Title: What if? The economic effects for Germany of a stop of energy imports from Russia

Authors: Rüdiger Bachmann[1,7], David Baqaee[2], Christian Bayer[3], Moritz Kuhn[3,4], Andreas Löschel[5], Benjamin Moll[6], Andreas Peichl[7,8] *, Karen Pittel[7,8], Moritz Schularick[3,4,]

Affiliations:

[1] University of Notre Dame; Notre Dame, Indiana, United States.

[2] University of California; Los Angeles, United States.

[3] University of Bonn; Bonn, Germany.

[4] ECONtribute; Bonn, Germany.

[5] Ruhr-University Bochum; Bochum, Germany.

[6] London School of Economics; London, United Kingdom.

[7] Ifo Institute for Economic Research; Munich Germany.

[8] University of Munich; Munich Germany.

[9] Sciences Po; Paris, France.

[*] Corresponding author. Email: peichl@econ.lmu.de

Abstract: This article 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 a GDP decline relative to the baseline situation without the energy cut-off in a range of 0.5% and 3%.

One-Sentence Summary: We study a cut-off of Germany from Russian energy imports; the economic costs would likely be below 3% of GDP.

Main Text:

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? The economic effects crucially depend on substitution and reallocation of energy inputs across sectors.

To quantify these effects, we combine 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. First, we use a state-of-the-art multi-sectoral open economy model with production networks (*1*, see Appendix A.5). Second, we crosscheck these results with a simplified version of the model relying only on assumptions about elasticities of substitution (see Appendices A.2-4) leading to plausible bounds for the economic effects. The assumptions of the model relate 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) to the ease of reallocation of resources in the economy. This elasticity of substitution is challenging to discipline empirically, especially for large changes in the economy's input mix of the type that we are concerned with (see Appendix A.4 for a survey of the literature).

About half of German imports of gas and coal, and about 1/3 of oil originate from Russia. Germany depends on Russia for about 1/3 of total energy consumption (see Table 1 and Appendix A.1). Gas is used in industry (37%), by households (31%), as well as trade and commerce (13%), in the case of the last two predominantly for heating purposes (*2,3*). Power providers (12%) and district heating (7%) use the rest. In industry, about 3/4 are used for heating and cooling. About 1/3 of industrial use goes to the chemical industry (*4*). Final energy from oil is predominantly (about 70%) used in transport (*5*).

Table 1: German primary energy usage, 2021

	Oil	Gas	Coal	Nuclear	Renew-ables	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[§]	26	0	0	0	30

Notes: [§]In 2020 – already lower in 2021-2022. The German Council of Economic Experts uses 40% for 2021 (*6*). Estimates of net imports from Russia depend on the attribution of ring flows and exports (*7*). Source: (*8,9*).

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 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.

The size of economic losses stemming from a Russian import stop depends crucially on the period over which adjustments take place. In the estimated model, we find modest losses of around 0.2-0.3% of German Gross National Expenditure (GNE), or around €80-120 per year per citizen. GNE is about 94% of GDP so that 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); (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. We discipline these estimates with empirical elasticities found in the literature for industrial energy usage on 4-digit Standard Industrial Classification level (*10*), as well as estimates for short-run residential demand for natural gas (*11, 12*). 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 of gas of 0.1 or 0.04 of fossil fuels, substantially lower than the observed estimates in the literature.

Table 2 shows the results of the different approaches, i.e. the more complex Baqaee-Farhi model (columns 1&2) and the simpler model (columns 3&4). The first column summarizes results from a sufficient-statistics approach for models with production networks (supply chains, see Appendix A.5.3). The resulting losses to German GNE from these calculations remain below 1% 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. The second column crosschecks these numbers with simulations from a computational version of the Baqaee-Farhi model, which yields GNE losses of 0.2-0.3% or €100 (see Appendix A.5.5 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, the third column 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, i.e., more than twice as high as the €100 to €400 implied by the Baqaee-Farhi model (see Appendix A.7 for details).

Table 2: Overview of results from different approaches

	Baqaee-Farhi sufficient statistic	Baqaee-Farhi simulation	Simplest model 10% oil, gas, coal shock	Simplest model 30% gas shock

GNE Loss, %	<1	<0.3	1.5	2.3
As % of GDP	<1	<0.3	1.3	2.2
Per Capita €	400	100	600	900

It is important to stress that the model 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 potential trade-off between stabilizing output and inflation. Our model also omits amplification effects due to financial frictions (see Appendices A.5.5 and A.8 for a discussion of limitations A.6-7 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. Hence, we document that while, resulting from an import stop, Germany could face a shortfall equivalent to about 30% of gas usage, substitution and reallocation would likely keep the economic costs below 3% of GDP - unlike frequent fears voiced in the public debate. Indeed, a subsequent analysis (*13*) 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).

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 A.11 for details). We find that expenditure shares vary between 3.5-5% 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. Especially 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 a "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, a "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- 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.

References

1. D. Baqaee, E. Farhi, Networks, Barriers, and Trade. Working Paper (2021).
2. BDEW, Energy Market Germany 2019. Bundesverband der Energie- und Wasserwirtschaft e.V. (2019).
3. BDEW, Die Energieversorgung 2021 - Jahresbericht. = Bundesverband der Energie- und Wasserwirtschaft e.V. (2022).
4. Zukunft Gas, Erdgas in Deutschland: Zahlen Und Fakten Für Das Jahr 2021. Berlin (2022).
5. Umweltbundesamt, Energieverbrauch nach Energieträgern und Sektoren. https://www.umweltbundesamt.de/daten/energie/energieverbrauch-nach-energietraegern-sektoren#entwicklung-des-endenergieverbrauchs-nach-sektoren-und-energietragern (2022).
6. Sachverständigenrat zur Begutachtung der gesamtwirtschaftlichen Entwicklung, Auswirkungen eines möglichen Wegfalls russischer Rohstofflieferungen auf Energiesicherheit und Wirtschaftsleistung. https://www.sachverstaendigenrat-wirtschaft.de/fileadmin/dateiablage/Konjunkturprognosen/2022/KJ2022_Kasten3.pdf (2022).
7. Bundesnetzagentur, Monitoringbericht 2021. https://www.bundesnetzagentur.de/SharedDocs/Mediathek/Monitoringberichte/Monitoringbericht_Energie2021.pdf;jsessionid=C2FDAA244CF43A6F422F3F0523E0D286?__blob=publicationFile&v=7 (2022).

8. Agora Energiewende, Die Energiewende in Deutschland: Stand Der Dinge 2021. Rückblick Auf Die Wesentlichen Entwicklungen sowie Ausblick auf 2022. (2022)

9. V. Eckert, K. Abnett, Factbox: How Dependent Is Germany on Russian Gas? Frankfurt, Brussels: Reuters. https://www.reuters.com/world/europe/how-much-does-germany-need-russian-gas-2022-01-20/ (2022).

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

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

12. X. Labandeira, J. M. Labeaga, X. Lopez-Otero, A meta-analysis on the price elasticity of energy demand. Energy Policy 102, 549–568 (2017).

13. C. Bayer, A. Kriwoluzky, F. Seyrich, Energieembargo gegen Russland wurde Wirtschaft in Deutschland kalkulierbar belasten, Fiskalpolitik wäre in der Verantwortung, Nr. 80, DIW Aktuell (2022).

Only cited in the Supplement:

14. M. Rashad, I. Binnie, Brimming, European LNG Terminals Lack Room for More Gas. Reuters February 2022. https://www.reuters.com/business/energy/ brimming-european-lng-terminals-have-limited-space-more-gas-2022-02-17/ (2022).

15. IEA, A 10-Point Plan to Reduce the European Union's Reliance on Russian Natural Gas. March 2022. https://www.iea.org/reports/a-10-point-plan-to-reduce-the-european-unions-reliance-on-russian-natural-gas (2022).

16. B. McWilliams, G. Sgaravatti, S. Tagliapietra, G. Zachmann, Preparing for the first winter without Russian gas. Bruegel February 2022. https://www.bruegel.org/2022/01/ can-europe-survive-painlessly-without-russian-gas/ (2022).

17. B. McWilliams, G. Sgaravatti, S. Tagliapietra, G. Zachmann, Preparing for the first winter without Russian gas. Bruegel February 2022 https://www.bruegel.org/2022/02/ preparing-for-the-first-winter-without-russian-gas/.

18. B. McWilliams, G. Sgaravatti, G. Zachmann, European Natural Gas Imports. Bruegel April 2022. https://www.bruegel.org/publications/datasets/ european-natural-gas-imports (2022).

19. Chris Papageorgiou, Marianne Saam, and Patrick Schulte. Substitution between Clean and Dirty Energy Inputs: A Macroeconomic Perspective. The Review of Economics and Statistics, 99(2):281–290, May 2017.

20. Ara Jo. Substitution between Clean and Dirty Energy with Directed Technical Change. Working paper, ETH, 2021.

21. M. P. Timmer, E. Dietzenbacher, B. Los, R. Stehrer, G. J. Vries, An Illustrated User Guide to the World Input–Output Database: the Case of Global Automotive Production. Review of International Economics, 23 (3), 575–605 (2015).

22. K. E. Dynan, J. Skinner, S. P. Zeldes, Do the rich save more?. Journal of political economy, 112 (2), 397–444 (2004).

23. E. Gholz, L. Hughes, 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), 611–634 (2021).

24. A. I. Johnston, How New and Assertive Is China's New Assertiveness?. International Security, 37 (4), 7–48 (2013).

25. E. Ilzetzki, Learning by Necessity: Government Demand, Capacity Utilization, & Productivity. Working Paper (2022).

26. R. E. Smith, The Army and Economic Mobilization, 1991 ed., Center of Military History, United States Army (1959).

27. M. Harrison, Economic warfare: Insights from Mancur Olson. in Stephen Broadberry and Mark Harrison, eds., The Economics of the Second World War: Seventy-Five Years On, VoxEU (2020).

28. D.C. Gompert, H. Binnendijk, B. Lin, Germany's Decision to Conduct Unrestricted U-boat Warfare, 1916. in "Blinders, Blunders, and Wars: What America and China Can Learn," RAND Corporation, pp. 63–70 (2014).

29. B, Russell, International Law at Sea, Economic Warfare, and Britain's Response to the German U-boat Campaign during the First World War. PhD dissertation, The Open University (2008).

30. R. Bachmann, D. Baqaee, C. Bayer, M. Kuhn, A.s Löschel, B., A. Peichl, K. Pittel, M. Schularick, What if? The Economic Effects for Germany of a Stop of Energy Imports from Russia. Policy Brief No. 028, ECON- tribute (2022).

31. H. S. Houthakker, The Pareto Distribution and the Cobb-Douglas Production Function in Activity Analysis. Review of Economic Studies, 23 (1), 27–31 (1955).

32. Sachverständigenrat, Estimates of the Consequences of an Intensification of the Conflict on the Economic Outlook. Technical Report,German Council of Economic Experts, https://www.sachverstaendigenrat-wirtschaft.de/fileadmin/dateiablage/Konjunkturprognosen/2022/KJ2022_Box3_Excerpt.pdf (2022).

33. E. Berger, S. Bialek, N. Garnadt, V. Grimm, L. Other, L. Salzmann, M. Schnitzer, A. Truger, V. Wieland, A potential sudden stop of energy imports from Russia: Effects on energy security and economic output in Germany and the EU. Technical Report, German Council of Economic Experts, https://www.sachverstaendigenrat-wirtschaft.de/fileadmin/dateiablage/ Arbeitspapiere/Arbeitspapier_01_2022.pdf (2022).

34. IMK, Ukraine-Krieg erschwert Erholung nach der Pandemie. Technical Report, IMK, https://www.imk-boeckler.de/fpdf/HBS-008284/p_imk_report_174_2022.pdf (2022)

35. Goldman Sachs, The Impact of Gas Shortages on the European Economy. Technical Report (2022).

36. Gemeinschaftsdiagnose, Von der Pandemie zur Energiekrise – Wirtschaft und Politik im Dauerstress. Technical Report, Gemeinschaftsdiagnose, https://gemeinschaftsdiagnose.de/wp-content/uploads/2022/04/GDF2022_Gesamtdokument_unkorrieigert_12.4_13h.pdf (2022).

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

Acknowledgments:

We are grateful to Sven Eis, Marina Feliciano, Lennard Schlattmann and Borui Zhu for excellent research assistance, as well as Sebastian Dullien, Clemens Fuest, Veronika Grimm and Tom Krebs for comments on earlier drafts.

Funding:

- Deutsche Forschungsgemeinschaft (DFG, German Research Foundation) under Germany's Excellence Strategy – EXC 2126/1 – 390838866 (MK)
- Deutsche Forschungsgemeinschaft (DFG, German Research Foundation) CRC TR 224 (CB, MK)
- Deutsche Forschungsgemeinschaft (DFG, German Research Foundation) CRC TRR 190 (project number 280092119) (AP)

Author contributions:

All authors contributed equally to this work-

Competing interests:

Authors declare that they have no competing interests.

Data and materials availability:

Replication materials for all results can be found here https://benjaminmoll.com/RussianGas_Replication/

Supplementary Materials

A Material and Methods for: "The macroeconomic effects of a stop of energy imports from Russia on the German economy"

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

Rüdiger Bachmann, David Baqaee, Christian Bayer, Moritz Kuhn, Andreas Löschel, Benjamin Moll, Andreas Peichl, Karen Pittel, Moritz Schularick

May 9, 2022

Contents

A Material and Methods for: "The macroeconomic effects of a stop of energy imports from Russia on the German economy"

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 (1) 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 and in which energy is a critical input in production.

Our findings are as follows:

1. In appendix 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 we are concerned with, 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 that the size of economic losses depends crucially on the time frame over which adjustments take place.

4. We review empirical evidence on this elasticities of substitution (which also equals the own-price elasticity of energy). The meta-analysis by (12) 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 Gross National Expenditure (GNE) or around €80-120 per year per German citizen.[1] 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 GNI (which equals a modest 2.5%) as well as the predicted

[1] German GNE is €3,175 billion (see World Bank, 2022 https://data.worldbank.org/indicator/NE.DAB.TOTL.CN?locations=DE) 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 are €80-120.

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, i.e. 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 is (a) inconsistent with empirical evidence and (b) makes a number of nonsensical predictions.

8. Rather than aggregating 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 2 can be found here `https://benjaminmoll.com/RussianGas_Replication/`.

A.1 Fact Sheet: Energy Dependence of the German Macroeconomy

This appendix summarizes some key statistics that provide important guide posts for assessing the macroeconomic effects of an import stop.[2]

Germany's dependence on Russian energy If Germany decides to embargo Russian energy imports or Russia decides to impose export restrictions Germany would need to compensate for the decline of Russian energy imports either 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 use 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 IEA estimates that imports via pipeline to the EU from Norway, Algeria and Azerbaijan could be increased by 10 billion cubic meters (bcm) compared to 155 bcm imports from Russia in 2021, and LNG imports theoretically by 60 bmc (up from 110 bcm in 2021 (14)). The IEA considers 20 bcm additional LNG more realistic in the current market (15). 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 five-fold) 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 ((16), (17)). In its 10-point-plan to reduce the European dependency on Russian gas, the (15) 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 bmc 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.

[2] Some of the numbers are generated using simple back-of-the-envelope calculations because we were unable to find more direct data sources. Please contact b.moll@lse.ac.uk if you are aware of such more direct data sources.

Russian gas imports already decreased substantially in the second half of 2021 and especially in the first months of 2022. On the EU level, its import share fell from about 40% to 20-30% (18). Liquified natural gas (LNG) surpassed Russian imports, although capacity for further increases of LNG imports are limited (14). During the last few months, 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 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 only be partially able to compensate 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 recent months. (6) 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.

4. In sum, we conservatively assume that savings in gas consumption in the power sector, more gas imports from other countries, and the refilling of gas storage during the summer leaves 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".

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 Gross National Expenditure (GNE). For comparison German GNE was €3,175 billion in 2020 and therefore somewhat larger than German GDP of €3,097 billion (i.e. GNE was 2.5% larger than GDP) .[3]

2. Total German *imports* of gas, oil and coal are about 2.5% of GNE.[4]

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.[5]

4. Table S.1 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 & 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 S.1: Gas usage and economic importance of broad sectors of German economy

	Households	Industry	Services, T&C	Electricity Gen.	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 (2), (3). 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): 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, repectively. 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 & 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 & fishing, mining & quarrying, water supply; sewerage, waste management & remediation activities and activities of households as employers; undifferentiated goods - and services - producing activities of households for own use.

[3] As discussed in Table 1 in the main text, Germany imports about 60% of its gas, oil and coal. Total and total German imports of gas, oil and coal are roughly €80 bn in 2021 (see https://www.destatis.de/DE/Themen/Wirtschaft/Aussenhandel/Tabellen/einfuhr-ausfuhr-gueterabteilungen.html;jsessionid=7345586EA38C7821B58F6C63E9DAC7A2.live731) implying that total German consumption of gas, oil and coal was €80 bn / 60% = €133 bn. German 2020 GNE is €3,175 billion (see World Bank, 2022 https://data.worldbank.org/indicator/NE.DAB.TOTL.CN?locations=DE) so that German consumption of gas, oil and coal is roughly 4% of GNE. German 2020 GDP is €3,097 billion (see World Bank, 2022 https://data.worldbank.org/indicator/NY.GDP.MKTP.KN?locations=DE).

[4] German GNE is €3,175 billion and total German imports of gas, oil and coal are roughly 80 bn in 2021.

[5] German GNE is €3,175 billion and total German imports of gas and oil are roughly 75 bn in 2021 (see https://www.destatis.de/DE/Themen/Wirtschaft/Aussenhandel/Tabellen/einfuhr-ausfuhr-gueterabteilungen.html;jsessionid=7345586EA38C7821B58F6C63E9DAC7A2.live731). 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 $0.5 \times 73/3,175 \approx 1.2\%$

5. Table S.2 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 for 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 = 1,564). 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 = 2,653) and thus 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 most affected industries by an import stop would likely be able to continue operating to some extent.

Table S.2: Key statistics for hardest hit industries

	2022 Crisis (Import Stop)			2020 Crisis (Covid-19)		
	Chemicals	Food+	Metal	Air Trans.	Hospitality	Entert.
Gross Value Added (in € bln)	46	47	21	7	51	43
Gross Output (in € bln)	137	195	104	25	104	69
Wage Bill (in € bln)	27	35	16	5	35	21
Employees (in 1,000)	352	941	271	66	1894	693
Employees (% of total)	0.78	2.08	0.60	0.15	4.18	1.53
Share males (in %)	74	52	88	46	47	49
Capital (in € bln)	179	123	152	30	119	362
Share gas in production (%)	37	12	10			

Notes: The source for the table is the Volkswirtschaftliche Gesamtrechnungen (2019)

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 which is produced using "brown" energy (gas, oil, and coal, i.e. the energy sources imports from Russia) denoted by E as well as other inputs X (like labor 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.[6] To this end, it is useful to specialize the production function further to a constant-elasticity of substitution (CES) production function

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

where $\alpha > 0$ parameterizes 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 only features two factors of production and no input-output linkages. However, Lemma 1 in Appendix A.5 shows that such an analysis can be a good approximation even in a much richer environment like 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 S.1 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 Appendix A.9.[7]

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

$$\Delta \log Y = \alpha \times \Delta \log E \tag{2}$$

   Hence production Y declines with energy E but with an elasticity of only α. In our calibration (see Appendix 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 Appendix A.9) reduces production by $\Delta \log Y = 0.04 \times 0.1 = 0.004 = 0.4\%$. The solid purple line in Figure S.1 provides a graphical illustration and shows that production is quite insensitive to energy E as expected.

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

$$\Delta \log Y = \Delta \log E \tag{3}$$

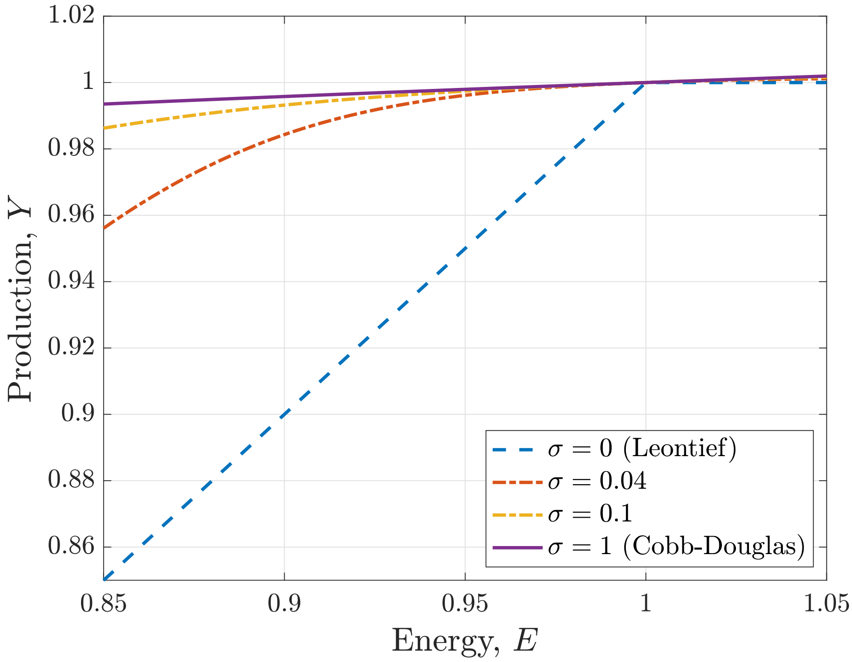
   Therefore, if the elasticity of substitution is exactly zero, production Y drops one-for-one with energy supply E. This is illustrated by the dashed blue line in Figure S.1 which plots production Y as a function of energy E for the Leontief case. For example, a drop in energy supply of $\Delta \log E = -10\%$ 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

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

[7] The code for producing the figure as well as Figures S.2 and S.3 below is available at https://benjaminmoll.com/elasticity/.

of production X lose all their value (their marginal product drops to zero) and hence production Y falls by 10%.

Figure S.1: Output losses following a fall in energy supply for different elasticities of substitution



Outside of the simple Cobb-Douglas and Leontief cases laid out above, the dependence of production Y on energy E is more complicated. However, one can derive a simple second-order approximation to (1)

$$\Delta \log Y \approx \alpha \times \Delta \log E + \frac{1}{2}\left(1 - \frac{1}{\sigma}\right)\alpha(1-\alpha) \times (\Delta \log E)^2 \quad (4)$$

This approximation illustrates in a transparent fashion the importance of the elasticity of substitution σ. When $\sigma = 1$ we recover the Cobb-Douglas special case in (2). 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).

One can also simply plot the production function for different values of σ. To this end, consider the red and yellow dash-dotted lines in Figure S.1 which plots the cases $\sigma = 0.04$ and $\sigma = 0.1$.[8] Unsurprisingly, the two cases lie in 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 Appendix A.6 below.

[8] The figure is generated using the Matlab code referenced in footnote 7 (also see the replication materials https://benjaminmoll.com/RussianGas_Replication/). In particular we do *not* use the second-order approximation (4) 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.

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 (2)). In richer multi-sector models like that of Appendix 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.

For future reference, we also provide another version of the approximation (4). In particular, one can show that the expenditure share of energy $\frac{p_E E}{PY}$ (see Appendix A.9 for the definition) satisfies $\Delta\left(\frac{p_E E}{PY}\right) \approx \left(1-\frac{1}{\sigma}\right)\alpha(1-\alpha)\Delta \log E$.[9] Therefore, we can write (4) as

$$\Delta \log Y \approx \frac{p_E E}{PY} \times \Delta \log E + \frac{1}{2} \times \Delta\left(\frac{p_E E}{PY}\right) \times \Delta \log E. \tag{5}$$

This formula says that the change in the energy expenditure share is informative about the elasticity of substitution σ and hence in turn the output losses from a negative energy shock. An advantage of this formula over (4) 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 we will return to in appendix A.6 below.

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 we are concerned with.

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 the short run. This result also applies to elasticities of substitution. Intuitively, in the very short run, production processes can be quite inflexible, i.e. the elasticity of substitution is low; however, over time, production processes can at least partially adapt to the different environment without Russian energy imports, i.e. 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 time horizon, more macro

[9] For example in the Cobb-Douglas case $\sigma = 1$, $\frac{p_E E}{PY} = \alpha$ and so $\Delta\left(\frac{p_E E}{PY}\right) = 0$.

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 section, 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.

(12) 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 short-run all demand changes within one year and otherwise as 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 then 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, (12) 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.[10]

The paper by (11) provides 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 (12). Notably, price elasticities have a strong seasonal component. During the summer, (11) find households to be inelastic to price changes 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 households expectations of high elasticties during the winter months.

The analysis in (10) 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, or 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 (12).

[10] They also survey the older literature on energy demand elasticities. Short-run demand elasticities in the older literature for natural gas and oil vary over similar ranges as the results reported in (see Table 1 in (12)).

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 and -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 (1) implies the following 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. (19) and Jo (20). The estimated elasticities are considerably larger (typically above one) than the own-price elasticities 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 (1) Multi-Sector Open-Economy Model

A.5.1 Brief description of the model

We briefly describe the main features of the computational model of (1). For a more detailed description see their paper and in particular Section 8 and Appendix K. The Baqaee-Farhi model is a state-of-the-art multi-sector model with rich input-output linkages and 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, i.e. 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 (1) was to examine gains from trades in the presence of said production chains and one the paper's main finding 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 Section 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 any model, the Baqaee-Farhi model has some limitations which we discuss in Appendix 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 (21). Each entry of the World Input-Output matrix represents a country-sector pair, e.g. 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 parameterizations used in (1), we also experiment with lower values for these elasticities so as to be conservative.

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

We follow (1) and focus on Gross National Expenditure (GNE) or domestic absorption as our main metric for judging macroeconomic damage to the German domestic economy. The main reason is that in many macroeconomic and trade models including the Baqaee-Farhi model, GNE has a welfare interpretation; in contrast, GDP does not. We also note that in the Baqaee-Farhi model, nominal GNE is equivalent to nominal Gross National Income (GNI) so our numbers can also be interpreted as GNI losses.

A.5.3 Theoretical results and back-of-the-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 section 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).

Notation: Let W be real GNE, b_i be the share of good i in GNE, and c_i be 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. Let D be the set of domestic producers.

Lemma 1. *To first order*

$$\Delta \log W = \sum_{j \notin D} \frac{p_j m_j}{GNE} \Delta \log m_j - \sum_{i \in D} \frac{p_i x_i^X}{GNE} \Delta \log x_i^X \quad \textit{where} \quad m_j = \left(\sum_{i \in D} x_{ij} + c_j \right) \textit{ for } j \notin D.$$

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:

$$\begin{aligned} \Delta \log W = & \sum_{j \notin D} \frac{p_j m_j}{GNE} \Delta \log m_j - \sum_{i \in D} \frac{p_i x_i^X}{GNE} \Delta \log x_i^X \\ & + \frac{1}{2} \left[\sum_{j \notin D} \Delta \frac{p_j m_j}{GNE} \Delta \log m_j - \sum_{i \in D} \Delta \frac{p_i x_i^X}{GNE} \Delta \log x_i^X \right]. \end{aligned} \tag{6}$$

As we will explain in more detail below, equation (6) in Lemma 1 is the natural generalization of the approximation (5) for the simple model in appendix A.2. A surprising implication of Lemma 1 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 $\Delta \frac{p_j m_j}{GNE}$ are that are important determinants of the economy's overall response to shocks like an import stop – see the second line of (6). 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.[11]

Application of Lemma 1 to cutting imports from Russia. Denote energy imports by m_E and their price by p_E. Assume that the only import which falls is energy, i.e. $\Delta \log m_j = 0$ for all $j \neq E$. Also assume that other exports are not affected $\Delta \log x_i^X = 0$.[12] Then the first-order approximation is $\Delta \log W \approx \frac{p_E m_E}{GNE} \Delta \log m_E$ and the second-order approximation is

$$\Delta \log W \approx \frac{p_E m_E}{GNE} \Delta \log m_E + \frac{1}{2} \Delta \frac{p_E m_E}{GNE} \Delta \log m_E. \tag{7}$$

[11] 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.

[12] Alternatively, we could assume that exports do not rise following the shock, $\Delta \log x_i^X \leq 0$, and that imports of other goods do not fall, $\Delta \log m_j \geq 0$ for $j \neq E$, in which case $\Delta \log W \geq \frac{p_E m_E}{GNE} \Delta \log m_E + \frac{1}{2} \Delta \frac{p_E m_E}{GNE} \Delta \log m_E$, i.e. equation (7) provides an upper bound on GNE losses $|\Delta \log W|$.

Note that the approximation (7) takes exactly the same form as the approximation (5) for the simple model in appendix A.2. The differences are that (i) it holds in a much richer open-economy model with a complex production network, (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 $\Delta \frac{p_E m_E}{GNE}$ 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-the-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 Appendix 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 also requires a prediction for the change in the energy share of GNE following the embargo $\Delta \frac{p_E m_E}{GNE}$.[13] An extreme scenario would be that this share triples from 2.5% to 7.5%, i.e. $\Delta \frac{p_E m_E}{GNE} = 5\%$. 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 only be 1.5%.

Next consider a case in which Germany manages to substitute for Russian oil and coal but not gas, the main scenario we argued for in Section 1 of the main text. This corresponds to a reduction in energy imports of $\Delta \log m_E = -17\%$.[14] Now assume that the GNE share of energy imports doubles from 2.5% to 5% so that $\Delta \frac{p_E m_E}{GNE} = 2.5\%$. 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 S.3 below.

Finally, an important possibility is that gas is a separate input that cannot be substituted with oil and coal. See Appendix 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 $\Delta \log m_E = -30\%$.[15] Now assume, very pessimistically, that the GNE share of gas imports triples from

[13] 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.

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

[15] See Fact 3 in Appendix 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 that the reduction in

1.2% to 3.6% so that $\Delta \frac{p_E m_E}{GNE} = 2.4\%$. This yields our preferred back-of-the-envelope calculation:

$$\Delta \log W \approx 1.2\% \times -30\% + \frac{1}{2} \times 2.4\% \times -30\% = -0.36\% - 0.36\% = 0.72\% \tag{8}$$

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 S.3 below.

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 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 and 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 modeling choices make the numbers as big as possible.

Table S.3: German GNE losses predicted by Baqaee-Farhi multi-sector model

	Parameterization 1 (as in Baqaee-Farhi)	**Parameterization 2 (low elasticities)**	**Parameterization 3 (very low elast's I)**	**Parameterization 4 (very low elast's II)**
	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
	B. German GNE Loss			
DEU	0.19%	0.22%	0.26%	0.30%

We now turn to the parameterization of the elasticities σ, θ, γ and ε we already discussed in appendix A.5.1. The elasticity γ is irrelevant for our experiment because of our assumption that factors of production (the three types of labor 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 (1). In contrast, the elasticities σ and particularly θ and ε are extremely important. We therefore present computational results for four different parameterizations that differ according to the

gas imports is also 30%.

values we choose for θ, ε and σ. Table S.3, panel A, summarizes the parameter choices. Parameterization 1 is the same as (1). Parameterizations 2 to 4 purposely pick lower elasticities, again in the spirit of being as conservative as possible.

Table S.3, panel B states the main computational results, namely the losses of German GNE predicted by the model. With the Baqaee-Farhi baseline parameterization the GNE loss is 0.19%; with the lower elasticities in parameterization 2 this number increases to 0.22%; with the even lower elasticities in parameterizations 3 and 4 GNE losses rise to 0.26% and 0.3% respectively. In summary, even for very low elasticities of substitution (as in parameterizations 2 and 3), the Baqaee-Farhi multi-sector model predicts modest losses of around 0.2-0.3% of German Gross National Expenditure (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 (1) 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 0.2-0.3% reported in Table 2, column 1 in the main text as well as Appendix Table S.3:

1. **Gas is not a separate input.** The model features 30 sectors that are based on the classification in the World Input-Output Database (21) and which are listed in Table 5 of (1). As stated there, the model features an aggregated “Electricity, Gas and Water Supply” rather than a separate “Gas” sector, i.e. 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-the-envelope calculation (8) which covers precisely the case of gas as a separate and critical input in production generates larger GNE losses of 0.72%.

   Appendix 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 3, labelled “Simplified model, 30% gas shock”.

2. **No Keynesian demand effects.** We discuss this limitation further in Appendix A.8. At the same time, a complementary analysis by (13) 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-the-envelope calculations in Section A.5.3 are not subject to this criticism. Indeed, our preferred back-of-the-envelope calculation (8) 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 Appendix 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 and 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 section A.5, our simulations and back-of-the-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 Section 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:

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 Section A.2, a reasonable worst-case scenario may be the case $\sigma = 0.04$, i.e. values of σ below 0.04 are nonsensical. An elasticity of 0.04 is also very conservative compared to the empirical evidence in appendix A.4.

4. As we report in appendix 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

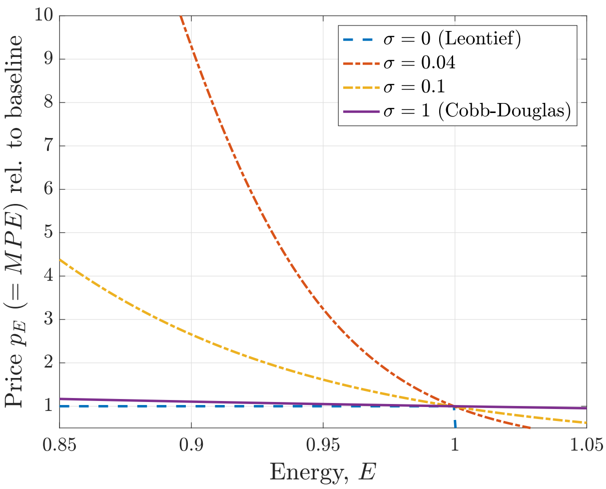
The blue dashed line in Figure S.1 showed that output falls one-for-one with energy supply in the Leontief case. The blue dashed lines in Figures S.2 and S.3 plot additional implications of falling energy supply with Leontief production. Figure S.2 shows that the marginal product of energy $\partial F(E, X)/\partial E$ jumps to $1/\alpha$ while the marginal product of other factors $\partial F(E, X)/\partial X$ falls to zero. If factors markets are competitive so that factor prices equal marginal products, this then implies that similarly the price of energy jumps to $1/\alpha$ and the prices of other factors fall to zero. Figure S.3 shows that this then 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?

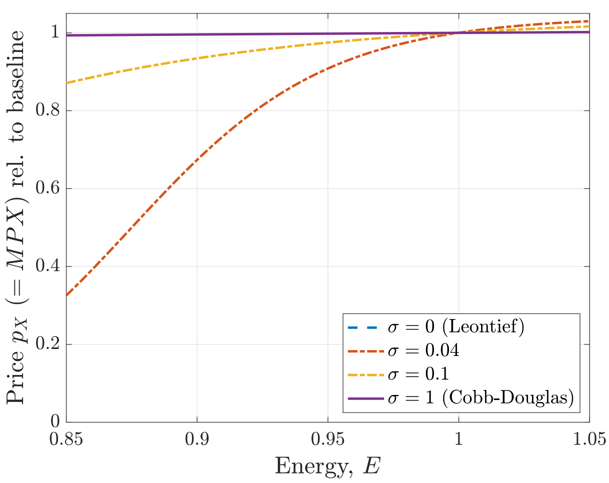
This raises the question: what values of elasticities of substitution are still reasonable? To this end, Figures S.2 and S.3 plot the behavior of marginal products/prices and the expenditure share for two different values of σ that are close to zero. An elasticity of $\sigma = 0.1$ (yellow dashed line) 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 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 dashed 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 Section 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 Appendix A.4.

Figure S.2: Price of energy and other inputs following a fall in energy supply for different elasticities of substitution



(a) Energy price



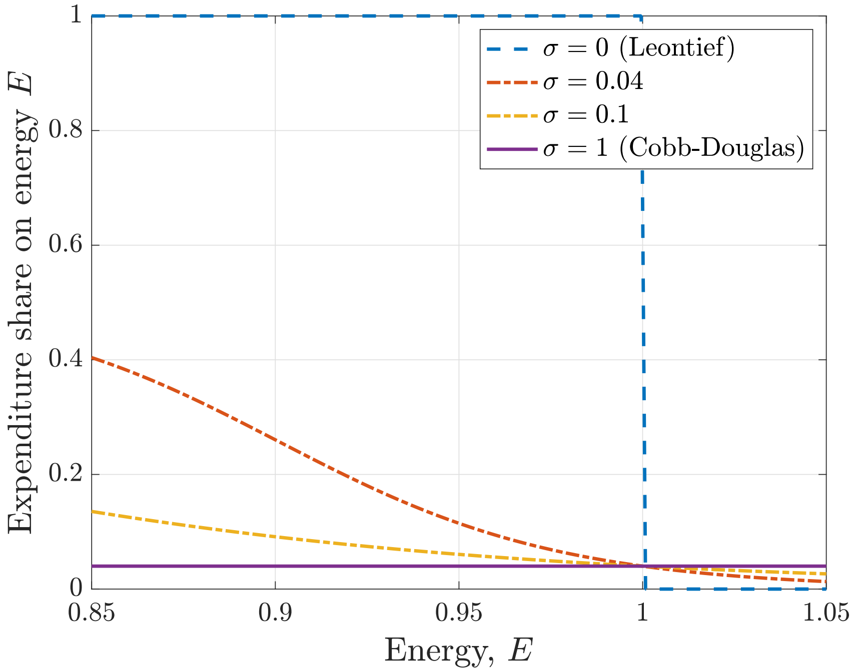
(b) Price of other inputs

A.7 Computational results from simple model in Table 2 in main text

We briefly explain here how we obtain the computational results in the third and fourth columns in Table 2 in the main text.

Third column: 10% oil, gas, coal shock. Figure S.1 plots the output loss for the worst-case scenario with $\sigma = 0.04$ we just discussed in appendix A.6.2. We use the calibration in Appendix 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

Figure S.3: Expenditure share on energy following a fall in energy supply for different elasticities of substitution



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.

Fourth column: 30% gas shock. In the computational experiment in column 3 of Table 2, we aggregated 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 Appendix 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 to 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 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 that aggregate demand decreases and this sets in motion a standard Keynesian multiplier effects. 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 labor incomes; this then means that households have less disposable income and spend less; and so on.

The reason 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 stabilising output and inflation. At the same time, fiscal policy needs and can, through insurance mechanisms like e.g. 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 stabilise 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 stabilising 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 to 2.2% of GDP reported in Table 1 in the main text (note: 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 coauthors of this paper and his collaborators (13) 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, e.g. 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 Simple CES Production Function in Appendix A.2

Calibration of α. As explained in Appendix 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 (1) so as to match the share of consumption of gas, oil and coal in German GNE which is given by about 4% – see Fact 1 in Appendix A.1 – or just gas which is given by 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, i.e. we can vary σ while always matching this import share by construction. Cost minimization of (1) implies the following optimal factor demands

$$E = \frac{\alpha p_E^{-\sigma}}{\alpha p_E^{1-\sigma} + (1-\alpha) p_X^{1-\sigma}} PY, \qquad X = \frac{(1-\alpha) p_X^{-\sigma}}{\alpha p_E^{1-\sigma} + (1-\alpha) p_X^{1-\sigma}} PY \tag{9}$$

where p_E is the price of energy, p_X is the price of the other input and $P = \left(\alpha p_E^{1-\sigma} + (1-\alpha) p_X^{1-\sigma}\right)^{\frac{1}{1-\sigma}}$ is a price index. Therefore expenditure shares are

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

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

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

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 (1) 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 $\alpha = 0.012$.

Calibration of σ. For the calibration of the elasticity σ we make use of the empirical evidence in Appendix A.4 and additionally apply the reasoning in Appendix 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 Appendix A.4.

A.10 Proof of Lemma 1

The proof uses the notation of Baqaee and Farhi (2021) and appendix 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

$$d \log W = \sum_i b_i d \log c_i.$$

Production of good i is used either 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 either purchased by domestic or foreign customers)

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

Therefore

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

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

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

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 $j \notin D$.

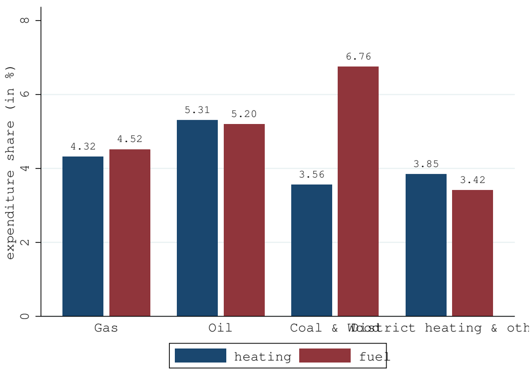
Using these relationships we have:

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

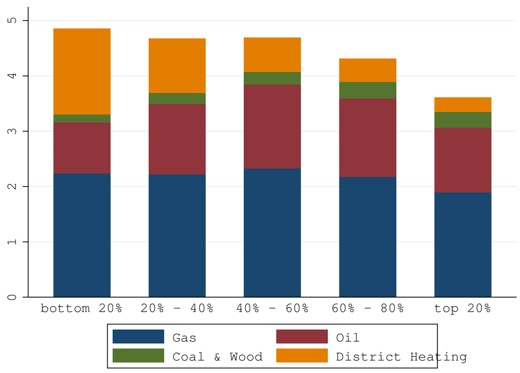
A.11 Distributional effects

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 the strongest over the last year (almost 10-fold increase). Nevertheless, price increases for oil and hard coal of course add to the overall additional burden on households, especially in the case of gasoline, diesel and electricity. The EVS data provide representative data for the German population on their consumption and 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 S.4: Energy expenditure shares



(a) By heating source



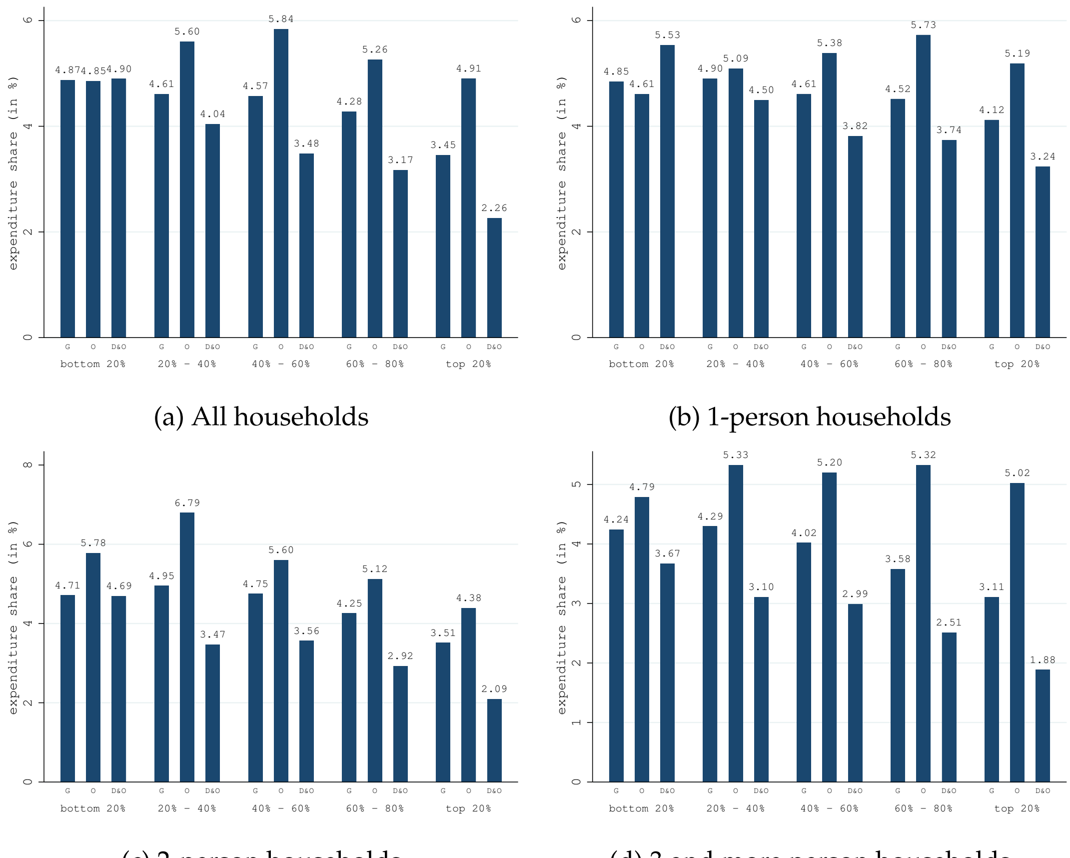
(b) By income

Notes: Left panel shows expenditure shares for all households by type of heating for heating (blue bars) and for fuel (red bars). Right panel shows energy expenditure shares for different heating sources along the income distribution.

Figure S.4 shows the expenditure shares depending on the main source of heating (Figure S.4a) and by income quintiles (Figure S.4b) for both heating and car fuel (only left panel). We find that typically households spend between 3 and 6 percent on heating. Similar expenditure shares apply to car fuel that vary between 3.4 and 6.8 percent. If we consider only gas and oil as the two by far most important heating sources, the heating expenditures are 4.3 and 5.3 percent and car fuel varies between 4.5 and 5.2 percent as well. Gas is the most important source for heating energy and oil comes in second. One exception are the bottom 20% of the income distribution where district heating is the second most important expenditure category, see Figure S.4b. 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 S.5 splits up the data further and distinguishes not only along the income distribution but also along the main type of heating and household size. The top left panel of Figure S.5 first looks at all households independent of household size. We find again that expenditure shares for oil are the highest and do vary only 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 the fifth quintile. District and other heating shows the lowest expenditure share throughout and also shows a strongly declining trend along the income distribution from 4.9 percent in the bottom 20% to 2.3 percent in the top 20%. Panels (b) to (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 are households with 3 and more members. They have lower expenditure shares in general and the decline of expenditure shares from 3.7 percent to 1.9 percent in income is the strongest.

Figure S.5: Heating expenditure shares by income, heating source, and household size



(a) All households

(b) 1-person households

(c) 2-person households

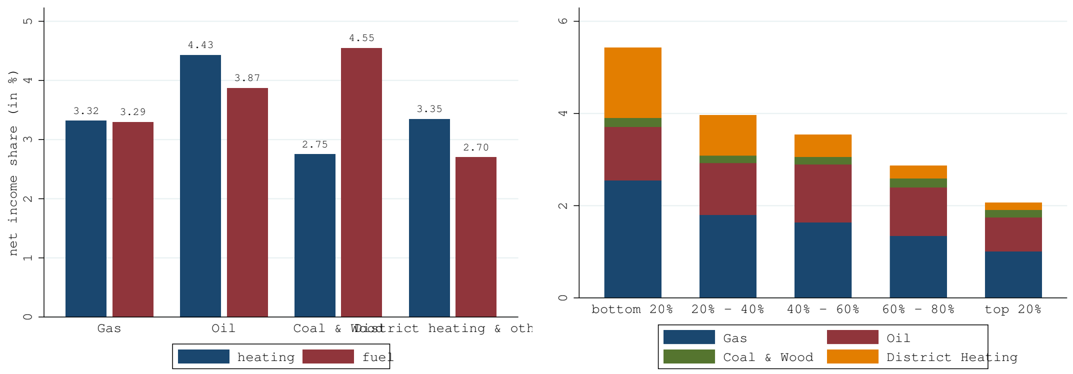
(d) 3 and more person households

Notes: Heating expenditure shares for households along the income distribution and by source of heating. Panel (a) shows all households, panel (b) 1-person households, panel (c) 2-person households, and panel (d) households with 3 and more members. Income deciles are separately computed for each household group. Heating sources are labelled "G" for gas, "O" for oil, and "D&O" for district and other.

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 that a stronger increase in the gas price than in the price of oil might lead to an equalisation 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) 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 will be 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 ECB not manage to stabilise the overall inflation rate by inducing offsetting price decreases elsewhere.

Thus far, we have focussed 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, households will be able to buy less 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 (22). 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 S.6 presents the equivalent results to Figure S.4 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 S.6: Energy expenditure as share of household net income



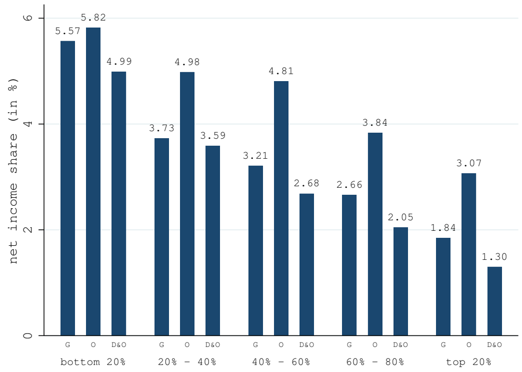
(a) By heating source

(b) By income

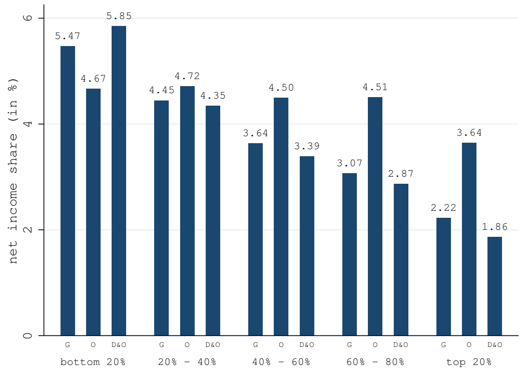
Notes: Left panel shows expenditure as a share of household net income for all households by type of heating for heating (blue bars) and for fuel (red bars). Right panel shows cost shares as a fraction of household net income for different heating sources along the income distribution.

Figure S.7 repeats the results from Figure S.5 but showing heating expenditures as a share of household net income rather than total household expenditures. The same conclusions as for the comparison between Figure S.4 and Figure S.6 apply: We find shares in income to be lower and we find a noticeable decline of the expenditure shares with income.

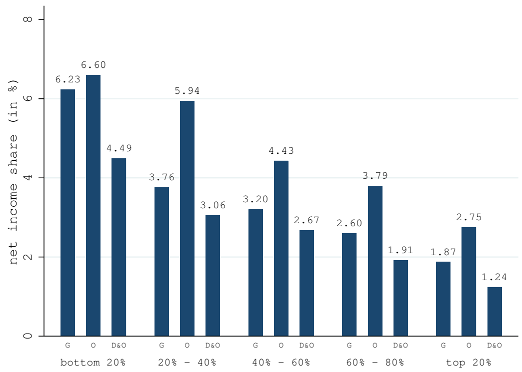
Figure S.7: Heating expenditures as share of household net income by income, heating source, and household size



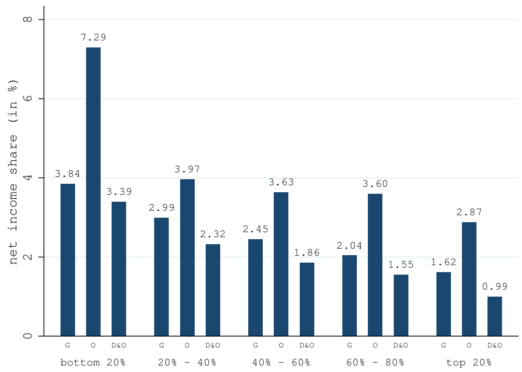
(a) All households



(b) 1-person households



(c) 2-person households



(d) 3 and more person households

Notes: Heating expenditures as shares of household net income for households along the income distribution and by source of heating. Panel (a) shows all households, panel (b) 1-person households, panel (c) 2-person households, and panel (d) households with 3 and more members. Income deciles are separately computed for each household group. Heating sources are labelled "G" for gas, "O" for oil, and "D&O" for district and other.

B Real-World Examples of Substitution and Substitution in the Macroeconomy

May 9, 2022

for latest version, see https://benjaminmoll.com/RussianGas_Substitution/

This appendix discusses in more detail the economic idea of substitution.[16] Section B.1 provides some historical real-world examples that demonstrate how firms do find ways to substitute in adversity (perhaps unexpectedly even for themselves). Section 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

1. 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.[17] As noted by (24), in the short run, Japanese firms reduced demand both at the intensive and extensive margin: 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 its low cost - rather 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 which too 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.

2. 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

[16]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.

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

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 Rostock, which enabled all refineries to continue operating, although not necessarily at normal capacity. In the case of an oil embargo as is under consideration now, the oil would have to come via ship, but not from Russia as in 2019 and it would need to be of a similar quality as 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.

Sources: Twitter thread by Janis Kluge, [18] DW article (in German), [19] local news (in German)[20]

3. Shortages during World War II. During big wars, countries must often react to strong, unanticipated shocks to both demand and supply. (25) shows that for the massive increase in U.S. government procurement of combat aircraft during WWII, this pressure made firms operate more productively, e.g. 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 goals of producing a total of 50,000 aircraft throughout the entire war were "impossible" to achieve.[21] But as (25) points out, within a short time frame, the U.S. aircraft industry ended up surpassing production goals by a wide margin, with almost 100,000 planes produced just in a single year, the year 1944.

As an example for supply shocks during WWII, Germany faced a major petrol crisis as it was cut off from main suppliers like the US or the USSR. Prioritising 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 S.8. 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).

Sources: Wikipedia Article on Wood Gas

4. Ball-bearings production in World War II. During WWII, ball-bearings were a crucial component in tanks, airplanes, machine guns, heavy artillery, and submarines. With the goal

[18] Twitter: Janis Kluge, https://twitter.com/jakluge/status/1502974281361285120

[19] DW: "Wie man das Druschba-Desaster am Ende der Pipeline wahrnimmt", 02 July 2019, https://www.dw.com/de/wie-man-das-druschba-desaster-am-ende-der-pipeline-wahrnimmt/a-49440013 (content only in German)

[20] Leipziger Volkszeitung: "Raffinerie Leuna von Öl-Stopp betroffen – Versorgung gesichert", 26 April 2019, https://www.lvz.de/Region/Mitteldeutschland/Raffinerie-Leuna-von-Stopp-der-Druschba-Pipeline-betroffen (content only in German)

[21] (25) 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." Also see (26) pp.154

Figure S.8: Car in Berlin 1946. See the "boiler" and the pipe that funnels the extracted wood gas into the internal combustion engine.

of stopping Germany's war machine, the US 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 they were able to spread the 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, they redesigned war equipment 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.

Sources: Twitter thread by Joachim Voth, Twitter thread by John Cochrane, National Museum Of American History, Business Insider article, United States Strategic Bombing Survey Summary Report, 30 September 1945, (27)

5. German U-boat campaign against Britain during World War I. Since the beginning of WWI, 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 them to surrender before the possible entry of the US in 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 US, Britain was able to minimize the consequences of the unrestricted U-boat company (1917-1918): 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 over-come these problems, the government initiated a tractor scheme, importing tractors from the US and also buying internally produced tractors. Additionally, with men being drafted to the war, the labor 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 labor force, facilitated by available training to work in farms.

Sources: Twitter thread by Joachim Voth, Imperial War Museums, Harwich Haven: Surrender & Sanctuary, National Farmers' Union, (28), (29)

6. 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 produce masks or face shields.

7. Global Microchip Shortage 2020-present. The automotive industry is an important user of integrated circuits (IC), also known as "microchips", using about 15% of its 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 AC require microchips. Recent car models also feature sophisticated infotainment and assisted driving systems, all based on IC components.

During the Covid-19 pandemic both the production and sales of vehicles dropped considerably. Car manufacturers hence slashed orders for microchips. However, as demand for cars rebounded, carmakers 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 AC control from the rear seats, GM shipping SUVs without wireless smartphone charging, HD radios, or fuel management modules, similar adjustments by Renault, Nissan, Cadillac, or BMW. Peugeot has exchanged digital speedometers for analog units.

8. 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 has 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.[22] 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 states that this bag is starting to be sold in 10 supermarket chains in Luxembourg and the French supermarket chain Auchan is expanding its use to other countries, like Portugal as stated in a Sol article. Clothing stores (and other stores) have also replaced their plastic bags, mostly with paper ones, like Zara.

Other innovative solutions arise in the cosmetic and hygiene industry, with L'Oréal replacing the classic liquid shampoo with solid shampoos, so that instead of plastic they can be wrapped in carton. 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 and replacing ones made from plastic or aluminium.[23]

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, companies in the US like 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 McDonalds and Wagamama in the UK, that have stopped providing plastic straws and replaced them with alternatives based on paperboard. Also in the UK, Burger King 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 (30) 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.

[22] According to a Bublle (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", 14 June 2019, https://sol.sapo.pt/artigo/660793/-folhas-de-bananeira-substituem-plastico-em-supermercados-na-asia- (content only in Portuguese)

[23] Sol: "As cápsulas de café amigas do ambiente", 16 May 2019, https://sol.sapo.pt/artigo/658521/as-capsulas-de-cafe-amigas-do-ambiente (content only in Portuguese)

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 only be assembled by one specific machine, which can only be delivered by a specific truck, that can only be constructed 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%, the production of trucks will decline by 10%, leading to 10% fewer machines being delivered, leading to 10% less bottles being produced, i.e. 10% less production of every single good.

If we apply this logic to the expected shock of a ban of Russian gas imports, 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.

The "economic view" of substitution. The economic view of substitution is broader than this 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, i.e. 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 (31) who showed that an economy in which individual firms that have Leontief production technologies (i.e. individual elasticities of substitution of zero) can aggregate up to a Cobb-Douglas aggregate production function (i.e. an aggregate elasticity of substitution of one). 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.)

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 the following twitter thread by Christian Bayer about the electric furnace steel industry (in German): https://twitter.com/christianbaye13/status/1504785656815497226?s=21.

C Review of other studies: no single study with deviation of yearly GDP from baseline larger than 5.3%, no recession with GDP drop larger than 2.5%

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 parameterization 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 (32) and (33). In a nutshell, no single study has thus far provided quantitative model simulations with deviation of yearly GDP from baseline larger than 5.3%.[24] 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 are completely implausible.[25]

Summary table by German Council of Economic Experts. Table S.4 summarizes the literature as of 9 April 2022. It is drawn from a very useful survey by the German Council of Economic Experts (33). We refer the reader to that paper for an in-depth discussion of several of these studies. The second-to-last column of Table S.4 summarizes GDP deductions relative to baseline found by various studies. As can be seen from the Table, the highest number in the table is the 6% GDP deduction computed by (34). All other studies in the Table predict GDP deductions of less than or equal to 3%. The table lists a study by (35) which finds a GDP deduction of 2.2% for the Euro area. The Goldman study, in fact, also reports a number for Germany alone which is not listed in the table and which is somewhat larger at around 3.5%. As discussed by (32) and (33) 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 which likely features substantial positive GDP growth, implying smaller effects on year-to-year GDP.

Important studies not covered in Table S.4. Two important studies, (36) and (37), have appeared after (33) produced Table S.4. (36) conducts a full-blown macro analysis including a

[24]One study by (34) 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.

[25]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.

Table S.4: Review of Literature by German Council of Economic Experts (33)

Institution	Publication date	Scenario	Assumptions	GDP-deduction[1]	Additional inflation[1]	Region
Effects relative to a baseline scenario incorporating the state of the conflict and sanctions at time of publication						
Deutsche Bank Research[2]	09.03.2022	Negative scenario with a temporary import stop of natural gas and oil from Russia	Sharply higher energy prices (oil 140 US-$/ barrel; natural gas 150 €/MWh)	1.5	1–1.5	Germany
ifo[2] (Wollmershäuser et al.)	23.03.2022	Alternative scenario	Sharper and longer increase of natural gas and oil prices (oil 140 US-$/barrel in May; natural gas 200 €/MWh in May); longer lasting uncertainty and supply chain shortages	0.9	1.0	Germany
IMK[2] (Behringer et al.)	29.03.2022	Risk scenario	Sharper and longer increase of natural gas and oil prices (annual average of oil 141 US-$/barrel; natural gas 200 €/MWh in Q2); longer lasting uncertainty	2.4	2.0	Germany
IMK[2] (Behringer et al.)	29.03.2022	Partial stop of Russian natural gas imports	Increase of natural gas price to 900 €/MWh	6.0	–	Germany
Oxford Economics[2]	02.03.2022	Stop of Russian natural gas imports for 6 months	Oil price between 100 and 115 US-$/barrel, natural gas price at 190 €/MWh	1.5	2.6	Euro area
Goldman Sachs[2]	06.03.2022	Stop of russian natural gas imports		2.2	–	Euro area
ECB[2]	10.03.2022	Adverse scenario	Sharp temporary increase of natural gas prices and increase of oil prices	1.2	0.8	Euro area
ECB[2]	10.03.2022	Severe scenario	Sharper and longer increase of natural gas and oil prices; strong second round effects	1.4	2.0	Euro area
IMK[2]	29.03.2022	Risk scenario	Sharper and longer increase of natural gas and oil prices (annual average of oil 141 US-$/barrel; natural gas 200 €/MWh during Q2); longer lasting uncertainty	2.2	2.1	Euro area
Effects relative to a baseline scenario not incorporating the state of the conflict and sanctions at time of publication						
NIESR[2] (Liadze et al.)	02.03.2022		Oil price at 140 US-$/barrel higher public spending	0.8	2.5	Euro area
EcoAustria[2] (Köppl-Turyna et al.)	08.03.2022	Increase of natural gas prices and stop of exports to Russia	Natural gas price of 172 €/ MWh and no exports to Russia and to Ukraine	1.3	–	Austria
OECD[2]	17.03.2022		Shocks of the commodity and financial sectors observed during the first weeks of the war extend to one year	1.4	2.0	Euro area
Estimates of Felbermayr et al. (2022), Bachmann et al. (2022), Bayer et al. (2022) and Baqaee et al. (2022)						
Felbermayr et al.	03.03.2022	Decoupling between Russia and the US and its allies (Scenario 3C)	Doubling of non-tariff barriers in the Kiel Institute Trade Policy Evaluation Model, which lead to a drop of bilateral trade between Russia and the US and its allies by more than 95 %	0.4 [a]	–	Germany
Bachmann et al.[3]	07.03.2022	Cessation of trade between Russia and the EU	Introduction of trade barriers in the model of Baqaee and Farhi (2021), which lead to a stop of all imports from Russia to the EU	0.2–0.3	–	Germany
Bachmann et al.[4]	07.03.2022	Stop of Russian natural gas imports	30 % decline of natural gas imports; elasticity of substitution between natural gas and other inputs of 0.1	2.2	–	Germany
Bachmann et al.[5]	07.03.2022	Stop of Russian energy imports	30 % decline of energy imports; change of the cost share of energy imports in the GNE by 5 percentage points to 7.5 %	1.4	–	Germany
Bayer et al.[6]	29.03.2022	Stop of Russian energy imports	Stop of Russian energy imports decreases productivity (−2.2 %) temporarily and eliminates part of capital stock (−3 %) in a DSGE model	3.0	2.3	Germany
Baqaee et al.	04.04.2022	Stop of Russian energy imports	Introduction of trade barriers in the model of Baqaee and Farhi (2021), which lead to a stop of all imports from Russia to the EU	0.2	–	France
Baqaee et al.	04.04.2022	Stop of Russian energy imports	15 % decline of natual gas imports	0.3	–	France

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.[26] (36) 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 and so 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).

(37) conduct 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, the other one capturing rationing and supply chain effects of an import stop and resulting in a GDP deduction up to 3.25%.[27] Adding the results from the two model simulations, (37) argue for GDP deductions of 5.1% in 2022, 3.5% in 2023 and 3.4% in 2024.[28] 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).

Study with largest GDP deduction by IMK. As shown in Table S.4, the study with the largest predicted GDP deduction of 6% is (34).[29] 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 (34) feed into the model 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.[30] 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%.[31] The extreme gas price movement in combination with the small quantity response

[26]See the appendix at https://gemeinschaftsdiagnose.de/wp-content/uploads/2022/04/GD22F_Hintergrund-Alternativszenario_final.pdf, in particular p.5.

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

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

[29]The IMK or "Institut für Makroökonomie und Konjunkturforschung" is a German union-funded think tank. It is funded by the Hans-Böckler Stiftung, the foundation of the German Trade Union Confederation DGB.

[30]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/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.

[31]See https://twitter.com/ngarnadt/status/1514907211159556099?s=20&t=vQyWdLwtNjJAlSmVn56vbQ. (34) justify 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 only closes 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 sizable quantity reduction indicates that the NiGEM model – or more precisely the parameterization used by (34) – is not suitable for conducting the attempted import-stop experiment. This is perhaps not surprising given that the NiGEM model was originally developed and parameterized for simulating counterfactuals with respect to much smaller shocks or policies.

leads us to view the IMK's computational experiment as implausible.

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 Appendix 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 (32) and (33) that some of the effects in different studies may be additive because they quantify different mechanisms.