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This article discusses the economic effects of a potential cut-off of the German economy from Russian energy imports. We show that the effects are likely to be substantial but manageable. In the short run, a stop of Russian energy imports would lead to a GDP decline in range between 0.5% and 3% (cf. the GDP decline in 2020 during the pandemic was 4.5%).

(i) In the case of an import stop, imports of oil and coal from Russia can be substituted from other countries, but the situation in the gas market is more challenging. An increase in gas imports from other countries, substitution of gas used for electricity production by coal or nuclear as well as refilling of storage facilities over the summer can only reduce the shortfall to about 30% of gas consumption or 8% of German energy consumption over the next 12 months.

(ii) How would the German economy cope with such a shortfall of gas deliveries? The economic effects crucially depend on substitution and reallocation of energy inputs across sectors. To quantify these effects, we use a state-of-the-art multi-sectoral open economy model following Baqaae and Farhi (2021) that accounts for elasticities of substitution and reallocation between different intermediate inputs. In a second step, we turn to a simplified model that helps us derive plausible bounds for the economic effects using observed elasticities for energy inputs. In the Baqaae-Farhi model, the output costs of a Russian import stop remain firmly below 1% of Gross Domestic Product (GDP), or between 80 and 120 Euros per German citizen per year. In a more pessimistic scenario where it proves very difficult to substitute Russian gas in the short-run outside the electricity sector, the economic costs would rise to about 2-2.5% of GDP, or about 1000 Euros per German citizen over 1 year. This comes potentially on top of a large increase in energy prices for household and industry even without a shortfall of gas deliveries. Of course the effects are more detrimental in energy intensive sectors.

(iii) Data from the Income and Consumption Survey (EVS) show variation in the expenditure share on energy across the income distribution. However, the distributional consequences of an increase in energy prices appear manageable. A targeted policy towards low-income households without reducing the incentives for households to save energy would be a cost effective way of ensuring a fair burden-sharing across households. It is important to maintain strong incentives for households to reduce gas usage.

(iv) Economic policy should aim at strategically increasing incentives to substitute and save fossil energies as soon as possible. In case that an active embargo is politically desired, it should start as soon as possible so that economic agents can use the summer period for adjustment. To reduce dependence on imported energy, it is advisable for the government to commit to elevated fossil energy prices, in particular for natural gas, for an extended period to create incentives for households and industry to adjust quickly.

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How would the German economy cope with a sudden stop of energy imports from Russia, either triggered by a further tightening of the sanctions regime, or following a stop of energy deliveries by Russia? In this paper, 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 elasticities of substitution to estimate the short-run costs.

Section 1 looks at Germany's energy dependence from Russia and shows that in the case of an import stop, the country would face a shortfall equivalent of ~30% of gas usage net of what can be substituted in electricity production, or 8% of total energy usage. Section 2 asks how the economy would adjust to such a shock, and at what cost. We show that losses to the German economy of embargoing energy imports from Russia are highly sensitive to the degree of substitutability of gas with other inputs. We use observed elasticities of substitution in industry to derive estimates of economic costs. Unlike frequent fears voiced in the public debate, substitution and reallocation would likely keep the economic costs below 3% of GDP, provided that fiscal and monetary policies cushion potential demand-side Keynesian effects.

Section 3 discusses the distributional effects of the import stop by looking at expenditure shares of high/low income households. Section 4 draws policy implications and in particular stresses the point that economic policy should encourage the adjustment, not try to delay it. Policy measures should aim at strategically increasing incentives to substitute and save fossil energies as soon as possible. If an embargo of Russian energy becomes politically necessary, a case can be made that actions should be taken as early as possible in order to trigger adjustments in industry and households before the winter while gas demand is seasonally low over the summer.

1. Germany's dependence on Russian energy

Germany imports about 60% of its energy use (World Bank 2022), with import quotas between 94% and 100% for oil, gas and hard coal (Umweltbundesamt 2022). In 2021, the value of imports of fossil fuels and electricity amounted to about 80 bn Euros, or slightly over 2% of GDP (Statistisches Bundesamt (2022b). About half of German imports of gas and hard coal, and about one third of oil imports originate from Russia. Germany depends on Russia for about 1/3 of total energy consumption (Table 1). Total goods imports from Russia in 2021, including other products, stood at 33 billion Euros (Statistisches Bundesamt 2022a). Trade with Russia accounts for only 2.3% of total German trade.

In the German economy, gas is predominantly used in industry (36%), by households (31%), as well as trade and commerce (13%), in the case of the last two predominantly for heating purposes (BDEW 2019, 2021). The usage of gas for electricity production is comparatively small. In industry, about three quarters of the gas are used for heating and cooling, as well as for material use. About a third of industrial use goes to the chemical industry (Zukunft Gas 2022). Regarding the use of hard coal, about ⅗ went to the steel industry and ⅝ to public electricity generation in 2018 (Sandau et al. 2021). Oil was predominantly (about 75% in 2017) used in the form of gasoline and diesel fuels (Wissenschaftliche Dienste des Deutschen Bundestages 2019).

Table 1 German primary energy usage 2021

	Oil	Gas	Coal (Lignite and Hard Coal)	Nuclear	Renew-ables	Others	Total
ThW	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 and 2022.
Source: Agora Energiewende (2022); Eckert, and Abnett (2022).

If Germany decides to embargo Russian energy imports or Russia decides to impose export restrictions in reaction to, say, an embargo on oil sales, 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-intense 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 (Rashad, and Binnie 2022)). The IEA considers 20 bcm additional LNG more realistic in the current market (IEA 2022). Some of this gas would have to be stored pre-winter to compensate for missing Russian gas in the cold months. Moreover, switching from comparatively cheap contract prices with Russia to world market spot prices would imply a substantial (currently five-fold) increase of the gas price.

A recent study by Bruegel (2022) 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 (McWilliams et al. 2022a, 2022b). In its 10-point-plan to reduce the European dependency on Russian gas, the IEA (2022) also lists increasing coal and nuclear power production and renewables deployment as well as a number of demand-related measures that could theoretically contribute another 33 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 later two options will play a minor role in the very short run.

There are few historic examples of energy supply disruptions on the scale of a potential Russian energy import stop. Comparisons might be drawn to the shutdown of nuclear power plants in Japan following Fukushima. Nuclear power at the time generated about 30% of electricity in Japan which was almost driven to zero in a time span of one year. Estimates show that the shutdown of nuclear power plants increased electricity prices, depending on the initial energy mix of a region, between 10% and 40% (Neidell, Uchida, and Veronesi 2019). This being said, with respect to overall energy consumption, nuclear energy accounted for only 13% in 2010 and due to previous overinvestment in LNG import capacities, substitution by natural gas was not subject to physical limits (Nesheiwat, and Cross 2013).

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% (McWilliams, Sgaravatti, and Zachmann 2021). Liquified natural gas (LNG) surpassed Russian imports, although capacity for further increases of LNG imports are limited (Rashad, and Binnie 2022). During the last few months, prices for coal, oil and gas have already increased dramatically.[1] 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 make up 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:

- Russia's import share in German gas consumption stood at 55% in 2020, but has declined in recent months. We make cautious assumptions with respect to the potential for increases in supply via LNG in the short run. We assume that capacity increase is

[1] For crude oil (Brent) from 60 USD/Bbl in March 2021 to 90 USD/Bbl in the beginning of February 2022 to 110 USD/Bbl, coal (API2) from 65 USD/metric tonne of thermal coal in March 2021 to 145 USD/tcoal in the beginning of February 2022 to 345 USD/tcoal and for gas (TTF Gas) from 17 Euro/MWh in March 2021 to 70 Euro/MWh in the beginning of February 2022 to 160 Euro/MWh (March 3, 2022).

limited to 5% over the next year, meaning that the German economy would have to cope with a shortfall of 50% of gas deliveries.

- 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 free up close to 20% of total German gas consumption.
- We are thus left 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%. Households account for about ⅓ of total gas consumption and services for 15%. Gas is used mainly for heating purposes in both. The best available evidence points to elasticities of substitution in the household sector between 0.2. and 0.4 in the short-run (Aufhammer and Rubin 2018).
- Industrial use accounts for 36% of the total, of which 11% are used as a direct input into chemical production and can likely not be substituted at all. The bulk of industrial gas use is for heat and cold applications. The potential for substitution is difficult to estimate, but likely substantially higher than for direct production usage. Existing studies for the UK manufacturing industry point to considerable short-run substitutions possibilities in heat generation of up to 0.5 (Steinbuks 2012).
- In the main scenario studied here, we assume that a reduction of gas deliveries of 30% or about 8% of total German energy consumption will result from a Russian energy embargo. This will have to be borne by domestic industry, households, and services. 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”.

While some part of this gap can potentially be closed by filling reserves over the summer when heating demand from households is low without hurting industrial usage, our baseline assumption is that in the short-run the Germany economy would be forced to adjust to such a shock. What would be the economic effects?

2. The macroeconomic effects of a stop of energy imports from Russia on the German economy

In the following we will approximate the effects of a reduction of German gas consumption triggered by a stop of gas imports from Russia. To estimate the macroeconomic effect, we build on a state-of-the-art multi-sector macro model with production networks based on work by Baqaae and Farhi (2021). The aim is to estimate the economic costs of a stop of Russian energy imports for the German economy in the current situation. We use the multi-sector model to conduct counterfactual simulations of the macroeconomic effects of cutting energy imports from Russia. We will cross-check the results of the complex model with a simplified version relying on different assumptions about elasticities of substitution.

The details of the model are explained in the Appendix, but a few words of explanation are important. The Baqaee-Farhi model is a state-of-the-art multi-sector model with rich input-output linkages in which energy is a critical input in production. The key economic assumptions of the model relate to (i) the degree of substitutability between different intermediate inputs in the production process, in particular between the type of energy imported from Russia and other inputs, measured by various elasticities of substitution, and (ii) to the ease of reallocation of resources in the economy. Both factors influence each other. A low elasticity is less of a problem if resources can be reallocated to other parts of the economy to maintain production in the critical sector.

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. A macroeconomic analysis is therefore subject to a considerable degree of uncertainty. It seems plausible to assume, however, that the elasticity of substitution is larger in the medium- and long-run, and smaller in the very short run (see e.g. Caballero, 1994). The size of economic losses stemming from a Russian import stop therefore depends crucially on the time frame over which adjustments take place.

It is implausible, however, to assume that even in the short-run the elasticity of substitution is zero. Producers and households will switch to other inputs to some extent, change their consumption baskets, or outrightly import energy, especially gas, or products with high energy content that can be transported in bulk. This qualification is important as the difference between a very low, but non-zero, and a literally zero elasticity translates into much smaller economic losses than in the case of zero substitutability (a Leontief production function). Estimations assuming zero short-run substitution are not suited for policy analysis. .

In the estimated model, for low elasticities of substitution, 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. GNE is about 94% of German GDP so that the corresponding GDP effects are somewhat smaller and remain firmly below 1%.

The key reasons why the model-implied economic losses are relatively small are the following: (i) the share of fossil energy imports (gas, oil and coal) in German production is small to begin with at about 2-2.5% of GDP, and (ii) the model predicts that, while this share rises considerably, it will not rise by an unreasonably large amount. In the model, the change in the share of energy imports in GNE summarizes in a succinct fashion the substitutability implied by model choices about elasticities and changes in the input-output structure. Beliefs about substitutability boil down to beliefs about changes in the energy import share in GNE.

While the numbers coming out of the Baqaee-Farhi model imply limited costs, we acknowledge that the uncertainty surrounding elasticities of substitution (and the corresponding change in the import share) could be large. To derive a plausible upper bound of the costs, 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 (SIC) level (Steinbuks, 2012). Similar estimates are found for short-run residential demand for natural gas (Auffhammer and Rubin, 2018) and they also lie in the middle of the estimates for short-run demand elasticities across a large set of studies (Labandeira et al., 2017). In the first exercise, we calculate the effects of an 8% aggregate reduction in overall German energy use. In the second scenario we model a 30% reduction in gas inputs as a shock to that specific energy source.

Table 2 shows the results of the different approaches, starting with the most complex Baqaee and Farhi (2020) model. Assuming very low short-run substitution elasticities, an 8% energy adjustment to oil, gas, and coal consumption leads to a 1.4% of GDP loss, or costs of €500-700. In a last scenario where we model a more extreme 30% adjustment in gas usage, the economic losses rise to 2.2% of GDP (2.3% of GNE), equivalent to up to €1,000 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.

It is important to stress that the model we use is a real model with no further business cycle amplification. In other words, it calculates the economic response based on the assumption that monetary and fiscal policy can undo further effects from nominal rigidities in the economy. On the monetary side, a firm commitment to stable prices can soften the potential trade off between stabilising output and inflation. If one views the energy price shocks as akin to a productivity shock, then this would require the central bank to raise interest rates in order to stabilise inflation. Through 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, which are more difficult to deal with for the central bank as they raise a conflict between stabilising output and inflation. At the same time, fiscal policy needs and can, through insurance mechanisms (like short term work) take care of second-round demand effects. With appropriately calibrated demand-side stabilization policies, it should in principle be possible to avoid additional costs.

This being said, it is important to note that our estimations assume that such second round effects can be avoided and potential problems in the financial sector through bad loans or house price declines in specific regions and industries can be dealt with without further amplification. We also assume that central bank policy avoids a potentially costly inflation surge that unanchors inflation expectations of the public.

Table 2

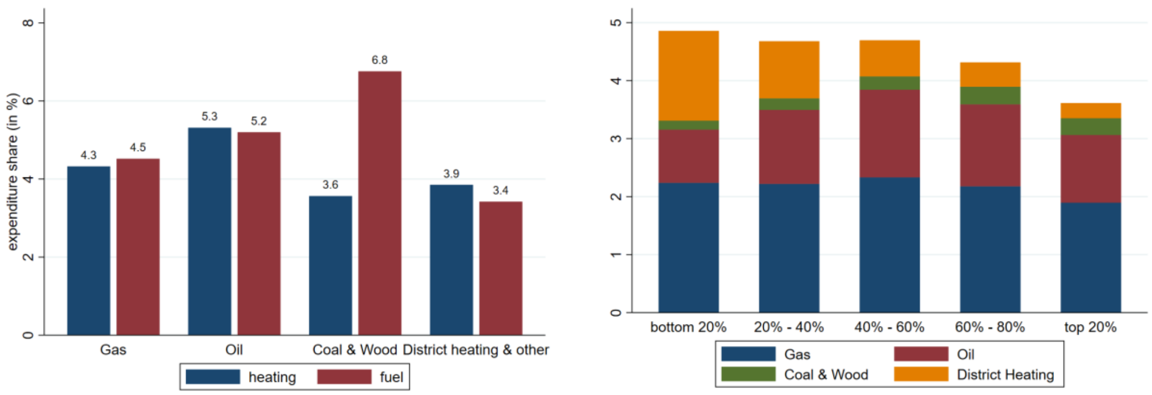
	Baqaee-Farhi (2021), full model	Simplified model, 10% oil, gas, coal shock	Simplified model, 30% gas shock
GDP, %	0.2-0.3	1.3	2.2
GNE, %	0.2-0.3	1.5	2.3
Cost per citizen	€80-120	€500-700	€800-1000

3. 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 1: Energy expenditure shares



(a) By heating source (b) By income

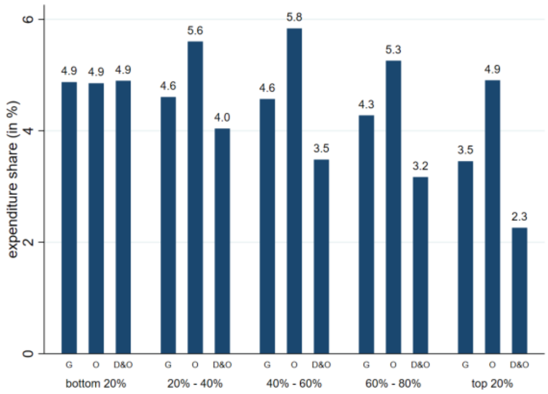
Notes: Left panel shows expenditure shares for all households by type of heating for heating (blue bars) and for fuel (red bars). Right panel shows energy expenditure shares for different heating sources along the income distribution.

Figure 1 shows the expenditure shares depending on the main source of heating (a, left panel) and by income quintiles (b, right panel) 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 and 5 percent and car fuel varies between 3.4 and 5.3 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

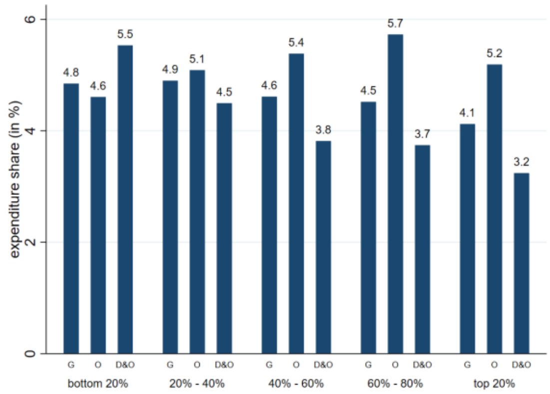
Figure 1b. Changes in expenditure for this heating source can also arise, however, as only 17.4% are estimated to be generated from renewable energy.[2] What is striking is the fact that the income gradient in the expenditure share for heating is small. Potentially, differences in household size might be a confounding factor here. Therefore, Figure 2 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 2 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.

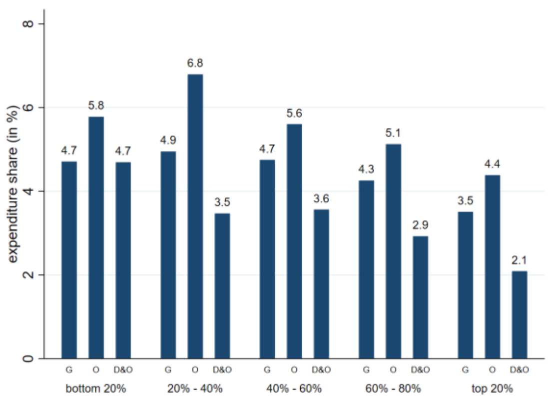
Figure 2: Heating expenditure shares by income, heating source, and household size

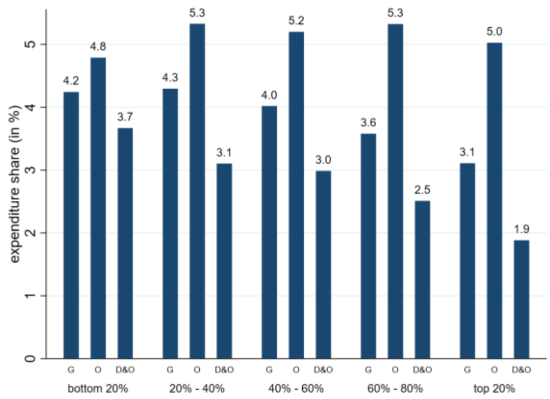


(a) All households



(b) 1-person households





[2] https://www.bdew.de/online-magazin-zweitausend50/schwerpunkt-netze/fernwaerme-waermenetze-fuer-die-energiewende/

(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.

4. Policy implications

The discussion above shows that the macroeconomic effects highly depend on how much the production structure can adjust to the reduction of fossil energy imports and on how substitutable these imports from Russia are in terms of replacing them by imports from other suppliers. In the very short run, this substitutability is of course limited and depends on the final usage of these fossil resources: electricity production can adjust quickly and at relatively low costs while replacing their material use, for example, will be more difficult up to impossible. 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 this year or in 2023 should push come to shove. While the currently high energy prices create some adjustment incentives, existing insurance schemes (e.g., emergency rationing plans for gas to favour households, expected bail outs for affected industries), have a tendency to lull decision makers in industry and households into not fully internalising potential costs of delaying their adjustments, and instead might induce them to gamble on a no-embargo scenario with a normalisation of energy prices. This, in turn, might severely limit political options to strengthen the sanctions regime down the road.

By the same token, if an embargo of Russian energy turns into a political necessity in the short-run, a case can be made that such action has the lowest economic costs if it is taken as early as possible. The main reason is the seasonality of gas demand. A cut-off from Russian gas over the summer months could be substituted from Norwegian and other sources, keeping industrial supply going. At the same time, such an early move would immediately trigger the substitution and reallocation dynamics that are central to reducing the economic costs. It has, however, to be taken into consideration whether it will be possible to fill up storage capacities during the summer if Russian imports are stopped now. A continuation of Russian gas imports today, might reduce uncertainty of whether this will be feasible. Otherwise, the economic costs of an embargo might be considerably higher and give additional leverage to Russia.

Absent imminent action, 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 even if no embargo realises. This could include, for example, some sort of “energy security levy” on natural gas. It also means that there should be a firm commitment to climate policy driven increases in energy prices. On the European level, this implies support of tightening the EU emission trading scheme as planned in the EU’s Fit for 55 Package. More importantly, however, this also makes a case for increasing German CO2-prices that are predominantly levied on mobility and heating. This would also prepare these sectors for the introduction of an EU emission trading system as intended in the EU Fit for 55 package.

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 realising, revenues from CO2-pricing and/or 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 if 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 under early completion. This includes encouraging private investors to privately assume risks, like when Tesla builds a factory without all constructions being finally approved by the public authorities. This will increase costs, but it is important to view these as an insurance premium. If no embargo realises, having LNG terminals ready earlier serves little purpose, but in case of an embargo, they are of great value. This also needs to be taken into account when designing the public processes of approving.

Let us close with more on the consequences of a potential embargo on the household sector, as much of the current discussion revolves around this topic. While power shortages or cold homes are highly unlikely, rising energy prices will be felt acutely. One concrete remedy could be to rebate (artificially) increased gas, oil and electricity prices through lump-sum payments. If not only poor households are targeted, these payments could be made independent of income purely on a per capita basis. This still would have regressive effects without impeding the incentives to reduce energy consumption. Alternatively, such a scheme could be carried out by gas or power providers who would then be compensated by the state. This would allow for the lump-sum payments to be based on actual past energy consumption. This would, however, also imply that higher income households who on average have higher absolute heating and electricity expenditures would receive more.

Other candidates for policies targeting especially poor households would be, for example, increasing the basic amount of social assistance payments ("Hartz IV Regelsatz") or the housing allowance. Also, lowering electricity prices through a reduction of the electricity tax would help poor households most and, at the same time, incentivize the use of increasingly green electricity in mobility and heating. Furthermore, regarding adjustments of the tax system, raising the basic allowance of the personal income tax is one of the measures suggested by the German governance. Increasing Hartz IV and the basic allowance of the personal income tax both by 5% (10%) each could result in total fiscal costs of approximately 5 (10) bn Euro per year while slightly reducing inequality and poverty.[3] This being said, a more targeted policy towards low-income households would likely be more cost effective and hence preferred - not only from an efficiency point of view but also a redistributive one.

In case of an actual embargo and consequently rising energy prices, additional energy price increasing measures should be dropped or adjusted. Payments to households would still be necessary to avoid economic hardship, but should be decreased over time to induce necessary investments and behavioural adjustments. Given their temporary nature, these payments could in the meantime be financed through government debt.

[3] See ifo microsimulation model.

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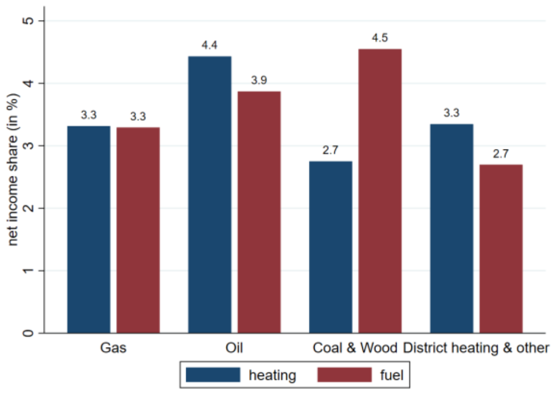
Appendix A

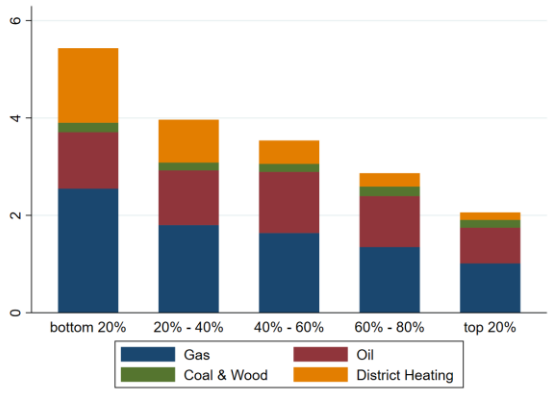
A Energy expenditure shares of income

In the main part of the analysis, we focus 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 (Dynan et al. 2004). Hence, we expect that the level of household expenditures as a fraction of income declines with income because income exceeds expenditures for most households while differences in expenditure shares of households increase because of different saving rates along the income distribution. Figure A presents the equivalent results to Figure 1 from the main text 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 A: Energy expenditure as share of household net income



(c) By heating source

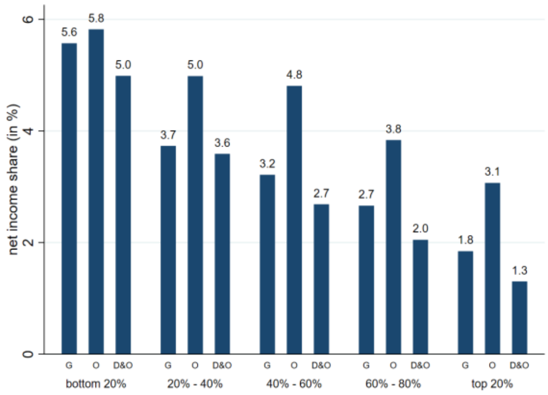


(d) By income

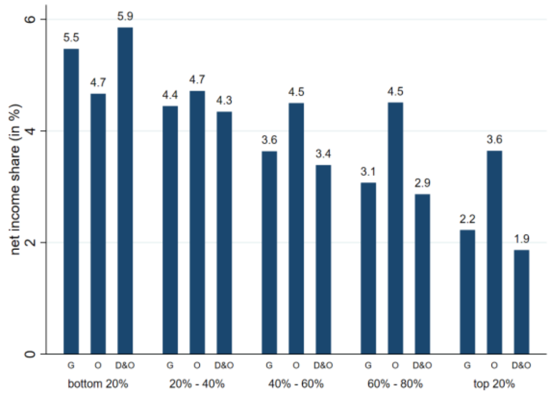
Notes: Left panel shows expenditure as a share of household net income for all households by type of heating for heating (blue bars) and for fuel (red bars). Right panel shows cost shares as a fraction of household net income for different heating sources along the income distribution.

Figure B repeats the results from Figure 2 of the main text 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 1 and Figure A apply: We find shares in income to be lower and we find a noticeable decline of the expenditure shares with income.

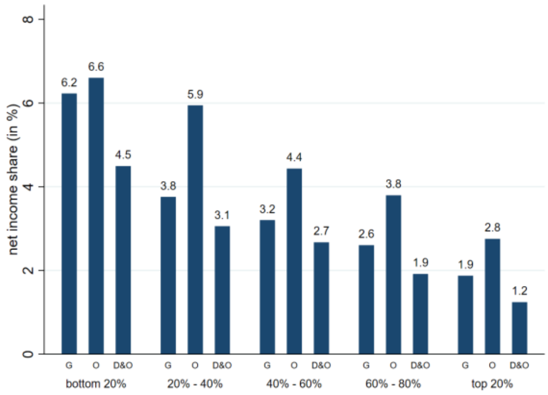
Figure B: heating expenditures as share of household net income by income, heating source, and household size



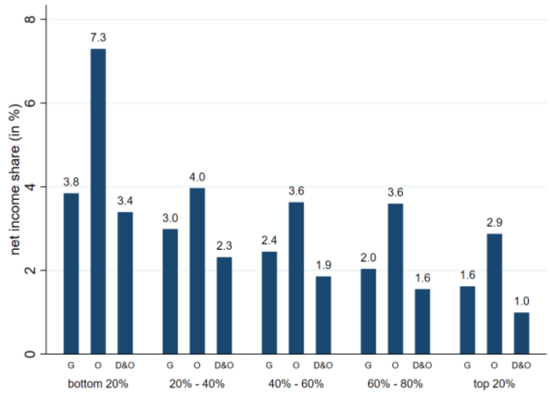
(a) All households



(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.

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

April 29, 2022

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

A Appendix to Section 2 "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 Baqaee and Farhi (2021) 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 Labandeira et al. (2017) provides a summary of the existing estimates on own-price elasticities for energy consumption differentiated between the short run (less than one year) and the long run (after one year). The relevant short-run average short-run elasticity for energy is -0.22, for natural gas it is -0.18, and the least elastic in the short run is heating oil with -0.02. Differences between residential and industrial consumers are small.

5. Even for elasticities of substitution below this range, the Baqaee-Farhi multi-sector model predicts modest losses of around 0.2-0.3% of German 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 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.

10. A supplement available at https://benjaminmoll.com/RussianGas_Substitution/ discusses in more detail the economic idea of substitution. We provide some historical real-world examples that demonstrate how firms do find ways to substitute in adversity (perhaps unexpectedly even for themselves). And we make 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.

11. A supplement available at https://benjaminmoll.com/RussianGas_Literature/ reviews other studies providing quantitative estimates of an import stop.

Replication materials for all results in section 2 as well as the empirical results in section 3 can be found here https://benjaminmoll.com/RussianGas_Replication/.

[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.

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]

Facts on the German economy's energy dependence:

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 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%).

5. Table 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 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 to be most affected by an import stop. It is

[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.

[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 $0.5 \times 73/3,175 \approx 1.2\%$

	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

Table 1: Gas usage and economic importance of broad sectors of German economy

Notes: The source for gas usage is BDEW (2021). 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.

	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			

Table 2: Key statistics for hardest hit industries

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

also important that the most affected industries were essentially completely shut down during the Covid-19 pandemic but would likely be able to continue operating to some extent after an import stop.

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 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 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 1 which plots production Y as a function of energy E for the Leontief case. For example, a drop

[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 2 and 3 below is available at `https://benjaminmoll.com/elasticity/`.

in energy supply of $\Delta \log E = -10\%$ implies a drop in production of $\Delta \log Y = -10\%$. Intuitively, the Leontief assumption means that energy is an extreme bottleneck in production: when energy supply falls by 10%, the same fraction 10% of the other factors of production X lose all their value (their marginal product drops to zero) and hence production Y falls by 10%.

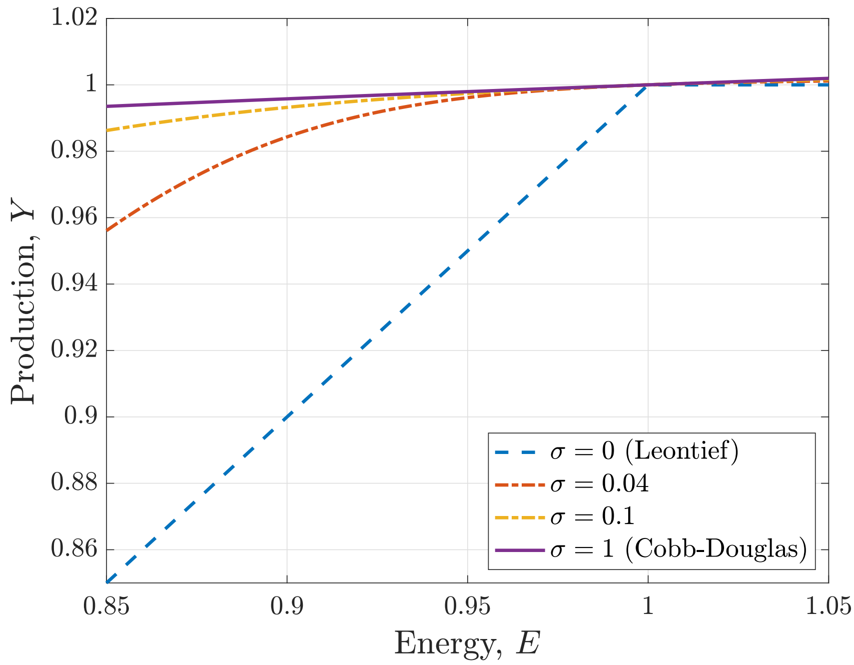


Figure 1: Output losses following a fall in energy supply for different elasticities of substitution

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)

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

where $\tilde{\alpha} = \frac{\alpha^{\frac{1}{\sigma}}}{\alpha^{\frac{1}{\sigma}} + (1-\alpha)^{\frac{1}{\sigma}}}$. 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 1 which plot 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

[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.

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.

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

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

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 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.

Labandeira et al. (2017) provide a comprehensive overview of the existing estimates in their meta-analysis of existing elasticity estimates for energy demand with a sample of estimates starting in the 1970s. Their analysis distinguishes carefully between short-run and long-run elasticity estimates where they consider all demand changes within one year as short-run 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, Labandeira et al. (2017) find an average short-run elasticity for natural gas of -0.18 and a long-run elasticity of -0.684. For heating oil, the average short- and long-run estimates across the 44 studies are -0.017 and -0.185, respectively. For the 376 studies that consider energy in general, the estimates are similar with a short-run elasticity of -0.221 and a long-run elasticity of -0.584. They also report differences between industrial consumers and residential consumers but the differences between consumer groups are within 10% of the average estimates.[10]

The paper by Auffhammer and Rubin (2018) provides cleanly identified residential household demand elasticities for natural gas. They find find price elasticities between -0.17 and -0.2 in line with the estimates for short-run demand elasticities in Labandeira et al. (2017). Notably price elasticities have a strong seasonal component. During the summer, Auffhammer and Rubin (2018) 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 Steinbuks (2012) focuses on energy demand elasticities in manufacturing. The study is particularly interesting as it considers in great detail also different production

[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 Labandeira et al. (2017)).

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 Labandeira et al. (2017).

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

A.5 Baqaee-Farhi Multi-Sector Open-Economy Model

A.5.1 Brief description of the model

We briefly describe the main features of the computational model of Baqaee and Farhi (2021). 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 Baqaee and Farhi (2021) 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 (Timmer et al., 2015). 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 Baqaee and Farhi (2021), 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 Baqaee and Farhi (2021) 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 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 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 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 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 Baqaee and Farhi (2021). 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 values we choose for θ, ε and σ. Table 3, panel A summarizes the parameter choices.

gas imports is also 30%.

Parameterization 1 is the same as Baqaee and Farhi (2021). Parameterizations 2 to 4 purposely pick lower elasticities, again in the spirit of being as conservative as possible.

Table 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 Baqaee and Farhi (2021) 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 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 (Timmer et al., 2015) and which are listed in Table 5 of Baqaee and Farhi (2021). 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 Bayer et al. (2022) shows that, even taking into account such demand effects, the overall costs would still remain below 3%.

Regarding point 1 about gas not being a separate input in the computational model, it is worth emphasizing again that the back-of-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%.

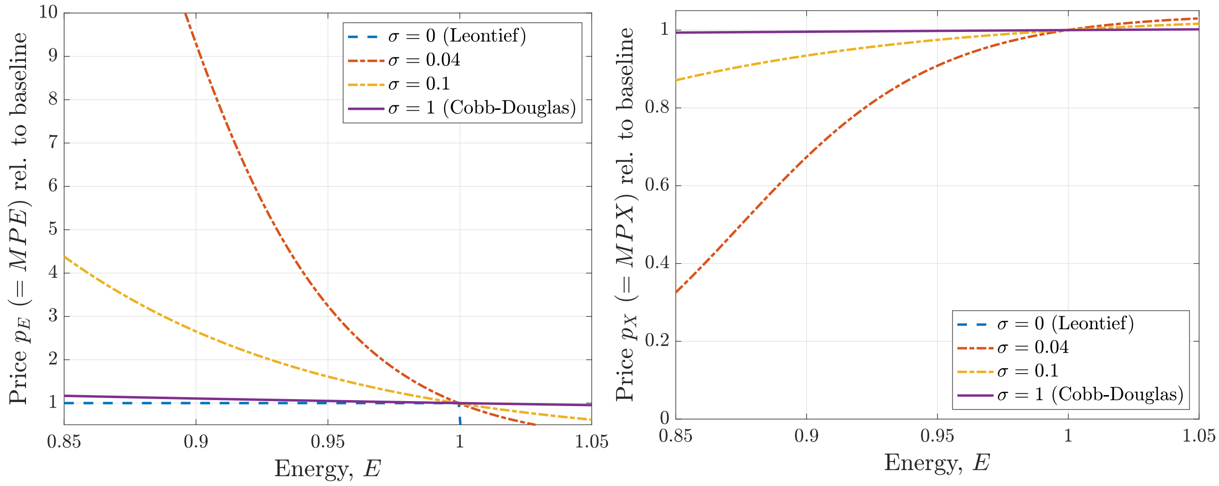
A.6.1 Leontief production $\sigma = 0$ makes nonsensical predictions

The blue dashed line in Figure 1 showed that output falls one-for-one with energy supply in the Leontief case. The blue dashed lines in Figures 2 and 3 plot additional implications of falling energy supply with Leontief production. Figure 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 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 2 and 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.



(a) Energy price

(b) Price of other inputs

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

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

Here we briefly explain 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 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

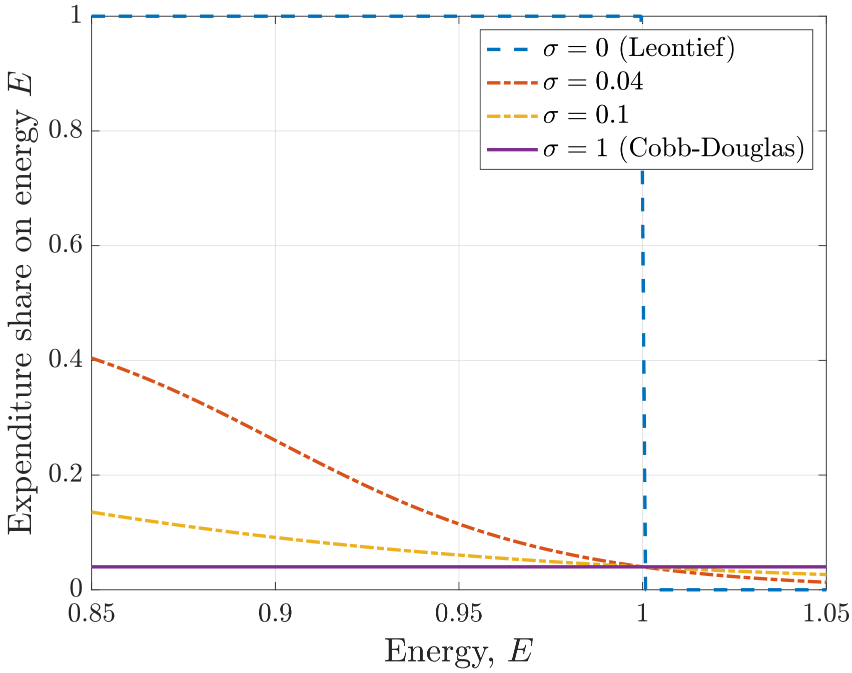


Figure 3: Expenditure share on energy following a fall in energy supply for different elasticities of substitution

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 (Bayer et al., 2022) shows that, even taking into account such demand effects, the overall costs would still remain below 3% of GDP.

A.8.2 Financial Amplification Effects

The model also does not include any financial amplification effects. For example, one could imagine that, in the event of an import stop, firms that are heavily gas-reliant could experience short-run liquidity problems and hits to their balance sheets. This may be the case even for firms that remain viable in the long-run because they are able to substitute for gas or other intermediate inputs affected by an import stop over time. In the event that such problems occur, policy should likely step in to minimize such financial amplification effects, 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:

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

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