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

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

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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 Baqaee 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 Baqaee-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  $\frac{3}{5}$  went to the steel industry and  $\frac{5}{8}$  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% <sup>§</sup>	26%	0%	0%	0%	30%

Notes: <sup>§</sup>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-intensive production of certain products by direct imports. In the medium and long term, increased use of renewable energy use and energy efficiency improvements can contribute significantly to lowering energy demand.

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

The IEA estimates that imports via pipeline to the EU from Norway, Algeria and Azerbaijan could be increased by 10 billion cubic meters (bcm) compared to 155 bcm imports from Russia in 2021, and LNG imports theoretically by 60 bmc (up from 110 bcm in 2021 (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). Liquefied 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.<sup>1</sup> 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

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<sup>1</sup> 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/tonne in the beginning of February 2022 to 345 USD/tonne 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  $\frac{1}{3}$  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 Baqaee 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

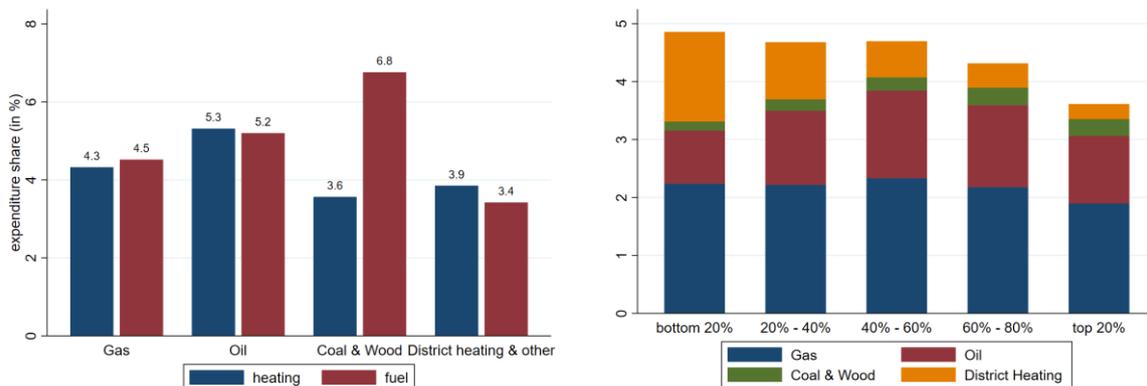
	Baqaee-Farhi (2021), full model	Simplified model, 10% oil, gas, coal shock	Simplified model, 30% gas shock
GDP, %	0.2-0.3	1.3	2.2
GNE, %	0.2-0.3	1.5	2.3
Cost per citizen	€80-120	€500-700	€800-1000

### 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

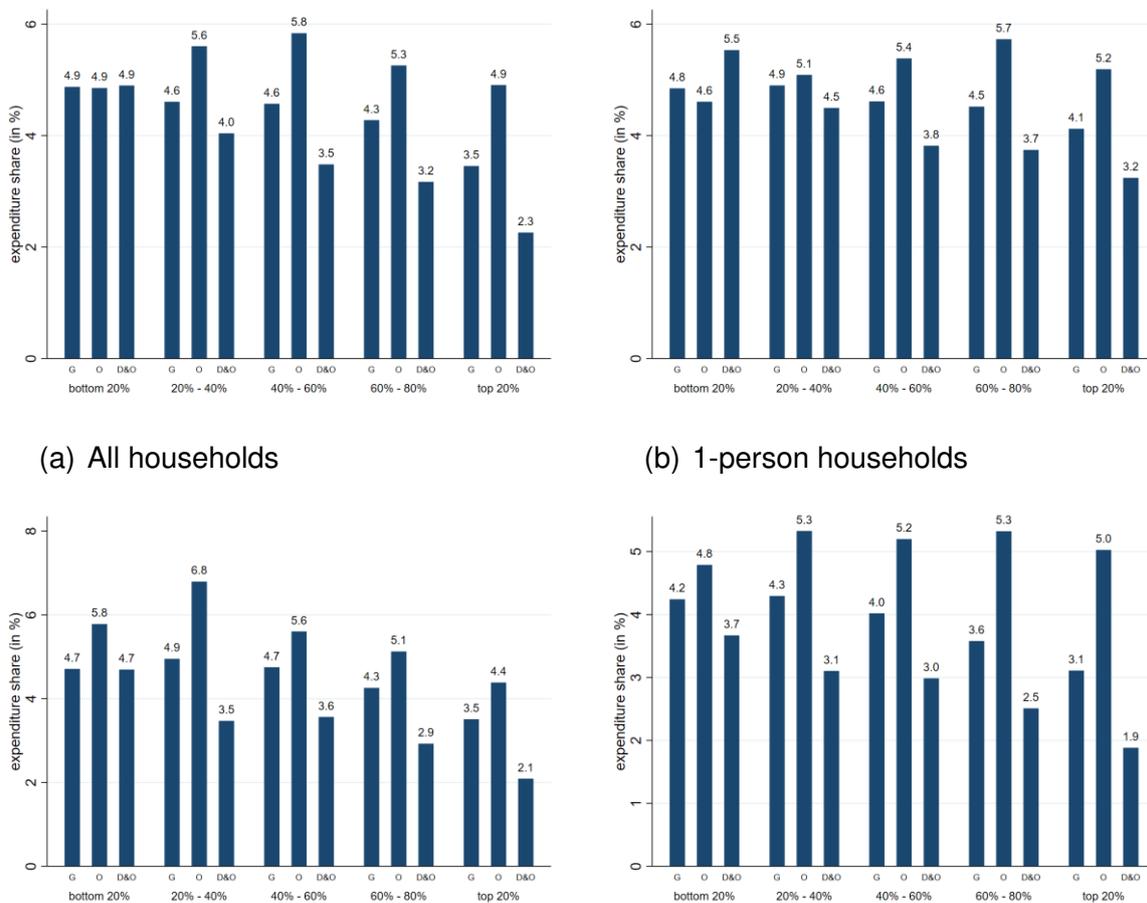
Notes: Left panel shows expenditure shares for all households by type of heating for heating (blue bars) and for fuel (red bars). Right panel shows energy expenditure shares for different heating sources along the income distribution.

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.<sup>2</sup> 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**



<sup>2</sup> <https://www.bdew.de/online-magazin-zweitausend50/schwerpunkt-netze/fernwaerme-waermetetze-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 CO<sub>2</sub>-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 CO<sub>2</sub>-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.<sup>3</sup> 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.

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<sup>3</sup> See ifo microsimulation model.

## References

- Agora Energiewende. 2022. "Die Energiewende in Deutschland: Stand Der Dinge 2021. Rückblick Auf Die Wesentlichen Entwicklungen sowie Ausblick auf 2022."
- Auffhammer, Maximilian, and Edward Rubin. 2018. "Natural gas price elasticities and optimal cost recovery under consumer heterogeneity: Evidence from 300 million natural gas bills." *NBER Working Paper No. 24295*. National Bureau of Economic Research.
- Baqae, David, and Emmanuel Farhi. 2021. Networks, Barriers, and Trade. Working Paper.
- BDEW. 2019. "Energy Market Germany 2019." BDEW Bundesverband der Energie- und Wasserwirtschaft e.V.
- . 2021. "Die Energieversorgung 2021 - Jahresbericht." BDEW Bundesverband der Energie- und Wasserwirtschaft e.V.
- Caballero, Ricardo J. 1994. "Small Sample Bias and Adjustment Costs." *The Review of Economics and Statistics* 76 (1): 52–58.
- Deryugina, Tatyana, Alexander MacKay, and Julian Reif. 2017. "The Long-Run Dynamics of Electricity Demand: Evidence from Municipal Aggregation." *NBER Working Paper No. 23483*. National Bureau of Economic Research.
- Dynan, Karen E., Jonathan Skinner, and Stephen P. Zeldes. 2004. "Do the Rich Save More?" *Journal of Political Economy* 112 (2): 397–444. <https://doi.org/10.1086/381475>.
- Eckert, Vera, and Kate Abnett. 2022. "Factbox: How Dependent Is Germany on Russian Gas?" Frankfurt, Brussels: Reuters. <https://www.reuters.com/world/europe/how-much-does-germany-need-russian-gas-2022-01-20/>.
- IEA. 2022. "A 10-Point Plan to Reduce the European Union's Reliance on Russian Natural Gas." Paris: IEA. <https://www.iea.org/reports/a-10-point-plan-to-reduce-the-european-unions-reliance-on-russian-natural-gas>.
- Labandeira, Xavier, Jose M. Labeaga, and Xiral Lopez-Otero. 2017. "A meta-analysis on the price elasticity of energy demand." *Energy Policy* 102: 549–568.
- McWilliams, Ben, Giovanni Sgaravatti, Simone Tagliapietra, and Georg Zachmann. 2022a. "Can Europe Survive Painlessly without Russian Gas?" *Bruegel*. February 27, 2022. <https://www.bruegel.org/2022/02/preparing-for-the-first-winter-without-russian-gas/>.
- . 2022b. "Preparing for the First Winter without Russian Gas." *Bruegel*. February 28, 2022. <https://www.bruegel.org/2022/02/preparing-for-the-first-winter-without-russian-gas/>.

McWilliams, Ben, Giovanni Sgaravatti, and Georg Zachmann. 2021. "European Natural Gas Imports." Bruegel Datasets, first published 29 October. Accessed March 3, 2022. <https://www.bruegel.org/publications/datasets/european-natural-gas-imports/>.

Neidell, Matthew, Shinsuke Uchida, and Marcella Veronesi. 2019. "Be Cautious with the Precautionary Principle: Evidence from Fukushima Daiichi Nuclear Accident." *IZA Discussion Paper* 12687.

Nesheiwat, Julia, and Jeffrey S. Cross. 2013. "Japan's Post-Fukushima Reconstruction: A Case Study for Implementation of Sustainable Energy Technologies." *Energy Policy* 60 (September): 509–19. <https://doi.org/10.1016/j.enpol.2013.04.065>.

Rashad, Marwa, and Isla Binnie. 2022. "Brimming European LNG Terminals Lack Room for More Gas." London, Madrid: Reuters. <https://www.reuters.com/business/energy/brimming-european-lng-terminals-have-limited-space-more-gas-2022-02-17/>.

Sandau, Fabian, Stephan Timme, Corinna Baumgarten, Rolf Beckers, Wolfgang Bretschneider, Sebastian Briem, Jörg Frauenstein, et al. 2021. "Daten Und Fakten Zu Braun- Und Steinkohlen." 28/2021. Texte. Umweltbundesamt.

Statistisches Bundesamt. 2022a. "Facts on Trade with Russia." Press release. Wiesbaden: Statistisches Bundesamt. [https://www.destatis.de/EN/Press/2022/02/PE22\\_N010\\_51.html](https://www.destatis.de/EN/Press/2022/02/PE22_N010_51.html).

———. 2022b. "Exporte Und Importe (Spezialhandel) Nach Güterabteilungen Des Güterverzeichnisses Für Produktionsstatistiken." Wiesbaden: Statistisches Bundesamt. <https://www.destatis.de/DE/Themen/Wirtschaft/Aussenhandel/Tabellen/einfuhr-ausfuhr-gueterabteilungen.html;jsessionid=7345586EA38C7821B58F6C63E9DAC7A2.live731>.

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

Umweltbundesamt. 2022. "Primärenergiegewinnung Und -Importe." Umweltbundesamt. <https://www.umweltbundesamt.de/daten/energie/primaerenergiegewinnung-importe>.

Wissenschaftliche Dienste des Deutschen Bundestages. 2019. "Erdölverbrauch in Deutschland." Dokumentation, WD 5 - 3000 - 033/19.

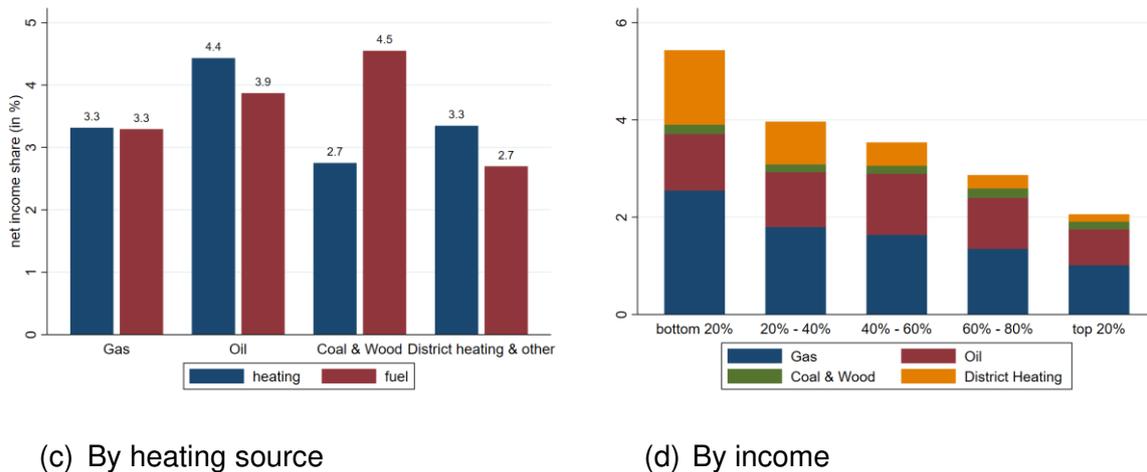
Zukunft Gas. 2022. "Erdgas in Deutschland: Zahlen Und Fakten Für Das Jahr 2021." Berlin: Zukunft Gas.

# 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 (Dyner 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.

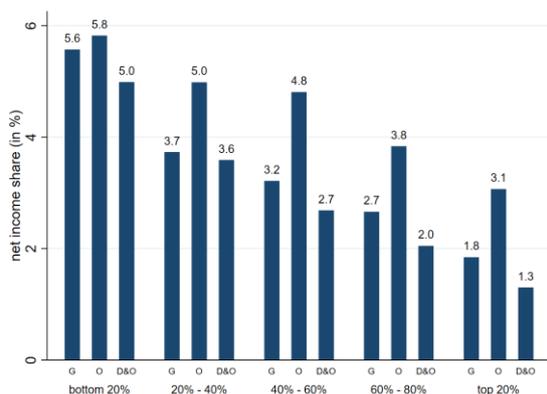
**Figure A: Energy expenditure as share of household net income**



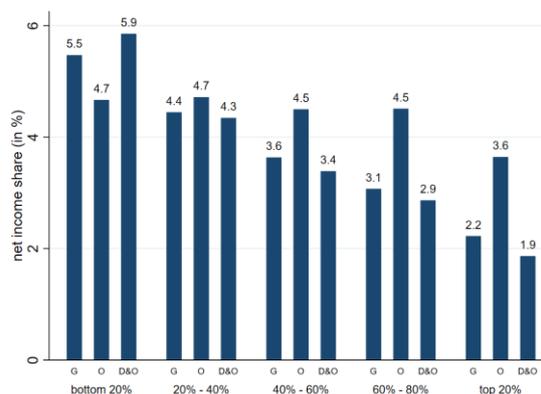
Notes: Left panel shows expenditure as a share of household net income for all households by type of heating for heating (blue bars) and for fuel (red bars). Right panel shows cost shares as a fraction of household net income for different heating sources along the income distribution.

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.

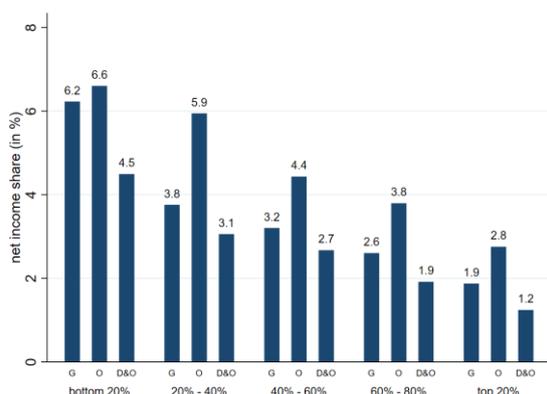
**Figure B: heating expenditures as share of household net income by income, heating source, and household size**



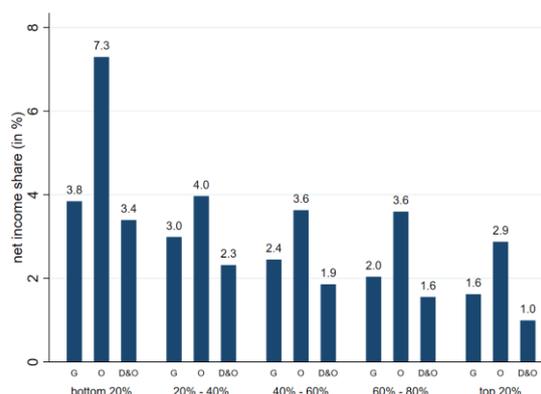
(a) All households



(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”

March 7, 2022

for latest version, see [https://benjaminmoll.com/RussianGas\\_Appendix/](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)<sup>1</sup> 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. 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.
2. 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.
3. 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.
4. 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)

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<sup>1</sup>Baqaee, David and Emmanuel Farhi (2021) “Networks, Barriers, and Trade”, Working Paper.

or around €80-120 per year per German citizen.<sup>2</sup> 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.

5. 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.
6. 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.
7. 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. We additionally assume German households do not substitute gas at all so that the shock falls entirely on firms and 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.
8. 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).

### **A.1 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

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

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<sup>2</sup>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.

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.<sup>3</sup> To this end, it is useful to specialize the production function further to a constant-elasticity of substitution (CES) production function

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

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.4 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  $\sigma$ , 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  $\sigma$  for a simple calibration of the parameter  $\alpha$  described in Appendix A.8.<sup>4</sup>

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

$$\Delta \log Y = \alpha \times \Delta \log E \quad (2)$$

Hence production  $Y$  declines with energy  $E$  but with an elasticity of only  $\alpha$ . In our calibration (see Appendix A.8) 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.8) reduces production by  $\Delta \log Y = 0.025 \times 0.1 = 0.0025 = 0.25\%$ . 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

$$\log Y = \Delta \log E \quad (3)$$

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 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

<sup>3</sup>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.4.

<sup>4</sup>The code for producing the figure as well as Figures 2 and 3 below is available at <https://benjaminmoll.com/elasticity/>.

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

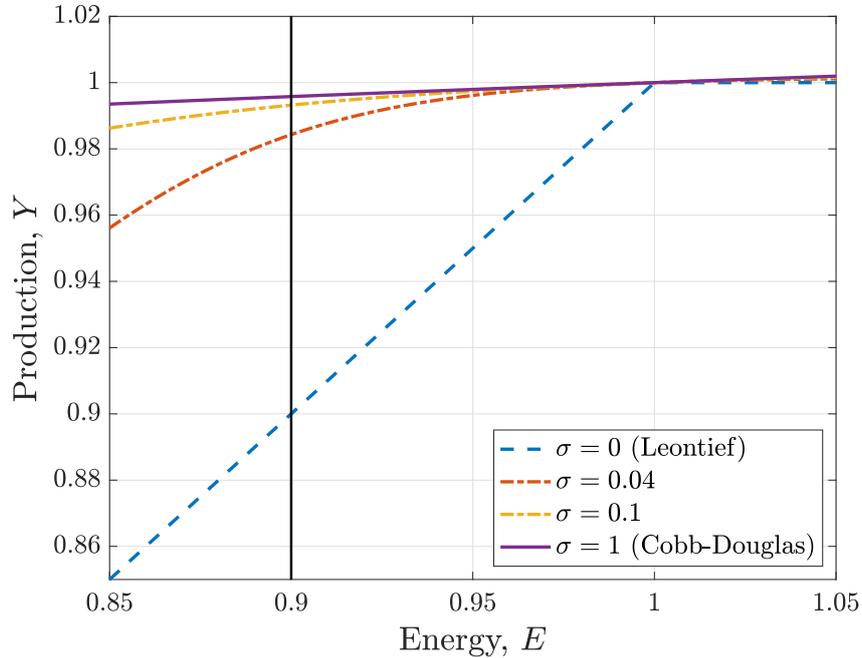


Figure 1: Output losses following a fall in energy supply for different elasticities of substitution

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

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

This approximation illustrates in a transparent fashion the importance of the elasticity of substitution  $\sigma$ . 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  $\sigma$ ).

One can also simply plot the production function for different values of  $\sigma$ . To this end, consider the red and yellow dash-dotted lines in Figure 1 which plots the cases  $\sigma = 0.04$  and  $\sigma = 0.1$ . Unsurprisingly, the two cases lie in between the cases  $\sigma = 0$  and  $\sigma = 1$ . Somewhat more interestingly, even though both of these two elasticities  $\sigma = 0.04$  and  $\sigma = 0.1$  are numerically close to zero, the figure reveals that the implications for the dependence of production on energy are potentially quite different from the Leontief case with  $\sigma = 0$ : even the case  $\sigma = 0.04$  lies considerably closer to the Cobb-Douglas case  $\sigma = 1$  than the Leontief case  $\sigma = 0$ . We will return to this point in Appendix A.5 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  $\alpha$  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.4 there is also another important de-

terminant 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.8 for the definition) satisfies  $\Delta \left( \frac{p_E E}{PY} \right) \approx \left( 1 - \frac{1}{\sigma} \right) \alpha (1 - \alpha) \Delta \log E$ .<sup>5</sup> Therefore, we can write (4) as

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

This formula says that the change in the energy expenditure share is informative about the elasticity of substitution  $\sigma$  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.5 below.

These examples show that, even in an extremely simple model like the one above, depending on the value of the elasticity of substitution  $\sigma$ , 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.2 Time-dependence of the elasticity of substitution.

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

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

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<sup>5</sup>For example in the Cobb-Douglas case  $\sigma = 1$ ,  $\frac{p_E E}{PY} = \alpha$  and so  $\Delta \left( \frac{p_E E}{PY} \right) = 0$ .

### A.3 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 short-run all demand changes within one year and otherwise as long run. In total, their sample contains 966 short-run elasticity estimates and 1010 long-run elasticity estimates and they report an average short-run elasticity of -0.236 and a long-run elasticity of -0.596. After dropping outliers the respective mean (median) elasticities are -0.186 (-0.140) and -0.524 (-0.429). Hence, the long-run elasticity is about three times larger than the short-run elasticity. Their meta-analysis controls then for characteristics of the respective study from which the elasticity estimate is taken. For the 230 studies that consider only natural gas and controlling for the characteristics of the studies, [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.<sup>6</sup>

The paper by [Auffhammer and Rubin \(2018\)](#) provides cleanly identified residential household demand elasticities for natural gas. They find price elasticities between -0.17 and -0.2 in line with the estimates for short-run demand elasticities in [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 elasticities during the winter months.

The analysis in [Steinbuks \(2012\)](#) focuses on energy demand elasticities in manufacturing. The study is particularly interesting as it considers in great detail also different production processes in the manufacturing production process such as heating, cooling, 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

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<sup>6</sup>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. \(2017\)](#)).

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  $\sigma$  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  $\sigma$ .

## A.4 Baqaee-Farhi (2021) Multi-Sector Open-Economy Model

### A.4.1 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. It 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. The model features a nested CES structure. Besides the input-output matrices, the key parameters of the model are the elasticities  $\sigma$ ,  $\theta$ ,  $\gamma$  and  $\varepsilon$

- $\sigma$  is the elasticity of substitution across consumption sectors (30 sectors)
- $\theta$  is the elasticity of substitution across value-added and intermediate inputs
- $\gamma$  is the elasticity of substitution across primary factors
- $\varepsilon$  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.4.2 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.4.3 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*

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

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

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

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.1. 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."

**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  $\Delta \log x_i^X = 0$ .<sup>7</sup> 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

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

<sup>7</sup>Alternatively, we could assume that  $\Delta \log x_i^X = 0$  in which case we have an upper bound on GNE losses:  $\Delta \log W \leq \frac{p_E m_E}{GNE} \Delta \log m_E$ .

Note that the approximation (7) takes exactly the same form as the approximation (5) for the simple model in appendix A.1. 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  $\Delta \frac{p_{ENE}^{EME}}{GNE}$  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%.<sup>8</sup>

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  $\Delta \frac{p_{ENE}^{EME}}{GNE}$ .<sup>9</sup> An extreme scenario would be that this share triples from 2.5% to 7.5%, i.e.  $\Delta \frac{p_{ENE}^{EME}}{GNE} = 5\%$ . 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  $\Delta \log m_E = -17\%$ .<sup>10</sup> Now assume that the GNE share of energy imports doubles from 2.5% to 5% so that  $\Delta \frac{p_{ENE}^{EME}}{GNE} = 2.5\%$ . 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 the computational results in Table 1 below.

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<sup>8</sup>German GNE is €3,175 billion (see World Bank, 2022 <https://data.worldbank.org/indicator/NE.DAB.TOTL.CN?locations=DE>) 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>)

<sup>9</sup>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.

<sup>10</sup>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  $10\%/60\% = 17\%$ .

#### A.4.4 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 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 1: German GNE losses predicted by Baqaee-Farhi multi-sector model

	<b>Parameterization 1</b> <b>(as in Baqaee-Farhi paper)</b>	<b>Parameterization 2</b> <b>(low elasticities)</b>	<b>Parameterization 3</b> <b>(very low elasticities)</b>
A. Parameter Values			
$\theta$	0.5	0.1	0.05
$\varepsilon$	0.2	0.2	0.05
B. German GNE Loss			
DEU	0.19%	0.22%	0.26%

We now turn to the parameterization of the elasticities  $\sigma, \theta, \gamma$  and  $\varepsilon$  we already discussed in appendix A.4.1. The elasticities  $\sigma$  and  $\gamma$  are less relevant for the question at hand and so we follow the baseline parameterization of Baqaee and Farhi (2021), setting them to  $\sigma = 0.9$  and  $\gamma = 0.5$ . In contrast, the elasticities  $\theta$  and  $\varepsilon$  are extremely important. We therefore present computational results for three different parameterizations that differ according to the values we choose for  $\theta$  and  $\varepsilon$ . Table 1, panel A summarizes the parameter choices. Parameterization 1 is the same as Baqaee and Farhi (2021). Parameterizations 2 and 3 purposely pick lower elasticities, again in the spirit of being as conservative as possible.

Table 1, 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 parameterization 3 GNE losses rise to 0.26%. 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 Extreme scenarios with low elasticities of substitution and why Leontief production at the macro level is nonsensical

As discussed in section A.4, our simulations 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 around 0.2-0.3%.

However, we have also seen in Section A.1 that *in principle* these losses can be much larger: if the elasticity of substitution  $\sigma$  between brown energy and other inputs is literally zero (Leontief) then production falls one-for-one with energy supply. We here 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.1, a reasonable worst-case scenario may be the case  $\sigma = 0.04$ , i.e. values of  $\sigma$  below 0.04 are nonsensical. An elasticity of 0.04 is also very conservative compared to the empirical evidence in appendix A.3.
4. In this extreme case with  $\sigma = 0.04$ , the simple model predicts output losses following a -10% energy supply shock of 1.5%.

### A.5.1 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.5.2 What values of $\sigma$ 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  $\sigma$  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.1, a reasonable worst-case scenario may be the case  $\sigma = 0.04$ : lower values of  $\sigma$  yield nonsensical results.

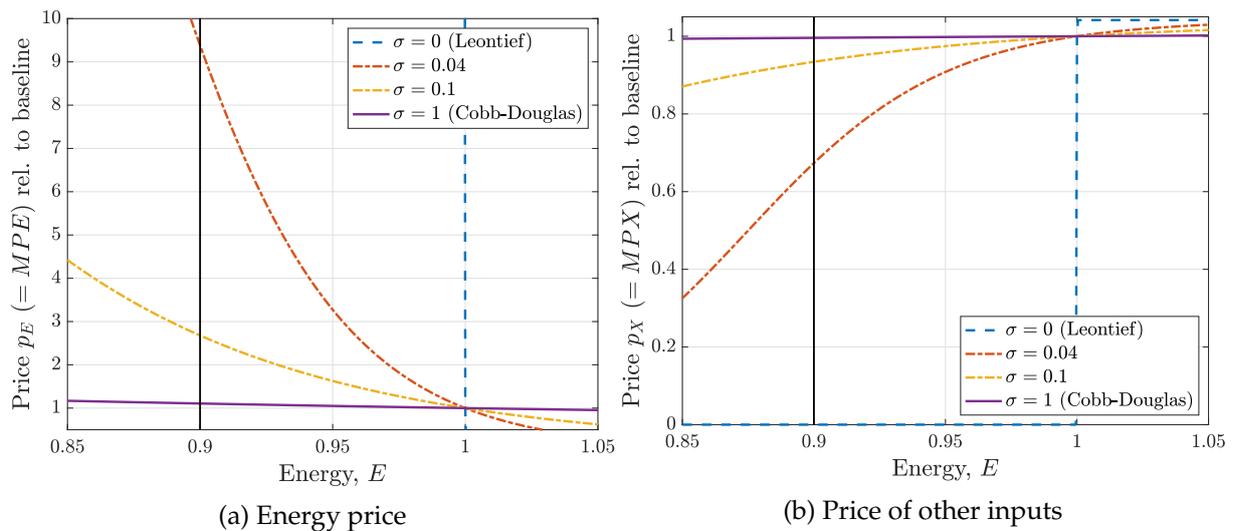


Figure 2: Price of energy and other inputs following a fall in energy supply for different elasticities of substitution

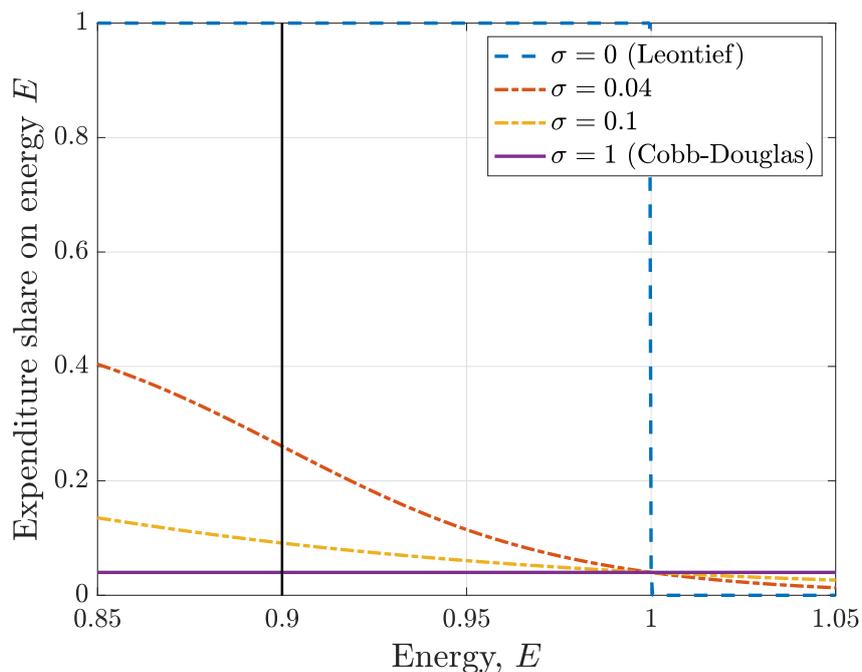


Figure 3: Expenditure share on energy following a fall in energy supply for different elasticities of substitution

### A.5.3 Economic losses in this worst-case scenario

Figure 1 plots the output loss for this worst-case scenario with  $\sigma = 0.04$ . For the calibrated energy supply shock of 10% (see Appendix A.8), the implied output loss is 1.5%. While Lemma 1 showed that, to first and second order, input-output linkages only amplify GNE losses to the extent that they show up in changes in the GNE share of energy imports, these may in principle be important in a fully non-linear analysis. Purely in the spirit of being conservative, we therefore postulate a worst-case scenario that doubles the number without input-output linkages from 1.5% to 3% or €1,200 per year per German citizen. This number is an order of magnitude higher than the 0.2-0.3% or €80-120 implied by the Baqaee-Farhi model. We should emphasize that this is an extreme scenario and we consider economic losses as predicted by the Baqaee-Farhi model to be the more likely outcome.

## A.6 Gas as a separate input that cannot be substituted with oil and coal

### A.6.1 No gas substitution by households so that shock falls entirely on firms

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 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. The resulting savings of gas currently used for electricity generation free up close to 20% of total German gas consumption. Households, industry, services will have to cope with a reduction in aggregate gas supply of 30%. Households account for about one third of total gas consumption and services for 15%. 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, 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". We use an elasticity of  $\sigma = 0.1$  which lies considerably below the range estimated in the literature (e.g. Steinbuks, 2010, estimates an elasticity of 0.16 to 0.5)

## **A.7 Mechanisms outside the model and worst-case scenario**

### **A.7.1 Keynesian Demand Effects**

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. 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 e.g. 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

## A.8 Calibration of Simple CES Production Function in Appendix A.1

**Energy supply shock.** We map a stop of Russian energy imports into a negative 10% energy supply shock. The reasoning was explained in Section 1: Imports of oil and coal from Russia can be substituted at world market prices by imports from other countries, leaving a residual of 15% of German energy consumption depending directly on Russian gas. 5% of these 15% can likely be substituted but this leaves shortfall of about 10% of energy consumption.

**Calibration of  $\alpha$ .** We choose the parameter  $\alpha$  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%.<sup>11</sup> 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  $\sigma$ , i.e. we can vary  $\sigma$  while always matching this import share by construction.

Cost minimization of (1) implies the following optimal factor demands

$$E = \frac{\alpha p_E^{-\sigma}}{\alpha p_E^{1-\sigma} + (1-\alpha)p_X^{1-\sigma}} PY, \quad X = \frac{(1-\alpha)p_X^{-\sigma}}{\alpha p_E^{1-\sigma} + (1-\alpha)p_X^{1-\sigma}} PY \quad (8)$$

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

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

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

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

To match the GNE share of energy imports of 4% 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  $\sigma$ .

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<sup>11</sup>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 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.

## A.9 Proof of Lemma 1

Using the notation of Baqaee and Farhi (2021) and appendix A.4 we have

$$d \log W = \sum_i b_i d \log c_i, \quad y_i = c_i + \sum_{j \in D} x_{ji} + x_i^E$$

$$d \log c_i = \frac{p_i y_i}{p_i c_i} d \log y_i - \sum_j \frac{p_i x_{ji}}{p_i c_i} d \log x_{ji} - \frac{p_i x_i^X}{p_i c_i} d \log x_i^X, \quad d \log y_i = \sum_{j \in D} \frac{p_j x_{ij}}{p_i y_i} d \log x_{ij} + \sum_{j \notin D} \frac{p_j x_{ij}}{p_i y_i} d \log x_{ij}$$

Then

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

## References

**Auffhammer, Maximilian and Edward Rubin**, "Natural gas price elasticities and optimal cost recovery under consumer heterogeneity: Evidence from 300 million natural gas bills," Technical Report, National Bureau of Economic Research 2018.

**Labandeira, Xavier, Jose M. Labeaga, and Xiral Lopez-Otero**, "A meta-analysis on the price elasticity of energy demand," *Energy Policy*, 2017, 102, 549–568.

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