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A Silver Lining? The European Energy Crisis through the Lens of Directed Technical Change

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ABSTRACT: This paper examines how productivity dynamics and, as a consequence, potential output, are affected by energy price shocks. We do this through the lens of a model of endogenous technical change where firms adjust their investment in non-energy productivity and energy productivity in reaction to the economic environment. Higher energy prices prompt a shift in investment from enhancing non-energy (capital and labor) productivity to improving energy efficiency. The resulting gains in energy efficiency act as an important macroeconomic buffer, but cannot fully offset the adverse input price effect and the transitional cost of shifting investment away from non-energy productivity. We thus find that the change in European energy prices following the 2022 shock reduces the *level* of euro area potential GDP by 0.8 percent by 2027. The impact on potential *growth* is temporary, and will have dissipated by that time. Energy efficiency itself is projected to rise by about three percent, offering a silver lining to the crisis. We estimate that the output effect would have been around two-thirds larger had energy efficiency not cushioned the impact of the price shock.

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WORKING PAPERS

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Contents

Executive Summary

This paper investigates how the sharp rise in energy prices following the 2022 European energy crisis has affected productivity and potential output in the euro area. We do this through the lens of a model of directed technical change where firms respond to higher energy prices by reallocating investment from non-energy productivity toward energy productivity. While this shift helps mitigate the economic impact of the shock, it cannot fully offset it - at least in the short- to medium-term - and comes with its own cost as non-energy productivity is negatively affected.

The model estimates suggest that the 2022 energy price shock will reduce euro area potential GDP by 0.8 percent by 2027. The impact on potential growth is temporary, however, and is expected to have faded by 2027. Importantly, energy efficiency is projected to rise by approximately three percent. Without this improvement in energy efficiency, the decline in potential output would have been two-thirds larger.

The paper also highlights that the effect of the shock varies across countries. Italy and Germany are expected to experience larger declines in potential output, at around 1.2 and 0.9 percent, respectively, while Spain and France are less affected, with losses of 0.6 and 0.4 percent. These differences are due to variations in energy mix, substitution elasticities, and investment responsiveness

Finally, we find that the volatility of energy prices matters: an exogenous shock that results in a gradual increase in prices results in a much smaller output loss compared to the sharp exogenous price spike observed in 2022.

The findings of this paper re-enforce policy implications set out in recent IMF work. Rather than suppressing energy price movements through subsidies, which can dampen incentives for innovation, policies that reduce underlying energy price volatility and support long-term investment in energy-saving technologies are important. Moreover, the productivity tradeoff identified in the model—where gains in energy efficiency come at the cost of non-energy productivity—highlights the need for complementary reforms in Europe. These include national-level structural reforms, deeper integration of the EU single market, and coordinated public investment at the EU level to revitalize Europe's long-term productivity growth.

I. Introduction

This paper contributes to a growing literature on the productivity and potential output effects of energy price shocks. Key papers by Acemoglu (2002b) and Hassler, Krusell, and Olovsson (2021), among others, provide the theoretical basis for modeling directed technical change in response to resource scarcity, including energy. Our approach extends this framework by jointly modeling non-energy and energy productivity responses to price shocks in a European context. Concretely, our contribution lies in quantifying the medium-term potential output effects of the 2022 energy price shock for the euro area. This leads us to highlight the role of energy efficiency (gains) as a macroeconomic buffer.

The 2022 energy price shock was the largest increase in fossil fuel prices in advanced economies, particularly in Europe, since the 1970s. In the summer of 2022, European natural gas prices briefly surged to more than ten times their early 2021 levels and by mid-2025, gas prices remained twice their historical average. In nominal terms, European fossil fuel prices more broadly are expected to stay higher and more volatile than prior to 2022 well into the medium term. Adjusting for inflation, pricing in futures markets as of mid-2025 suggests that a composite index of European fossil fuel prices (crude oil, natural gas and coal) will return to its pre-pandemic average by 2027, after a multi-year deviation to the upside.

Early estimates of the output impact of the 2022 shock focused mainly on the short-run. As part of their analysis of the gas shock for Germany, Lan, Sher, and Zhou (2022) provide a comprehensive review of that literature and the modeling assumptions used.[2] Most studies adopt a sectoral input-output framework (including or not additional demand-side channels) while typically treating productivity as exogenous. The resulting estimates vary widely, reflecting, at the core, a high degree of uncertainty around various elasticities of substitution.[3] These include the ease with which Russian gas could be replaced with other sources, the extent to which gas-dependent production processes could switch to alternative inputs, and how these changes would cascade through the economy.[4]

In this paper, we approach the question by focusing on the endogenous dynamics of productivity, across different inputs. This comes at the cost of our model operating at an aggregate level and not capturing sectoral or input-output dynamics - our work should thus be seen as complementary to analyses at a more disaggregated level. By incorporating endogenous technical change, our model captures a key adjustment channel: rising energy efficiency. Improved energy efficiency comes at a cost, however, as resources are diverted from improving other technologies, and reallocation entails transition frictions.

Our framework can to some degree reconcile different views on the elasticity of substitution between energy and other inputs. We argue that while the elasticity of substitution is likely very low in the short run, it endogenously rises in the medium term depending on the degree of firm investment in energy efficiency, thus limiting the output effect of energy price shocks.

[2] Whenever a paper relied on comparative statics from trade models, strictly speaking the estimated effects refer to the long-run, but were sometimes assumed to apply at a one or two year horizon. Many early studies zoomed in specifically on the impact of a hypothetical complete shut-off of Russian pipeline gas supply to Europe (a quantity shock).

[3] Assuming low elasticities of substitution, the economic effect of a full shutoff of Russian gas was esti- mated in some studies to be as high as 6 percent of GDP for Germany (e.g., Bundesbank (2022); Krebs (2022)) and over 2 percent of GDP for the European Union (e.g. Oxford Economics (2022); European Commission (2022)). Other studies such as Bachmann and others (2022) argued that substitution possibilities across sectors and countries would limit the aggregate output impact of even very severe increases in natural gas prices (Bachmann and others (2024) updates their earlier work with some additional ex post analysis).

[4] Also see DiBella and others (2024) for modeling work on how estimates of the impact of a full Russian gas shutoff change depending on whether infrastructure bottlenecks are assumed to be binding and whether demand-side trade spillovers are included. In a recent empirical contribution studying the link between energy prices and productivity, André and others (2023) find that less energy-intensive firms can benefit from moderate energy price increases through an investment channel.

Our starting point is the work by Hassler, Krusell, and Olovsson (2021) who show that historical US data patterns can be matched by a production function which explicitly allows for an energy efficiency (energy productivity) parameter.[5] [6] They also show that in US data, the energy (fossil fuels) share of income strongly co-moves with prices, suggesting a very low (short-run) elasticity of substitution between energy and other factors of production. At the same time, over a longer time horizon the energy share is rather stable, with the energy intensity of production decreasing almost continuously since the 1970s.[7]

The same data patterns as in the US also hold for Europe, with energy consumption and real output rising at a similar speed prior to the 1970s oil price shocks and decoupling thereafter. Looking more closely at data from the last few years, there appears to have been another step up in energy efficiency following the 2022 energy price shock.

Motivated by these stylized facts, we specify an endogenous growth model based on Hassler, Krusell, and Olovsson (2021). Using the relative prices and quantities of energy, capital and labour across European countries, we then estimate that the short-run elasticity of substitution between energy and other inputs for European countries is very low at 0.04-0.06. The two values come from different approaches (an empirical specification derived as the reduced form of the optimized production function, and the model parameter estimate obtained using Bayesian methods, respectively) but reassuringly are close to each other. We estimate that the elasticity of substitution increases to 0.3 in the medium term. These results are qualitatively in line with the recent literature estimating energy substitution elasticities at the macro and micro level (see for instance, Jo (2025) and Papageorgiou, Saam, and Schulte (2017)).

We then use the calibrated and estimated model to simulate the impact of higher energy prices since 2022 for the euro area. We consider three different price scenarios. The baseline price scenario corresponds to how energy prices developed over 2022-24 and how they are projected to develop over 2025-27 (according to futures prices as of July 2025). We also study the impact of a "severe" shock that corresponds to price expectations during the winter of 2023 while an "extreme" shock corresponds to futures pricing at the peak of the 2022 crisis.[8] Comparing the baseline shock with the severe and extreme ones sheds light on how much larger the estimated loss in potential output would have been had global and European natural gas and broader energy markets not been able to adjust to the loss of supply better than originally expected.

For the euro area aggregate, the estimated impact on potential output - holding other factors constant - ranges from a decline of 0.8 percent by 2027 in the baseline shock scenario to a drop of 2.2 percent in the "extreme shock" scenario. Given that the baseline shock corresponds to actual and currently expected price developments, a number somewhat under 1 percent is the model's most plausible estimate of the potential output loss from the 2022 energy crisis.[9] Although this is a significant decline, the impact would have nearly tripled if futures prices from autumn 2022 had materialized.

[5] The work by Hassler, Krusell, and Olovsson (2021) itself builds on a long tradition of endogenous technical change work, especially the strand related to the energy sector such as Acemoglu and others (2012). Hanlon (2015) provides empirical evidence on the causal link from resource scarcity shocks to input saving technological progress. Aghion and others (2016) study technological change in the car sector and show that firms react to higher fuel prices by increasing clean innovation (and there is path dependency in clean/dirty innovation).

[6] A related relevant literature studies the impact of carbon pricing on output and energy and carbon efficiency of production (see for example, IMF (2023). Using firm level administrative data, Colmer and others (2025) show that the European Union's Emissions Trading System (EU-ETS) significantly reduced emissions of manufacturing firms without changing output. This is achieved through targeted investments that reduced the emissions intensity of production. Germeshausen (2020) shows that fossil power plants in Ger- many improved the efficiency with which they use fuel in reaction to the EU-ETS. Calel and Dechezleprêtre (2016) document an increase in low-carbon innovation in reaction to the EU-ETS.

[7] While Hassler, Krusell, and Olovsson (2021) focus on the role of energy price shocks - an approach that we follow - Känzig and Williamson (2024) take the view that energy-saving technology shocks - which they define as being orthogonal to energy price shocks - are needed to rationalize the data.

[8] We later sometimes label the baseline scenario as the "large" shock, to highlight that it was a historically important shock, but less adverse than the two alternative scenarios considered.

[9] When trying to compare the estimated potential output effect given in this paper to changes in macroeconomic projections such as the IMF's World Economic Outlook (IMF WEO), it is important to recall that the numbers given here are ceteris paribus. Other changes over the past few years (e.g. infrastructure and spending packages) are also affecting the WEO projections of potential growth.

For a more general understanding of the relationship between energy prices and potential output, it is also instructive to compare the baseline shock to the severe one. The loss in potential output in 2027 is 0.5 percentage points larger in the latter, for an energy price path that is about 30 percent higher each year over a five year period. This implies that movements in the energy price basket that are below 10 percent, and that last for only a year or two, have negligible effects on euro area potential output.

Note that the above estimates all refer to potential output *level* effects. We show that in the model framework the potential *growth* effect in the baseline scenario is concentrated in the first years and will have faded by 2027 as the economy returns to its balanced growth path. At the same time, energy efficiency will have increased by 3 percent relative to the no-shock counterfactual by 2027.

To lay out the model intuition it is informative to first consider what would happen without directed technical change. The shock increases the price of energy, one of the inputs to production. Without directed technical change, the amount of energy required to produce a given level of output remains unchanged. Given that energy is difficult to substitute (i.e., it has a low elasticity of substitution), output drops. With directed technical change, higher energy prices prompt a shift in investment from enhancing capital-labor productivity to improving energy efficiency. This shift results in lower productivity of the capital- labor composite but higher energy efficiency relative to the balanced growth path.[10]10 In the short to medium term, such energy efficiency gains cannot fully offset the adverse price effect and the transitional cost of shifting investment from capital-labor productivity to energy productivity. While the shock is attenuated relative to a situation without directed technical change, potential growth and output still drop compared to a no-energy shock scenario. Over the long run, the economy is expected to adjust and return to the balanced growth path, but the temporary deviation from the balanced path will lead to a permanent output loss.

How large was the cushioning effect of increased energy efficiency? We estimate that if the responsiveness of energy efficiency to price shocks had been 80 percent lower, the euro area's potential output loss from the energy price shock would have been around two-thirds larger (i.e. there would be a drop of around 1.3 percent in euro area potential output by 2027).

To explore cross-country heterogeneity, we re-run the simulations under the baseline price shock scenario individually for the four largest euro area economies (France, Germany, Italy and Spain). The drop in potential output by 2027 is estimated to be highest in Italy at around 1.2 percent, followed by Germany at 0.9 percent, and then Spain and France at 0.6 and 0.4 percent, respectively, due to a different energy mix (and hence price shock) and different estimated elasticities of substitution and investment efficiencies.

We also compare the impact of the extreme price shock to the impact of an exogenous shock that smoothly increases fossil fuel prices over several years to yield the same energy price endpoint by 2027. We find that the impact on potential output is more than four times smaller with the gradual price increase. This is because larger price movements, coupled with the transition costs of abruptly switching investment from capital-labor saving to energy saving, entail larger deviations from the balanced growth path. This suggests that a lower volatility of energy prices (understood in a low-frequency sense here given the model is annual), and absence of sharp price spikes, has its own benefits over the medium term. In the long run, however, the level of potential output converges between the two scenarios, given the economy faces the same steady state energy prices in both cases.

Fuel switching or sectoral reallocation are two possible confounding factors for our ana- lysis. Fossil energy price increases can lead to substitution, both between fossil fuels and towards other sources of energy. The so-called Messmer plan in France following the 1973 oil price shock is a famous example, where the government decided to redirect research and resources towards the roll out of a large scale nuclear energy program as a result of higher energy prices. This is exactly the logic of our argument, except that rather than investing in energy efficiency, the investment went to non-fossil fuel energy. In line with this, Hassler, Krusell, and Olovsson (2022) show that explicitly

[10] "Non-energy productivity" and "capital-labor productivity" are used interchangeably, as are "energy productivity" and "energy efficiency".

incorporating renewables into their model does not qualitatively change the model implications but energy efficiency investments are directed towards renewables.

In terms of sectoral reallocation, it could be a confounder in so far as aggregate energy efficiency gains could be driven by composition effects rather than a reduction in energy use per unit of value added at the sectoral or even firm level. This cannot be ruled out, especially at highly disaggregated levels without the use of comprehensive microdata, but the available sectoral level data suggests that energy efficiency gains have played a key role in reduced energy consumption in 2022 and 2023.

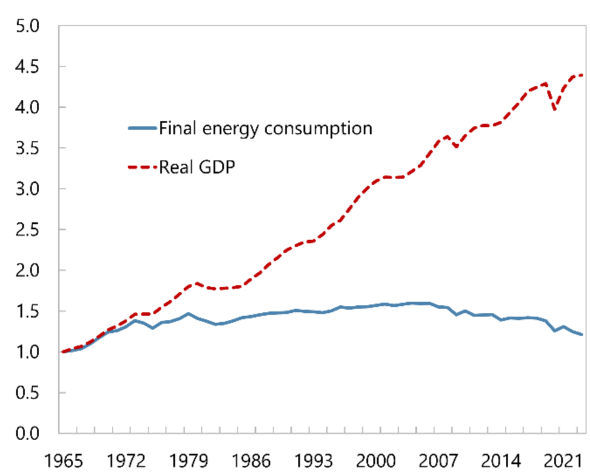
Finally, it is worth noting that at the time of the energy price shock, energy efficiency was a stated policy goal in the European Union - as, for example, set out in the EU's directive on energy efficiency. The results we discuss in this paper thus have to be considered as conditional on this policy environment.

The remainder of the paper proceeds as follows. Section presents empirical evidence on the magnitude of the 2022 energy price shock and the observed changes in energy efficiency across Europe. The model is presented in section III. The simulated impact of the energy price shock on potential output at the euro area level and for individual euro area countries is shown in IV. Finally we discuss a few caveats at the end of the results section before concluding with policy implications in section V.

II. Stylized Facts

In this section we make the case that energy efficiency is an important, and endogenous, economic parameter and that in response to high energy prices, firms increase energy efficiency. This is supported by data on energy efficiency around the time of the oil price shock of the 1970s and the natural gas price shock in Europe in 2022, recent firm surveys and previous literature.

Figure 1. Real GDP and Energy Consumption in Europe (1965-2019)
(Index, 1965=1)



Sources: Penn World Tables and 2024 Energy Institute Statistical Review.
Note: Europe here is the sum of France, Germany, Italy and the UK.

As noted among others by Hassler, Krusell, and Olovsson (2021) and Känzig and Williamson (2024), in the United States output growth started to decouple from energy consumption growth following the oil price shocks of the 1970s. Figure 1 restates the point for Europe, using data available since 1965. As can be seen, GDP and energy consumption grew at a similar speed prior to the oil price shocks, but energy consumption flat-lined thereafter even as GDP continued to grow.[11]

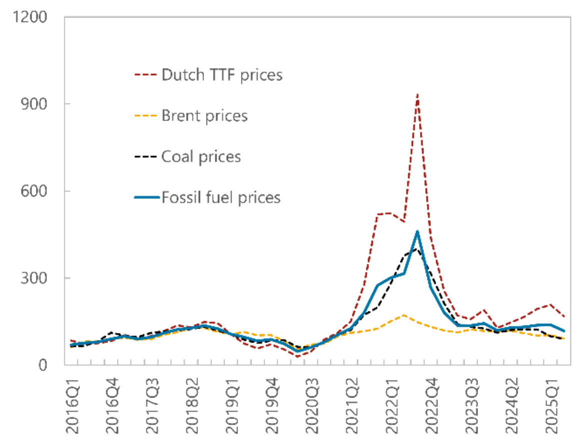
With only limited data available from the 1970s, the recent, large natural gas price shock in the European Union allows us to study the impact of a surge in fossil energy prices on energy efficiency in a more granular way. As shown in Figure 2, following the Russian invasion of Ukraine, real wholesale natural gas prices spiked with the average natural gas price (Dutch TTF) in 2022 about six times the 2016-19 average and the euro area fossil fuel price basket more than three times the pre-shock average. Prices have since stabilized at lower levels but natural gas prices in 2025 are still around 90 percent and the fossil fuel price index around 30 percent above pre-shock levels.

[11] Energy consumption refers to primary energy consumption in Exajoules (an exajoule is 24 million tons of oil equivalent) as compiled by the Statistical Review of Energy.

Figure 3 shows that there has been a broad-based reduction in natural gas consumption in the EU, extending across all sectors of the economy (electricity and heat generation, industry, transport, commercial and public services, households, and agriculture) and across all months of the year. In principle, this reduced natural gas consumption following the increase in prices could reflect several factors. Beyond energy efficiency, these include behavioral changes, lower demand due to reduced output (reduced capacity utilization of capital and labor) and fuel switching. The latter are all possible confounders from our perspective, given that we are interested in energy efficiency changes.[12]

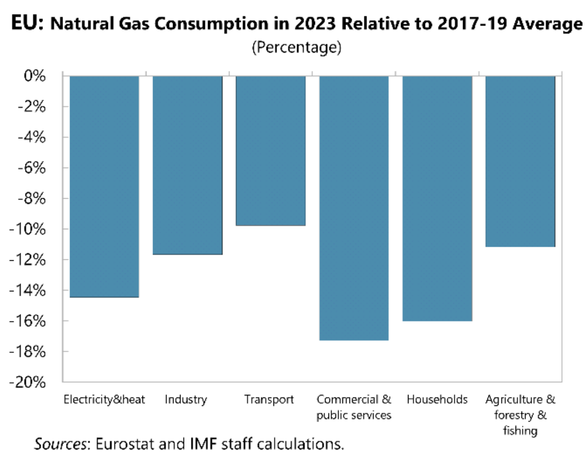
Figure 4 gives a first sense that lower output does not explain (all of) the drop in natural gas consumption. It plots the quarterly spot wholesale natural gas price in Europe (proxied by the Dutch TTF price) along with energy productivity measured by gas per unit of output. As can be seen in the figure, energy productivity increases shortly after gas prices start rising and stabilizes after gas prices drop back significantly.[13]

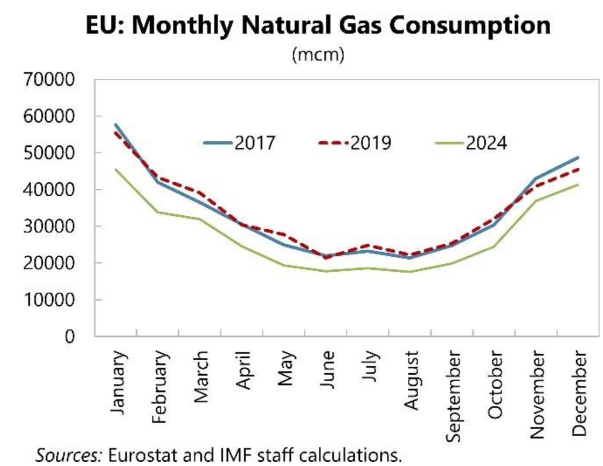
Figure 2. European Fossil Fuel Prices
(Index, average 2016/19=100, energy prices deflated by the euro area GDP deflator)



Sources: IMF, World Economic Outlook database and Authors' calculations.
Note: Prices are deflated by the Euro Area GDP deflator.

Figure 3. Natural Gas Consumption in the EU





For context, the graph also plots a proxy for labor productivity, namely output per labor hour in the industrial sector. Labor productivity flat-lined or even declined. While only illustrative, this is in line with the intuition behind the directed technical change model, whereas a response to energy price increases, firms raised their energy productivity by shifting resources towards this input, but at the cost of not increasing labor/capital productivity.

The gas efficiency result shown in figure 4 might in principle be driven by fuel switching rather than genuine energy efficiency gains. To investigate this, Figure 5 moves from a measure of energy productivity proxied by natural gas efficiency to an aggregate energy efficiency metric. Concretely, we combine annual data on value added in industry to construct measures of energy intensity of output, by type of energy.

[12] Behavioral change, such as turning down the thermostat and accepting colder indoor temperatures in winter, are likely to be more important for households than industry. And while the latter is the focus of our paper, to some degree behavioral change might remain as a confounder and is hard to distinguish from energy efficiency gains in aggregate data, especially in the short-run.

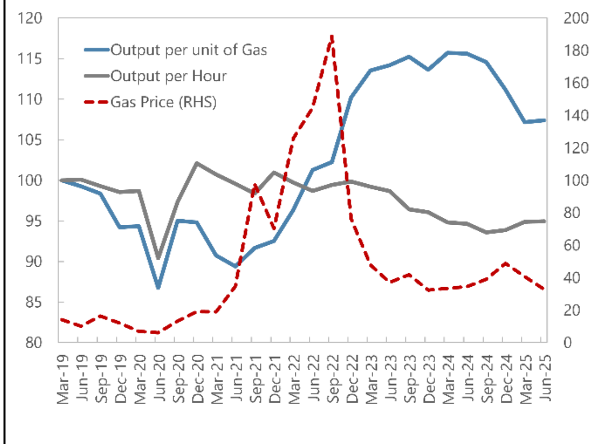
[13] In the case of Germany, roughly two-thirds of the decline in gas per unit of output is within sectors while one-third is accounted for by a switch to less energy-intensive sectors (Chen and others (2023)).

As figure 5 shows, energy intensity drops in 2022 and then falls further in 2023 to levels noticeably below the pre-pandemic trend or even the pandemic average. This is the case for natural gas as well as other fossil fuels and "other energy". In the case of renewables, energy intensity was broadly stable. The different magnitudes of the drop indicate that there was indeed some fuel switching, specifically away from natural gas. This makes sense of course given the relative price of natural gas increased. But at the same time, the data also show that aggregate energy intensity fell, implying that overall energy productivity increased.[14] Taken at face value, the improvement in energy efficiency by 2023 was as much as 10 percent relative to the pre-shock trend.[15]

Surveys corroborate an active role of firm decision making in boosting energy efficiency. A German IFO survey from 2022, for example, showed that in response to high prices, many firms reported adjusting production processes without reducing output (figure 6). The 2024 large-scale investment survey from the European Investment Bank also shows that 50 percent of European firms are investing in energy efficiency (EIB (2024)). On average, investment in energy efficiency accounts for 12 percent of the investment of EU firms.[16]

Figure 4. European Union: Output per unit of gas and per hour vs Gas prices

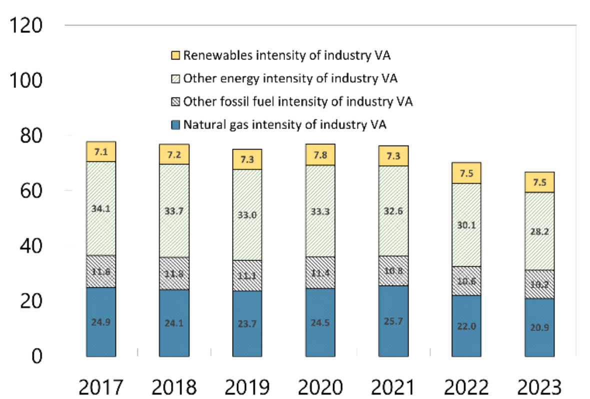
(Output per unit of gas and per hour as index, 2019=100, gas prices in EUR/MWh



Sources: EIA; Eurostat; and Authors' calculations.

Figure 5. Energy Intensity of Industrial Value Added in the European Union

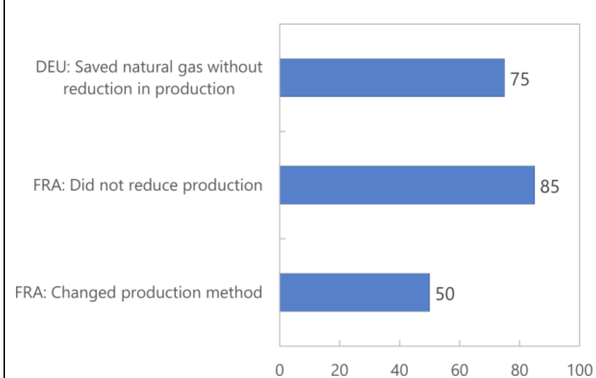
(kilo tonnes of oil equivalent per billion of constant 2020 Euros)



Sources: Eurostat and Authors' calculations.

Figure 6. Survey Evidence on Firm Response to High Prices in 2022

(percent of firms)



Sources: IFO; INSEE and Authors' calculations.

[14] Bastos and others (2024) argue that technological diffusion plays a key role in generating both energy efficiency gains and inducing fuel switching to renewables. In particular, they show that across 16 advanced economies, firms with a higher pre-shock dependence on imports of natural gas and a higher overall energy intensity (where the shock refers to the 2022 gas price increase) saw differentially increased hiring for low-carbon-technology-related roles from March 2022 onwards.

[15] One needs to be cautious in taking the aggregate data too literally in quantitative terms - considering compositional effects at the sectoral or even firm level the "true" improvement in energy efficiency was likely noticeably less than 10 percent. This is important when trying to compare the model-implied change in energy productivity to the changes in energy/output which we pick up in the aggregate data. Qualitatively the empirical improvement in energy efficiency and the direction of change seems rather clear, however.

[16] See also Archanskaia and others (2024) on recent energy efficiency gains in the EU corporate sector.

III. Production Function Dynamics Under Directed Technical Change

Building on the empirical patterns observed in Section II, we now formalize the mecha- nisms through which energy prices can influence productivity by developing a model of directed technical change. We follow Acemoglu (2002b), Acemoglu and others (2012), and most closely Hassler, Krusell, and Olovsson (2021) in the model setup.[17]

A. Endogenous Directed Technical Change

Production Function Assume that aggregate domestic output y_t is produced using three inputs: aggregate capital k_t, aggregate labor l_t and aggregate energy e_t. The production is expressed as follows[18],

$$y_t = \left[(1-\gamma)(A_t k_t^{\alpha} l_t^{1-\alpha})^{\frac{\epsilon-1}{\epsilon}} + \gamma\left(A_{e,t} e_t\right)^{\frac{\epsilon-1}{\epsilon}}\right]^{\frac{\epsilon}{\epsilon-1}}, \tag{1}$$

where ε denotes the elasticity of substitution between capital (k_t) and labor (l_t) with respect to energy (e_t), A_t represents capital-labor productivity, $A_{e,t}$ denotes energy productivity, α is the labor share in the Cobb-Douglas composite and γ is the share parameter in the CES production function.

Technology Assume that at each period t, a fixed amount of R&D investment is allocated to enhance the efficiency of the capital-labor bundle and energy efficiency. Under this assumption, we define

$$A_{t+1}/A_t \equiv f(n_t), \tag{2}$$

$$A_{e,t+1}/A_{e,t} \equiv f_e(1-n_t), \tag{3}$$

where n can be interpreted as the share of a fixed amount of R&D resources allocated to enhancing the efficiency of the capital-labor bundle, while $1-n$ represents the fraction devoted to improving energy efficiency. And the technology constraint is written as,[19]

$$G[f(n_t), f_e(1-n_t)] = 0, \tag{4}$$

[17] See Kennedy (1964) for an important earlier contribution.

[18] Capelle and others (2023) reach similar conclusions and emphasize the trade-off between short-term costs and long-term benefits of subsidies for energy efficiency investments. In the limiting case where $\varepsilon \to 1$, our production function simplifies to a Cobb-Douglas form, consistent with the specification in Capelle and others (2023).

[19] As discussed in Acemoglu (2002a), sustained economic growth requires the innovation possibilities frontier to take one of two forms. The first is the lab equipment specification, in which final goods are used to generate new innovations. In this formulation, the key accumulation equation is linear and does not rely on scarce factors. The second form assumes that spillovers from past research are essential for current productivity and, consequently, for sustaining growth. In our framework, we adopt the first approach for its simplicity. Acemoglu (2002a) provides a detailed discussion of both formulations.

where $G(.)$ is strictly increasing in both arguments, implying a trade-off between the two forms of technological investment, improving the productivity of one technology comes at the cost of the other.

Planner's Problem. *A*t the aggregate level, the social planner's problem is to maximize utility subject to resource and technological constraints.[20]

The social planner maximizes utility

$$\max_{c_t, k_{t+1}, e_t, A_{t+1}, A_{e,t+1}} \sum_{t=0}^{\infty} \beta^t \frac{c_t^{\sigma-1}-1}{1-\sigma}, \tag{5}$$

by choosing the allocation of investment n_t towards labor/capital productivity, and $1 - n_t$ towards energy efficiency,

$$G[f(n_t), f_e(1-n_t)] = 0, \tag{6}$$

subject to the energy resource constraint,

$$\sum_{t=0}^{\infty} e_t = R_0 \tag{7}$$

and a budget constraint,

$$c_t + k_{t+1} = y_t + (1-\delta)k_t, \tag{8}$$

where

$$y_t = \left[(1-\gamma)(A_t k_t^{\alpha} l_t^{1-\alpha})^{\frac{\epsilon-1}{\epsilon}} + \gamma\left(A_{e,t} e_t\right)^{\frac{\epsilon-1}{\epsilon}}\right]^{\frac{\epsilon}{\epsilon-1}} \tag{9}$$

Solving the social planner's problem yields several key results. First, with an interior solution for technology allocation, both $A_t k^{\alpha}$ and $A_{e,t} e_t$ grow at a common rate g. Second, the allocation of technological effort n and output growth rate g are jointly determined by the condition $f(n)^{\sigma/(1-\alpha)} = g^{\sigma}$. Third, the long-run share of energy in output is governed solely by the relative cost of improving energy efficiency, specifically, how costly it is in terms of foregone productivity gains in capital and labor.

A sketch of the dynamic version. The framework can be extended to a dynamic setting in which firms operate in perfectly competitive markets, acquire inputs, and choose input-saving technologies to maximize static profits. To illustrate, at time period $t + 1$, a representative firm decides how much labor, capital, and energy to hire and selects technology levels A_{t+1} and $A_{e,t+1}$ subject to the technological constraint $G(.)$, taking as given the technology levels chosen in period t. Importantly, firms do not internalize the dynamic spillovers of their current technology choices on future outcomes. Investing more heavily in one type of technology today improves the productivity potential of that technology in the future (a positive spillover), but simultaneously reduces the future potential for gains in the alternative technology (a negative spillover). As a

[20] For simplicity and to build intuition, we first set up the planner's problem. At the end of Section III.A, we extend the analysis to a perfectly competitive decentralized economy, where firms make joint input and technology choices.

result, due to the presence of externalities in the technology accumulation process, the decentralized equilibrium may be inefficient.[21]

B. Data

The data used to calibrate and estimate the model are annual. The period considered is 1995-2021 for the main advanced European countries, including Germany, Italy, France, Spain, and the Euro Area (EA).

Energy: The data on energy consumption are taken from the BP Statistical Review of World Energy, including the primary consumption of oil, natural gas, and coal, all of which are converted to millions of BTUs.

Fossil fuel price data are also taken from the BP Statistical Review of World Energy. For the oil price, we use "Europe Brent: Spot Crude Oil Prices"; for the natural gas price, we use "Avg: Natural Gas Prices"; for coal prices we use "Northwest Europe Market Price: Coal Prices". All fossil fuel prices are expressed in 2015 EUR per million Btu (deflated with the country-level GDP deflator in 2015 prices from the IMF World Economic Outlook database).

Note that primary energy consumption is only available at the country level, so the euro area energy consumption level is aggregated from the available euro area countries, which excludes Malta from the EA for oil and coal, and Malta and Cyprus from the EA for natural gas.

Data on net exports of fossil fuels for EA countries are obtained from Eurostat and we use the variable "Trade balance: mineral fuels and lubricants". This variable only provides data between 1999 and 2020 for the euro area. Therefore, to obtain a longer time series, the values for 1995-1998 are estimated from the growth rate of net export of fossil fuels from the Eurostat energy balance. For the United Kingdom, we use the trade balance for oil, coal, gas and electricity from the Office for National Statistics to get the measure that is closest to that of other countries.

The data are deflated with the GDP deflator at the country level to be measured in mil- lions of 2015 EUR.

Output, labor and capital: The annual GDP data at the country level are taken from the expenditure side and expressed in millions of chained 2015 EUR. The output relevant for the model, y, is then calculated as GDP minus net exports of fossil fuels in 2015 EUR (assuming that the final energy consumption of households is negligible), i.e.:

$$y = \text{GDP} - (\text{exports of fossil fuel} - \text{imports of fossil fuels}).$$

Data on the number and compensation of employees are taken from Eurostat. The labor share of income is calculated as compensation of employees divided by GDP. Compensation is expressed in millions of EUR and was converted to millions of 2015 EUR using the GDP deflator.

The capital stock is taken from Eurostat and the variable is denoted as "net stock of fixed assets" in millions of EUR and was deflated to millions of 2015 EUR.

[21] See Hassler, Krusell, and Olovsson (2021) for further details

C. Calibration and Estimation

In this section, we describe the calibration and estimation of the structural model that underpins our quantitative and counterfactual analyses. Once estimated, the structural model laid out in section III.A allows us to conduct quantitative exercises, including an assessment of the evolution of energy-saving technology and output growth.

To bring the model to the data, we proceed in three steps. First, following Hassler, Krusell, and Olovsson (2021), we introduce three types of shocks: (i) shocks to labor/capital productivity (TFP), denoted z_A; (ii) shocks to energy-saving technology, z_{A_e} ; and (iii) shocks to energy price $z_{p_e,t}$.

Second, we parameterize the technology investment functions in equations (2) and (3), denoted by $f(\cdot)$ and $f_e(\cdot)$, following the specification in Hassler, Krusell, and Olovsson (2021),

$$f(n_t, z_{At}) = exp(z_{At})(1 + Bn_t^{\phi}) \tag{10}$$

$$f(1 - n_t, z_{A_e t}) = exp(z_{A_e t})(1 + B_e(1 - n_t)^{\phi}) \tag{11}$$

where parameters B, B_e, and ϕ govern the efficiency of R&D investment, while z_{At} represents the shock to the growth rate of labor and capital productivity, and $z_{A_e t}$ is the shocks to energy efficiency.

Finally, we transform the system into a stationary form. We define $x_t \equiv k_t^{\alpha} A_t$ and introduce the normalized variables $\hat{c_t} = \frac{c_t}{x_t}$ and $\hat{k_t} = \frac{k_t}{x_t}$. To account for the energy sector, we define $a_{e,t} = \frac{A_{e,t}}{p_{e_0}\gamma_{p_e}^t}$ where $\gamma_{p_e}^t$ denotes the exogenous growth factor for energy prices. Since both $A_{e,t}$ and $\gamma_{p_e}^t e_t$ must grow at the same rate as output, $A_{e,t}$ evolves along a balanced growth path with growth rate γ_{p_e}. We also define normalized energy consumption as $\hat{e_t} = \frac{e_t p_{e_0}\gamma_{p_e}^t}{x_t}$. With these transformations, the household's dynamic problem can be reformulated in stationary terms as choosing $\hat{c_t}, \widehat{k_{t+1}}, x_{t+1}, a_{e,t+1}$ and $\hat{e_t}$ to maximize utility.

$$max_{\hat{c_t}, \widehat{k_{t+1}}, x_{t+1}, a_{e,t+1}, \hat{e_t}} \sum_{t=0}^{\infty} \frac{(\hat{c_t} x_t)^{1-\delta}}{1-\delta} \tag{12}$$

subject to the budget constraint

$$\hat{c_t} + \frac{\widehat{k_{t+1}}}{exp(q_t)} \frac{x_{t+1}}{x_t} = \left[(1-\gamma) + \gamma\left(a_{e,t}\hat{e_t}\right)^{\frac{\epsilon-1}{\epsilon}}\right]^{\frac{\epsilon}{\epsilon-1}} + (1-\delta)\hat{k_t} - exp(z_{p_e,t})\hat{e_t} \tag{13}$$

and the technology constraint

$$\frac{a_{e,t+1}}{a_{e,t}} \frac{\gamma_{p_e}}{exp(z_{A_e,t})} - B_e\left(1 - \left[\frac{1}{B}\left(\frac{1}{exp(z_{At})}\left(\frac{x_{t+1}}{x_t}\right)^{1-\alpha}\left(\frac{\widehat{k_{t+1}}}{\hat{k_t}}\right)^{-\alpha} - 1\right)\right]^{1/\phi}\right)^{\phi} - 1 = 0 \tag{14}$$

where $1/ exp(q_t)$ denotes the relative price of investment and q_t is assumed to follow a stationary autoregressive process of order one (AR(1)) with autocorrelation coefficient ρ_q. The variable $z_{p_e,t}$ represents the shock to the energy price, which is modeled as trend-stationary with a deterministic trend growth factor γ_{p_e}.

The shocks $z_{A,t}$ and $z_{A_e,t}$ correspond to growth rate shocks to general productivity and energy efficiency, respectively.

These shocks are assumed to be independent and identically distributed (i.i.d.).

Parameters α, β, δ, σ and γ are calibrated from data or from the literature as shown in Table 1.

The parameter elasticity of substitution ε, parameters B, B_e, and ϕ that governs the efficiency of R&D investment, and autocorrelation coefficient ρ_q are jointly estimated using Bayesian methods. Table 2 provides a summary of the prior distributions used in the Bayesian estimation and the corresponding posterior estimates of the parameters. Note that the elasticity of substitution parameter is estimated at around 0.06 here.

Table 1. Calibration

Parameters	Description	Value	Sources
α	capital-labor share		KLEMS
β	discount factor	0.985	Hassler, Krusell, and Olovsson (2021)
δ	depreciation rate	0.05	Hassler, Krusell, and Olovsson (2021)
σ	risk aversion	1	Hassler, Krusell, and Olovsson (2021)
γ	energy share		BP Statistical Review of World Energy

Note: Capital and labor shares are country-specific and calibrated using data from EU KLEMS, while country-specific energy shares are obtained from the BP Statistical Review of World Energy.

Table 2. Estimation Results

Coefficient	Prior			Posterior									
				EA		DEU		FRA		ITA		ESP	
	Prior Density	Mean	Sd	Mean	Sd	Mean	Sd	Mean	Sd	Mean	Sd	Mean	Sd
ε	Beta	0.200	0.160	0.061	0.046	0.076	0.057	0.071	0.059	0.054	0.044	0.052	0.041
B	Beta	0.015	0.030	0.012	0.002	0.013	0.002	0.011	0.002	0.012	0.002	0.012	0.002
B_e	Beta	0.200	0.030	0.170	0.024	0.174	0.025	0.161	0.023	0.167	0.025	0.173	0.025
φ	Beta	0.900	0.015	0.904	0.014	0.902	0.014	0.890	0.015	0.904	0.014	0.908	0.014
ρ_q	Inv Gamma	0.200	0.100	0.196	0.098	0.196	0.098	0.196	0.097	0.199	0.099	0.205	0.101

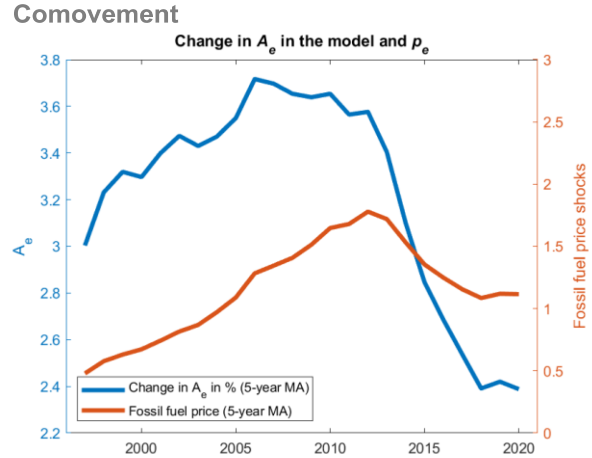
Note: The posterior estimates are based on five Markov chains, each with 100,000 draws. We discard the initial 50,000 draws as burn-in. The average acceptance rate across chains is approximately 30%.

D. Energy Use in the Production Function and Response to Price Signals

Before turning to the model results, we briefly discuss the relevance of the directed technical change channel both in terms of the model and empirically estimate the elasticity of substitution between energy and capital/labor inputs ε. The latter exercise is based on energy price and quantity trends of European countries.

Figure 7 plots the changes in energy-saving productivity (A_e) over time in a simulation of our estimated model, where all shocks other than the energy price shock are shut down (i.e., z_a, z_{A_e}, and q remain on trend). This shows that as energy prices rise, firms increase investment in energy-saving technologies, leading to a close correlation between energy prices and energy-saving productivity.

Figure 7. Model Predicted Energy and Price Comovement



Sources: Authors' calculations.

To further validate the key point that the elasticity of substitution is low (but non-zero) in the short-run and increases in the medium-run we now empirically estimate it. We also estimate the direction of technical change.

This is done using panel data on energy and other input use for European countries. Our empirical specification can be derived as the reduced form of the optimized production function. To see this, we first explicitly solve for the trends in capital-labor and energy productivity conditional on a given value of the elasticity of substitution and assuming perfect competition in input markets, based on equation (1):

$$A_t = \frac{y_t}{k_t^{\alpha} l_t^{1-\alpha}} \left[\frac{w_t l_t / y_t}{(1-\alpha)(1-\gamma)}\right]^{\epsilon/(\epsilon-1)} \tag{15}$$

and

$$A_{e,t} = \frac{y_t}{e_t}\left[\frac{p_{e,t} e_t / y_t}{\gamma}\right]^{\epsilon/(\epsilon-1)} \tag{16}$$

where $w_t l_t / y_t$ represents the labor share, and $p_t e_t / y_t$ represents the energy share. Then, dividing Equation (15) by Equation (16) we obtain:,

$$\frac{k_t^{\alpha} l_t^{1-\alpha}}{e_t} = \frac{A_{e,t}}{A_t} \times \left[\frac{w_t l_t/(1-\alpha)}{p_{e,t} e_t}\right]^{\frac{\epsilon}{\epsilon-1}} \times \left[\frac{\gamma}{1-\gamma}\right]^{\frac{\epsilon}{\epsilon-1}}. \tag{17}$$

Through cost minimization of the production function, the expression [ ] can be rewritten as,[22]

$$\frac{w_t l_t/(1-\alpha)}{p_{e,t} e_t} = \left(\frac{A_{e,t}}{A_t}\right)^{1-\epsilon} \frac{(1-\gamma)^{\epsilon} (r_t^{\alpha} w_t^{1-\alpha})^{1-\epsilon}}{\gamma^{\epsilon} p_{e,t}^{1-\epsilon}} \tag{18}$$

Plugging Equation (18) into Equation (17) yields:

$$\frac{k_t^{\alpha} l_t^{1-\alpha}}{e_t} = \left(\frac{A_{e,t}}{A_t}\right)^{1-\epsilon} \times \left(\frac{\gamma}{1-\gamma}\right)^{-\epsilon} \times \left[\frac{r_t^{\alpha} w_t^{1-\alpha}}{p_{e,t}}\right]^{-\epsilon}, \tag{19}$$

where r_t is the rental price of capital.

Assuming that along the balanced growth path, energy productivity and labor productivity grow at rates τ_e and $\tau_{k,l}$, respectively, we have[23]

$$A_{e,t} = A_{e,0} ex\,p(\tau_e \cdot t) \text{ and } A_t = A_0 \exp(\tau_{k,l} \cdot t).$$

[22] The expression $\frac{w_t l_t/(1-\alpha)}{p_{e,t} e_t}$ can be rewritten as $\frac{w_t l_t/(1-\alpha)}{y_t} / \frac{p_{e,t} e_t}{y_t}$, which corresponds to the ratio of the labor cost share to the energy cost share, i.e., $\frac{1-\text{energy share}}{\text{energy share}}$

[23] Note that the expressions for $A_{e,t}$ and A_t differ from the parametrization provided in (10) and (11) as those pertain to the dynamics outside the balanced growth path. For ease of estimation, we choose a more concise expression for productivity evolution under a balanced growth path involving constant productivity growth parameters that scale with time.

Further note that a log-linear approximation of the firm optimization equation (19) yields the following sufficient statistic for empirical estimation:

$$\underbrace{log\left(\frac{k_t^{\alpha} l_t^{1-\alpha}}{e_t}\right)}_{\text{Relative input share}} = \underbrace{\epsilon \cdot log\left(\frac{p_t}{r_t w_t}\right)}_{\text{Relative input price}} + \underbrace{(1-\epsilon)(\tau_e - \tau_{k,l})t}_{\text{Technical Bias}} \quad (20)$$

As discussed in Acemoglu (2002b), as assessment of directed technical change is guided by two competing forces which shape the profitability of various types of innovation. On the one hand, a *price effect* incentivizes the development of technologies associated with higher-priced goods or those reliant on costly inputs[24]. In contrast, a *market size* effect encourages innovation in technologies with a larger market share, particularly those that: complement abundant factors[25]. These effects operate in opposition: the price effect favors scarce factors, while the market size effect promotes innovations benefiting abundant factors. The relative strength of these forces depends on the elasticity of substitution be- tween factors. When the elasticity of substitution is low, scarce factors command higher prices, amplifying the price effect. Conversely, when the elasticity of substitution is high, the market size effect becomes dominant, driving innovation toward technologies that complement abundant factors.

Equation (20) allows for an estimation of both the elasticity of subsitution ε but also the *bias* of directed technical change towards a specific input. This is captured by the technical bias coefficient $\tau_e - \tau_{k,l}$. When this coefficient is positive, it suggests that the price effect dominates and innovation is directed to *energy saving technology* - typically this is the case when energy is a complement. We estimate equation (20) across a panel of European countries since 2000 on an annual frequency, both with and without country fixed-effects. The specification with fixed-effects captures short-run substitution, and the one without (exploiting mostly cross-sectional variation) captures long-run substitution (Arnberg and Bjørner, 2007). In addition the specification without fixed effects captures also the firms' extensive margin response whereby they start/stop using a particular energy input or exit completely (Jo, 2025).

Table 3 reports results from this exercise. We find that energy is generally a complement to capital and labor. At least in the short run, there is very low substitutability between energy and other inputs (columns 2 and 4 with ε at about 0.04).[26] Over the medium-term, ε increases to 0.3, reflecting also improvements to energy efficiency.[27]

[24] Since inputs that rely on a scarce factor tend to command higher prices, as shown in Equation (19), this effect suggests that innovation will be disproportionately directed toward the scarce factor (energy, in our case)

[25] The market size effect indicates that a larger potential consumer base for a technology encourages more innovation. In our framework, the number of workers using a technology determines its market size.

[26] Recall from 2 that the Bayesian estimation of the model parameters yielded an ε of 0.06 for the euro area, so somewhat larger than these regression estimates.

[27] As noted by Hassler, Krusell, and Olovsson (2021) the low substitutability in the short run does not rule out that the own-price elasticity of fossil fuels could be high even in the short run. To make the two elasticities consistent would require that capacity utilization of labor and capital adjusts in line with energy use.

Table 3. Energy Substitution

	Dep. Var: Relative Energy Share			
	Euro-Area		Euro-Area + UK	
	Short-term	Medium-term	Short-term	Medium-term
Elasticity of Substitution (ε)	0.04***	0.30***	0.04***	0.30***
	(0.02)	(0.02)	(0.02)	(0.02)
Technical Bias	0.02***	0.02***	0.02***	0.02***
(+ve = Energy favoring)	(0.00)	(0.00)	(0.00)	(0.00)
Observations	363	363	383	383
Country F.E.	Yes	No	Yes	No

Robust standard errors in parentheses; *** significant at 1%; ** at 5%; * at 10%.

Importantly, the direction of technical change favors improving energy efficiency over other inputs. This suggests that, at least in the short-term, directed technical change into energy works through the price channel: with low substitutability in the short-term, energy price shocks spur innovation into energy-saving technology with the aim to economize on this scarce input.

IV. Results

With the model calibrated and estimated, we turn to our simulation results that quantify the impact of energy price shocks on productivity and potential output across the euro area. We focus on the impact of energy price shocks but the framework would allow additional exercises which can be explored in future work, related for example to shocks to investment efficiency.

We simulate our estimated model using changes in energy prices based on different energy price assumptions over 2021-2027, while shutting down all drivers other than the energy price. Ultimately, we are interested in the growth and productivity impact of the energy price shock following the Russian invasion of Ukraine. The results will also allow us to shed light on how energy efficiency has been affected, how energy efficiency gains buffer losses to potential output and how the volatility of energy prices impacts the output losses.

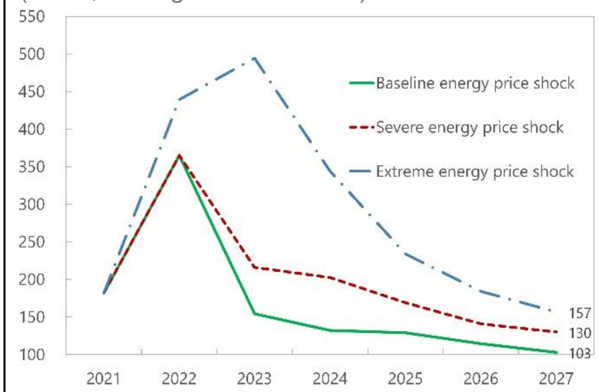
A. Baseline Results: The Impact of the 2022 Energy Price Shock

It is important to note upfront that when we talk about the 2022 energy price shock we refer to the change in the whole price path until 2027. Strictly speaking, since the simulations cover 2021-27, the shock begins in 2021 - this is to some degree for implementation reasons as the model estimation covered data through 2020 but also since the natural gas price shock did partly start in 2021 with lower deliveries from Gazprom during the gas storage season.

We study three different scenarios for European fossil fuel prices which are defined relative to the 2016/19 average. Energy prices are deflated using the euro area GDP deflator. We label those scenarios the "baseline" or "large" shock, "severe" shock and finally "extreme" shock.[28] The three price shock paths correspond to different vintages of actual and expected (through futures pricing) energy price developments. While the baseline shock is what we are mostly going to focus on, using different price assumptions is helpful in exploring the model workings and getting a sense of how much worse potential output would have been affected in a worst case scenario.[29]

Figure 8. Energy Price Shocks

(Index, average 2016/19=100)



Note: Nominal energy prices are deflated by the euro area GDP deflator. Base- line corresponds to prices as in the July 2025 IMF World Economic Outlook (WEO). Severe and extreme correspond to the January 2023 and October 2022 WEO energy price paths, respectively. *Sources*: IMF World Economic Outlook and authors' calculations.

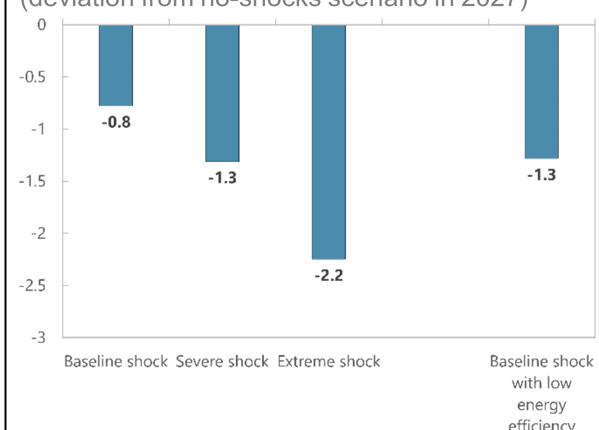
As Figure 8 shows, the price shock over the past few years was very large but turned out smaller than initially expected. At the worst of the crisis in 2022, prices were expected to remain several hundred percent above the 2016-19 average until 2025, and 57 per- cent above still in 2027. Expectations quickly adjusted in 2023, as Europe's gas supply- demand balance held up better than anticipated (see DiBella and others (2024)). Ex post, a large part of the chunk unwound already by 2023, with prices around 50 percent higher than pre-shock by then.

The first three bars in figure 9 plot the impact on euro area potential output in 2027 of the baseline, severe and extreme energy price shocks. The simulated impact ranges from a loss of 0.8 percent to as high as 2.2 percent.

Given the ex-post price developments we have observed so far, we take a decline of somewhat below one percent in euro area potential output as a plausible estimate of the actual effect of the 2022 energy price shock.

Figure 9. Impact of Energy Price Shocks on Euro Area Potential Output

(deviation from no-shocks scenario in 2027)



Sources: Authors' calculations.

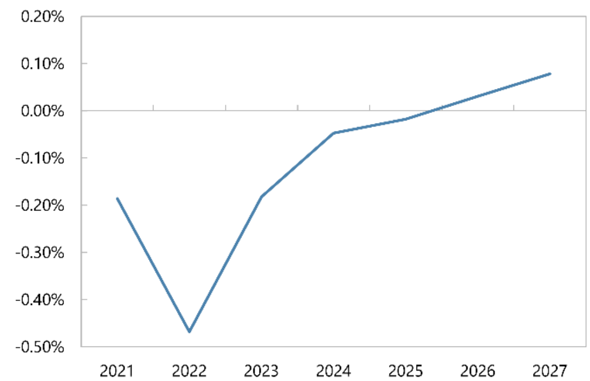
[28] While the labeling might look like it tends towards hyperbole, the "baseline" or "large" shock is a several standard deviation event and only comparable to the oil price shocks of the 1970s.

[29] Concretely, the price paths use the weighted average (using expenditure weights) natural gas (Dutch TTF), crude oil (Brent) and coal (IMF coal price index) prices. The "extreme" shock corresponds to energy pricing as of the fall of 2022 when the energy crisis was at its most acute, while the "severe" shock corresponds to pricing as of the winter of 2023. The "baseline" or "large" shock uses futures prices as of July 2025.

It is instructive to compare the baseline shock to the severe one. The loss in potential output in 2027 is 0.5 percentage points larger in the latter, for an energy price path that is about 30 percent higher each year over a five-year period. This allows a broad sense of the relationship between energy prices and potential output. In particular, it implies that movements in the energy price basket that are below perhaps 10 percent, and that last for only a year or two, have negligible effects on euro area potential output.

By the end of the period, potential *growth* effects, which are large in the first years, will be essentially zero (see figure 10).[30] Despite a persistent increase in energy prices, the shock thus ultimately has a level not a growth effect on potential output as the economy returns to the balanced growth path.

Figure 10. Impact of 2022 Energy Price Shock on Euro Area Potential Growth
(deviation from no-shocks scenario)

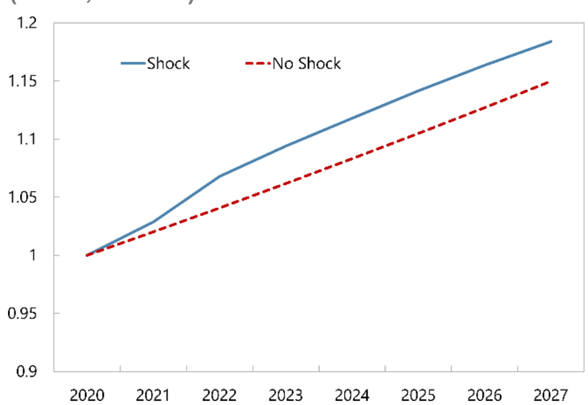


Sources: Authors' calculations.

The model also allows us to comment directly on how much energy efficiency has im- proved as a result of the shock - for the baseline shock scenario, we estimate an improvement in energy efficiency of 3 percent (figure 11), relative to a no-shock counterfactual.

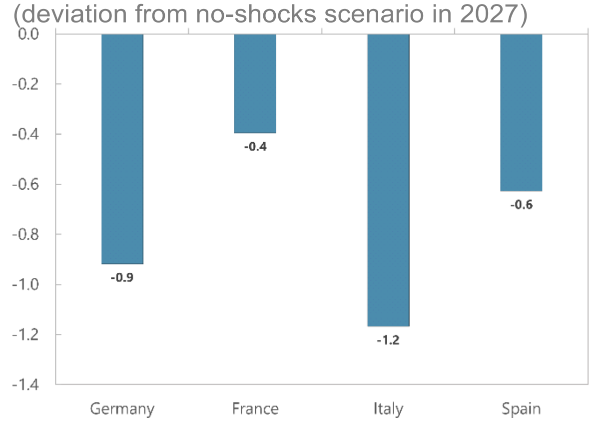
To highlight how these energy efficiency gains buffered the impact of the shock on potential output, the fourth bar in figure 9 runs a counterfactual simulation in which the base- line energy price shock hits an economy which has 80 percent lower responsiveness of energy efficiency to prices than the estimated euro area one does. We find that the loss in potential output would have been about 1.3 percent by 2027, i.e. a lower degree of energy efficiency response would have reduced potential output by an additional 0.5 percentage point.

Figure 11. Predicted Energy Efficiency Paths (Index, 2020=1)



Sources: Authors' calculations.

Figure 12. Impact of Baseline Energy Price Shock on Potential Output of Individual Euro Area Countries
(deviation from no-shocks scenario in 2027)



Sources: Authors' calculations.

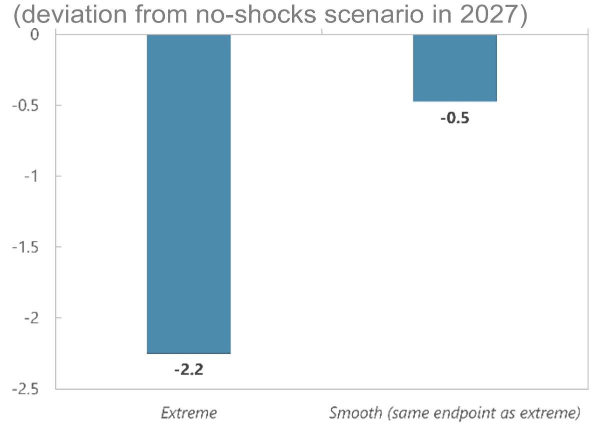
[30] The effect is in fact slightly positive - temporarily - in 2027 as there is some offset for the earlier losses.

Figure 12 shows large cross-country differences in the estimated potential output effects. Under the baseline shock scenario, potential output losses are around 1.2 percent in Italy, 0.9 percent in Germany, 0.6 percent in Spain and 0.4 percent in France. These differences are mainly due to two factors. First, we find variation in the response of energy efficiency and the elasticity of substitution parameters across countries, and second the price shock is not homogeneous due to differing energy shares.

B. A Few Thoughts on Price Volatility

How would the impact of a shock that leads to a smooth increase in energy prices to reach the same endpoint as the extreme shock scenario compare? Since an input to production gets more expensive and the trade-off with capital-labor productivity and the transition costs continue to hold, the impact on potential output is still unambiguously negative. But significantly less so at a medium-term horizon.

Figure 13. Impact of Extreme Price Shock vs Gradual Price Shock (leading to same energy price level in 2027)
(deviation from no-shocks scenario in 2027)



Sources: Authors' calculations.

Figure 13 documents exactly this. The underlying price path for the "smooth" shock starts from the same base (the average price over 2016-19) and then reaches the same endpoint by 2027 as does the "extreme" shock but it does so monotonically and linearly. The estimated impact on potential output is more than four times smaller. In other words, the deviation from the balanced growth path is greater when price increases are sharp and partially reversed, compared to a scenario with a slow and steady rise. The result is driven by a combination of the overall size of the energy shock being smaller (the integral of the price shock is smaller) and the fact that transition frictions make it costly to shift investment from capital-labor to energy saving technology.

This insight might have two noteworthy implications - first, sharp price spikes have their own cost and avoiding them would be desirable.[31] And second, we should not extrapolate from the effects of sharp energy price shocks to the effects of shocks that slowly increase energy prices.

It is important to note, however, that beyond the medium-term, the impact of the two scenarios on potential output will eventually converge. That is because by 2027 the economy in the two scenario faces the same energy prices (and structural parameters were always the same).

Finally, it is worth stressing that the exercise in this section compares a volatile exogenous price increase to a steady exogenous price increase. This is not the same as comparing a volatile exogenous price increase to a volatile exogenous price increase that is smoothed by temporary price subsidies since temporary price

[31] Note that the concept of a price spike is low frequency here since the model is annual. But this seems appropriate - high frequency movements in wholesale energy prices do not usually impact firms directly since industry pricing includes many fixed term and otherwise slower moving contracts.

subsidies impose costs (e.g., they have to be paid for by distortionary taxation).[32] A scenario which studies how policy should or should not react to volatile exogenous price shocks is outside the scope of this paper.

C. Possible Confounders: Substitution across Fossil Fuels, Substitution between Fossil Fuels and Renewables, and Structural Transformation

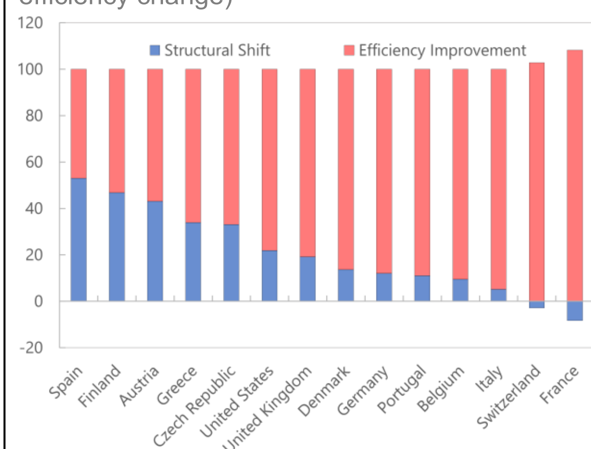
Before concluding we briefly discuss three possible confounders to our results. First, since we model an energy aggregate, we could be missing fuel switching whereby energy efficiency efforts are directed to a specific fuel, perhaps without changing the total. We are not particularly concerned with this possibility. Although fossil fuel switching has been one adjustment mechanism (as shown in II), we also found notable gains in overall fossil fuel energy efficiency.

Second, fuel switching between the fossil fuel aggregate and renewables is possible. This is a larger potential concern since the literature has documented high elasticities of substitution between fossil fuels and renewables of around 2 (Jo (2025); Papageorgiou, Saam, and Schulte (2017)). But again, the concrete data for Europe documented above show that energy intensity dropped for both fossil fuels and other sources of energy (which includes renewables). Hassler, Krusell, and Olovsson (2022) find that explicitly incorporating renewables into their model does not qualitatively change the model implications (but energy efficiency investments are directed towards renewables).

Finally, given that our model is aggregate we do not capture any sectoral, and even less so firm level, dynamics. Yet, it is conceivable that aggregate energy efficiency gains are driven by compositional factors. The insight from the model extends to all sectors and firms - price increases should induce energy efficiency in all sectors, mitigating the need for reallocation. But of course energy intensity and other factors differ across sectors in reality. To understand whether sectoral reallocation was at play during our sample period, we examine energy use data across sectors in different countries. Changes in aggregate country-wide energy use can be decomposed into changes in output, changes in the structural mix of sectors, and changes in energy efficiency i.e., the amount of energy required for each unit of output in each sector.

Figure 14 shows the results from such a simple shift share analysis for European countries, based on the International Energy Association's (IEA) decomposition of energy use database (see IEA (2025) for methodological details on the decomposition). The figure de- composes for each country the aggregate change in energy use in 2019 (relative to 2000) due to

Figure 14. Contributions of Within-Sector Energy Efficiency Gains and Structural Shifts in the Sectoral Composition of Output to Change in Aggregate Energy Use
(percent contribution to aggregate energy efficiency change)

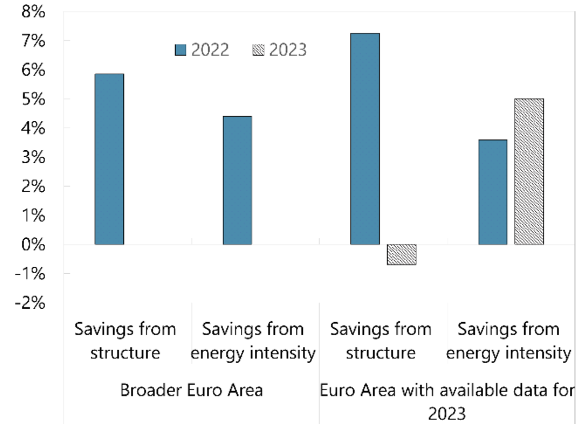


Sources: IEA and Authors' calculations.

[32] It is also different from studying the impact of a policy-driven (endogenous) increase in fossil fuel prices.

structural shifts and energy efficiency gains, net of output changes. The idea is simply to show that historically within-sector energy efficiency gains have been the main driver in all countries, albeit to a differing degree (in no country does reallocation account for more than fifty percent).

Figure 15. Energy Savings As a Percent of Previous Year's Consumption in Industry and Services



Sources: IEA and Authors' calculations.
Note: The broader euro area group covers data for Austria, Belgium, Czechia, Finland, France, Germany, Greece, Italy, Latvia, Lithuania, the Netherlands, Portugal, Spain and Slovenia. The subgroup for which 2023 data is available includes Austria, Belgium, Czechia, Finland, Greece, the Netherlands, Spain, and Slovenia.

Looking specifically at the years since the 2022 shock shows that both structure and energy efficiency have contributed to reduced energy consumption. In 2022, for a broad group of euro area countries, compositional effects reduced energy consumption in industry and services by 5.9 percent while lower energy intensity lowered it by 4.4 percent (higher output increased consumption by 3.3 percent). For this comprehensive group of countries data for 2023 is not yet available, but the subgroup for which data is available, and accounts for around 40 percent of the broader group's energy consumption, has historically seen very similar developments (correlation of 0.92). Looking at the 2023 data for this subgroup suggests that in 2023 energy savings came exclusively from lower energy intensity with compositional effects slightly increasing consumption (see Figure 15).[33]

V. Conclusion

This final section summarizes our key findings and discusses their implications for policy and future research. We found evidence that in reaction to the adverse energy price shock they faced, euro area firms redirecting resources towards energy-saving technology, thereby significantly increasing their energy productivity and buffering the adverse output effect of the shock. This involved a tradeoff as, under a limited budget constraint, resources were diverted away from efforts to save on other inputs which contributed to lower labor productivity. To provide an order of magnitude, holding other things constant and incorporating this endogenous response of firms to price shocks, we find that as a con- sequence of the energy shock, European potential output in 2027 was reduced by about 0.8 percent relative to a baseline without shocks. The implied energy productivity gain is about 3 percent and was crucial to limit the impact of the price shock, which would have been around two-thirds higher had energy efficiency barely reacted. At the country level there is substantial heterogeneity in size of the impact, with larger effects in Germany and Italy than France and Spain.

All in all, in terms of the implications for the current situation of the euro area economy, the results suggest that (a) productivity growth should improve from the low of 2022-23 as the energy shock's impact fades while at the same time

[33] The sectoral analysis is relatively granular - for example, covers 12 sectors within industry - but is not granular enough to rule out that compositional effects within narrowly defined sub-sectors could be key drivers of energy efficiency gains.

(b) the temporary nature of the energy price drag on productivity means that energy prices are unlikely to be the core reason behind Europe's ongoing productivity malaise which is longer-lasting.[34]

In line with previous IMF research, our findings also suggest that energy price signals are important[35] and persistently suppressing them can hinder improvements in energy efficiency. Energy efficiency in turn acts as a buffer and builds resilience against possible future adverse energy price shocks.

At the same time, we find that abrupt price spikes are harmful. Rather than policies that subsidize retail energy prices persistently, steps that lower wholesale price volatility - such as further integration of the European energy system - would be important (see Kammer (2025)). Another way to put this is to say that energy price volatility should be lowered by removing economic distortions (e.g., the artificial fragmentation of European energy markets across national lines) and not by introducing new economic distortions (e.g., price subsidies).

The productivity tradeoff at the heart of our model calls for a focus on capital-labor productivity in Europe since the friction generated by diverted resources in labor/capital augmenting technology accentuates Europe's long-standing productivity challenges. Ambitious policy action is needed to tackle these and boost Europe's productivity. This includes national structural reforms (Budina and others (2025)), deepening the EU single market (Arnold and others (2025)) and a joint provision of key public goods at the EU level (Busse and others (2025)).

[34] See IMF (2024) for a detailed look at the firm-level roots of Europe's long-standing productivity challenges and Draghi (2024) for a comprehensive discussion of policies to boost Europe's productivity. The European Central Bank in Dias da Silva and others (2024) notes that "The euro area's significantly lower productivity growth over the last four years [2020-24, relative to the US] is partly explained by the more pronounced cyclical nature of productivity growth in this region, a stronger and longer-lasting suppression of production and real incomes by the increase in energy prices, and a stronger impact of the uncertainty related to the Russian war against the Ukraine. However, over the two decades preceding the pandemic, labour productivity in the United States increased around twice as fast as in the euro area. This points to the role of structural factors."

[35] See also Arregui and others (2022)

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