invasion. Such import or export boycotts are at times considered as policy instruments in international economic relations. For example, the USA has a long history of imposing trade sanctions, including import sanctions on Iran. In 2007, Argentina suddenly stopped its supply of natural gas to Chile. In 2010, China effectively imposed a rare earths export embargo on Japan. However, Europe did not decide to ban the import of Russian natural gas. Instead, in late summer of 2022, Russia essentially stopped exporting natural gas by pipeline to Europe. To analyse the economic effects of such boycotts, one needs a framework that captures substitution patterns in factor inputs, sectoral input–output relationships, and international trade linkages.

The impact of stopping natural gas imports from Russia was a particularly hot topic in the German public debate. Most politicians and pundits predicted complete economic doom for the German economy: the German Foreign Minister, Annalena Bärbock, claimed shortly after

24 February 2022 that 'it would be lights out' in Germany if Russian energy imports were cut off (Mertins 2022). The Vice Chancellor and the Minister of Economic Affairs, Robert Habeck, predicted 'severe damage to the German economy' (Olk 2022). And none other than the Chancellor Olaf Scholz himself was worried in the major national political TV talk show 'Anne Will' about an 'unbelievable number of jobs' being in jeopardy.[1] The CEO of German chemical industry giant BASF, Manfred Brudermüller, asked in a major interview: 'Do we knowingly want to destroy our entire economy?' (Brankovic and Theurer 2022); and Michael Hüther, the chief economist of the Federation of German Industries, claimed that up to four million jobs could be destroyed by an import ban on Russian fossil fuel (Brücken 2022).

Against the backdrop of this debate, on 7 March 2022, we published a policy brief with an economic analysis of this issue in real time (Bachmann *et al.* 2022). The upshot of this analysis was that the economic damage, while significant, would not be nearly as bad. Specifically, our analysis foresaw an output cost in the first year following a gas cut-off of up to 3% relative to a no-cut-off baseline scenario. The present paper published in 2024 is a revised version of our original March 2022 analysis that preserves, for the historical record, the key statistics and results of the original (specifically Tables 1 and 2 below) but which has also been revised and slightly expanded with the benefit of hindsight.[2]

The question that we set out to answer in March 2022 was: how would the German economy cope with a sudden stop of energy imports from Russia, triggered by either a tightening of sanctions or following a stop of deliveries? To quantify these effects, we combined the latest theoretical advances in multi-sectoral open-economy macroeconomics with an in-depth look at German energy usage and empirical estimates for the relevant parameters.

Section 2 looks at Germany's energy dependence from Russia. In the case of an import stop, imports of oil and coal from Russia can be substituted from other countries, but the situation in the gas market is more challenging. The country would face a shortfall equivalent of 30% of gas usage net of what can be substituted in electricity production, or 8% of total energy usage.

Section 3 asks how the economy would adjust to such a shock, and at what cost. We pursue a two-pronged approach to assess the macroeconomic effects of an import stop relative to a no-cut-off baseline. First, we use a state-of-the-art multi-sectoral open-economy model with production networks (Baqaee and Farhi 2024). Second, we cross-check these results with a simplified version of the model relying only on assumptions about elasticities of substitution leading to plausible bounds for the economic effects. We show that losses to the German economy of embargoing energy imports from Russia are highly sensitive to (i) the degree of substitutability between different intermediate inputs in production, in particular between the type of energy imported from Russia and other inputs; and (ii) the ease of reallocation of resources in the economy. We use observed elasticities of substitution in industry to derive estimates of economic costs. Unlike frequent fears voiced in the public debate, substitution and reallocation would likely keep the economic costs below 3% of GDP.

Section 4 draws policy implications, and in particular stresses the point that economic policy should encourage the adjustment, not try to delay it. Policy measures should aim to strategically increase incentives to substitute and save fossil energies as soon as possible. If an embargo of Russian energy became politically necessary, a case could be made that actions should be taken as early as possible in order to trigger adjustments in industry and households before the winter while gas demand was seasonally low over the summer.

The Appendix has a three-part structure. Appendix A provides additional facts about the German economy and its energy dependence from Russia, a detailed discussion of the quantitative exercises in Section 3 and their limitations, and a discussion of the likely distributional effects of stopping imports of Russian natural gas. Appendix B collects real-world historical examples of the power of substitution, and provides a discussion of substitution in the technical versus economic sense. Appendix C summarizes the results of other studies that quantify the effects of an import stop of Russian natural gas.

Some time has passed since we released the original version of this research in early March 2022. The intervening period has seen Russia cutting off gas exports to Germany via the Nordstream pipeline, a scenario that we intentionally allowed for. A natural question is therefore how the actual performance of the German economy compares to the predictions of our original paper. For the details, we refer the reader to Moll *et al.* (2023), which provides a retrospective view on the 'Great German gas debate of 2022', emphasizing the power of economic substitution. Suffice to say, the German economy withstood the end of Russian gas imports quite well and in line with the predictions of Bachmann *et al.* (2022). German GDP expanded by 1.8% for the entire year 2022, and contracted by 0.3% in 2023 (Gemeinschaftsdiagnose 2024), all despite a approximate 20% drop in gas consumption. While this is not a counterfactual, it reasonably limits what the impact of the import stop might have been. To measure the impact more narrowly, we look at the 'Gemeinschaftsdiagnose', the economic forecast published jointly by the five major economic research institutes in Germany. This consensus forecast from spring 2022 provides a reasonable counterfactual if we assume that the energy crisis was the only major shock to hit the German economy after the forecast was made. We find that the spring 2022 forecast of real GDP (Gemeinschaftsdiagnose 2022) for the four quarters from the third quarter 2022 to the second quarter 2023 was 1.9% higher than realized GDP over this period. The gap between realization and forecast grew to 3% after one year. This is also in line with the predictions of Bachmann *et al.* (2022), especially since the assumption that no other negative shock hit the German economy in the second half of 2022 and the first half of 2023 makes this rather an upper bound estimate for the negative effect.

Gemeinschaftsdiagnose (2024) also shows that employment continued to grow in 2022 and 2023, albeit at a slower pace than in 2021, while the number of unemployed increased by about 350,000 between the third quarter 2022 to the end of 2023. By any measure, the doomsday predictions of companies, industry associations and unions, and associated think tanks, turned out to be far off the mark. Moll *et al.* (2023) also highlight the political economy of these doomsday predictions: it was mostly the studies published by industry and union lobby groups that deviated significantly downwards from the mainstream predictions (including ours from 7 March 2022), with one lobby-financed study predicting a real GDP impact of almost −13% due to a halt in natural gas imports. As foreseen, producers partly switched to other fuels or fuel suppliers (30% of the approximately 40% reduction in natural gas was offset by switching to other suppliers), and a further 20% was achieved through demand reduction, for example, by importing products with high energy content and households adjusting their consumption patterns (see Ruhnau *et al.* (2023) for empirical evidence on how Germany reduced gas demand and substituted at only moderate economic costs). Finally, Moll *et al.* (2023) show that Germany would have withstood a 1 April gas cut-off as well.

2 | GERMANY'S DEPENDENCE ON RUSSIAN ENERGY

About half of German imports of gas and about a third of oil originate from Russia. Germany depends on Russia for about a third of total energy consumption (see Table 1 and Appendix Subsection A.1). Gas is used in industry (37%) and by households (31%), as well as trade and commerce (13%)—in the case of the last two, predominantly for heating purposes (BDEW 2019, 2022). Power providers (12%) and district heating (7%) use the rest. In industry, about three-quarters is used for heating and cooling. About a third of industrial use goes to the chemical industry (Zukunft Gas 2022). The final energy from oil is predominantly (about 70%) used in transport (Umweltbundesamt 2022).

Substituting Russian imports of oil and coal will likely not pose a major problem as sufficient world market capacity exists. The challenge is to find short-run substitutes for Russian gas because of the existing pipeline network and limited terminal capacities for liquified natural gas

TABLE 1 German primary energy usage, 2021.

	Oil	Gas	Coal	Nuclear	Renewables	Others	Total
TWh	1077	905	606	209	545	45	3387
%	31.8	26.7	17.9	6.2	16.1	1.3	100
Of which Russia %	34	55[a]	26	0	0	0	30

Notes: [a] In 2020—already lower in 2021–22.
The German Council of Economic Experts uses 40% for 2021 (Sachverständigenrat 2022). Estimates of net imports from Russia depend on the attribution of ring flows and exports (Bundesnetzagentur 2022).
Sources: Agora Energiewende (2022), Eckert and Abnett (2022), Zachmann *et al.* (2022a, Fig. 6).

(LNG). To construct a plausible size for the shock from a Russian import stop to Germany, we make conservative assumptions concerning savings in gas consumption, more gas imports from other countries, and the refilling of gas storage during the summer. This leaves us with a situation where the consumers of energy will have to cope with a 30% reduction in aggregate gas supply (see Appendix Subsection A.1 for details on how we arrive at this scenario).

3 | MODELLING A STOP OF ENERGY IMPORTS TO GERMANY

We now turn to assessing the macroeconomic effects of such a reduction in aggregate gas supply. We pursue a two-pronged approach. First, we use a state-of-the-art multi-sector open-economy model with production networks (Baqaee and Farhi 2024; see Appendix Subsection A.5). Second, we cross-check these results with a simplified version of the model relying only on assumptions about elasticities of substitution (see Appendix Subsections A.2–A.4) leading to plausible bounds for the economic effects.

The Baqaee–Farhi model is a multi-sector model with rich input–output linkages in which energy is a critical input in production. The model is *designed* to address questions in which supply chains or production networks play a key role. Specifically, it is designed to think about the ‘cascading effects’ that have featured prominently in the popular debate, that is, how a shock to an upstream product (e.g. an energy input) propagates downstream along the supply chain. The idea that input–output linkages can serve as a propagation mechanism for such shocks is well established in the literature. See Carvalho and Tahbaz-Salehi (2019) for a review of this literature, and Carvalho *et al.* (2021) for a prominent example studying the propagation of the 2011 Japan earthquake that destroyed the Fukushima nuclear plant.

The size of economic losses stemming from a Russian import stop depends crucially on the period over which adjustments take place. In the Baqaee and Farhi (2024) multi-sector model, we find modest losses of up to 1% of German gross national expenditure (GNE), or around €400 per year per citizen.[3] GNE is about 94% of GDP, so the corresponding GDP effects are somewhat smaller and remain below 1%. The key reasons why the economic losses are relatively small are: (i) the share of fossil energy imports in production is small to begin with (about 2–2.5% of GDP, and about 1% of GDP for gas); (ii) the model predicts that while this share rises considerably, it will not rise unreasonably much; and (iii) energy-intensive goods used in production can themselves be imported. In the model, the change in the share of energy imports in GNE summarizes succinctly the substitutability implied by elasticities and the input–output structure.

The numbers from this model come with uncertainty surrounding elasticities of substitution. To derive a plausible upper bound, we complement our calculations from the rich multi-sector model, with an analysis of a simpler model. This simple model is an aggregate production function with one key parameter, the elasticity of substitution between energy and other inputs. We discipline these estimates with empirical elasticities found in the literature for industrial energy usage at the 4-digit Standard Industrial Classification level (Steinbuks 2012), as well as estimates for short-run residential demand for natural gas (Auffhammer and Rubin 2018; Labandeira *et al.* 2017). We assume a reduction of gas deliveries of 30%, or about 10% (rounded up from 8%) of total German energy consumption. To build in a dose of caution, we assume an elasticity of substitution for gas of 0.1, or 0.04 for fossil fuels—substantially lower than the observed estimates in the literature.

Table 2 shows the results of the different approaches, that is, the more complex Baqaee–Farhi model (columns (1) and (2)) and the simpler model (columns (3) and (4)). Column (1) summarizes results from a sufficient statistics approach for models with production networks (supply chains; see Appendix Subsubsection A.5.3). The resulting losses to German GNE from these calculations remain below 1% per year, or around €400 per capita. The key idea of the approach is that the extent to which the upstream energy supply shock propagates through the production chain shows up in a sufficient statistic, namely, the change of the energy expenditure share in GNE induced by an import stop. Column (2) cross-checks these numbers with simulations from a computational version of the Baqaee–Farhi model, which yields GNE losses of 0.2–0.3%, or €100 per capita (see Appendix Subsubsection A.5.5 for why this is likely an underestimate). Using the simple model, with no further imports of energy-intensive goods and a very low short-run substitution elasticity of 0.04,[4] column (3) shows that a 10% energy adjustment to oil, gas and coal consumption leads to a 1.3% of GDP loss, or costs of €600. In a last scenario, where we model a more extreme 30% adjustment specifically in gas usage, the economic losses rise to 2.2% of GDP (2.3% of GNE), equivalent to up about €900 per year per German citizen, that is, more than twice as high as the €100 to €400 implied by the Baqaee–Farhi model (see Appendix Subsection A.7 for details).

As already noted, a key idea of the Baqaee–Farhi approach is that the extent to which the upstream energy supply shock propagates through the supply chain shows up in a sufficient statistic, namely, the change of the energy expenditure share in GNE induced by an import stop. Intuitively, when there are important bottlenecks along the supply chain, and elasticities of substitution are low, energy prices skyrocket when energy supply falls, which implies that the energy expenditure share rises strongly. This observation can then be used to bound the GNE loss from the shock: GNE losses larger than 1% or 3% that would occur with even stronger complementarities and ‘cascading effects’ would imply unreasonably large increases in this expenditure share, say that gas expenditure would rise from 1% of GNE to 20% of GNE. It is worth noting that this logic applies not just to the Baqaee–Farhi model but also to the simpler aggregate production function. In fact, it applies to a class of general equilibrium models much wider than the one considered in this paper. Other analyses of import supply shocks should therefore always examine their model’s predictions for changes in expenditure shares for their reasonableness. See also Berger *et al.* (2022), who put this sufficient statistics approach to good use.

It is important to stress that the model that we use is a real model with no further business cycle amplification. In particular, it omits standard Keynesian demand-side effects in the presence of nominal rigidities. On the monetary side, a firm commitment to stable prices can soften the

TABLE 2 Overview of results from different approaches.

	Baqaee–Farhi multi-sector model		Simplest model	
	Sufficient statistic	Simulation	10% energy ↓	30% gas ↓
	(1)	(2)	(3)	(4)
GNE loss (%)	≈ 1.0	< 0.3	1.5	2.3
As % of GDP	≈ 1.0	< 0.3	1.3	2.2
Per capita cost	€400	€100	€600	€900

potential trade-off between stabilizing output and inflation. Our model also omits amplification effects due to financial frictions (see Appendix Subsubsection A.5.5 and Subsection A.8 for a discussion of limitations, and Subsections A.6 and A.7 for sensitivity checks). A full analysis of an import stop would need to add such amplification effects on top of the 0.3–2.2% GDP losses in Table 2. To acknowledge this possibility and allow ourselves a 'safety margin', we round up our headline numbers to 0.5–3% of GDP. Indeed, a subsequent analysis (Bayer *et al.* 2022) confirms that even taking into account Keynesian demand effects, the overall cost still remains around 3% of GDP (Appendix C discusses other studies on this).

In summary, our model calculations suggest that while Germany could face a shortfall equivalent to about 30% of gas usage following an import stop, substitution and reallocation would likely keep the economic costs below 3% of GDP—unlike frequent fears voiced in the public debate.

4 | POLICY IMPLICATIONS

Fiscal insurance elements would be particularly important if, beyond their macroeconomic consequences, increased fuel and gas prices are redistributive. To explore the distributional consequences of a rise in energy prices, we therefore take data from the German Income and Consumption Survey and construct expenditure shares for energy along the income distribution (see Appendix Subsection A.12 for details). We find that expenditure shares vary between 3.5% and 5%, and are slightly declining along the income distribution. High-income households can absorb expenditure shocks from rising energy prices better than low-income households, as the former can reduce savings (or use accumulated wealth) to smooth out transitory cost increases. Hence targeted transfers to low-income households can be a cost-efficient way to compensate for an unequal impact of rising energy prices. The macroeconomic effects highly depend on how much the production structure can adjust to the reduction of energy imports and on how substitutable imports from Russia are. In the very short run, this substitutability is of course limited. However, the overall economic costs can be affected by targeted policy measures and their timing.

First and foremost, policy measures should aim at strategically increasing incentives to substitute and save fossil energies as soon as possible, even if an embargo is not imminent. Beginning to take action immediately avoids even harsher adjustments later in 2022 or in 2023. In particular, the seasonality of gas demand allows for a smoother adjustment process over the summer. At the same time, such an early move would immediately trigger the substitution and reallocation dynamics that are central to reducing the economic costs. Otherwise, the economic costs of an embargo might be considerably higher and give additional leverage to Russia.

Absent imminent action on an embargo, there is a strong case for forward guidance in energy markets for the next couple of years. Governments should commit to elevated fossil energy prices for an extended period of time—for example, with some sort of 'energy security levy' on natural gas. Although raising high energy prices will be the political equivalent of a hot potato, only this will create the needed incentives for households and industry to take immediate action, by increasing efforts to improve energy efficiency and substitute towards renewable energy. Of course, such a persistent increase in energy prices would have implications for households as well as industry. As we have seen, the costs are distributed relatively evenly across households but would still need to be addressed with respect to the poor. In case of no embargo realizing, an 'energy security levy' would create government revenues that can be used to finance such measures. Regarding industry, a blanket compensation for higher energy prices cannot be efficient. However, targeted policies can help adjustment in the short term if the long-term outlook for an industry under lower energy use or a fuel switch is positive. This way, such policies have the potential to accelerate the transition to a carbon-neutral economy.

Another area of action concerns the energy infrastructure. Given the higher costs of adjustment in the short run compared to the long run, it makes a difference whether an LNG terminal is ready by autumn 2023 or 2026. Government subsidies and contracts should therefore create clear incentives here as well, providing substantially higher payments for early completion.

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The original version of this paper was published on 7 March 2022, less than two weeks after the Russian invasion of Ukraine on 24 February 2022. The current version has been shortened and edited for readability. The last paragraph of the Introduction briefly discusses how real-world developments compare with the predictions made in this paper.

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ENDNOTES

[1] For more details on this interview, see https://benjaminmoll.com/Scholz (accessed 13 June 2024).

[2] We render this policy brief here with the following changes: edited and shortened body of text; the current Section 4 is an amalgamation of the previous section on 'Distributional effects', whose main text body has been moved to Appendix Subsection A, and the previous 'Policy implications' section; and the summary of results Table 2 in Section 3 presents the same results as the original except that the first column has been added for the calculation of the sufficient statistic approach.

[3] GNE is an economy's total expenditure defined as the sum of household expenditure, government expenditure and investment. That is, in the GDP accounting identity $GDP = C + I + G + (X - M)$, GNE is defined as $GNE = C + I + G$. GNE is also known as 'domestic absorption'. GNE (rather than GDP) is the welfare-relevant quantity in many macroeconomic and trade models, including the Baqaee–Farhi model. See also the discussion in Appendix Subsubsection A.5.2.

[4] We argue in Appendix Subsubsection A that an elasticity of substitution between energy and other inputs below 0.04 yields implausible results for the reaction of factor prices and factor shares to an energy supply shock.

[5] German GNE is €3175 billion—see World Bank, https://data.worldbank.org/indicator/NE.DAB.TOTL.CN?locations=DE (accessed 13 June 2024)—and Germany has a population of 83 million, implying a per capita GNE of €40,000. It then follows that 0.2–0.3% of GNE is €80–120.

[6] Some of the numbers are generated using simple back-of-envelope calculations because we were unable to find more direct data sources.

[7] As discussed in Table 1 in the main text, Germany imports about 60% of its gas, oil and coal. Total German imports of gas, oil and coal are roughly €80 billion in 2021 (see https://www.destatis.de/DE/Themen/Wirtschaft/Aussenhandel/Tabellen/erdgas-jaehrlich.html and https://www.destatis.de/DE/Themen/Wirtschaft/Aussenhandel/Tabellen/rohoel-jaehrlich.html, both accessed 28 June 2024), implying that total German consumption of gas, oil and coal was €80 billion/60% = €133 billion. German 2020 GNE is €3175 billion (see World Bank, https://data.worldbank.org/indicator/NE.DAB.TOTL.CN?locations=DE, accessed 13 June 2024), so that German consumption of gas, oil and coal is roughly 4% of GNE. German 2020 GDP is €3097 billion (see World Bank, https://data.worldbank.org/indicator/NY.GDP.MKTP.KN?locations=DE, accessed 13 June 2024).

[8] German GNE is €3175 billion, and total German imports of gas, oil and coal are roughly €80 billion in 2021.

[9] German GNE is €3175 billion, and total German imports of gas and oil are roughly €75 billion in 2021 (see the first two links in note 7). According to Table 1 in the main text, gas imports are roughly the same order of magnitude in volume as oil imports. Hence we calculate the share of gas imports in GNE as $0.5 \times 73/3175 \approx 1.2\%$.

[10] In our application, Y is really domestic absorption, not output (GDP). This is because energy E is an imported good, so GDP has to net imports. We ignore this distinction in the current subsection but are more careful when discussing our quantitative open-economy model in Subsection A.5.

[11] The code for producing Figure A1, as well as Figures A2 and A3 below, is available at https://benjaminmoll.com/elasticity (accessed 13 June 2024).

[12] Figure A1 is generated using the Matlab code referenced in note 11 (see also the replication materials https://benjaminmoll.com/RussianGas_Replication, accessed 13 June 2024). In particular, we do *not* use the second-order approximation (A4) to compute any of our numerical results for the simplified model. The reason is that the second-order approximation is potentially inaccurate for values of the elasticity of substitution σ very close to zero.

[13] Labandeira *et al.* (2017) also survey the older literature on energy demand elasticities. Short-run demand elasticities in the older literature for natural gas and oil vary over ranges similar to those for the results reported (see Table 1 in Labandeira *et al.* 2017).

[14] It is also worth noting that this result is not special to our model; instead, it is a consequence of production efficiency and therefore holds in a larger class of models with this feature.

[15] Alternatively, we could assume that exports do not rise following the shock, $\Delta \log x_i^X \le 0$, and that imports of other goods do not fall, $\Delta \log m_j \ge 0$ for $j \ne E$, in which case $\Delta \log W \ge (p_E m_E / GNE)\, \Delta \log m_E + \frac{1}{2}\, \Delta(p_E m_E / GNE)\, \Delta \log m_E$, that is, equation (A7) provides an upper bound on GNE losses $|\Delta \log W|$.

[16] In contrast, the first-order approximation requires only the initial GNE share, i.e. $\Delta \log W \approx 2.5\% \times -30\% = -0.75\%$. But as we will see, second-order terms can be large.

[17] As we explained in the main text, in this scenario, German energy consumption falls by 10%. Germany imports roughly 60% of its energy, so the reduction in energy imports is $10\%/60\% = 17\%$.

[18] See fact 3 in Subsection A.1 for the size of German gas imports. As we explained in the main text, in this scenario, German gas consumption falls by 30%. Germany imports essentially all of its gas, so the reduction in gas imports is also 30%.

[19] We are grateful to Vasco Carvalho, Basile Grassi, Camille Landais, Guido Lorenzoni and Lukasz Rachel for useful comments, and to Marina Feliciano and Borui Niklas Zhu for excellent research assistance.

[20] Some 37% of Chilean gas usage in 2004 was used to generate electric energy, with fewer alternatives for that than Germany faces now.

[21] The Argentinian supply stop came during the Chilean winter, whereas Germany has a longer time to prepare until winter. Due to the mild winter in Chile and low share of household consumption, we do not list this as a main argument.

[22] Sources: article on Project Syndicate by Andrés Celasco and Marcelo Tokman (https://www.project-syndicate.org/commentary/russian-gas-chiles-lessons-for-germany-europe-by-andres-velasco-and-marcelo-tokman-2022-04); EIA data on Chilean gas consumption and imports (https://www.eia.gov/international/overview/country/CHL); IPS news article (http://www.ipsnews.net/2004/05/chile-argentina-relations-strained-by-gas-dispute); brief by the Institute for Energy Law (https://www.cailaw.org/media/files/IEL/Publications/2014/ela-lng-chile-vol8-no4.pdf); IEA report on Chile (https://iea.blob.core.windows.net/assets/a823ead0-aa33-4baf-93d1-54d60909e70b/chile2009.pdf); a report by the Central Bank of Chile. All links accessed 14 June 2024.

[23] Some authors argue that the embargo was not fully effective; see, for example, Johnston (2013). However, the embargo seems to have triggered some substitution by Japanese firms so it arguably must have been effective to some extent.

[24] Sources: Twitter thread by Janis Kluge (https://twitter.com/jakluge/status/1502974281361285120); DW article (https://www.dw.com/de/wie-man-das-druschba-desaster-am-ende-der-pipeline-wahrnimmt/a-49440013); local news (https://www.lvz.de/Region/Mitteldeutschland/Raffinerie-Leuna-von-Stopp-der-Druschba-Pipeline-betroffen). All links accessed 14 June 2024.

[25] Ilzetzki (2022) writes: 'At the time, this was viewed as a nearly impossible task, with economists Robert Nathan and Simon Kuznets estimating that the US didn't have the productive capacity to meet this aim.' He quotes a similar statement by a Ford Motor Company executive from the time, as well as that of a historian: 'Nobody had yet found a way to bring mass-production techniques to airplane building, and prospects for doing so did not look promising.' See also Smith (1959, p. 154).

[26] Source: Wikipedia article on wood gas (https://en.wikipedia.org/wiki/Wood_gas, accessed 14 June 2024).

[27] Sources: Twitter thread by Joachim Voth (https://twitter.com/joachim_voth/status/1506174063466659842?s=20&t=aZD--CdFcgQNNJYXB6Jkpg); Twitter thread by John Cochrane (https://twitter.com/JohnHCochrane/status/1505978362098974722); National Museum of American History (https://americanhistory.si.edu/collections/search/object/nmah_846532); Business Insider article (https://www.businessinsider.com/black-thursday-for-wwii-us-army-air-force-over-schweinfurt-germany-2018-10?r=US&IR=T∖#the-targets-of-the-august-17-raid-were-damaged-but-not-destroyed-allied-strategists-thought-a-second-raid-was-necessary-while-the-german-factories-were-able-to-recover-from-one-attack-nazi-planners-saw-their-vulnerability-and-started-dispersing-production-and-moved-fighters-from-the-russian-front-to-counter-the-bombers-3); US Strategic Bombing Survey Summary Report, 30 September 1945 (https://www.ibiblio.org/hyperwar/AAF/USSBS/ETO-Summary.html); Harrison (2020). All links accessed 14 June 2024.

[28] Sources: Twitter thread by Joachim Voth (see note 27); Imperial War Museums (https://www.iwm.org.uk/history/the-u-boat-campaign-that-almost-broke-britain); Harwich Haven Surrender and Sanctuary Project (https://harwichhavenhistory.co.uk/new-history-on-our-doorstep-research-booklet); National Farmers' Union (https://www.nfuonline.com/archive?treeid=33538); Gompert *et al.* (2014); Russell (2008). All links accessed 14 June 2024.

[29] See https://www.theverge.com/2022/3/13/22975246/ford-ship-sell-incomplete-vehicles-missing-chips (accessed 14 June 2024).

[30] See https://www.theverge.com/2021/7/13/22575836/gm-wireless-charging-cadillac-chevy-tahoe-chip-shortage (accessed 14 June 2024).

[31] See https://www.scmp.com/business/companies/article/3132505/carmakers-are-stripping-out-digital-bells-and-whistles-global (accessed 14 June 2024).

[32] See https://www.theverge.com/2021/9/29/22701086/cadillac-super-cruise-2022-escalade-semiconductor-shortage (accessed 14 June 2024).

[33] See https://www.theverge.com/2021/11/5/22765709/bmw-chip-shortage-touchscreen-car-suv-manufacturing (accessed 14 June 2024).

[34] See https://www.nytimes.com/2021/04/23/business/auto-semiconductors-general-motors-mercedes.html (accessed 14 June 2024).

[35] This is according to a Bubble Goods (US online marketplace) article, 'Leaf your plastic packaging for eco-friendly banana leaves', 26 August 2019 (https://bubblegoods.com/blogs/news/leaf-your-plastic-packaging-for-eco-friendly-banana-leaves) and a Sol article 'Folhas de bananeira substituem plástico em supermercados na Ásia', 4 June 2019 (https://sol.sapo.pt/artigo/660793/-folhas-de-bananeira-substituem-plastico-em-supermercados-na-asia). Both links accessed 14 June 2024.

[36] See https://today.rtl.lu/news/luxembourg/a/1367448.html?fbclid=IwAR1UatwIhP7B-Ss5sT5c9NzfnF_7WSJII7vQf7yfsY_E0cYqTWFu0niH24I (accessed 14 June 2024).

[37] See https://sol.sapo.pt/artigo/663797/sustentabilidade-ambiental-auchan-vendera-sacos-de-poliester-em-alternativa-aos-de-plastico (accessed 14 June 2024).

[38] See https://www.zara.com/uk/en/--c2056922.html (accessed 14 June 2024).

[39] See https://www.loreal.com/en/group/about-loreal/our-purpose/reducing-plastic-packaging (accessed 14 June 2024).

[40] See Sol article 'As cápsulas de café amigas do ambiente', 16 May 2019 (https://sol.sapo.pt/artigo/658521/as-capsulas-de-cafe-amigas-do-ambiente (accessed 14 June 2024).

[41] See https://www.forbes.com/sites/jeffkart/2021/07/29/the-future-of-takeout-is-plastic-free/?sh=16285740e40c (accessed 14 June 2024).

[42] See https://www.bbc.co.uk/news/uk-44492352 (accessed 14 June 2024).

[43] See (https://www.independent.co.uk/climate-change/news/plastic-pollution-wagamama-end-straws-use-uk-restaurants-a8163581.html (accessed 14 June 2024).

[44] See https://www.cnbc.com/2019/09/19/burger-king-stops-giving-away-plastic-toys-to-uk-customers.html (accessed 14 June 2024).

[45] See https://twitter.com/christianbaye13/status/1504785656815497226?s=21 (accessed 14 June 2024).

[46] One study by IMK (2022) argues for a single-year GDP drop of 6% or larger. As we discuss in more detail below, we view the computational experiment that generates this GDP drop as implausible. We therefore did not include it in the previous summary sentence.

[47] Words like 'mass unemployment' and 'poverty' (Minister of the Economy Robert Habeck) or 'the loss of millions of jobs' (Chancellor Olaf Scholz) arguably suggest such scenarios.

[48] See the appendix at https://gemeinschaftsdiagnose.de/wp-content/uploads/2022/04/GD22F_Hintergrund-Alternativszenario_final.pdf (accessed 14 June 2024), in particular p. 5.

[49] The rationing effects are almost entirely due to gas rather than oil and coal, consistent with our analysis.

[50] The paper features a useful discussion about whether and to what extent one can add the two numbers.

[51] The IMK, or 'Institut für Makroökonomie und Konjunkturforschung', is a German think tank. funded by the Hans-Böckler Stiftung, the foundation of the German Trade Union Confederation (DGB).

[52] This 45-fold increase is partly due to the import stop and partly due to heightened energy prices even in the absence of an import stop. Without the import stop, the gas price increases from about €20 per MWh to €160, so an 8-fold increase. The import stop then increases this price by an *additional* factor of around 5.5 to €900 per MWh. See https://twitter.com/ben_moll/status/1512911428629446658?s=20&t=N5I2FSL9YTNmvM04qsdzrg.

[53] See https://twitter.com/ngarnadt/status/1514907211159556099?s=20&t=vQyWdLwtNjJAlSmVn56vbQ (accessed 14 June 2024). IMK (2022) justifies this strategy as follows: the goal is to increase the gas price until the NiGEM model generates a 30% gas reduction. However, even with a gas price of €900 per MWh, it closes only less than half of this 30% gap; for larger gas price increases, the model becomes unstable. Our view is instead that a 45-fold gas price increase without a sizeable quantity reduction indicates that the NiGEM model—or more precisely the parametrization used by IMK (2022)—is not suitable for conducting the attempted import stop experiment. This is perhaps not surprising given that the NiGEM model was originally developed and parametrized for simulating counterfactuals with respect to much smaller shocks or policies.

REFERENCES

Agora Energiewende (2022). Die Energiewende in Deutschland: Stand der Dinge 2021. Rückblick auf die wesentlichen Entwicklungen sowie Ausblick auf 2022. Analysis, 7 January.

Auffhammer, M. and Rubin, E. (2018). Natural gas price elasticities and optimal cost recovery under consumer heterogeneity: evidence from 300 million natural gas bills. NBER Working Paper no. 24295.

Bachmann, R., Baqaee, D., Bayer, C., Kuhn, M., Löschel, A., Moll, B., Peichl, A., Pittel, K. and Schularick, M. (2022). What if? The economic effects for Germany of a stop of energy imports from Russia. ECONtribute Policy Brief no. 028.

Baqaee, D. and Farhi, E. (2024). Networks, barriers, and trade. *Econometrica*, **92**(2), 505–41.

Bayer, C., Kriwoluzky, A. and Seyrich, F. (2022). Energieembargo gegen Russland würde Wirtschaft in Deutschland kalkulierbar belasten, Fiskalpolitik wäre in der Verantwortung. DIW Aktuell no. 80.

BDEW (2019). Energy Market Germany 2019; available online at https://www.bdew.de/media/documents/Pub_20190603_Energy-Market-Germany-2019.pdf (accessed 15 June 2024).

——— (2022). Die Energieversorgung 2021—Jahresbericht; available online at https://www.bdew.de/media/documents/Jahresbericht_2021_UPDATE_Juni_2022.pdf (accessed 28 June 2024).

Berger, E., Bialek, S., Garnadt, N., Grimm, V., Other, L., Salzmann, L., Schnitzer, M., Truger, A. and Wieland, V. (2022). A potential sudden stop of energy imports from Russia: effects on energy security and economic output in Germany and the EU. German Council of Economic Experts Working Paper no. 01/2022; available online at https://www.sachverstaendigenrat-wirtschaft.de/fileadmin/dateiablage/Arbeitspapiere/Arbeitspapier_01_2022.pdf (accessed 15 June 2024).

Brankovic, M. and Theurer, M. (2022). BASF-Chef im Interview: ‘Wollen wir sehenden Auges unsere gesamte Volkswirtschaft zerstören?’ *Frankfurter Allgemeine Zeitung*, 31 March (updated 4 April).

Brücken, T. (2022). Michael Hüther im Interview: Diskussion um Gas-Embargo: Das wäre das Ende der Grundstoffproduktion in Deutschland. *Tagesspiegel*, 24 March.

Bundesbank (2022). Zu den möglichen gesamtwirtschaftlichen Folgen des Ukrainekriegs: Simulationsrechnungen zu einem verschärften Risikoszenario. Monthly Report Article, April.

Bundesnetzagentur. Monitoringbericht 2021; available online at https://www.bundeskartellamt.de/SharedDocs/Publikation/DE/Berichte/Energie-Monitoring-2021.pdf?_blob=publicationFile&v=2 (accessed 28 June 2024).

Carvalho, V., Nirei, M., Saito, Y. U. and Tahbaz-Salehi, A. (2021). Supply chain disruptions: evidence from the Great East Japan Earthquake. *Quarterly Journal of Economics*, **136**(2), 1255–321.

——— and Tahbaz-Salehi, A. (2019). Production networks: a primer. *Annual Review of Economics*, **11**(1), 635–63.

Dynan, K. E., Skinner, J. and Zeldes, S. P. (2004). Do the rich save more? *Journal of Political Economy*, **112**(2), 397–444.

Eckert, V. and Abnett, K. (2022). How dependent is Germany on Russian gas? Reuters, 24 February; available online at https://www.reuters.com/world/europe/howmuch-does-germany-need-russian-gas-2022-01-20 (accessed 15 June 2024).

Gemeinschaftsdiagnose (2022). Von der Pandemie zur Energiekrise—Wirtschaft und Politik im Dauerstress; available online at https://gemeinschaftsdiagnose.de/wp-content/uploads/2022/04/GDF2022_Gesamtdokument_unkorrieigert_12.4_13h.pdf (accessed 15 June 2024).

——— (2024). Deutsche Wirtschaft kränkelt—Reform der Schuldenbremse kein Allheilmittel. Gemeinschaftsdiagnose, **Spring**.

Gholz, E. and Hughes, L. (2021). Market structure and economic sanctions: the 2010 rare earth elements episode as a pathway case of market adjustment. *Review of International Political Economy*, **28**(3), 611–34.

Goldman Sachs (2022). The impact of gas shortages on the European economy. 7 March; available online at https://benjaminmoll.com/GS_Russian_Gas (accessed 15 June 2024).

Gompert, D. C., Binnendijk, H. and Lin, B. (2014). Germany's decision to conduct unrestricted U-boat warfare, 1916. In *Blinders, Blunders, and Wars: What America and China Can Learn*. Santa Monica, CA: RAND Corporation, pp. 63–70; available online at http://www.jstor.org/stable/10.7249/j.ctt1287m9t.12 (accessed 15 June 2024).

Harrison, M. (2020). Economic warfare: insights from Mançur Olson. In S. Broadberry and M. Harrison (eds), *The Economics of the Second World War: Seventy-Five Years On*. London: CEPR Press.

Houthakker, H. S. (1955). The Pareto distribution and the Cobb–Douglas production function in activity analysis. *Review of Economic Studies*, **23**(1), 27–31.

IEA (2022). A 10-point plan to reduce the European Union's reliance on Russian natural gas; available online at https://www.iea.org/reports/a-10-point-plan-to-reduce-the-european-unions-reliance-on-russian-natural-gas (accessed 15 June 2024).

Ilzetzki, E. (2022). Learning by necessity: government demand, capacity utilization, & productivity. LSE Working Paper; available online at https://www.ilzetzki.com/_files/ugd/b3763a_096c73ce52ab47bdbaf506cce0e221ca.pdf (accessed 15 June 2024).

IMK (2022). Ukraine-Krieg erschwert Erholung nach der Pandemie. IMK Report no. 174; available online at https://www.imk-boeckler.de/fpdf/HBS-008284/p_imk_report_174_2022.pdf (accessed 15 June 2024).

Jo, A. (2021). Substitution between clean and dirty energy with directed technical change. ETH Working Paper.

Johnston, A. I. (2013). How new and assertive is China's new assertiveness? *International Security*, **37**(4), 7–48.

Labandeira, X., Labeaga, J. M. and Lopez-Otero, X. (2017). A meta-analysis on the price elasticity of energy demand. *Energy Policy*, **102**, 549–68.

Mertins, S. (2022). Deutschland reisst das Steuer herum. *Neue Zürcher Zeitung*, 26 February.

Moll, B., Schularick, M. and Zachmann, G. (2023). The power of substitution: the great German gas debate in retrospect. *Brookings Papers on Economic Activity*, **Fall**.

Olk, J. (2022). Hitzige Ökonomen-Debatte: Welche Auswirkungen hätte ein Embargo für russische Energie wirklich? *Handelsblatt*, 13 March.

Papageorgiou, C., Saam, M. and Schulte, P. (2017). Substitution between clean and dirty energy inputs: a macroeconomic perspective. *Review of Economics and Statistics*, **99**(2), 281–90.

Rashad, M. and Binnie, I. (2022). Brimming European LNG terminals lack room for more gas. Reuters, 1 February; available online at https://www.reuters.com/business/energy/brimming-european-lng-terminals-have-limited-space-more-gas-2022-02-17 (accessed 15 June 2024).

Ruhnau, O., Stiewe, C., Muessel, J. and Hirth, L. (2023). Natural gas savings in Germany during the 2022 energy crisis. *Nature Energy*, **8**, 621–8.

Russell, B. (2008). International law at sea, economic warfare, and Britain's response to the German U-boat campaign during the First World War. PhD thesis, The Open University.

Sachverständigenrat (2022). Estimates of the consequences of an intensification of the conflict on the economic outlook. German Council of Economic Experts; available online at https://www.sachverstaendigenrat-wirtschaft.de/fileadmin/dateiablage/Konjunkturprognosen/2022/KJ2022_Box3_Excerpt.pdf (accessed 15 June 2024).

Smith, R. E. (1959). *The Army and Economic Mobilization*. Washington, DC: Center of Military History, US Army.

Steinbuks, J. (2012). Interfuel substitution and energy use in the UK manufacturing sector. *Energy Journal*, **33**(1), 1–29.

Timmer, M. P., Dietzenbacher, E., Los, B., Stehrer, R. and de Vries, G. J. (2015). An illustrated user guide to the World Input–Output Database: the case of global automotive production. *Review of International Economics*, **23**(3), 575–605.

Umweltbundesamt (2022). Energieverbrauch nach Energieträgern und Sektoren; available online at https://www.umweltbundesamt.de/daten/energie/energieverbrauch-nach-energietraegern-sektoren#entwicklungdes-endenergieverbrauchs-nach-sektoren-und-energietragern (accessed 15 June 2024).

Zachmann, G., Keliauskaitė, U., McWilliams, B. and Sgaravatti, G. (2024). European natural gas imports. Bruegel dataset; available online at https://www.bruegel.org/dataset/european-natural-gas-imports (accessed 15 June 2024).

———, Tagliapietra, S., McWilliams, B. and Sgaravatti, G. (2022a). Can Europe survive painlessly without Russian gas? Bruegel blog post, 27 January; available online at https://www.bruegel.org/2022/01/can-europe-survive-painlessly-without-russian-gas (accessed 15 June 2024).

———, ———, ——— and ——— (2022b). Preparing for the first winter without Russian gas. Bruegel blog post, 28 February; available online at https://www.bruegel.org/2022/02/preparing-for-the-first-winter-without-russian-gas (accessed 15 June 2024).

Zukunft Gas (2022). Erdgas in Deutschland: Zahlen Und Fakten Für Das Jahr 2021; available online at https://gas.info/fileadmin/Public/PDF-Download/Faktenblatt-Erdgas.pdf (accessed 28 June 2024).

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APPENDIX

This appendix has a three-part structure. Appendix A provides additional facts about the German economy and its energy dependence from Russia, a detailed discussion of the quantitative exercises in Section 3 of the main text, and their limitations, and a discussion of the likely distributional effects of stopping imports of Russian natural gas. Appendix B collects real-world historical examples of the power of substitution, and provides a discussion of substitution in the technical versus economic sense. Appendix C summarizes the results of other studies that quantify the effects of an import stop of Russian natural gas.

We begin, in Subsection A.1, by detailing the use of natural gas by various sectors of the German economy, and the contribution of Russian natural gas to meeting this demand, *as of* *early 2022*. Subsections A.2–A.4, as well as Subsections A.6 and A.9, review the economic properties of an aggregate constant elasticity of substitution (CES) production function in energy and other input factors, the key substitution elasticity in it, the available empirical evidence for it by 2022, and our calibration. Subsection A.5 revisits the model by Baqaee and Farhi (2024), and describes the quantitative exercises that we perform with it. Subsection A.8 provides some transparency with regards to the caveats to our analyses: the absence of Keynesian demand and financial amplification effects, both of which would need to be stabilized by appropriate monetary and fiscal policy measures. Subsection A.12 documents expenditure and income shares for different heating sources along the income distribution and by household type, again *as of early 2022*, to provide a sense of the likely distributional impact of stopping Russian energy imports.

Subsection B.1 provides a number of case studies that illustrate the power of substitution in the face of extreme shocks. Specifically, we discuss the sudden stop of Argentine gas supplies to Chile in 2007, China's rare earth embargo against Japan in 2010, a shutdown of the Druzhba oil pipeline, shortages during the Second World War, ball-bearings production in the Second World War, the German U-boat campaign against Britain during the First World War, face masks during the Covid-19 pandemic, the global microchip shortage from 2020, and the replacement of single-use plastics. Subsection B.2 discusses the 'engineering' versus 'economic' view of substitution, and reveals the transfer of low or even zero substitutability at the production process level to the sectoral or aggregate level as a micro-to-macro fallacy: in the aggregate, at any stage of the production process, intermediate goods can be imported even when the upstream value chain breaks down completely; in the more medium term, creative destruction towards less energy-intensive products will occur.

Finally, Appendix C provides an overview of other studies, *as of April 2022*, mostly in the wake of Bachmann *et al.* (2022), which estimates the impact of a cessation of Russian energy imports, and shows that most of them conclude with numbers close to those in Bachmann *et al.* (2022)—slightly larger if they take demand effects into account. Studies by lobby groups with implausible calibrations constitute the exception to the rule.

A MAIN APPENDIX

We pursue a two-pronged approach for assessing the macroeconomic effects.

First, we use economic theory to isolate two of the key determinants of the macroeconomic effects of cutting energy imports from Russia. These are (i) the importance of Russian imports of gas, oil and coal ('brown' energy) in production, and (ii) the elasticity of substitution between these energy sources and other inputs (e.g. 'green' energy).

Second, we use the multi-sector model of Baqaee and Farhi (2024) to run counterfactual simulations of the macroeconomic effects of cutting energy imports from Russia. The Baqaee–Farhi model is a state-of-the-art multi-sector model with rich input–output linkages in which energy is a critical input in production.

Our findings are as follows.

1. In Subsection A.1, we summarize some statistics relating to the German economy's energy dependence that provide important signposts for assessing the effects of an import stop.
2. Standard theory predicts that the losses to the German economy of embargoing energy imports from Russia are extremely sensitive to the degree of substitutability of brown energy with other inputs as measured by the elasticity of substitution between these factors. This elasticity of substitution is hard to discipline empirically, especially for large changes in the economy's input mix of the type with which we are concerned, so that any macroeconomic analysis is necessarily subject to a large degree of uncertainty.

3. This elasticity of substitution is likely low in the very short run but larger in the medium and long run, so the size of economic losses depends crucially on the time frame over which adjustments take place.
4. We review empirical evidence on this elasticity of substitution (which also equals the own-price elasticity of energy). The meta-analysis by Labandeira *et al.* (2017) provides a summary of the existing estimates on own-price elasticities for energy consumption differentiated between the short run (less than one year) and the long run (after one year). The relevant short-run average short-run elasticity for energy is −0.22, for natural gas it is −0.18, and the least elastic in the short run is heating oil with −0.02. Differences between residential and industrial consumers are small.
5. Even for elasticities of substitution below this range, the Baqaee–Farhi multi-sector model predicts modest losses of around 0.2–0.3% of German GNE, or around €80–120 per year per German citizen.[5] To explain what drives these low losses, we provide a simple formula that points to two key sufficient statistics: first, the share of energy imports in German gross national income (GNI) (which equals a modest 2.5%), as well as the predicted change in this share (which is determined by the elasticity of substitution). Unless the change in this share is unrealistically large (which would happen for an extremely low elasticity), the GNI loss remains small.
6. Given the uncertainty surrounding elasticities of substitution as well as the structure of production, we use our simple and transparent model to consider some potential worst-case scenarios for extremely low elasticities. We argue that economic losses from a −10% energy shock could be up to 1.5% of German GNE, or €600 per year per German citizen, that is, an order of magnitude higher than the 0.2–0.3% or €80–120 implied by the Baqaee–Farhi model.
7. When the elasticity of substitution is not just low but exactly zero (Leontief production) the economic losses can be even larger. But this case (i) is inconsistent with empirical evidence, and (ii) makes a number of nonsensical predictions.
8. Rather than combining gas, oil and coal into an aggregate ‘brown energy’ input, we treat gas as a separate input that cannot be substituted with oil and coal. As explained in the main text, the resulting shock to gas supply is up to −30%. With an elasticity of substitution between gas and other inputs considerably below estimates in the literature of 0.1, this scenario results in GNE losses of 2.3%, or €912 per year per German citizen.
9. We discuss a number of mechanisms that are outside of our model and that could potentially further amplify economic losses (depending on the policy response). To provide a ‘safety margin’ for such missing mechanisms, we round up the 2.3% GNE losses to 3%, which is the headline worst-case number featured in the paper’s abstract.

Replication materials for all results in Section 3 can be found at https://benjaminmoll.com/RussianGas_Replication (accessed 13 June 2024).

A.1 Fact sheet: energy dependence of the German macroeconomy

This subsection summarizes some key statistics that provide important guide posts for assessing the macroeconomic effects of an import stop.[6]

A.1.1 Germany’s dependence on Russian energy

If Germany decides to embargo Russian energy imports, or Russia decides to impose export restrictions, then Germany would need to compensate for the decline of Russian energy imports through alternative supply sources, fuel shifting and economic reallocation, or demand reduction. The different channels are likely to operate differently in the short and long term. In the short run, a stop of Russian exports has to be compensated through alternative energy sources from other countries and domestic sources to meet electricity, transport, heating and industrial demand, or through substituting energy-intensive production of certain products by direct imports. In the medium and long term, increased use of renewable energy and energy efficiency improvements can contribute significantly to lowering energy demand.

To start with, substituting Russian imports of oil and coal will likely not pose a major problem. Sufficient world market capacity exists from other oil and coal exporting countries to make up the shortfall. The greater challenge is to find short-run substitutes for Russian gas. Russian gas accounts for about 15% of Germany's total energy consumption. While oil and coal can likely be shipped from other countries, the situation in the gas market is more complex. Owing to the existing pipeline network and ultimately limited terminal capacities, a short-term substitution via LNG is challenging, while raising pipeline imports from other countries is also subject to limitations.

The International Energy Agency (IEA) estimates that imports via pipeline to the EU from Norway, Algeria and Azerbaijan could be increased by 10 billion cubic metres (bcm) compared to 155 bcm imports from Russia in 2021, and LNG imports theoretically by 60 bcm (up from 110 bcm in 2021; Rashad and Binnie 2022). The IEA considers 20 bcm additional LNG more realistic in the current market (IEA 2022). Some of this gas would have to be stored pre-winter to compensate for missing Russian gas in the cold months. Moreover, switching from comparatively cheap contract prices with Russia to world market spot prices would imply a substantial (currently fivefold) increase of the gas price. A recent study by the European think tank Bruegel comes to the conclusion that it will be possible through substitution and European cooperation to meet demand in electricity generation, transport and heating in the EU without encountering physical shortages (Zachmann *et al.* 2022a,b).

In its 10-point plan to reduce the European dependency on Russian gas, the IEA (2022) also lists increasing coal and nuclear power production and renewables deployment as well as a number of demand-related measures that could theoretically contribute another 33 bcm reduction of gas usage in the EU. While switching to coal or nuclear can be considered plannable options, it remains uncertain to which extent potentials from changing consumer heating habits, increasing renewables deployment and energy efficiency of buildings can be raised. Most likely at least the latter two options will play a minor role in the very short run.

Russian gas imports already decreased substantially in the second half of 2021 and especially in the first months of 2022. At the EU level, its import share fell from about 40% to 20–30% (Zachmann *et al.* 2024). Imports of LNG surpassed Russian imports, although capacity for further increases of LNG imports are limited (Rashad and Binnie 2022). During the first months of 2022, prices for coal, oil and gas have already increased dramatically. It remains hard to pin down to what extent gas, hard coal and oil prices will rise further in the short term, and what scenarios are priced in. We take this high degree of uncertainty into account in the next section by providing different scenarios. It is clear that prices had already increased before the Ukraine war broke out due to the revitalization of the world economy when Covid-19 restrictions were lifted, the appreciation of the US dollar, and in the case of oil, the reluctance of OPEC to increase extraction substantially.

Taken together, the available evidence suggests at this point in time that other gas producers will be able to compensate only partially for the shortfall from Russia. Substitution and reallocation will thus be crucial. To construct a plausible size for the shock to the German economy from an Russian import stop, we make the following assumptions.

1. Russia's import share in German gas consumption stood at 55% in 2020, but has declined in the first months of 2022. Sachverständigenrat (2022) estimates this number for 2021 at 40%. To be conservative, we start with 55%. In addition, we make cautious assumptions with respect to the potential for increases in supply via LNG in the short run. We also assume that pipeline imports from Norway or North Africa, for example, could be increased only moderately. To be specific, we assume that capacity increase is limited to 5% over the next year.

2. Looking at gas consumption, there is consensus that gas that is currently used for electricity generation can be saved by switching to lignite or hard coal. Nuclear energy can play a role here too, but in view of existing surplus capacity in coal-based power generation, the debate seems somewhat less crucial at the moment. The resulting savings of gas currently used for electricity generation could free up a maximum of 20% of total German gas consumption (under the simplifying assumption that the production of electricity in industry-owned power plants can also be switched to other energy sources).
3. In addition, refilling gas storage during the summer, when household heating demand is low, should close another part of the gap without affecting industrial use.

In sum, we assume conservatively that savings in gas consumption in the power sector, more gas imports from other countries, and the refilling of gas storage during the summer leave us with a situation where the remaining consumers of energy (households, industry, services) will have to cope with a reduction in aggregate gas supply of 30%. To build in a dose of caution, for our simplified model we will assume a low elasticity of substitution of 0.1 in these sectors. This is substantially lower than the observed elasticities in the literature. We do so to account for potential rigidities of adjustment of the household sector related to the so-called 'Kaskadenmodell'.

A.1.2 Relevant facts on the German economy's energy dependence for the macroeconomic analysis

1. German consumption of gas, oil and coal is about 4% of GNE. For comparison, German GNE was €3175 billion in 2020, and therefore somewhat larger than German GDP of €3097 billion (i.e. GNE was 2.5% larger than GDP).[7]
2. Total German *imports* of gas, oil and coal are about 2.5% of GNE.[8]
3. German consumption of gas only is about 1.2% of GNE@. Since all gas is imported, this is also the size of total German *imports* of gas relative to GNE.[9]
4. Table A1 summarizes the gas usage of broad economic sectors: households, industry, services, and so on. It compares this to the economic importance of these sectors in terms of employment and gross value-added. For example, industry uses 36.9% of total gas while accounting for 22.6% of total employment and 25.9% of gross value-added. In contrast, services, trade and commerce use only 12.8% of all gas but account for a much larger fraction of employment (72.8%) and gross value-added (69.7%).

TABLE A1 Gas usage and economic importance of broad sectors of German economy.

	Households	Industry	Services, trade and commerce	Electricity generation	Other
Gas usage (% of total)	30.8	36.9	12.8	12.6	6.9
Employment (% of total)		22.6	72.8	0.6	2.9
Gross value-added (%)		25.9	69.7	2.2	2.3

Notes: The source for gas usage is BDEW (2019, 2022). In the first row on gas usage, 'Other' includes heating suppliers and transportation. The source for employment and value-added is the National Accounts from Eurostat (2020), at https://ec.europa.eu/eurostat/databrowser/view/NAMA_10_A64_E_custom_2410757/default/table?lang=en and https://ec.europa.eu/eurostat/databrowser/view/NAMA_10_A64_custom_2410837/default/table?lang=en, respectively. The categories 'Industry', 'Services, trade and commerce', 'Electricity generation' and 'Other' are aggregated from the NACE classification of economic activities (see https://ec.europa.eu/eurostat/ramon/nomenclatures/index.cfm?TargetUrl=LST_NOM_DTL&StrNom=NACE_REV2&StrLanguageCode=EN) as follows. Industry is defined as manufacturing and construction. Services, trade and commerce includes: wholesale and retail trade; repair of motor vehicles and motorcycles; transportation and storage; accommodation and food service activities; information and communication; financial and insurance activities; real estate activities; professional, scientific and technical activities; administrative and support service activities; public administration and defence; compulsory social security; education, human health and social work activities; arts, entertainment and recreation; and other service activities. 'Other' is agriculture, forestry and fishing; mining and quarrying; water supply; sewerage, waste management and remediation activities; activities of households as employers; undifferentiated goods- and services-producing activities of households for own use. (All links accessed 15 June 2024.)

TABLE A2 Key statistics for hardest hit industries.

	2022 crisis (import stop)			2020 crisis (Covid-19)		
	Chemicals	Food+	Metal	Air transportation	Hospitality	Entertainment
Gross value-added (€bn)	46	47	21	7	51	43
Gross output (€bn)	137	195	104	25	104	69
Wage bill (€bn)	27	35	16	5	35	21
Employees (1000)	352	941	271	66	1894	693
Employees (% of total)	0.78	2.08	0.60	0.15	4.18	1.53
Share males (%)	74	52	88	46	47	49
Capital (€bn)	179	123	152	30	119	362
Share gas in production (%)	37	12	10			

Notes: Source for the table is Volkswirtschaftliche Gesamtrechnungen (2019) at destatis.de (accessed 28 June 2024).

5. Table A2 lists key statistics for three industries that would likely be hardest hit by an import stop: Chemicals, Food+ and Metal. These three industries make up 59% of gas usage within the industrial sector. The combined number of employees in these three industries is about 1.5 million ($352 + 941 + 271 = 1564$). For comparison, the table also lists the same statistics for the three industries that were hardest hit during the 2020 Covid-19 pandemic: Air Transportation, Hospitality and Entertainment. All of gross value-added, wages and number of employees of the industries most likely to be affected by an import stop are roughly comparable in order of magnitude to the hardest hit sectors in 2020. For example, the combined number of employees in the Air Transportation, Hospitality and Entertainment industries was about 2.6 million ($66 + 1894 + 693 = 2653$) and thus was higher than the 1.5 million in the industries likely most affected by an import stop. It is also important to note that the most affected industries were essentially completely shut down during the Covid-19 pandemic, whereas the industries most affected by an import stop would likely be able to continue operating to some extent.

A.2 Using simple economic theory to identify key parameters determining the macroeconomic effects

We now use simple economic theory to isolate two of the key determinants of the macroeconomic effects of cutting energy imports from Russia. These are (i) the importance of Russian imports of gas, oil and coal ('brown' energy) in production, and (ii) the elasticity of substitution between these energy sources and other inputs (e.g. 'green' energy).

We start by considering an extremely simple and purposely stylized setup. In this setup, we assume that Germany consumes a good Y that is produced using 'brown' energy (gas, oil and coal, i.e. the energy sources imported from Russia), denoted by E, as well as other inputs X (such as labour and capital) according to an aggregate production function

$$Y = F(E, X).$$

The goal is to assess the effect of a drop in energy supply E on Y, and to identify what features of the production function F are important for determining the size of this effect.[10] To this end, it is useful to specialize the production function further to a CES production function

$$Y = \left(\alpha^{1/\sigma} E^{(\sigma-1)/\sigma} + (1-\alpha)^{1/\sigma} X^{(\sigma-1)/\sigma}\right)^{\sigma/(\sigma-1)}, \tag{A1}$$

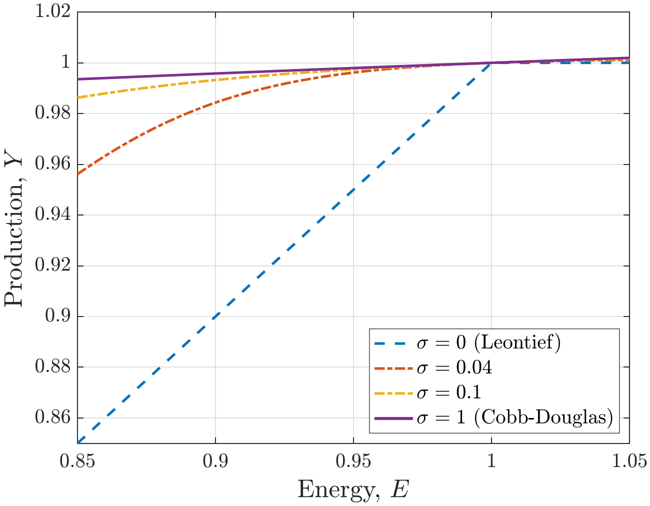


FIGURE A1 Output losses following a fall in energy supply for different elasticities of substitution.

where $\alpha > 0$ parametrizes the importance of brown energy in production, and $\sigma \in [0, \infty)$ is the elasticity of substitution between brown energy and other inputs. The setup is, of course, extremely simplistic in that it features only two factors of production and no input–output linkages. However, Lemma 2 in Subsection A.5 shows that such an analysis can be a good approximation even in a much richer environment such as the Baqaee–Farhi model.

The following special cases show that, depending on the value of σ, the macroeconomic effects of a decrease in energy supply E could be extremely different. The examples are complemented by Figure A1, which plots production Y as a function of energy E for different values of the elasticity σ for a simple calibration of the parameter α described in Subsection A.9.[11]

1. $\sigma = 1$, that is, Cobb–Douglas production $Y = E^{\alpha} X^{1-\alpha}$, so that

$$\Delta \log Y = \alpha \times \Delta \log E. \tag{A2}$$

Hence production Y declines with energy E but with an elasticity of only α. In our calibration (see Subsection A.9), we choose $\alpha = 0.04$. Therefore, for example, a drop in energy supply of $\Delta \log E = -10\%$ (also a reasonable value; again see Subsection A.9) reduces production by $\Delta \log Y = 0.04 \times 0.1 = 0.004 = 0.4\%$. The solid purple line in Figure A1 provides a graphical illustration and shows that production is quite insensitive to energy E, as expected.

2. $\sigma = 0$, that is, Leontief production $Y = \min\{E/\alpha, X/(1-\alpha)\}$. Starting from an initial optimum, a reduction in E implies that $Y = E/\alpha$, hence

$$\Delta \log Y = \Delta \log E. \tag{A3}$$

Therefore if the elasticity of substitution is exactly zero, then production Y drops one-for-one with energy supply E. This is illustrated by the dashed blue line in Figure A1, which plots production Y as a function of energy E for the Leontief case. For example, a drop in energy supply of $\Delta \log E = -10\%$ implies a drop in production of $\Delta \log Y = -10\%$. Intuitively, the Leontief assumption means that energy is an extreme bottleneck in production: when energy supply falls by 10%, the same fraction 10% of the other factors of production X lose all their value (their marginal product drops to zero), hence production Y falls by 10%.

Outside of the simple Cobb–Douglas and Leontief cases laid out above, the dependence of production Y on energy E is more complicated. However, we can simply plot the production function for different values of σ. To this end, consider the red and yellow dash-dotted lines in Figure A1, which plot the cases $\sigma = 0.04$ and $\sigma = 0.1$.[12] Unsurprisingly, the two cases lie between the cases $\sigma = 0$ and $\sigma = 1$. Somewhat more interestingly, even though both of these two elasticities $\sigma = 0.04$ and $\sigma = 0.1$ are numerically close to zero, the figure reveals that the implications for the dependence of production on energy are potentially quite different from the Leontief case with $\sigma = 0$: even the case $\sigma = 0.04$ lies considerably closer to the Cobb–Douglas case $\sigma = 1$ than the Leontief case $\sigma = 0$. We will return to this point in Subsection A.6.

One can also derive two simple second-order approximations to equation (A1).

Lemma 1. *The production function* (A1) *satisfies the approximation*

$$\Delta \log Y \approx \widetilde{\alpha} \times \Delta \log E + \frac{1}{2}\left(1 - \frac{1}{\sigma}\right)\widetilde{\alpha}(1-\widetilde{\alpha}) \times (\Delta \log E)^2, \tag{A4}$$

where

$$\widetilde{\alpha} := \frac{\alpha^{1/\sigma}\overline{E}^{(\sigma-1)/\sigma}}{\alpha^{1/\sigma}\overline{E}^{(\sigma-1)/\sigma} + (1-\alpha)^{1/\sigma}\overline{X}^{(\sigma-1)/\sigma}}.$$

Alternatively, we can write this approximation in terms of the expenditure share of energy $p_E E/(PY)$ defined in Subsection A.9 *as*

$$\Delta \log Y \approx \frac{p_E E}{PY}\,\Delta \log E + \frac{1}{2} \times \Delta\left(\frac{p_E E}{PY}\right) \times \Delta \log E, \tag{A5}$$

where we have used that the expenditure share is $p_E E/(PY) = \widetilde{\alpha}$ and that the change in the expenditure share is

$$\Delta\left(\frac{p_E E}{PY}\right) \approx \left(1 - \frac{1}{\sigma}\right)(1-\widetilde{\alpha})\,\Delta \log E.$$

Proof. See Subsection A.10. ∎

The first approximation (A4) illustrates in a transparent fashion the importance of the elasticity of substitution σ. When $\sigma = 1$, we recover the Cobb–Douglas special case in equation (A2). However, the formula also shows that with $\sigma < 1$, the losses can be considerably larger (the second term is negative, and more so the lower is σ). The second approximation (A5) says that the change in the energy expenditure share is informative about the elasticity of substitution σ and hence in turn about the output losses from a negative energy shock. An advantage of this formula over approximation (A4) is that it is likely easier to decide on what is a reasonable change in the expenditure share than what is a reasonable elasticity of substitution. This is a point to which we will return in Subsection A.6.

Besides showcasing the importance of the elasticity of substitution, these examples show that (outside of the extreme cases of zero or infinite substitutability) the parameter α also plays a key role for determining the size of economic losses (see the Cobb–Douglas special case in equation (A2)). In richer multi-sector models such as that of Subsection A.5, there is also another important determinant of macroeconomic losses, namely whether factors of production are stuck in their sectors or can reallocate across sectors. In such models, a low elasticity can be compensated for if resources can be reallocated to maintain production in the critical sector. However, in the short run, factors are likely relatively immobile, and we therefore focus on that case.

These examples show that even in an extremely simple model like the one above, depending on the value of the elasticity of substitution σ, economic losses of an embargo on Russian energy imports can be very small or large. One main implication of this result is that any macroeconomic analysis of the size of these effects is necessarily subject to a large degree of uncertainty. The reason is that the relevant elasticities of substitution are very hard to discipline empirically, especially for large changes in the economy's input mix of the type with which we are concerned.

A.3 Time dependence of the elasticity of substitution

A classic result in economic theory is that elasticities tend to be larger in the long run than in the short run. This result also applies to elasticities of substitution. Intuitively, in the very short run, production processes can be quite inflexible, that is, the elasticity of substitution is low; however, over time, production processes can adapt at least partially to the different environment without Russian energy imports, that is, the elasticity of substitution increases over time. This idea immediately implies that the size of economic losses depends crucially on the time frame over which adjustments take place, with economic losses likely being smaller in the medium and long run.

As already noted, another determinant of economic losses is how easy it is to reallocate resources across sectors. This likely also differs between the short and long run. Thus even if structural (micro) elasticities of substitution do not depend on the time horizon, more macro elasticities can depend on the time horizon (because the long-run macro elasticities also capture reallocation across sectors).

A.4 Empirical evidence on elasticities of substitution

In this subsection, we provide a summary of existing estimates on price elasticities for energy demand. Below, we also explain how to relate them to the elasticity of substitution between inputs that is the parameter of interest for our analysis.

Labandeira *et al.* (2017) provide a comprehensive overview of the existing estimates in their meta-analysis of existing elasticity estimates for energy demand with a sample of estimates starting in the 1970s. Their analysis distinguishes carefully between short-run and long-run elasticity estimates, where they consider as short run all demand changes within one year, otherwise long run. In total, their sample contains 966 short-run elasticity estimates and 1010 long-run elasticity estimates, and they report an average short-run elasticity of −0.236 and a long-run elasticity of −0.596. After dropping outliers, the respective mean (median) elasticities are −0.186 (−0.140) and −0.524 (−0.429). Hence the long-run elasticity is about three times larger than the short-run elasticity. Their meta-analysis controls for characteristics of the respective study from which the elasticity estimate is taken. For the 230 studies that consider only natural gas and controlling for the characteristics of the studies, Labandeira *et al.* (2017) find an average short-run elasticity for natural gas of −0.18, and a long-run elasticity of −0.684. For heating oil, the average short- and long-run estimates across the 44 studies are −0.017 and −0.185, respectively. For the 376 studies that consider energy in general, the estimates are similar, with a short-run elasticity of −0.221, and a long-run elasticity of −0.584. They also report differences between industrial consumers and residential consumers, but the differences between consumer groups are within 10% of the average estimates.[13]

Auffhammer and Rubin (2018) provide cleanly identified residential household demand elasticities for natural gas. They find price elasticities between −0.17 and −0.2, in line with the estimates for short-run demand elasticities in Labandeira *et al.* (2017). Notably, price elasticities have a strong seasonal component. Auffhammer and Rubin (2018) find households to be inelastic to price changes during the summer, whereas elasticities are high during the winter. These seasonal differences can be important for policy if policy wants to induce households to invest in substitution technologies during the summer, although it could be that high demand elasticities during the winter could result from household expectations of high elasticities during the winter months.

The analysis in Steinbuks (2012) focuses on energy demand elasticities in manufacturing. The study is particularly interesting as it considers in great detail also different production processes in the manufacturing production process, such as heating, cooling and electricity generation. When looking at all processes, the estimated short-run own-price demand elasticity for natural gas is −0.16, and −0.24 in the long run. For heating processes, the estimated elasticities are more than three times larger in absolute value. The estimates for all processes align with the average short-run estimates in Labandeira *et al.* (2017).

Overall, we find a range of estimates for own-price short-run elasticities of gas and energy demand that are mainly in the range from −0.15 to −0.25.

To see how the estimated own-price elasticities relate to the elasticity of substitution between inputs, denote the price of energy by p_E, and that of other inputs by p_X. It is easy to show that the CES production function (A1) implies the demand curve

$$\frac{E}{X} = \frac{\alpha}{1-\alpha}\left(\frac{p_E}{p_X}\right)^{-\sigma}.$$

Assuming that X and p_X are constant, the elasticity of substitution σ is therefore also the own-price elasticity of demand of the energy input. For example, Leontief production $\sigma = 0$ would imply a perfectly inelastic demand curve. Given this result, we can map evidence on this own-price elasticity directly into the elasticity of substitution σ.

In the macroeconomics literature, there are also some direct estimates of elasticities of substitution between clean and dirty energy; see, for example, Papageorgiou *et al.* (2017) and Jo (2021). The estimated elasticities are considerably larger (typically above 1) than the own-price elasticities that we just reviewed. In the spirit of providing pessimistic estimates, we work with the low own-price elasticities reviewed above, and additionally use values considerably below the range of empirical estimates.

A.5 The Baqaee and Farhi (2024) multi-sector open-economy model

A.5.1 Brief description of the model

We briefly describe the main features of the computational model of Baqaee and Farhi (2024). For a more detailed description, see their paper (in particular §8 and Appendix K). The Baqaee–Farhi model is a state-of-the-art multi-sector model with rich input–output linkages in which energy is a critical input in production. The model is *designed* to address questions in which production chains play a key role (the words ‘input–output linkages’, ‘production networks’ and ‘production chains’ all mean the same thing), and to think about the propagation of shocks along said production chains, that is, the ‘production cascades’ that have featured prominently in the popular debate. Put slightly differently (and with apologies for being repetitive): the model is designed to examine a shock to an upstream product (e.g. an energy input) and to make predictions about how this shock propagates downstream through the production chain.

Besides production chains, the Baqaee–Farhi model also features another important ingredient: international trade. This generates an important substitution possibility: when downstream goods become expensive to produce domestically following a stop of Russian energy imports, they can potentially be imported instead. The original application of Baqaee and Farhi (2024) was to examine gains from trades in the presence of said production chains, and one the paper’s main findings is that ‘accounting for nonlinear production networks significantly raises the gains from trade’. This fact is precisely why we chose to work with the Baqaee–Farhi model: it is known to generate large effects of trade barriers (for example, a complete import stop), in particular relative to other models in the literature.

In summary, relative to the simple model in Subsection A.2, the Baqaee–Farhi model is much richer. In particular, it adds production chains and international trade. These two ingredients have opposite effects on the size of economic losses of an import stop: on the one hand, production chains amplify the effects; but on the other hand, the ability to substitute via international trade dampens the effects. As with any model, the Baqaee–Farhi model has some limitations, which we discuss in Subsubsection A.5.5.

The model features 40 countries as well as a 'rest-of-the-world' composite country, and 30 sectors with interlinkages that are disciplined with empirical input–output matrices from the World Input–Output Database (Timmer *et al.* 2015). Each entry of the World Input–Output matrix represents a country–sector pair; for example,. we use data on the expenditure of the German 'Chemicals and Chemical Products' sector on 'Electricity, Gas and Water Supply', and how much of this expenditure goes to different countries, say how much goes to Germany itself and how much to Russia. The model features a nested CES structure. Besides the input–output matrices, the key parameters of the model are the elasticities ς, θ, γ and ε:

ς is the elasticity of substitution across consumption sectors (30 sectors),
θ is the elasticity of substitution across value-added and intermediate inputs,
γ is the elasticity of substitution across primary factors,
ε is the elasticity of substitution across intermediate input sectors.

In addition to the parametrizations used in Baqaee and Farhi (2024), we also experiment with lower values for these elasticities so as to be conservative.

A.5.2 Which metric for macroeconomic losses? GNE versus GDP

We follow Baqaee and Farhi (2024) and focus on GNE or domestic absorption as our main metric for judging macroeconomic damage to the German domestic economy. GNE is an economy's total expenditure defined as the sum of household expenditure, government expenditure and investment. That is, in the GDP accounting identity $GDP = C + I + G + (X - M)$, GNE is defined as $GNE = C + I + G$. GNE is also known as 'domestic absorption'.

The main reason for focusing on GNE is that in many macroeconomic and trade models, including the Baqaee–Farhi model, GNE has a welfare interpretation; in contrast, GDP does not. One reason is as follows: when imports of Russian energy fall, there is in principle a mechanical positive effect on $GDP = C + I + G + (X - M)$ because imports M fall; in contrast, GNE does not suffer from this problem.

We also note that in the Baqaee–Farhi model, nominal GNE is equivalent to nominal GNI, so our numbers can also be interpreted as GNI losses.

A.5.3 Theoretical results and back-of-envelope calculations

The following theoretical results show which model features and predictions are most informative about the size of GNE losses. These are: (i) the share of brown energy imports (gas, oil and coal) in German GNE, and (ii) by how much this share rises following an embargo of Russian imports. The data show that this share is small, at about 2.5% of GNE, and the model simulations in the next subsubsection imply that while this share rises considerably, it does not rise by an unreasonably large amount. This will imply that the GNE losses of an embargo on Russian energy are small. These results are new and are not featured in Baqaee and Farhi (2021).

Let W be real GNE, let b_i be the share of good i in GNE, and let c_i be the quantity of good i in GNE. Let x_{ij} be purchases by i of good j, let y_i be gross production of good i, let x_i^X be exports of good i, and let D be the set of domestic producers.

Lemma 2. *To first order,*

$$\Delta \log W = \sum_{j \notin D} \frac{p_j m_j}{GNE} \Delta \log m_j - \sum_{i \in D} \frac{p_i x_i^X}{GNE} \Delta \log x_i^X,$$

where

$$m_j = \sum_{i \in D} x_{ij} + c_j \quad \text{for } j \notin D.$$

Hence the change in domestic real GNE is the change in imports minus the change in exports. Additionally assuming that real GNE is homothetic, we can go one step further and obtain a second-order approximation:

$$\Delta \log W = \sum_{j \notin D} \frac{p_j m_j}{GNE} \Delta \log m_j - \sum_{i \in D} \frac{p_i x_i^X}{GNE} \Delta \log x_i^X + \frac{1}{2}\left[\sum_{j \notin D} \Delta \frac{p_j m_j}{GNE} \Delta \log m_j - \sum_{i \in D} \Delta \frac{p_i x_i^X}{GNE} \Delta \log x_i^X \right]. \tag{A6}$$

Proof. See Subsection A.11. ■

As we will explain in more detail below, equation (A6) in Lemma 2 is the natural generalization of the approximation (A5) for the simple model in Subsection A.2. A surprising implication of Lemma 2 is that one can approximately ignore the economy's input–output structure: the economy's input–output matrix does not make an appearance in the equations. Instead, the economy as a whole 'behaves like one large representative producer'.

It is important to note that this result does *not* mean that 'the economy's input–output structure does not matter for the macroeconomy' or the like (which would obviously defeat the purpose of working with a rich multi-sector model like the Baqaee–Farhi model to begin with); instead, the input–output structure will determine how large the changes in the expenditure shares $\Delta(p_j m_j / GNE)$ are that are important determinants of the economy's overall response to shocks like an import stop—see the second line of equation (A6). Put differently, this is a sufficient statistics result: of course input–output linkages matter, but their role is captured by how these expenditure shares respond to shocks.[14]

Now we apply Lemma 2 to cutting imports from Russia. Denote energy imports by m_E and their price by p_E. Assume that the only import that falls is energy, that is, $\Delta \log m_j = 0$ for all $j \neq E$. Also assume that other exports are not affected, $\Delta \log x_i^X = 0$.[15] Then the first-order approximation is $\Delta \log W \approx (p_E m_E / GNE)\, \Delta \log m_E$, and the second-order approximation is

$$\Delta \log W \approx \frac{p_E m_E}{GNE} \Delta \log m_E + \frac{1}{2} \Delta \frac{p_E m_E}{GNE} \Delta \log m_E. \tag{A7}$$

Note that the approximation (A7) takes exactly the same form as the approximation (A5) for the simple model in Subsection A.2. The differences are that (i) it holds in a much richer open-economy model with a complex production network, and (ii) it features the share of energy *imports* in GNE rather than total energy purchases (because the model is an open-economy model). The intuition for the second-order term is also the same: the change in the GNE share of energy imports $\Delta(p_E m_E / GNE)$ summarizes in a succinct fashion the substitutability implied by model choices about elasticities, the input–output structure, and so on.

We now conduct some simple back-of-envelope calculations to gauge the GNE losses of cutting imports from Russia. Total German imports of gas, oil and coal as a fraction of GNE were around 2.5%—see fact 2 in Subsection A.1.

Consider first an extreme case in which all energy imports from Russia are cut (all of gas, oil and coal), and Germany cannot substitute any of it (in contrast, in the main text we argued that it should be possible to substitute oil and coal). As explained in the main text, this accounts for roughly 30% of German energy imports, i.e. $\Delta \log m_E = -30\%$. The second-order approximation

TABLE A3 German GNE losses predicted by Baqaee–Farhi multi-sector model.

	Parametrization 1 (as Baqaee–Farhi)	Parametrization 2 (low elasticities)	Parametrization 3 (very low elasticities I)	Parametrization 4 (very low elasticities II)
Panel A: Parameter values				
θ	0.5	0.1	0.05	0.05
ε	0.2	0.2	0.05	0.05
ς	0.9	0.9	0.9	0.1
Panel B: German GNE loss				
Germany	0.19%	0.22%	0.26%	0.30%

also requires a prediction for the change in the energy share of GNE following the embargo $\Delta(p_E m_E/GNE)$.[16] An extreme scenario would be that this share triples from 2.5% to 7.5%, that is, $\Delta(p_E m_E/GNE) = 5\%$. Then

$$\Delta \log W \approx 2.5\% \times -30\% + \frac{1}{2} \times 5\% \times -30\% = -0.75\% - 0.75\% = -1.5\%.$$

Thus even in the case of an extreme scenario of cutting all Russian energy imports and not being able to substitute for any of them, and an extreme tripling in the share of energy imports (which reflects a very low elasticity of substitution), the GNE loss would be only 1.5%.

Next consider a case in which Germany manages to substitute for Russian oil and coal but not gas, the main scenario that we argued for in Section 2 of the main text. This corresponds to a reduction in energy imports of $\Delta \log m_E = -17\%$.[17] Now assume that the GNE share of energy imports doubles from 2.5% to 5% so that $\Delta(p_E m_E/GNE) = 2.5\%$. Then

$$\Delta \log W \approx 2.5\% \times -17\% + \frac{1}{2} \times 2.5\% \times -17\% = -0.42\% - 0.21\% = -0.63\%.$$

Thus even in a scenario where substitutability is so low that the GNE share of energy imports doubles, GNE losses are relatively modest at 0.63%. This number is of the same order of magnitude as (though somewhat higher than) the computational results in Table A3.

Finally, an important possibility is that gas is a separate input that cannot be substituted with oil and coal; see Subsection A.7 for more on this point. Total German imports of only gas as a fraction of GNE were around 1.2%, and total gas imports would likely fall by $\Delta \log m_E = -30\%$.[18] Now assume, very pessimistically, that the GNE share of gas imports triples from 1.2% to 3.6% so that $\Delta(p_E m_E/GNE) = 2.4\%$. This yields our preferred back-of-envelope calculation:

$$\Delta \log W \approx 1.2\% \times -30\% + \frac{1}{2} \times 2.4\% \times -30\% = -0.36\% - 0.36\% = 0.72\%. \tag{A8}$$

Thus even in a scenario where gas is a separate input in production, and substitutability is so low that the GNE share of gas imports triples, GNE losses are relatively modest at 0.72%. This number is again of the same order of magnitude as (though somewhat higher than) the computational results in Table A3.

A.5.4 Computational experiment

In all our computational experiments, we make choices that are designed to deliberately make the economic losses to Germany as large as possible.

We run the following experiment: the EU raises trade barriers against all imports from Russia (including energy) that are high enough to choke off of all imports from Russia into the EU. The experiment is therefore more extreme than the one that we consider in the rest of the paper for two reasons: first, all imports from Russia are choked off; second, the entire EU implements these trade barriers, not just Germany. The trade barriers take the form of iceberg costs rather than tariffs (tariffs would generate revenues). We also assume that each country has a sector-specific factor endowment that cannot move across sectors, thereby capturing that sectoral reallocation is difficult in the short run. These rigid factor markets mean, for example, that energy is produced with strong decreasing returns to scale. As already noted, these modelling choices make the numbers as big as possible.

We now turn to the parametrization of the elasticities ς, θ, γ and ε that we already discussed in Subsubsection A.5.1. The elasticity γ is irrelevant for our experiment because of our assumption that factors of production (the three types of labour and capital) are stuck in their respective sectors: γ governs how substitutable factors of production are across sectors, but since these are assumed stuck to begin with, γ does not matter. We therefore keep the value $\gamma = 0.5$ of Baqaee and Farhi (2024). In contrast, the elasticities ς and particularly θ and ε are extremely important. We therefore present computational results for four different parametrizations that differ according to the values that we choose for θ, ε and ς. Panel A of Table A3 summarizes the parameter choices. Parametrization 1 is the same as in Baqaee and Farhi (2024). Parametrizations 2–4 purposely pick lower elasticities, again in the spirit of being as conservative as possible.

Panel B of Table A3 states the main computational results, namely the losses of German GNE predicted by the model. With the Baqaee–Farhi baseline parametrization, the GNE loss is 0.19%; with the lower elasticities in parametrization 2, this number increases to 0.22%; with the even lower elasticities in parametrizations 3 and 4, GNE losses rise to 0.26% and 0.3%, respectively. In summary, even for very low elasticities of substitution (as in parametrizations 2 and 3), the Baqaee–Farhi multi-sector model predicts modest losses of around 0.2–0.3% of German GNE or around €80–120 per year per German citizen.

A.5.5 Limitations of applying the Baqaee–Farhi model to the particular question of a stop of Russian energy imports

While the Baqaee and Farhi (2024) model is a state-of-the-art multi-sector model with rich input–output linkages, we took it 'off the shelf' from an existing paper. It was therefore not 'custom built' for answering the particular policy question at hand: to assess the macroeconomic effects of a stop of energy imports from Russia on the German economy. This implies the following potential limitations, which need to be kept in mind when interpreting the GNE losses of less than 0.3% reported in column (2) of Table 2 in the main text, as well as Table A3.

1. *Gas is not a separate input.* The model features 30 sectors that are based on the classification in the World Input–Output Database (Timmer *et al.* 2015), as listed in Table 5 of Baqaee and Farhi (2024). As stated there, the model features an aggregated 'Electricity, Gas and Water Supply' rather than a separate 'Gas' sector; that is, gas is not a separate input in production. In reality, however, gas cannot be substituted with electricity and water in many production processes (e.g. in the chemicals industry). The aggregation therefore means that the GNE losses of 0.2–0.3% generated by the Baqaee–Farhi model are likely an underestimate. Consistent with this, our back-of-envelope calculation (A8), which covers precisely the case of gas as a separate and critical input in production, generates larger GNE losses of 0.72%.
   Subsection A.7 discusses this point further through the lens of our simplified model. The table with our main results, Table 2 in the main text, reports the corresponding results in column (4), labelled 'Simplified model, 30% gas ↓'.
2. *No Keynesian demand effects.* We discuss this limitation further in Subsection A.8. At the same time, a complementary analysis by Bayer *et al.* (2022) shows that even taking into account such demand effects, the overall costs would still remain below 3%.

Regarding point 1 about gas not being a separate input in the computational model, it is worth emphasizing again that the back-of-envelope calculations in Subsubsection A.5.3 are not subject to this criticism. Indeed, our preferred back-of-envelope calculation (A8) precisely covers the scenario where gas is a separate input in production. More generally, it is also worth repeating what we wrote at the beginning of Subsubsection A.5.4: within the possibilities of the 'off the shelf' Baqaee–Farhi model, we make choices that are designed to deliberately make the economic losses to Germany as large as possible. In particular, the computational exercise is fairly dramatic: it amounts to a total collapse of EU imports from Russia, not just stopping German gas imports.

A.6 Extreme scenarios with low elasticities of substitution, and why Leontief production at the macro level is nonsensical

As discussed in Subsection A.5, our simulations and back-of-envelope calculations using the Baqaee–Farhi multi-sector model imply that even for low values of elasticities of substitution, German GNE losses from an embargo of Russian energy imports would likely be modest and below 1%.

However, we have also seen in Subsection A.2 that *in principle*, these losses can be much larger: if the elasticity of substitution σ between brown energy and other inputs were literally zero (Leontief), then production would fall one-for-one with energy supply. Here, we examine some other predictions of this simple model, and use them to gauge what values of elasticities should be considered reasonable.

Our main takeaways are as follows.

1. The strict Leontief case makes nonsensical predictions with regard to the evolution of marginal products, prices and expenditure shares.
2. Models with elasticities very close to zero make similarly nonsensical predictions.
3. For a calibrated version of the simple model in Subsection A.2, a reasonable worst-case scenario may be the case $\sigma = 0.04$; that is, values of σ below 0.04 are nonsensical. An elasticity of 0.04 is also very conservative compared to the empirical evidence in Subsection A.4.
4. As we report in Subsection A.7, in this extreme case with $\sigma = 0.04$, the simple model predicts output losses following a -10% energy supply shock of 1.5%.

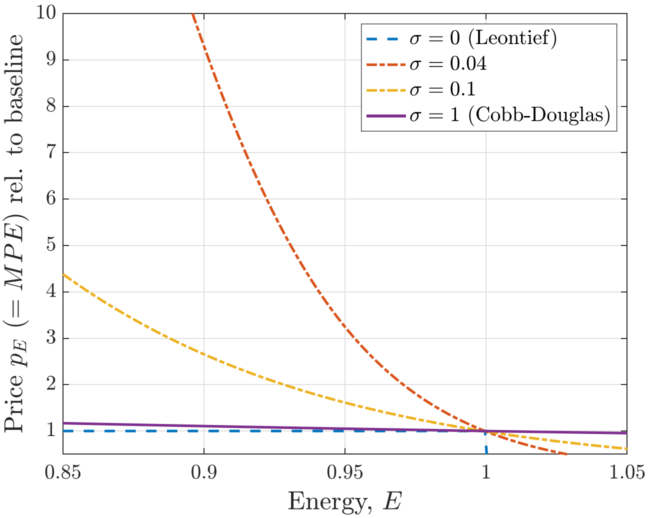
A.6.1 Leontief production $\sigma = 0$ makes nonsensical predictions

The blue dashed line in Figure A1 showed that output falls one-for-one with energy supply in the Leontief case. The blue dashed lines in Figures A2 and A3 plot additional implications of falling energy supply with Leontief production. Figure A2 shows that the marginal product of energy $\partial F(E,X)/\partial E$ jumps to $1/\alpha$, while the marginal product of other factors $\partial F(E,X)/\partial X$ falls to zero. If factor markets are competitive so that factor prices equal marginal products, then this implies that similarly the price of energy jumps to $1/\alpha$ and the prices of other factors fall to zero. Figure A3 shows that this also implies that the expenditure share on energy jumps to 100%, whereas the expenditure share on other factors falls to 0%. We consider these predictions to be economically nonsensical.

A.6.2 What values of σ are still reasonable?

This raises the question: what values of elasticities of substitution are still reasonable? To this end, Figures A2 and A3 plot the behaviour of marginal products/prices and the expenditure share for two different values of σ that are close to zero. An elasticity of $\sigma = 0.1$ (yellow dash-dotted line) implies that following a negative energy supply shock of 10%, the marginal product of energy and hence its price rise by a factor of 2.6, the marginal product/price of other factors falls by

(a) Energy price



(b) Price of other inputs

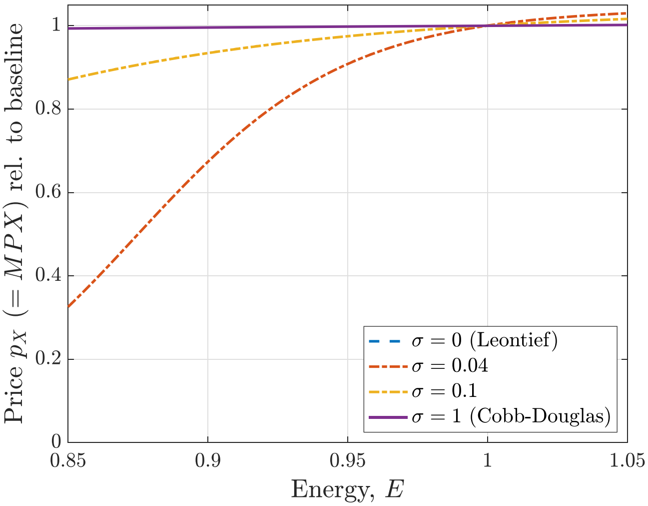


FIGURE A2 Price of energy and other inputs following a fall in energy supply for different elasticities of substitution.

roughly 7%, and the expenditure share of energy rises from 4% to 9%. While these numbers are large, they do not seem unreasonable.

Next, an elasticity of $\sigma = 0.04$ (red dash-dotted line) implies that the marginal product of energy and hence its price rise by a factor of almost 10, the marginal product/price of other factors falls by more than 30%, and the expenditure share of energy rises from 4% to 26%, an increase by a factor of 6.5. We consider these huge price and expenditure share movements 'borderline reasonable'. We therefore conclude that for a calibrated version of the simple model in Subsection A.2, a reasonable worst-case scenario may be the case $\sigma = 0.04$; lower values of σ yield nonsensical results. This value for the elasticity of substitution is also considerably below the range of empirical estimates reported in Subsection A.4.

A.7 Computational results from the simple model in Table 2

We briefly explain here how we obtain the computational results in columns (3) and (4) of Table 2 in the main text.

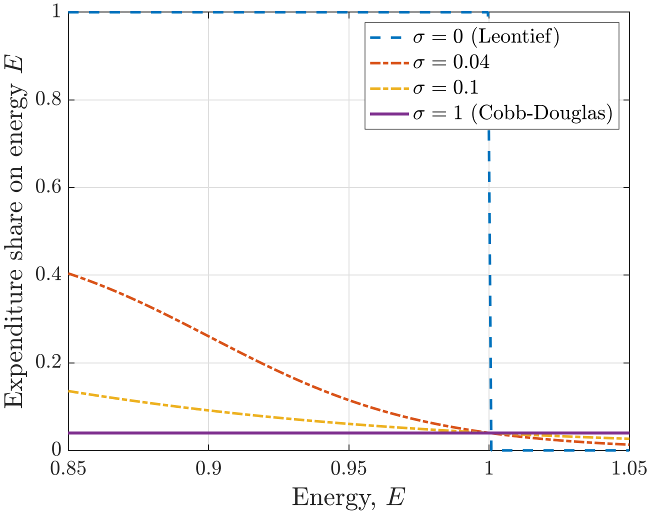


FIGURE A3 Expenditure share on energy following a fall in energy supply for different elasticities of substitution.

A.7.1 Column (3): 10% oil, gas, coal shock

Figure A1 plots the output loss for the worst-case scenario with $\sigma = 0.04$ that we just discussed in Subsubsection A.6.2. We use the calibration in Subsection A.9. For a 10% energy supply shock, the implied output loss is 1.5%, or €600 per year per German citizen. This number is substantially higher than the less than 1% or €400 losses using the sufficient statistics approach in column (1) of Table 2, or the 0.2–0.3% or €80–120 implied by the simulations from the Baqaee–Farhi model in column (2).

A.7.2 Column (4): 30% gas shock

In the computational experiment in column (3) of Table 2, we combined gas, oil and coal into an aggregate 'brown energy' input. This implicitly assumes that gas can be perfectly substituted with oil and coal, which is implausible. We therefore conduct an additional exercise in which we treat gas as a separate input that cannot be substituted with oil and coal. As explained in the main text, the resulting shock to gas supply is up to −30%. We calibrate the model as described in Subsection A.9, and use an elasticity of substitution between gas and other inputs considerably below estimates in the literature of 0.1 (e.g. Steinbuks (2010) estimates an elasticity of 0.16–0.5). As reported in column (4) of Table 2, the 30% gas shock results in GNE losses of 2.3%, or €912 per year per German citizen.

A.8 Mechanisms outside the model

A.8.1 Keynesian demand effects

The model that we use is a real model with no further business cycle amplification stemming from Keynesian demand-side effects in the presence of nominal rigidities. For example, the following mechanism is absent from the model: rising gas prices mean that households have less disposable income; they therefore spend less, so aggregate demand decreases, and this sets in motion a standard Keynesian multiplier effect. That is, because of nominal rigidities the decrease in aggregate demand is met by a decrease in aggregate supply (firm production and hiring), which results in a decrease in household labour incomes; this then means that households have less disposable income and spend less; and so on.

The reason why we abstract from such Keynesian aggregate demand effects is that they can, in principle, be undone by appropriate monetary and fiscal policy. However, it is important to stress that this appropriate policy response must not be taken for granted. Instead, it requires active intervention by the European Central Bank and the German fiscal authority. On the monetary side, a firm commitment to stable prices can soften the potential trade-off between stabilizing output and inflation. At the same time, fiscal policy needs to—and can, through insurance mechanisms such as short-term work—take care of second-round demand effects.

With regard to monetary policy, one can potentially view the energy price shocks as akin to a productivity shock. This view would then require the central bank to raise interest rates in order to stabilize inflation. Though dampening economic activity somewhat, this would also alleviate further the direct energy supply problem. Given that the shock also has the potential to increase the profit share of foreign energy importers, the shock has some elements of a shock to markups. In standard theories, these shocks are more difficult to deal with for the central bank because they raise a conflict between stabilizing output and inflation.

It is arguably unrealistic to assume that macro stabilization policy can undo such Keynesian demand effects. In this case, the resulting costs need to be added on top of the costs of 0.3–2.2% of GDP reported in Table 1 in the main text. (Note that to arrive at our headline worst-case scenario of 3% in the main text, we rounded up 2.2% so as to leave a 'safety margin'.) A complementary analysis by one of the co-authors of this paper and his collaborators (Bayer *et al.* 2022) shows that, even taking into account such demand effects, the overall costs would still remain below 3% of GDP.

A.8.2 Financial amplification effects

The model also does not include any financial amplification effects. For example, one could imagine that in the event of an import stop, firms that are heavily gas-reliant could experience short-run liquidity problems and hits to their balance sheets. This may be the case even for firms that remain viable in the long run because they are able to substitute for gas or other intermediate inputs affected by an import stop over time. In the event that such problems occur, policy should likely step in to minimize such financial amplification effects, for example by temporarily bailing out affected firms. If necessary, the government could acquire equity stakes in the affected companies (as happened in the case of Lufthansa during the Covid-19 pandemic).

A.9 Calibration of the simple CES production function in Subsection A.2

A.9.1 Calibration of α

As explained in Subsection A.7, we conduct two computational experiments using our simplest model (CES production function): a 10% energy shock in a model in which oil, gas and coal are aggregated into a common energy input, and a 30% gas shock in a model in which gas is a separate input in production. Depending on the experiment, we choose the parameter α in the CES production function (A1) so as to match the share of consumption of gas, oil and coal in German GNE, which is about 4% (see fact 1 in Subsection A.1) or just gas, which is about 1.2% (see fact 3).

The calibration proceeds as follows. Importantly, our calibration strategy ensures that the model fits the share of energy imports in German GNE for any value of the elasticity substitution σ; that is, we can vary σ while always matching this import share by construction. Cost minimization of equation (A1) implies the optimal factor demands

$$E = \frac{\alpha p_E^{-\sigma}}{\alpha p_E^{1-\sigma} + (1-\alpha) p_X^{1-\sigma}} PY, \quad X = \frac{(1-\alpha) p_X^{-\sigma}}{\alpha p_E^{1-\sigma} + (1-\alpha) p_X^{1-\sigma}} PY, \tag{A9}$$

where p_E is the price of energy, p_X is the price of the other input, and

$$P = \left(\alpha p_E^{1-\sigma} + (1-\alpha) p_X^{1-\sigma}\right)^{1/(1-\sigma)} \tag{A10}$$

is a price index. Therefore expenditure shares are

$$\frac{p_E E}{PY} = \frac{\alpha p_E^{1-\sigma}}{\alpha p_E^{1-\sigma} + (1-\alpha) p_X^{1-\sigma}}, \quad \frac{p_X X}{PY} = \frac{(1-\alpha) p_X^{1-\sigma}}{\alpha p_E^{1-\sigma} + (1-\alpha) p_X^{1-\sigma}}.$$

In the simulations below, we normalize $p_E = p_X = 1$. This implies

$$\frac{p_E E}{PY} = \alpha, \quad \frac{p_X X}{PY} = 1 - \alpha.$$

To match the GNE share of energy imports of 4% in the first experiment, we then set $\alpha = 0.04$. In particular, note that the CES specification in equation (A1) together with this calibration strategy implies that the model fits the share of energy imports in German GNE for any value of the elasticity substitution σ. Similarly, to match the GNE share of gas of 1.2%, we set $\alpha = 0.012$.

A.9.2 Calibration of σ

For the calibration of the elasticity σ, we make use of the empirical evidence in Subsection A.4, and additionally apply the reasoning in Subsubsection A.6.2. In the first experiment (10% energy shock), we use $\sigma = 0.04$. In the second experiment (30% gas shock), we use $\sigma = 0.1$. Both values lie considerably below the range of empirical estimates reviewed in Subsection A.4.

A.10 Proof of Lemma 1

The proof log-linearizes the production function (A1) around the point $(\overline{X}, \overline{E})$. Define $y = \log Y$, $e = \log E$, $x = \log X$, and $\overline{z}$ for any variable z as its value at the point of approximation. Taking logs, the production function (A1) can be rewritten as

$$y \equiv \log Y = \frac{\sigma}{\sigma - 1} \log\left(\alpha^{1/\sigma} (\exp(e))^{(\sigma-1)/\sigma} + (1-\alpha)^{1/\sigma} (\exp(x))^{(\sigma-1)/\sigma}\right) \equiv f(e, x).$$

The second-order Taylor approximation of the production function with respect to e around $(\overline{x}, \overline{e})$ is

$$y \approx \overline{y} + \frac{\partial}{\partial e} f(e,x)|_{e=\overline{e}, x=\overline{x}} \, (e - \overline{e}) + \frac{1}{2} \frac{\partial^2}{\partial e^2} f(e,x)|_{e=\overline{e}, x=\overline{x}} \, (e - \overline{e})^2.$$

The first-order derivative of $f(e, x)$ with respect to e is

$$\frac{\partial}{\partial e} f(e,x) = \frac{\partial}{\partial e} \frac{\sigma}{\sigma - 1} \log\left(\underbrace{\alpha^{1/\sigma} (\exp(e))^{(\sigma-1)/\sigma} + (1-\alpha)^{1/\sigma} (\exp(x))^{(\sigma-1)/\sigma}}_{g(e,x)} \right),$$

where we denote the argument of the log as $g(e, x)$ to simplify the notation for the rest of the proof. Hence

$$\frac{\partial}{\partial e} f(e,x) = \frac{\sigma}{\sigma - 1} \frac{\partial g(e,x)/\partial e}{g(e,x)} = \frac{\alpha^{1/\sigma} (\exp(e))^{(\sigma-1)/\sigma}}{\alpha^{1/\sigma} (\exp(e))^{(\sigma-1)/\sigma} + (1-\alpha)^{1/\sigma} (\exp(x))^{(\sigma-1)/\sigma}}.$$

Evaluating at $(\overline{x}, \overline{e})$, we have

$$\begin{aligned}\frac{\partial}{\partial e} f(e,x)|_{e=\overline{e},x=\overline{x}} &= \frac{\alpha^{1/\sigma}\big(\exp(\overline{e})\big)^{(\sigma-1)/\sigma}}{\alpha^{1/\sigma}\big(\exp(\overline{e})\big)^{(\sigma-1)/\sigma} + (1-\alpha)^{1/\sigma}\big(\exp(\overline{x})\big)^{(\sigma-1)/\sigma}} \\ &= \frac{\alpha^{1/\sigma}\overline{E}^{(\sigma-1)/\sigma}}{\alpha^{1/\sigma}\overline{E}^{(\sigma-1)/\sigma} + (1-\alpha)^{1/\sigma}\overline{X}^{(\sigma-1)/\sigma}} := \widetilde{\alpha},\end{aligned}$$

which defines $\widetilde{\alpha}$ in the lemma. The second derivative with respect to e is

$$\frac{\partial^2}{\partial e^2} f(e,x) = \frac{\sigma-1}{\sigma}\, \alpha^{1/\sigma}(\exp(e))^{(\sigma-1)/\sigma}\, \frac{g(e,x) - \alpha^{1/\sigma}(\exp(e))^{(\sigma-1)/\sigma}}{g(e,x)^2}.$$

Evaluating at $(\overline{x}, \overline{e})$, we have

$$\frac{\partial^2}{\partial e^2} f(e,x) = \left(1 - \frac{1}{\sigma}\right)\alpha^{1/\sigma}\big(\exp(\overline{e})\big)^{(\sigma-1)/\sigma}\left[\overline{Y}^{-(\sigma-1)/\sigma} - \alpha^{1/\sigma}(\exp(e))^{(\sigma-1)/\sigma}\overline{Y}^{-2(\sigma-1)/\sigma}\right],$$

where we have used the fact that $g(e,x) = Y^{(\sigma-1)/\sigma}$.

We next manipulate this expression so that $\widetilde{\alpha}$ appears:

$$\begin{aligned}\frac{\partial^2}{\partial e^2} f(e,x)|_{e=\overline{e},x=\overline{x}} &= \left(1 - \frac{1}{\sigma}\right)\alpha^{1/\sigma}\big(\exp(\overline{e})\big)^{(\sigma-1)/\sigma} \\ &\quad \times \left[\overline{Y}^{-(\sigma-1)/\sigma} - \overline{Y}^{-(\sigma-1)/\sigma}\, \underbrace{\alpha^{1/\sigma}(\exp(e))^{(\sigma-1)/\sigma}\overline{Y}^{-(\sigma-1)/\sigma}}_{\widetilde{\alpha}}\right] \\ &= \left(1 - \frac{1}{\sigma}\right)\alpha^{1/\sigma}\big(\exp(\overline{e})\big)^{(\sigma-1)/\sigma}\overline{Y}^{-(\sigma-1)/\sigma}[1-\widetilde{\alpha}] \\ &= \left(1 - \frac{1}{\sigma}\right)\widetilde{\alpha}[1-\widetilde{\alpha}].\end{aligned}$$

Replacing both derivatives in the Taylor expansion yields

$$y \approx \overline{y} + \widetilde{\alpha}(e - \overline{e}) + \frac{1}{2}\left(1 - \frac{1}{\sigma}\right)\widetilde{\alpha}[1-\widetilde{\alpha}](e-\overline{e})^2.$$

Since we had $z = \log Z$ for any variable Z, we have

$$\Delta \log Y = \widetilde{\alpha}\ \Delta \log E + \frac{1}{2}\left(1 - \frac{1}{\sigma}\right)\widetilde{\alpha}[1-\widetilde{\alpha}](\Delta \log E)^2,$$

which is equation (A4). This concludes the first part of the proof.

In order to derive the second approximation (A5), we first show that $\widetilde{\alpha}$ equals the energy expenditure share, namely,

$$\widetilde{\alpha} = \frac{\alpha^{1/\sigma}E^{(\sigma-1)/\sigma}}{Y^{(\sigma-1)/\sigma}} = \alpha^{1/\sigma}\left(\frac{E}{Y}\right)^{(\sigma-1)/\sigma} = \frac{P_E E}{PY}. \tag{A11}$$

Using equation (A9), we have

$$\frac{E}{Y} = \frac{\alpha P_E^{-\sigma}}{\alpha P_E^{1-\sigma} + (1-\alpha)P_X^{1-\sigma}}\, P.$$

Using the definition of the price index P in equation (A10), we have

$$\frac{\alpha^{1/\sigma}E^{(\sigma-1)/\sigma}}{Y^{(\sigma-1)/\sigma}}=\frac{\alpha P_E^{1-\sigma}}{\alpha P_E^{1-\sigma}+(1-\alpha)P_X^{1-\sigma}},$$

which is the expenditure share formula in Subsection A.9. This proves equation (A11), that $\widetilde{\alpha}$ equals the energy expenditure share $P_E E/(PY)$.

Next, the change in this expenditure share is given by

$$\begin{aligned}\Delta\log\left(\frac{P_E E}{PY}\right)&=\Delta\log\left(\frac{\alpha^{1/\sigma}E^{(\sigma-1)/\sigma}}{Y^{(\sigma-1)/\sigma}}\right)\\&=\frac{\sigma-1}{\sigma}\,\Delta\log E-\frac{\sigma-1}{\sigma}\,\widetilde{\alpha}\,\Delta\log E\\&=\left(1-\frac{1}{\sigma}\right)(1-\widetilde{\alpha})\,\Delta\log E,\end{aligned}$$

or using that

$$\Delta\log\left(\frac{P_E E}{PY}\right)=\left(\frac{P_E E}{PY}\right)^{-1}\Delta\left(\frac{P_E E}{PY}\right)=\widetilde{\alpha}^{-1}\,\Delta\left(\frac{P_E E}{PY}\right),$$

we have

$$\Delta\left(\frac{P_E E}{PY}\right)=\widetilde{\alpha}\,\Delta\log\left(\frac{P_E E}{PY}\right)=\left(1-\frac{1}{\sigma}\right)\widetilde{\alpha}(1-\widetilde{\alpha})\,\Delta\log E.$$

Plugging these into equation (A4), we have

$$\begin{aligned}\Delta\log Y&\approx\widetilde{\alpha}\times\Delta\log E+\frac{1}{2}\left(1-\frac{1}{\sigma}\right)\widetilde{\alpha}(1-\widetilde{\alpha})\times(\Delta\log E)^2\\&=\frac{P_E E}{PY}\,\Delta\log E+\frac{1}{2}\times\Delta\left(\frac{P_E E}{PY}\right)\times\Delta\log E,\end{aligned}$$

which is equation (A5).

A.11 Proof of Lemma 2

This proof uses the notation of Baqaee and Farhi (2021) and Subsection A.5, which we briefly recap for the reader's convenience:

W is real GNE,
b_i is the share of good i in GNE,
c_i is quantity of good i in GNE,
x_{ij} is purchases by i of good j,
y_i is gross production of good i,
x_i^X is exports of good i,
D is the set of domestic producers.

With this notation, we have that the change in real GNE satisfies

$$\mathrm{d}\log W=\sum_i b_i\,\mathrm{d}\log c_i.$$

Production of good i is either used for consumption c_i, as an intermediate in domestic production x_{ji} ($j \in D$), or exported x_i^X (i.e. good i is purchased by either domestic or foreign customers):

$$y_i = c_i + \sum_{j \in D} x_{ji} + x_i^E.$$

Therefore

$$\mathrm{d}\log c_i = \frac{p_i y_i}{p_i c_i}\,\mathrm{d}\log y_i - \sum_j \frac{p_i x_{ji}}{p_i c_i}\,\mathrm{d}\log x_{ji} - \frac{p_i x_i^X}{p_i c_i}\,\mathrm{d}\log x_i^X,$$

where, for example, $(p_i y_i)/(p_i c_i)$ is nominal production of good i divided by nominal consumption of the same good. Finally, production of good i satisfies

$$\mathrm{d}\log y_i = \sum_{j \in D} \frac{p_j x_{ij}}{p_i y_i}\,\mathrm{d}\log x_{ij} + \sum_{j \notin D} \frac{p_j x_{ij}}{p_i y_i}\,\mathrm{d}\log x_{ij},$$

where $(p_j x_{ij})/(p_i y_i)$ is the share of good i that is used by firm j, which is either domestic ($j \in D$) or foreign ($j \notin D$).

Using these relationships, we have

$$\begin{aligned}
\mathrm{d}\log W &= \sum_{i \in D} \frac{p_i c_i}{GNE}\left[\frac{p_i y_i}{p_i c_i}\,\mathrm{d}\log y_i - \sum_{j \in D} \frac{p_i x_{ji}}{p_i c_i}\,\mathrm{d}\log x_{ji} - \frac{p_i x_i^X}{p_i c_i}\,\mathrm{d}\log x_i^X\right] \\
&\quad + \sum_{i \notin D} \frac{p_i c_i}{GNE}\,\mathrm{d}\log c_i \\
&= \sum_i \left[\frac{p_i y_i}{GNE}\,\mathrm{d}\log y_i - \sum_{j \in D} \frac{p_i y_i}{GNE}\,\frac{p_i x_{ji}}{p_i y_i}\,\mathrm{d}\log x_{ji} - \frac{p_i y_i}{GNE}\,\frac{p_i x_i^X}{p_i y_i}\,\mathrm{d}\log x_i^X\right] \\
&\quad + \sum_{i \notin D} \frac{p_i c_i}{GNE}\,\mathrm{d}\log c_i \\
&= \left[\sum_{i \in D}\sum_{j \in D} \frac{p_i y_i}{GNE}\,\frac{p_j x_{ij}}{p_i y_i}\,\mathrm{d}\log x_{ij} + \sum_{i \in D}\sum_{j \notin D} \frac{p_i y_i}{GNE}\,\frac{p_j x_{ij}}{p_i y_i}\,\mathrm{d}\log x_{ij}\right] \\
&\quad - \sum_{i \in D}\sum_{j \in D} \frac{p_i y_i}{GNE}\,\frac{p_i x_{ji}}{p_i y_i}\,\mathrm{d}\log x_{ji} - \sum_{i \in D} \frac{p_i y_i}{GNE}\,\frac{p_i x_i^X}{p_i y_i}\,\mathrm{d}\log x_i^X + \sum_{i \notin D} \frac{p_i c_i}{GNE}\,\mathrm{d}\log c_i \\
&= \sum_{i \in D}\sum_{j \notin D} \frac{p_i y_i}{GNE}\,\frac{p_j x_{ji}}{p_i y_i}\,\mathrm{d}\log x_{ij} - \sum_{i \in D} \frac{p_i y_i}{GNE}\,\frac{p_i x_i^X}{p_i y_i}\,\mathrm{d}\log x_i^X + \sum_{i \notin D} \frac{p_i c_i}{GNE}\,\mathrm{d}\log c_i \\
&= \sum_{j \notin D} \frac{p_j}{GNE}\,\mathrm{d}\left(\sum_{i \in D} x_{ij}\right) - \sum_{i \in D} \frac{p_i x_i^X}{GNE}\,\mathrm{d}\log x_i^X + \sum_{i \notin D} \frac{p_i c_i}{GNE}\,\mathrm{d}\log c_i \\
&= \sum_{j \notin D} \frac{p_j}{GNE}\,\mathrm{d}\left(\sum_{i \in D} x_{ij} + c_j\right) - \sum_{i \in D} \frac{p_i x_i^X}{GNE}\,\mathrm{d}\log x_i^X \\
&= \sum_{j \notin D} \frac{p_j m_j}{GNE}\,\mathrm{d}\log m_j - \sum_{i \in D} \frac{p_i x_i^X}{GNE}\,\mathrm{d}\log x_i^X,
\end{aligned}$$

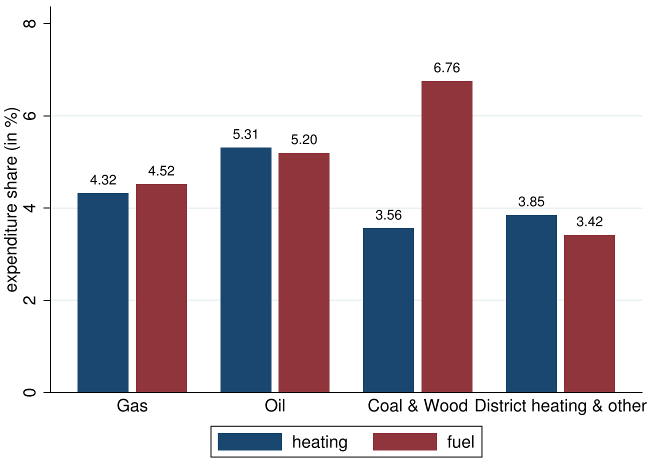
where

$$m_j = \sum_{i \in D} x_{ij} + c_j \quad \text{for } j \notin D.$$

A.12 Distributional effects

Fiscal insurance elements would be particularly important if, beyond their macroeconomic consequences, increased fuel and gas prices are redistributive. If, for example, the poorest households were overly exposed to such price changes, then this might be of independent concern. To explore the distributional consequences of a rise in energy prices, we take data from the German Income and Consumption Survey (Einkommens- und Verbrauchsstichprobe, EVS). We focus predominantly on expenditure for heating as gas prices have risen most strongly during 2021 (almost a tenfold increase). Nevertheless, price increases for oil and hard coal of course add to the overall additional burden on households, especially in the cases of gasoline, diesel and electricity. The EVS data provide representative data for the German population on their consumption and

(a) By heating source



(b) By income

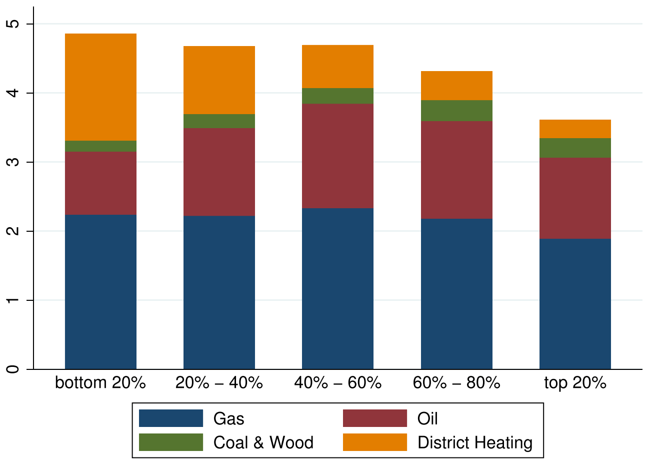
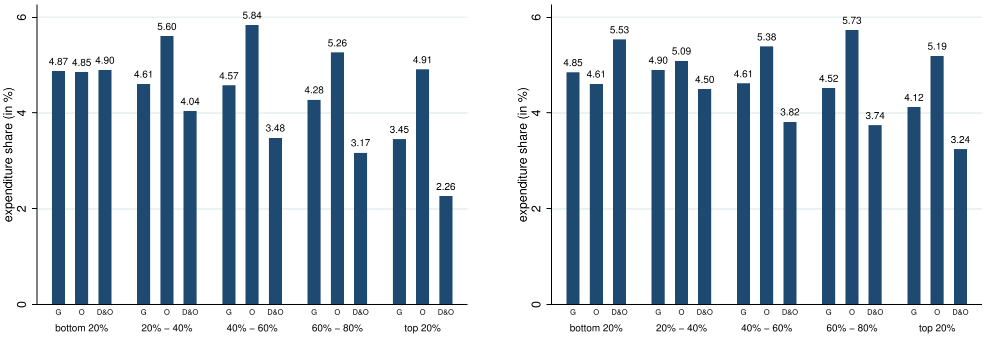


FIGURE A4 Energy expenditure shares. *Notes*: (a) Expenditure shares for all households by type of energy for heating (blue bars) and for fuel (red bars). (b) Energy expenditure shares for different heating sources along the income distribution.

(a) All households

(b) One-person households



(c) Two-person households

(d) Three or more person households

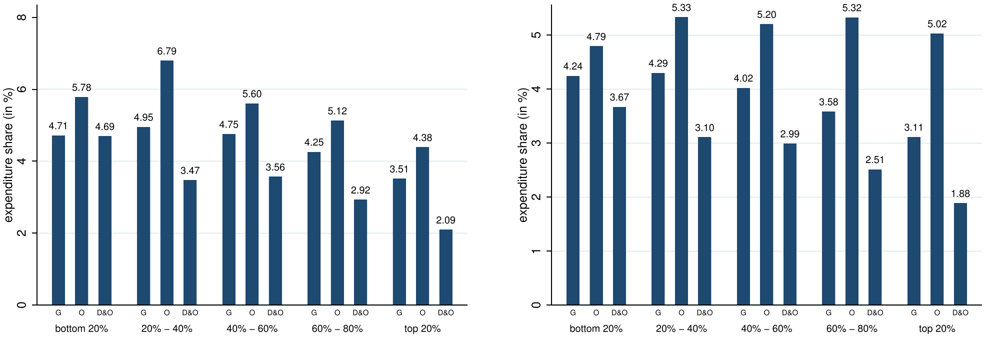


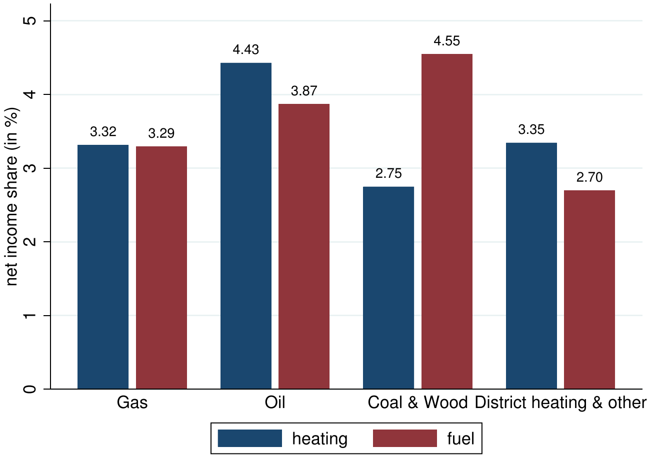
FIGURE A5 Heating expenditure shares by income, heating source and household size. *Notes*: Heating expenditure shares for households along the income distribution and by source of heating: (a) all households; (b) one-person households; (c) two-person households; (d) households with three or more members. Income deciles are computed separately for each household group. Heating sources are labelled ‘G’ for gas, ‘O’ for oil, and ‘D&O’ for district and other.

income. As the source of the German CPI consumption basket, the data provide a high granularity on the expenditure composition of households, including data on expenditures on different energy sources. We rely on the latest available microdata from the Research Data Center of the German Statistical Office. For our analysis, we group households by income, type of heating, and household size. For income, we use data on net household income, and group households into income quintiles.

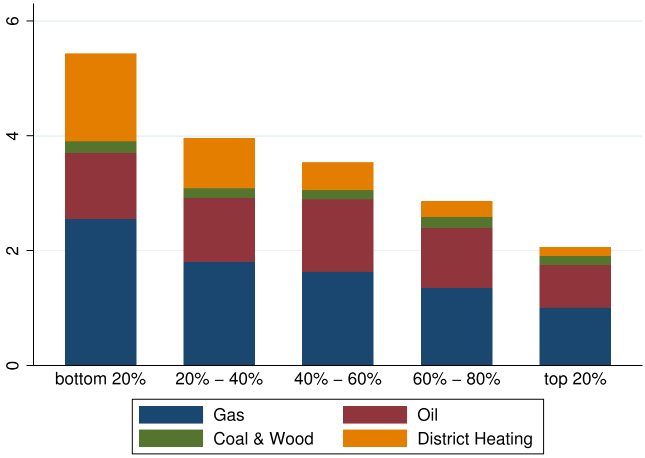
Figure A4(a) shows the expenditure shares depending on the main source of heating, for both heating and car fuel, and Figure A4(b) shows the expenditure shares by income quintiles. We find that typically, households spend between 3% and 6% on heating. Similar expenditure shares apply to car fuel, varying between 3.4% and 6.8%. If we consider only gas and oil as by far the two most important heating sources, then the heating expenditures are 4.3% and 5.3%, and car fuel varies between 4.5% and 5.2% as well. Gas is the most important source for heating energy, and oil comes in second. One exception is the bottom 20% of the income distribution, where district heating is the second most important expenditure category; see Figure A4(b). What is striking is the fact that the income gradient in the expenditure share for heating is small. Potentially, differences in household size might be a confounding factor here. Therefore, Figure A5 splits up the data further, and distinguishes not only along the income distribution but also along the main type of heating and household size. Figure A5(a) first looks at all households independent of household size. We find again that expenditure shares for oil are the highest, and vary only

FIGURE A6 Energy expenditure as share of household net income. *Notes*: (a) Expenditure as a share of household net income for all households by type of energy for heating (blue bars) and for fuel (red bars). (b) Cost shares as a fraction of household net income for different heating sources along the income distribution.

(a) By heating source



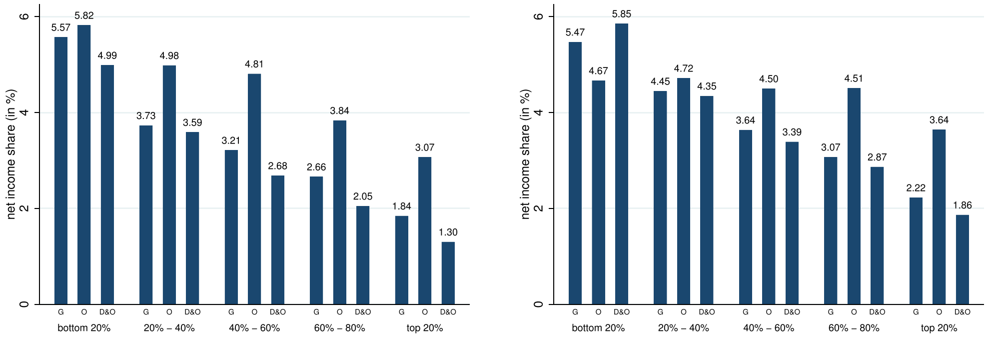
(b) By income



a little along the income distribution. Costs for gas are second, and decline slightly up to the fourth quintile, and decline by about 1 percentage point between the fourth and fifth quintiles. District and other heating shows the lowest expenditure share throughout, and also shows a strongly declining trend along the income distribution from 4.9% in the bottom 20% to 2.3% in the top 20%. Figures A5(b) to A5(d) offer a further breakdown by household size. The overall pattern is robust: there is relatively little variation in the expenditure share on heating across the income distribution. One exception is households with three or more members. They have lower expenditure shares in general, and the decline of expenditure shares from 3.7% to 1.9% in income is the strongest.

Along the income distribution and depending on household size, there are some differences in expenditure shares. High-income households and families have slightly lower expenditure shares. We also find that compared with oil heating, households that rely on gas heating have on average lower expenditure shares, so a stronger increase in the gas price than in the oil price might lead to an equalization in expenditure shares between these two largest household groups, albeit at a higher level. High-income households can absorb expenditure shocks from rising energy prices better than low-income ones, as the former can reduce savings (or use accumulated wealth)

(a) All households (b) One-person households



(c) Two-person households (d) Three or more person households

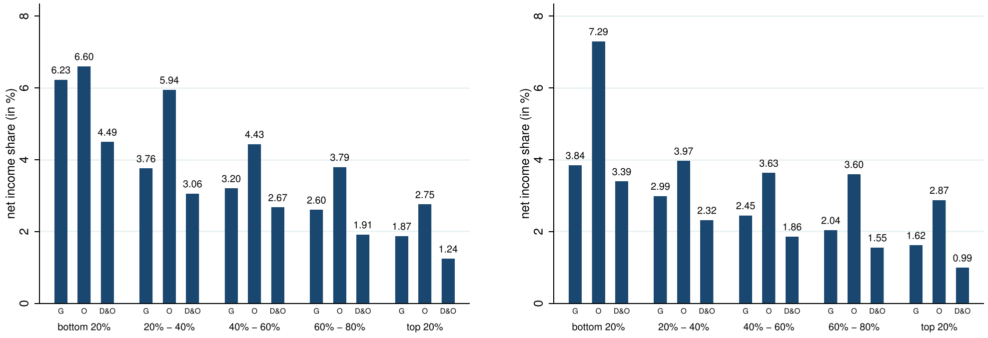


FIGURE A7 Heating expenditures as share of household net income, by income, heating source and household size. *Notes*: Heating expenditures as shares of household net income for households along the income distribution and by source of heating: (a) all households; (b) one-person households; (c) two-person households; (d) households with three or more members. Income deciles are computed separately for each household group. Heating sources are labelled ‘G’ for gas, ‘O’ for oil, and ‘D&O’ for district and other.

to smooth out transitory cost increases. Targeted transfers to low-income households can be a cost-efficient way to compensate for an unequal impact of rising energy prices along the income distribution. As inflation was very high in 2022, and rising energy prices will further contribute to rising price levels, it seems necessary to adjust the nominal values of certain parameters of the tax and transfer system should the European Central Bank not manage to stabilize the overall inflation rate by inducing offsetting price decreases elsewhere.

Thus far, we have focused on the share of energy expenditures in total household expenditures as this is directly related to purchasing power of households and welfare. If energy prices increase, then households will be able to buy fewer goods and services with the same amount of income. An alternative is to look at the share of energy expenditures in total household income. The difference between the share in household expenditures and the share in household income is the saving rate of households. It is well known that high-income households have higher saving rates (Dynan *et al.* 2004). Hence we expect that the level of household expenditures as a fraction of income declines with income because income exceeds expenditures for most households, while differences in expenditure shares of households increase because of different saving rates along the income distribution. Figure A6 presents results equivalent to those in Figure A4, but as a fraction of household net income rather than household expenditures. The main difference is that now because of higher saving rates with higher incomes, the energy expenditure share as a share of income declines along the income distribution, but it is also substantially lower.

The typical household in Germany (median household in income group 40%–60%) spends only between 3% and 4% of net income on energy, and gas expenditures are even below 2% of household net income.

Figure A7 repeats the results from Figure A5, but showing heating expenditures as a share of household net income rather than total household expenditures. The same conclusions as for the comparison between Figures A4 and A6 apply: we find shares in income to be lower, and we find a noticeable decline of the expenditure shares with income.

APPENDIX B. REAL-WORLD EXAMPLES OF SUBSTITUTION IN PRODUCTION AND IN THE MACROECONOMY

This appendix discusses in more detail the economic idea of substitution.[19] Subsection B.1 provides some historical real-world examples that demonstrate how firms do find ways to substitute in adversity (perhaps unexpectedly even for themselves). Subsection B.2 makes some additional general observations on substitution in the macroeconomy, in particular that a commonly held micro 'engineering view' of substitution is too narrow and misses important mechanisms through which the macroeconomy would adapt to an import stop.

B.1 Real-world examples of substitution in production

B.1.1 Sudden stop of Argentinian gas supply to Chile (2007)

In the early 2000s, Chile transformed itself from a coal- and diesel-centred economy to one making heavy use of pipeline-based natural gas, a fairly cheap fossil energy source with a lighter environmental footprint intended as a bridging source while transitioning towards a green economy. With few developed domestic sources of natural gas that yielded some constant 2 billion cubic metres (bcm) per year from its Magallanes fields, Chile had to look for imports from abroad. Due to historical border disputes, Argentina was the only neighbouring country willing to sign a supply deal. In 1995, an agreement between both countries laid the foundation for the energy transformation that led to a marked increase of Chilean natural gas usage from under 1.9 bcm in 1995 to 8.6 bcm in 2004. The latter year was the point where domestic supply shortfalls in Argentina started to emerge, commonly attributed to price capping policy by the Argentinian government. As a result, exports to Chile began to be limited in 2004, with a sudden stop in 2007 that cut down supplies by over 90% of the agreed volume.

Germany is sometimes said to have been in an extraordinarily tough situation in the first months of 2022 with its import dependence on Russia, high energy prices in general (particularly for oil), and further specific logistical challenges. Chile found itself to be in a similarly dire, if not even more precarious situation in 2007. It was almost completely dependent on Argentina as its only foreign supplier (75% in 2004); droughts emptied the country's water reservoirs, decreasing availability of hydro power; oil prices were on an increasing path towards a peak of \$140 per barrel (in May 2022: ca. \$105 per barrel for Brent); and it was the onset of the Global Financial Crisis, decreasing budgetary leeway for both households and government. Unlike Germany today, Chile could not rely on neighbouring countries with LNG terminals, could not switch to alternative electricity generation via coal quickly, and could not fall back on an integrated grid such as the EU electricity infrastructure, to mitigate the impact.

The Chilean government reacted in three ways: (i) the accelerated substitution of its Argentinian imports by fast-tracking the construction of LNG terminals in order to source imports worldwide; (ii) launching a nationwide energy-saving campaign, inducing a decrease in electricity usage by 10%;[20] and (iii) refraining from price-distorting measures such as capping prices or subsiding energy costs, while providing lump sum transfers to poor households. The economic damage resulting from the Argentinian supply stop is estimated at 0.5 percentage points of GDP by the Chilean Central Bank, with policymakers giving a conservative upper bound of 1 percentage point.

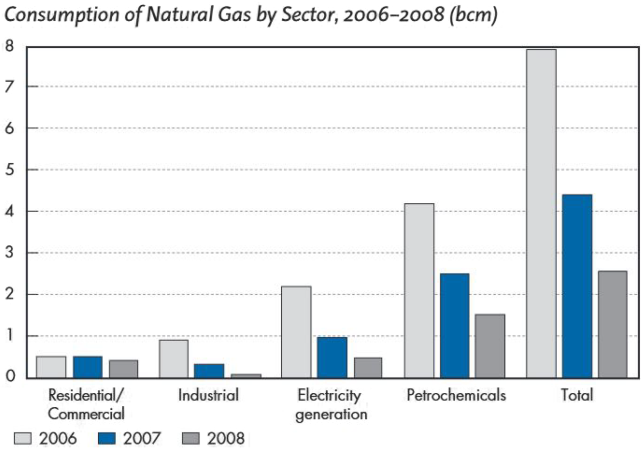


FIGURE A8 Consumption of natural gas by sector in Chile. *Notes*: Figure from the 2009 IEA report on Chile; underlying data from the Comisión Nacional de Energía (CNE Chile).

Figure A8 shows how consumption of natural gas changed by sector. The petrochemical industry had the largest consumption share pre-crisis in 2006, with a larger share (> 50%) than currently in Germany (< 40% for total industry). Residential consumption did not see any decrease at all, consistent with a government decree affording them priority usage, as is envisioned in German[21] emergency rationing plans.[22]

B.1.2 Rare earth embargo against Japan (2010)

In 2010 China effectively implemented an export embargo on rare earths against Japan. Superficially, this resembled a textbook example of effective sanctions: China was virtually the sole supplier of rare earths, while these were an important input for Japanese industry.[23] As noted by Gholz and Hughes (2021), in the short run, Japanese firms reduced demand at both the intensive and extensive margins: firms that crucially needed rare earths in their input came up with ways to use raw material more effectively, thus pushing the technology frontier outwards. For example, glass manufacturing companies started recycling cerium polish, which requires the eponymous rare earth mineral. Other firms such as headphone manufacturers that previously bought rare earths due to their low cost—rather than due to them being critical for the production process—substituted away completely. In the medium to long term, Japanese firms are working on technological innovations that also either reduce usage of rare earths or enable substitution with different materials. Reductions on the consumer side, such as post-consumption recycling, appear to play a lesser role due to practical difficulties. On the supply side, it took two years until alternative producers entered the market, even though investments for these projects had started long prior to the embargo. The Japanese government subsequently supported one of the firms via a long-term supply contract, which ensured its survival amidst price fluctuations in the years after the embargo subsided.

B.1.3 Shutdown of the Druzhba Pipeline due to contamination

The Druzhba Pipeline is one of the main oil networks in Europe, connecting oil fields in the Russian Tatarstan region with Poland and Eastern Germany (northern branch) as well as Slovakia, the Czech Republic and Hungary (southern branch). For Germany, the Druzhba Pipeline transports around one-third of total oil imports, and in particular supplies entire refineries in Eastern Germany. In 2019, it was discovered that oil pumped through Druzhba was contaminated with substances that damage petrochemical processing equipment through corrosion. As a result, pipeline operations were completely shut down for a few weeks.

The refineries that depend on Druzhba (in particular the Leuna and Schwedt refineries) quickly substituted its services with importing oil via ship to harbour terminals in Gdansk and

FIGURE A9 Car in Berlin, 1946.
Notes: See the 'boiler' and the pipe that funnels the extracted wood gas into the internal combustion engine.

Rostock, which enabled all refineries to continue operating, although not necessarily at normal capacity. In the case of an oil embargo, as in the beginning of 2022, the oil would have to come via ship, but not from Russia as in 2019, and it would need to be of a quality similar to the Russian blend. The 2019 experience thus provides some reason for optimism that German refineries could continue operating even in the case of an oil import stop.[24]

B.1.4 Shortages during the Second World War

During big wars, countries must often react to strong, unanticipated shocks to both demand and supply. Ilzetzki (2022) shows that for the massive increase in US government procurement of combat aircraft during the Second World War, this pressure made firms operate more productively, for example by adopting previously rejected methods such as moving assembly lines, or implementing measures to reduce employee absenteeism. Interestingly, in 1942, civilian economists and industry representatives argued that military planners' war production goal of producing a total of 50,000 aircraft throughout the entire war was 'impossible' to achieve.[25] But as Ilzetzki (2022) points out, within a short time frame, the US aircraft industry ended up surpassing production goals by a wide margin, with almost 100,000 planes produced in just a single year, the year 1944.

As an example for supply shocks during the Second World War, Germany faced a major petrol crisis as it was cut off from main suppliers such as the USA or the USSR. Prioritizing the highly volume-efficient petrol for military purposes, many civilian vehicles were fitted with a simple device that burned wood into gas, which subsequently was funnelled into its (mostly unmodified) internal combustion engine; see Figure A9. By the end of the war, up to 500,000 civilian vehicles are estimated to have been running on wood (compared to 600,000 military vehicles used during the initial attack on the Soviet Union).[26]

B.1.5 Ball-bearings production in the Second World War

During the Second World War, ball-bearings were a crucial component in tanks, aeroplanes, machine guns, heavy artillery and submarines. With the goal of stopping Germany's war machine, the USA bombed Schweinfurt, a small town in Germany where about 50% of the German production of ball-bearings took place. Reports point to a 34%–38% decrease in production of ball-bearings in September 1943 (compared with production pre-attacks), after the first bombings in August of the same year. However, the machinery was not as damaged as the factory structures, so it was possible to spread production across other regions of Germany, and there were some available stocks which, combined with imports from Sweden, minimized the impact of the attacks. Moreover, war equipment was redesigned to substitute with other types of bearings when needed. Reports at the time point to no effect on essential war production due to the bombings.[27]

B.1.6 German U-boat campaign against Britain during the First World War

Since the beginning of the First World War, Germany conducted U-boat (submarine) campaigns with the goal of preventing merchant ships from arriving in Britain. In an attempt to disrupt Britain's food supplies and force Britain to surrender before the possible entry of the USA into the war, Germany launched an unrestricted U-boat campaign in 1917. This blockade was very close to being successful, with Britain's wheat stock falling sharply. However, Britain was able to survive. This success was the result of careful management, mandatory government-enforced rationing, the increase of internal production (possible by dedicating more land to agriculture), and the prioritization of wheat cargo. Moreover, with the help of the USA, Britain was able to minimize the consequences of the unrestricted U-boat campaign (1917–18): through changed routes, merchant ships would arrive in groups protected by warships, which made U-boat attacks difficult.

Nonetheless, with the pressure to increase internal agricultural production, Britain needed to find a way around the smaller number of available horses and mechanical tools. To overcome these problems, the government initiated a tractor scheme, importing tractors from the USA and also buying internally produced tractors. Additionally, with men being drafted to the war, the labour force decreased and many of those trained to work in agriculture were no longer available. This led to an increase in women's participation in the agriculture labour force, facilitated by available training to work in farms.[28]

B.1.7 Face masks during the Covid-19 pandemic

During the initial months of the Covid-19 pandemic, there was a global shortage of face masks. People quickly substituted to using cloth masks in non-clinical settings, while some companies that did not previously produce medical protection adjusted their production process towards producing masks or face shields.

B.1.8 Global microchip shortage, 2020–present

The automotive industry is an important user of integrated circuits, also known as 'microchips', using about 15% of global production. In modern vehicles, these chips are used in an ever broader range of functions: they control when to inflate airbags, manage transmission or the engine status, and intervene as part of extensive sensor systems if drivers lose control. Even mundane functionalities like controlling the air conditioning require microchips. Recent car models also feature sophisticated infotainment and assisted driving systems, all based on integrated circuit components.

During the Covid-19 pandemic, both production and sales of vehicles dropped considerably. Car manufacturers hence slashed orders for microchips. However, as demand for cars rebounded, car makers have been struggling hard to find enough microchip supply to keep their production lines running, partially because of competing demand from the consumer electronics industry that saw increased demand for home entertainment.

Given this seemingly bleak situation, car manufacturers have come up with a surprising way to deal with the microchip shortage: they simply ship cars with some non-vital microchip components missing, sometimes promising customers to install them at a later date against a discount. The following examples demonstrate how dealers receive perfectly driveable and sellable cars, albeit stripped of some gimmicks: Ford shipping cars without air conditioning control from the rear seats;[29] GM shipping SUVs without wireless smartphone charging, HD radios or fuel management modules;[30] similar adjustments by Renault, Nissan,[31] Cadillac[32] and BMW;[33] Peugeot exchanging digital speedometers for analogue units.[34]

B.1.9 Substituting for single-use plastic

A concern in the current debate on stopping Russian gas imports is that gas is an important input in the chemicals industry, in particular in plastics production. It is therefore instructive to consider past experiences of substituting for plastics.

In recent years, given environmental concerns manifested in consumer demand or legislation, a significant number of firms across different industries have been 'forced' to reduce the use of single-use plastic. Supermarket chains have been focused on finding alternatives to plastic bags. Across Asia, supermarkets like Lotte Mart, Saigon Co.op and Big C are replacing plastic wrappers around fruit and vegetables with banana leaves as well, as studying the possibility of using this technique in other products.[35] Valorlux, a Luxembourgian non-profit company, has developed what they call a 'superbag'—a bag made of resistant fabric that is recyclable and washable. The goal of this bag is to replace the single-use bags used to carry vegetables and fruit. An article at RTL Today[36] states that this bag is starting to be sold in ten supermarket chains in Luxembourg, and the French supermarket chain Auchan is expanding its use to other countries, such as Portugal, as stated in a Sol article.[37] Clothing stores (and other stores) such as Zara[38] have also replaced their plastic bags, mostly with paper ones.

Other innovative solutions arise in the cosmetic and hygiene industry, with L'Oréal[39] replacing classic liquid shampoo with solid shampoos, so that instead of plastic they can be wrapped in cartons. Also driven by the need of reducing plastic packaging, the Portuguese coffee company Delta has started producing coffee capsules/pods from manioc, corn and sugar cane, yielding 100% biodegradable packaging to replace that made from plastic or aluminium.[40]

Restaurants are no exception. The reduction of single-use plastic has been counteracted by using classic tableware that can be washed and reused, but also by replacing plastic straws or cutlery by replicas made from paperboard or wood/bamboo. According to a Forbes article,[41] companies in the USA such as DeliveryZero and GreentoGo are working with restaurants to deliver food in reusable containers, which are returned and then used for further deliveries. More examples are McDonald's[42] and Wagamama[43] in the UK, which have stopped providing plastic straws and replaced them with alternatives based on paperboard. Also in the UK, Burger King[44] has stopped offering plastic toys to kids and is placing bins to collect old plastic toys for recycling, turning them into restaurant play areas or items such as trays.

B.2 Substitution in the macroeconomy

In Bachmann *et al.* (2022), we study the potential impact of a stop of Russian energy imports on the German *macro*economy. However, many arguments in the current policy debate focus on very *micro* physical production processes, with industry leaders claiming that substitutability of Russian energy imports is very close to zero. We argue that this micro 'engineering view' of substitution is too narrow and misses important mechanisms through which the macroeconomy would adapt to an import stop, for example through business destruction and creation. We instead emphasize a more appropriate 'economic view' of substitution that includes these additional adjustment mechanisms of the macroeconomy.

B.2.1 The 'engineering view' of substitution

In the current debate, many discussions of substitution focus on particular production processes at a very micro level. The following simple example represents this 'engineering view' of substitution. Imagine an economy that produces one final good, bottles, that can be assembled only by one specific machine, which can be delivered only by a specific truck, that can be constructed only with four wheels. And wheels are imported from abroad. In this economy with no substitution, a shock to a specific input fully propagates through the supply chain, even if the input represents only a tiny fraction of the overall value of the entire supply chain: if the imports of wheels from abroad decline by 10%, then the production of trucks will decline by 10%, leading to 10% fewer machines being delivered, leading to 10% fewer bottles being produced, that is, 10% less production of every single good.

If we apply this logic to the expected shock of a ban on Russian gas imports, then this means that in the total absence of substitution, a 30% reduction in gas imports would lead to a 30% decline in national income. However, we next argue that this narrow view misses important mechanisms through which the macroeconomy would adapt to an import stop.

B.2.2 The ‘economic view’ of substitution

The economic view of substitution is broader than the engineering view. It holds that even if substitution is completely impossible at the very micro level, this does not necessarily mean that there is no substitution in the aggregate economy.

The key observation is that the substitution may happen at a higher level than the individual production process or even individual firm: in response to a large enough energy supply shock, single production processes that are too reliant on gas or even entire firms may temporarily halt production or may ultimately become non-viable—that is, they may not survive. While this idea may appear dramatic, in part, it simply represents the functioning of the market economy: production processes or firms that are too reliant on gas and thus too expensive will be replaced by new processes or firms that are better adapted to the new environment with a smaller gas supply; alternatively, Germany may simply switch to importing some of the goods that become too expensive to produce domestically because they use gas upstream in the production chain (e.g. fertilizer). This substitution at the macro level is thus similar to the process of creative destruction that is important for generating long-run growth.

Technically, single production processes may be very close to displaying a zero elasticity of substitution (Leontief); but they may still aggregate up to an economy with a positive and potentially much higher elasticity of substitution. The observation that zero or low substitution at the micro level does not necessarily imply low substitution at the macro level goes back to a classic paper by Houthakker (1955), who showed that an economy in which individual firms that have Leontief production technologies (i.e. individual elasticities of substitution of 0) can aggregate up to a Cobb–Douglas aggregate production function (i.e. an aggregate elasticity of substitution of 1). More generally, it is a classic result in macroeconomic theory that the elasticity of substitution increases with the level of aggregation.

The apparent lack of substitutability is thus a classic ‘micro-to-macro fallacy’ (of which there are a number in economics). It also provides a straightforward explanation for why many industry representatives seem to believe that the world is one of little substitution (a ‘Leontief world’): they are actually right at the micro-micro level, and this ‘engineering viewpoint’ biases them to also view the macroeconomy in this fashion. (Of course, the alternative explanation for the apparent belief is simply industrial lobbying.)

B.2.3 A concrete example

For an example of how zero substitutability at the production process level does not necessarily imply zero substitutability for the aggregate economy, consider a Twitter thread by Christian Bayer about the electric furnace steel industry (in German).[45]

APPENDIX C. REVIEW OF OTHER STUDIES AS OF APRIL 2022

Any model-based quantitative assessment of the effects of a stop of Russian energy imports on the German macroeconomy is necessarily subject to considerable uncertainty, not only with respect to model parametrization, but also with respect to model choice ('model uncertainty'). An assessment of these costs should therefore not be based on a single study like ours. Fortunately, there exist a number of other studies providing alternative quantitative assessments of an import stop.

This appendix briefly reviews such studies published as of 23 April 2022, building on the careful reviews by Sachverständigenrat (2022) and Berger *et al.* (2022). In a nutshell, no single study has thus far provided quantitative model simulations with deviation of yearly GDP from baseline larger than 5.3%.[46] Similarly, taking into account GDP growth in a 'do nothing' baseline (which various estimates predict to be substantially positive), no study has found a recession with a year-to-year GDP drop larger than 2.5%.

At the end of this appendix, we briefly discuss what this combined body of work suggests for the likely economic consequences of an import stop. In short, we believe that a year-to-year GDP drop of more than about 5% seems highly unlikely, and a recession with a GDP drop of 10% or 15%, or even Great-Depression-type scenarios, is completely implausible.[47]

C.1 Summary table by the German Council of Economic Experts

The German Council of Economic Experts produced a very useful table summarizing the literature as of 9 April 2022—see Tables 1 and 2 (which are actually parts of the same table, split in two) in Berger *et al.* (2022). We refer the reader to that paper for an in-depth discussion of several of these studies. As can be seen from the table, the highest number in the table is the 6% GDP deduction computed by IMK (2022). All other studies in the table predict GDP deductions of less than or equal to 3%. The table lists a study by Goldman Sachs (2022) that finds a GDP deduction of 2.2% for the euro area. This study, in fact, also reports a number for Germany alone that is not listed in the table and which is somewhat larger, at around 3.5%. As discussed by Sachverständigenrat (2022) and Berger *et al.* (2022), some of the GDP deductions in the table are arguably additive because different studies quantify different mechanisms. Importantly, all these numbers are GDP deductions relative to a 'do nothing' baseline that likely features substantial positive GDP growth, implying smaller effects on year-to-year GDP.

C.2 Important studies not covered by the German Council of Economic Experts

Two important studies, Gemeinschaftsdiagnose (2022) and Bundesbank (2022), have appeared after Berger *et al.* (2022) produced their table summarizing the literature.

Gemeinschaftsdiagnose (2022) conducts a full-blown macro analysis, including a detailed modelling of the energy sector; for example, they model the fill level of German gas stores. One interesting aspect is that their model features a production network or supply chain with Leontief production in much of this chain.[48] Gemeinschaftsdiagnose (2022) predicts that a full cold-turkey import stop in April 2022 would result in GDP deductions relative to a 'do nothing' baseline of 0.8% in 2022 and 5.3% in 2023, thus an average deduction of 3.05% across the two years. Given substantially positive baseline growth, this results in year-to-year GDP changes of +1.9% in 2022 and −2.2% in 2023 (strikingly, their model predicts positive growth in 2022).

Bundesbank (2022) conducts two separate model simulations, one capturing the effects of higher energy prices (both because of the ongoing war and because of an embargo) and resulting in GDP deductions of 1.85% in 2022, 3.5% in 2023, and 3.4% in 2024, and the other capturing rationing and supply chain effects of an import stop and resulting in a GDP deduction up to 3.25%.[49] Adding the results from the two model simulations, Bundesbank (2022) argues for GDP deductions of 5.1% in 2022, 3.5% in 2023, and 3.4% in 2024.[50] Given substantial positive estimated baseline growth of 3.1%, the 5.1% deduction in 2022 implies a recession with a year-on-year GDP drop of 2% in 2022. (The implied year-to-year GDP changes in 2023 and 2024 do not seem to be reported.)

C.3 Study by IMK with the largest GDP deduction

As shown in the table discussed above, the study with the largest predicted GDP deduction (6%) is IMK (2022).[51] In fact, the paper suggests that this 6% number may be an underestimate because more appropriate model simulations 'run into stability problems'. We view the computational experiment that generates this GDP deduction as implausible, and therefore do not include it in this section's headline summary. The reason for this assessment is that IMK (2022) feeds into the model that they use (the National Institute of Economic and Social Research's NiGEM model) an extreme gas price increase by a factor of about 45 (i.e. 4500%), from around €20 per MWh to around €900 per MWh.[52] At the same time, this extreme price movement induces only a relatively small quantity response of less than 15% (i.e. less than half the 30% gas shortfall we argued for). The combination of these two model features implies that the share of gas expenditure in GDP likely shoots up to extreme values around 25 or 30%.[53] The extreme gas price movement in combination with the small quantity response leads us to view the IMK computational experiment as implausible.

C.4 Summary and takeaways for the likely economic consequences of an import stop

In summary, no single study has thus far predicted a deviation of yearly GDP from baseline larger than 5.3% or a recession with a year-to-year GDP drop larger than 2.5%. Put differently, all studies find GDP deviations from baseline in the low single digits and strongly bounded away from -10%. Similarly, no single study argues for a recession with a year-to-year GDP decline larger than the 4.5% observed in 2020 during the Covid-19 pandemic. We think that this is unsurprising given the facts about the German economy presented in Subsection A.1 (e.g. that industry accounts for about a quarter of economic activity).

As emphasized above, any model-based quantitative assessment of the effects of a stop of Russian energy imports on the German macroeconomy is necessarily subject to considerable uncertainty. This uncertainty comes in various forms, in particular both in the form of uncertainty with respect to parameter values and functional form assumptions and in the form of uncertainty about model choice ('model uncertainty').

Despite these large uncertainties, in particular those surrounding the estimates of any one single study, we believe that the combined body of work reviewed above suggests the following takeaways for the likely economic consequences of an import stop.

- A recession with a year-to-year GDP drop of more than about 5% seems highly unlikely.
- A recession with a GDP drop of 10% or 15%, or even a Great-Depression-type scenario, is completely implausible.

These assessments are conservative. For example, a 5% year-to-year GDP drop is more than twice as large as the recession predicted by any one single study (which all predict year-to-year GDP drops of less than 2.5%) and would require a GDP deduction from baseline of 7% or more. Despite the smaller estimates of individual studies, we use the pessimistic scenarios above to acknowledge the aforementioned large degree of uncertainty, and because we agree with Sachverständigenrat (2022) and Berger *et al.* (2022) that some of the effects in different studies may be additive because they quantify different mechanisms.