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What if? Revisiting the Macroeconomic Impact of the Energy Crisis with Peak-load Electricity

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Highlights

- We introduce a base--peak load structure to electricity modeling in large-scale CGE models to better capture merit order dispatch, capacity constraints and renewable intermittency.
- A transparent toy model demonstrates how ignoring peak load constraints systematically underestimates the macroeconomic impacts of energy shocks.
- We argue that second-order approximation are not well-suited for this kind of exercise, due to the large size of the shock compared to the value of the elasticity of substitution.
- We treat base load and peak load electricity as non-substitutable Leontief complements, reflecting operational constraints in electricity systems.
- Applying the refined model to the 2022 Russian gas shock reveals larger GDP and welfare losses in Germany and the EU than standard electricity representations predict.Applying the refined model to the 2022 Russian gas shock reveals larger GDP and welfare losses in Germany and the EU than standard electricity representations predict.

Abstract

Electricity generation presents distinctive modeling challenges due to the absence of storage, instantaneous demand-supply balancing requirements, and heterogeneous generation technologies with different cost structures. This paper addresses these challenges by incorporating a base--peak load structure into large-scale computable general equilibrium (CGE) models, offering a middle ground between detailed energy system models and multisectoral global economic frameworks. We first develop a transparent toy model inspired by \textcite{bachmann2022} to demonstrate that first-order approximations of cascading effects, following Hulten's theorem, are inadequate when shocks are large and elasticities of substitution are low. Building on the theoretical insights, we embed a base--peak structure into the MIRAGE CGE model, treating electricity as a Leontief production function between base load generation (coal, nuclear, hydro, and part of renewables) and peak load generation (gas, oil, and peak renewables). This refinement captures the merit order dispatch mechanism and bottleneck effects when peak generation is constrained. We apply the enhanced model to assess the 2022 Russian gas shock in Germany and the European Union. Our results demonstrate that the base--peak structure more accurately reproduces observed macroeconomic impacts compared to standard electricity representations, with significantly larger GDP and welfare losses particularly affecting energy-intensive industrial sectors, and less possible substitution from variable renewable energies. Theoretically, we show that third-order effects become important under conditions we explicitly identify, complementing recent findings on shock amplification in production networks. For policy, our findings highlight two key levers for responding to energy shocks: supply flexibility through storage and grid interconnection, and demand smoothing through dynamic pricing and interruptible contracts. The paper contributes methodologically by demonstrating how simplified yet realistic electricity representations can be integrated into global CGE frameworks without sacrificing the broader economic feedback mechanisms essential for policy analysis.

Keywords

Electricity Modeling, Base Load and Peak Load, Computable General Equilibrium, Energy Shocks,Russian Gas Crisis, MIRAGE Model.

JEL

C68, D58, Q41, Q43.

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What if? Revisiting the macroeconomic impact of the energy crisis with peak-load electricity

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1 Introduction

With growing policy concerns around energy security, climate change, and their interactions with international trade, large-scale general equilibrium models have been regaining attention among economists as valuable tools for energy and climate policy analysis (see, e.g., Bekkers and Cariola 2022; Bellora and Fontagné 2023; Clora and Yu 2022). However, there is a tension between tractability of the model and detailed representation of the energy, particularly with respect to electricity. As electrification and the widespread adoption of renewable energy are reshaping energy systems worldwide, enhancing the modeling of the electricity sector within models of the global economy becomes important for more accurate quantitative policy assessments.

Electricity generation presents modeling challenges due to several distinctive features. The first one is the (quasi) absence of storage, coupled to the necessity of equalizing supply and demand at all time if blackouts are to be avoided. The second one is that, contrary to what we would think of an electron identical to another one, electricity is differentiated: electricity produced by a nuclear plant is not the same, economically speaking, as electricity coming from a gas plant. Indeed, different technologies exist to produce electricity, each one representing a given trade-off between fixed cost and variable cost. For instance, building a nuclear plant is very expensive, but the variable costs are low, due to the very high density of energy contained in uranium; on the contrary, building a gas plant is very easy and cheap, but gas itself has a much higher cost. Therefore, given the infrastructure, the optimal generation mix is determined by the so-called *merit order curve*. This merit order curve determines the difference between the low price of base electricity, and the high price of peak electricity: in case of demand peak, gas plants with a high marginal cost must be called, hence the peak price.

This design has two implications for modeling strategies. First, a standard CES production function between the different electricity sectors would not be suited to represent the mechanism of electricity generation. Indeed, due to the merit order curve and the fixed capacities of the existing plants at short term, substitution between the different inputs cannot be encapsulated in a single parameter. Second, this design implies that electricity price is common to all producers. Since gas is required to generate electricity during peak demand, when gas prices increase, the electricity price rises for all generators, creating rent transfers to lower-cost producers.

These issues lead us to hypothesize that electricity should be split between base load and peak load electricity in the modeling. Although not fully realistic, such approach has the merit of being quite simple for the macroeconomic modeling, while still capturing part of electricity specificities. Because of the merit order curve on the supply side, and the very poor elasticity of electricity demand,[1] one can treat electricity generation as a Leontief production between base electricity and peak electricity, meaning that there is no possible substitution between these two "inputs", even though there is possible substitution inside each of these sectors.

Against this background, this paper aims at illustrating how adopting a more refined modeling of electricity helps reconsider the economic consequences of an energy shock as captured by a large scale model of the global economy. We first introduce a transparent toy model inspired by Bachmann et al. (2024) – the reference paper on the consequences of the energy crisis in Germany. We then embed the same base-peak structure into MIRAGE (Bouët, Fontagné, et al. 2026), a computable general equilibrium model. We apply the enhanced MIRAGE model to the 2022 Russian gas shock in Germany and the EU, a case that highlights how ignoring base–peak differences leads to systematic underestimation of macroeconomic impacts. To proceed, we enhance the representation of renewables by allocating their contributions to both base load and peak load. We treat electricity as a nested CES of base load generation (coal, nuclear, and part of renewables including hydro) and peak load generation (gas, oil, and peak renewables). This refinement enables the model to replicate the merit order and to capture bottleneck effects when peak generation is constrained.

This paper is related to four strands of literature. The first strand of literature related to our paper is the electricity-market and power-system literature, where the distinction between base-peak forms the foundation for analyses of generation investment, pricing, and capacity adequacy. Early theoretical models described the merit order of dispatch, in which low variable-cost generators (coal, nuclear, hydro) supply the base load, while higher-cost and more flexible units (gas turbines, oil) meet peak demand (Boiteux 1960; Steiner 1957; Williamson 1966). This base–peak framework underlies studies on peak-load

[1] In the 70s, electricity was considered as a pure inelastic good. In recent years, with real-time pricing, off-peak hours and so on, some progress has been made, but elasticity of demand still remains very low.

pricing (Borenstein and Bushnell 2022; Hirth 2013), real-time electricity pricing (Allcott 2011; Borenstein 2005), and the design of capacity markets to ensure long-term reliability (Cramton et al. 2013). These studies consistently show that ignoring peak-load constraints leads to biased welfare and investment estimates, as the marginal value of electricity varies sharply across load segments.

A second strand of literature, more closely related to energy system analysis, focuses on improving the modeling of the intermittency of variable renewable energy (VRE). In particular, Pietzcker et al. (2017), Sullivan et al. (2013), Ueckerdt, Brecha, et al. (2015), and Ueckerdt, Hirth, et al. (2013) employ residual load duration curves and system adequacy conditions to better represent the costs associated with VRE integration. While large scale models are constrained by their annual time step and thus cannot capture real-time fluctuations in VRE supply, some energy system models introduce time-slicing to represent seasons, weekdays versus weekends, and different times of day (Boer and D. D. v. Vuuren 2017; Stehfest et al. 2014), thereby accounting for intra-annual variability in renewable generation. The drawback of these detailed representations of the energy system is that they lack comprehensive representation of the overall economy with interactions between energy supply and demand.[2]

The third strand of literature is energy modeling in large-scale computable general equilibrium (CGE) models. Traditional CGE models are typically less detailed in the treatment of the energy system modeling. Many models consider electricity as one aggregate sector and do not identify electricity generating technologies. These include the standard GTAP model (Corong et al. 2017) or earlier versions of the MIRAGE model (Decreux and Valin 2007), whose primary purpose is to understand the economy-wide effects of trade policies; the MIRAGRODEP model (Bouët, Laborde Debucquet, et al. 2022) and the MAGNET model (Kavallari et al. 2014), who focus on agriculture, trade, and food security. The state-of-the-art in large-scale CGE modeling focusing on energy and climate policy is moving beyond treating electricity as a single homogenous good. The EPPA model (Chen et al. 2016; Paltsev et al. 2005) and the World Bank ENVISAGE model (Van der Mensbrugghe 2008) disaggregate the electricity sector into multiple generation technologies (coal, gas, oil, nuclear, hydro, wind, solar, biomass). However, more typically, the electricity generation technologies are substituted under a single level CES or Leontief function (Capros et al. 2013; Château et al. 2014). The WTO Global Trade Model differentiates electricity generation from an intermittent energy nest and a non-intermittent nest (Bekkers and Cariola 2022). Finally, Peters (2016) introduces a base–peak load structure into the GTAP-Power model, enabling it to better capture the economic impacts of electricity price spikes. This advanced treatment of electricity has yet

[2]Hybrid frameworks that link bottom-up energy system models with top-down models have been proposed, but integrating the two approaches remains challenging in practice (Böhringer and Rutherford 2008) and is beyond the scope of this study.

to be widely adopted or receive in-depth consideration within the broader CGE modeling community.

Finally, our simulation on the 2022 Russian gas shock in Europe connects to a growing body of literature examining the macroeconomic impacts of energy crises. Serving as the starting point of our analysis, Bachmann et al. (2024) assess the consequences of a Russian gas cutoff for Germany: they estimate output losses ranging from 0.5% to 3% of GDP, depending on the substitution of energy imports and reallocation along the production chain. Other recent studies confirm the severity of the shock. Alessandri and Gazzani (2025) find that gas supply disruptions between 2021 and 2023 raised inflation and depressed growth in the euro area, accounting for nearly half of the increase in core prices. Di Bella et al. (2024) simulate a complete Russian gas cutoff and show that parts of Eastern Europe could have experienced steep GDP declines, though Europe's integrated gas market helped cushion the impact. Liadze et al. (2023) estimate GDP losses exceeding 1% for the EU alongside substantial inflationary pressures. Emiliozzi et al. (2025) shows that the energy crisis pushed Europe from dependence on Russian pipeline gas toward a more globally integrated, LNG-based market. This shift maintained supply but imposed major economic and social costs. Together, these findings highlight the macroeconomic risk of energy dependence, the importance of substitution and reallocation mechanisms, and the need for a transition to cleaner energy systems.

Our paper contributes to the literature in three ways. First, we employ a simple and transparent theoretical model to analyze the sources of impacts and to understand how the structure of electricity modeling and key parameters influence model responses under a CES framework. Our approach is inspired by Bachmann et al. (2024), who use firstly, a simple model with back-of-the-envelope calculations, and secondly, a multi-sector open-economy general equilibrium model developed by Baqaee and Farhi (2024). We show that such approach based on second-order Taylor expansion fails to capture the full impacts of a shock when the elasticity of substitution is low and when the shock is large. We thus propose a simple model of the base peak load structure, and finally a numerical simulation using a full general equilibrium model. Building on the theoretical model and subsequently comparing the two versions of the MIRAGE model, with and without peak load, we contribute to the broader methodological discussion on validation and sensitivity in general equilibrium models.

Second, we contribute to the ongoing effort to improve the modeling of electricity within general equilibrium models. We refine the MIRAGE framework by introducing a differentiation between base-load and peak-load generation. In this setup, base-load supply encompasses coal, nuclear, hydro, and part of renewable generation, while peak-load supply includes gas, oil, and the remaining share of renewables. This extension allows the model to reproduce the merit-order dispatch mechanism and to reflect capacity constraints that arise when peak-load technologies reach their limits.

Finally, our paper provides a novel quantitative assessment of the macroeconomic impacts of the 2022 Russian gas shock on Germany and the EU, using the enhanced MIRAGE model. We show that incorporating the distinction between base-load and peak-load electricity intensifies the GDP and welfare impacts. In particular, energy-intensive industrial sectors are disproportionately affected due to constraints on peak-load generation, which makes it more difficult to substitute fossil fuel–based electricity with renewable generation.

The remainder of this paper is structured as follows. Section 2 introduces a simple toy model to illustrate the implications of incorporating the base–peak structure. Section 3 describes the structure of the standard MIRAGE model and details the implementation of the base–peak load extension. Section 4 applies the enhanced MIRAGE model to analyze the impacts of the 2022 Russian gas shock in Germany and the EU. Section 5 concludes.

2 Insights from a toy model

In order to better understand the mechanisms at play in the base-peak structure, it is instructive to start with a simple, transparent framework. This approach, inspired by Bachmann et al. (2024), allows us to grasp the essential features without relying on the complexity of a full-scale CGE model. We chose Bachmann et al. (2024) on purpose: it has been a prominent paper in the debate on the macroeconomic consequences of the energy crisis in Germany. This is consequently a good starting point.

Bachmann et al. (2024) propose a back-of-the-envelope calculation to estimate the impact of a Russian gas cut on Germany's GDP. Their toy model, based on a CES production function, elegantly captures the trade-off between gas and other inputs in the production process. The simplicity of this model makes it possible to isolate the role of key parameters, such as the share of gas in the economy and the elasticity of substitution, and to understand how these drive the aggregate effect of a supply shock. This approach is particularly useful for highlighting the amplification mechanisms that may be hidden in more complex models.

In this section, we first present the framework of Bachmann et al. (2024), focusing on the macroeconomic impact of a microeconomic shock. Then, we introduce our toy model, whose structure is based on the distinction between base and peak load electricity. We argue on the necessity to not compute the macroeconomic effect as a Taylor expansion of the microeconomic shock, due to the magnitude of the shock and the estimated value of the parameters. Finally, we discuss the results of the partial equilibrium analysis conducted with our toy model.

2.1 First-order terms and the necessity to go beyond

In order to compute the macroeconomic impact of a microeconomic shock, a first approximation consists in applying Hulten's theorem, which states that the first-order impact of a sectoral shock on aggregate output is proportional to the sector's share in GDP. Denoting GDP by Y, supply of good i by X_i, and the share of expenditures of i over GDP by λ_i, the first-order impact of a reduction in good supply[3] $\Delta \log X_i$ is:

$$\begin{aligned} \Delta \log Y|_0 &= \frac{\partial \log Y}{\partial \log X_i}|_0 \Delta \log X_i + \mathcal{O}((\Delta \log X_i)^2)\,, \\ \frac{\partial \log Y}{\partial \log X_i}|_0 &= \lambda_i\,, \end{aligned} \tag{1}$$

where the notation $|_0$ indicates that the derivative is evaluated at equilibrium. In the context of a gas supply shock, this means that the immediate effect on GDP is given by the share of gas expenditures times the percentage reduction in gas supply. For example, for a shock equivalent to a 30 % reduction in gas supply (as in the scenario considered by Bachmann et al. 2024), and considering that gas spendings represent about 1.2 % of Germany's GDP, the first-order effect can be written as:

$$\Delta \log Y|_0 = 0.012 \times 30\,\% = 0.36\,\%\,. \tag{2}$$

However, this first-order result, while being very attractive due to its invariance under any production structure, is often insufficient, especially when elasticities of substitution are low or the shock is large. As shown by Baqaee and Farhi (2019), higher-order effects and network interactions can significantly amplify or dampen the aggregate impact. Their framework extends the analysis to second order, introducing the role of elasticities of substitution and the structure of production networks.[4] In practice, this means that the true impact of a gas shock may be much larger than what Hulten's theorem predicts, especially when bottlenecks or limited substitution possibilities are present. We now explore the consequences of introducing one element of stickiness, namely the distinction between base and peak electricity.

[3]There is a little abuse of notation here. To define properly the impact of a shock in a general equilibrium context, it could be better to take the derivative with respect to the productivity A_i of sector i. However, in the case of partial equilibrium that will be our concern in this section, taking the derivative with respect to the supply of good i is easier to grasp.

[4]However, as will be discussed later on, second-order terms might not be enough in cases where elasticities of substitution are too low compared to the size of the shock.

2.2 The base-peak feature in a toy model

We now build on Bachmann's framework and incorporate a key feature: the distinction between base and peak electricity which has been discussed in the introduction. In such setting, gas is not only an input in general production but also plays a critical role as a peak energy source. This structure allows capturing the bottleneck effects that arise when substitution between energy sources is limited, especially during periods of peak demand. The model remains intentionally simple, with a limited number of parameters, but is designed to better reflect the real-world constraints of the energy system.

We focus on the supply side of the economy, with the production of only one final good Y representing GDP. This final good is produced with a CES function taking X and J as inputs; J is the energy bundle, while X is a bundle capturing all the other intermediate inputs or factors needed to produce Y. The energy bundle is then decomposed between electricity, gas and other fossils, and electricity itself follows a nesting with a Leontief production between base and peak load electricity. This Leontief structure captures the non-substitutability between base and peak load production: because storage capacities are almost inexistent, base and peak load electricities are two different goods that cannot be substituted on the demand side; because of the merit order curve and fixed capacities at short run, substitutions are also unlikely on the supply side.

The production structure is sketched in Fig. 1. It essentially incorporates two elements: the base-peak feature, and the usage of gas as an intermediate input for two different production processes. The latter is expected to produce network effects that further amplify the shock, as exposed in Baqaee and Farhi (2019). However, we should stress that in our framework, gas usage only concerns the energy bundle, not the other part of the economy, so that network effects are only partly captured. We come back to this issue later on.

2.3 Limits of Taylor expansions

A crucial point in the type of analysis conducted by Bachmann et al. (2024) or Baqaee and Farhi (2019) is the validity of the Taylor expansion used to approximate the impact of shocks. Indeed, the second-order expansion is only valid when the elasticity of substitution is not too small and the shock is not too large. When elasticities are very low (approaching the Leontief case), higher-order terms become significant, and the expansion breaks down. This limitation is particularly relevant in the context of energy shocks, where substitution possibilities are often limited. The second condition, related on the magnitude of the shock, is also important: energy shocks have been large in the past, especially for Germany in 2022, the study case of Bachmann et al. (2024). In such cases, the standard Baqaee–Farhi procedure cannot be reliably applied, and alternative approaches are needed.

In the case of Bachmann's toy model, a lower bound constraint for the elasticity of

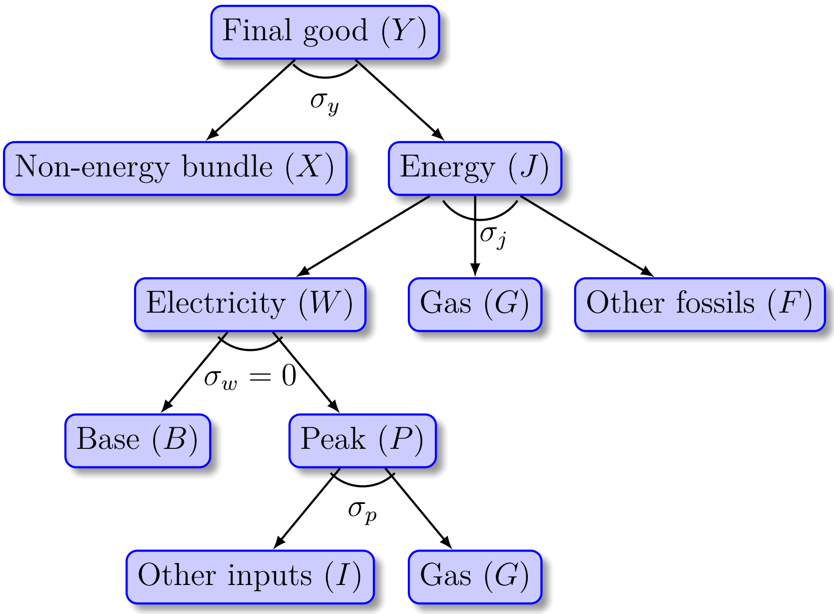

Figure 1: Toy model production structure

substitution can very easily be obtained. This model consists in a simple CES function to produce a final good Y from gas and a bundle of all the rest of the economy. Therefore, it is straightforward to Taylor expand the shock on GDP consecutive to a shock on gas supply, up to third order in $\Delta \log G$. Leaving the details for the Appendix, we derive

$$\begin{aligned} \frac{1}{2}\frac{\partial^2 \log Y}{\partial \log G^2}|_0(\Delta \log G)^2 &= \frac{1}{2}\frac{\sigma-1}{\sigma}\alpha(1-\alpha)(\Delta \log G)^2\,, \\ \frac{1}{6}\frac{\partial^3 \log Y}{\partial \log G^3}|_0(\Delta \log G)^3 &= \frac{1}{6}\left(\frac{\sigma-1}{\sigma}\right)^2\alpha(1-\alpha)(1-2\alpha)(\Delta \log G)^3\,, \end{aligned} \tag{3}$$

where α and σ are respectively the factor share of gas and the elasticity of substitution of this CES function. Although not very formal, we can be quite confident in the second-order approximation as long as the third-order term is at least one order of magnitude lower. Taking the ratio of the two, we find

$$\frac{\text{third order}}{\text{second order}} = \left|\frac{1}{3}\frac{\sigma-1}{\sigma}(1-2\alpha)\Delta \log G\right|\,. \tag{4}$$

Injecting Bachmann's value for α and $\Delta \log G$ (i.e. $\alpha = 0.012$ and $\Delta \log G = -0.3$)[5], we obtain a lower bound for the value of σ. Indeed, requiring this ratio to be lower than 0.1

[5]The parameter α being a CES factor share, it is calibrated by taking the GNE share of gas for Germany. Bachmann et al. (2024) use data from the German Federal Statistical Office to compute this ratio. The variation of gas volume $\Delta \log G$ is estimated roughly, with the argument that the 55 % of Russia's import share in German gas imports could be mitigated partially with 5 % of international substitution and 20 % of full substitution in the electricity generation sector. For comparison purposes, we keep these values in our calculation.

implies that[6]

$$\sigma > 0.5\,.$$

This result implies that third-order terms start to matter whenever the elasticity of substitution goes below one-half. This explains why Bachmann et al. (2024) find a non-continuous behavior between very low elasticities of substitution and a Leontief function: their second-order approximation breaks long before reaching Leontief's range, which is itself not expandable at any order of $\Delta \log G$. Moreover, it also confirms our prior thought, that a Baqaee–Farhi approach might not be suited for this kind of shock, which is both large (30 %) and related to low elasticities of substitution[7]. Together with the aggregation of gas among other sectors, this helps in explaining the low impact predicted by the Baqaee–Farhi model in Bachmann et al. (2024), even when the elasticities are reduced to the bare minimum.

2.4 Partial equilibrium analysis

Given these constraints, we conduct a partial equilibrium analysis that intentionally omits some of the mechanisms emphasized by Baqaee–Farhi, namely the network amplification and general equilibrium effects. In our toy model, the reduction in gas supply affects only the energy bundle, and does not propagate through other intermediate input linkages—because energy is only used to produce the final good. While this approach misses some important channels, it remains informative for understanding the direct effects of a gas shock, especially when the model is designed to highlight the base-peak feature and the resulting bottlenecks.

Our simplifying assumption is that every variable which is not linked (directly or not) to gas inputs will not vary in this partial equilibrium analysis. Taking the notations of Fig. 1, it means that X/X_0, F/F_0, B/B_0 and I/I_0 will all be equal to unity. We also assume that the gas shortage of $-30\,\%$ strikes equally peak electricity production and energy production, so that $G/G_0 = 0.7$ in both cases—which is also convenient to justify our abuse of notation with the same letter G. Therefore, the quantities we need to compute

[6] For $\sigma < 1$, the absolute value flips the sign of $\sigma - 1$. For $\sigma > 1$, the condition is always true. For $\sigma = 1$, the first-order term is the exact solution.

[7] Elasticities of substitution present in the second-order expansion of Baqaee-Farhi are general equilibrium elasticities that depend on the full structure of the model. They are often higher than the CES elasticities they are built on. However, the threshold on σ is quite high, which is why we should not be overly confident that a bottleneck in the energy produciton sector would be well captured by a second-order approximation. This goes without even mentioning the Leontief structure between base and peak electricity, which is impossible to Taylor expand.

are simply

$$\begin{aligned}
\frac{Y}{Y_0} &= \left(1-\alpha_j+\alpha_j\left(\frac{J}{J_0}\right)^{\frac{\sigma_y-1}{\sigma_y}}\right)^{\frac{\sigma_y}{\sigma_y-1}}, \\
\frac{J}{J_0} &= \left(1-\alpha_w-\alpha_g+\alpha_w\left(\frac{W}{W_0}\right)^{\frac{\sigma_j-1}{\sigma_j}}+\alpha_g\left(\frac{G}{G_0}\right)^{\frac{\sigma_j-1}{\sigma_j}}\right)^{\frac{\sigma_j}{\sigma_j-1}}, \\
\frac{W}{W_0} &= \frac{P}{P_0} \quad \text{(Leontief)}, \\
\frac{P}{P_0} &= \left(1-\alpha_p+\alpha_p\left(\frac{G}{G_0}\right)^{\frac{\sigma_p-1}{\sigma_p}}\right)^{\frac{\sigma_p}{\sigma_p-1}},
\end{aligned} \tag{5}$$

where the α's are the factor shares and the σ's the elasticities of substitution. These formulas derive straightforwardly from the exact hat algebra of the different CES functions, where the unity quantities have been injected.

2.4.1 Calibration of the parameters

To conduct this back-of-the-envelope calculation, we need seven parameters: four factor shares and three elasticities of substitution, corresponding to the different CES nests.

For the elasticities of substitution, we keep the same values as Bachmann et al. (2024) whenever possible. The authors use a meta-analysis from Labandeira et al. (2017), which provides $\sigma_y = 0.22$ and $\sigma_j = 0.23$. The elasticity σ_p is harder to estimate, but the results are not very sensitive to its value. We choose to take the same value as in the Mirage model, namely $\sigma_p = 0.5$. By sticking to the elasticity used in this CGE model, we privilege consistency with Section 3.

For the factor shares, we use GTAP data in 2017 to calibrate the share of each input inside its nest. The only problem could arise from the peak electricity bundle. We choose to attribute some renewable production to peak electricity. We here again follow the base-peak feature developed in Mirage and detailed in Section 3, for comparison purposes. Then, gas electricity represents 60 % of peak electricity, which is our factor share of gas. All parameters are summarized in Table 1. Notice that we also introduced α_b for comparison purposes, which is the factor share of Bachmann's toy model. This factor share slightly differs from the value taken by Bachmann ($\alpha = 0.012$) because GTAP data attributes more weight to oil imports relative to gas imports, whereas Bachmann et al. (2024) considered the two expenditure shares to be equal.

Table 1: Parameters of the toy model

Share parameter	Calibrated value	Elasticity	Estimated value
α_j	0.086	σ_y	0.22
α_w	0.43	σ_j	0.23
α_g	0.083		
α_p	0.61	σ_p	0.5
α_b	0.08	σ	0.22

2.4.2 Results and discussion

These back-of-the-envelope calculations yield the following results:

$$\begin{aligned} \Delta \log Y &= -0.57\,\% && \text{(Bachmann's toy model)}\,, \\ \Delta \log Y &= -1.73\,\% && \text{(Toy model with base-peak nesting)}\,. \end{aligned} \tag{6}$$

The bottom line is that the base-peak feature triples the impact found by a simple CES model without such extended production structure. The shock on gas supply creates a bottleneck in electricity production, because base load electricity cannot compensate peak load shortages. This bottleneck is further amplified at the energy level, when gas is consumed for other means than electricity production.

Apart from this result which confirms that the base-peak feature reproduces anecdotical evidence on the large impact of the energy crisis on the German economy, the number itself should be taken as illustrative. It is indeed quite sensitive to the value of σ_j, which captures substitution between energy and the rest of the economy, roughly accounted for by a CES function in this toy model. Even though it is less sensitive than Bachmann's toy model to the value of σ, it is still lacking a complete modeling outside the energy bundle, so it suffers from the same kind of drawbacks.

It is also worth noticing that second-order approximation indeed breaks down in this exercise. For Bachmann's toy model, computing the expansion at second order with our set of parameters[8] yields $\Delta \log Y = -0.36\,\%$, which is nearly half of the exact solution. It is also possible to Taylor expand all nested CES functions of our toy model (apart from the Leontief whose exact solution is easy to compute) in order to compare with the exact solution. Doing so, we find $\Delta \log Y = -1.36\,\%$, which again confirms that second-order expansions are not valid in the case at hand.

To conclude this section, while our toy model highlights the limitations of second-order approximations and the sensitivity of results to substitution parameters, it also sets the stage for a more comprehensive analysis featuring a refined modeling of the energy tree.

[8] Using the original parameters of the paper, $\alpha = 0.012$, the exact solution gives $\Delta \log Y = -0.84\,\%$, while the second-order expansion is $\Delta \log Y = -0.54\,\%$.

Moving to a general equilibrium framework is needed to allow for richer interactions and factor substitution, which is generally expected to mitigate the impact of shocks. We explore this direction by implementing the base-peak feature in a computable general equilibrium model with a detailed nesting of energy in the following section.

3 Implementation in a full general equilibrium model

After having grasped the key elements of the base-peak feature in a toy model, we can incorporate them to a full general equilibrium model to simulate a more realistic situation. The detailed modelling of energy is easier to introduce in a computable general equilibrium (CGE) model. Consequently, we use the MIRAGE model, with and without incorporating the type of nesting used in the toy model of the previous section. This section describes how we implement the base-peak structure in the MIRAGE model of the world economy. Besides the Leontief production that has already been presented, a new feature is presented in this section, related to the allocation of intermittent renewable energies to base and peak load production. In the following, we first present the traditional MIRAGE nesting for electricity generation, before moving on to the new model implementing the base-peak structure.

3.1 Nesting in MIRAGE

MIRAGE is a multi-regional, multi-sector dynamic computable general equilibrium (CGE) model devoted to trade policy analysis and, more recently, applied to long-term growth and environmental issues, and developed by the CEPII MIRAGE team.[9] In the model, firms interact either in a monopolistic competition where a number of identical firms in each sector and region compete one with another and charge a markup over marginal costs, or in a perfect competition framework where a representative firm by sector and region charges the marginal cost. Firms use intermediate inputs, value-added and energy for production, with value-added driven by five primary factors including land, natural resources, unskilled labor, skilled labor, and capital. The model features detailed representation of energy use. Energy is made of electricity and fossil fuels. The substitutability between capital and energy is low while an energy-capital bundle can be substituted to labor with higher elasticity. From the demand side, a representative agent (representing households and government) maximizes its utility under budget constraint. This representative agent saves a part of her income and spends the rest on final consumption, according to a Linear Expenditure System-Constant Elasticity of Substitution (LES-CES) functional form. Trade follows the Armington assumption of product differentiation by country of

[9] See Bouët, Fontagné, et al. (2026) for more details.

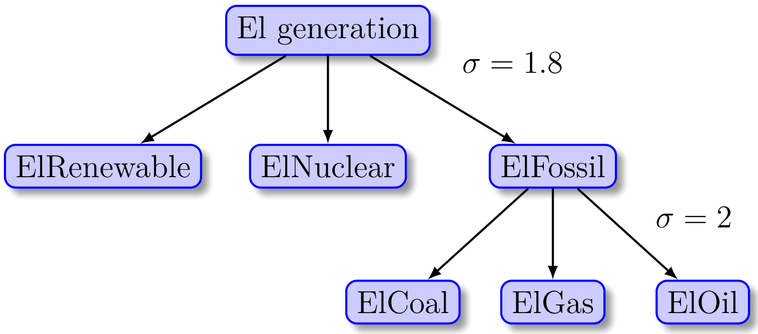

Figure 2: Standard MIRAGE production function for electricity generation

origin. Finally, MIRAGE is a recursive dynamic model where the dynamics is driven by capital accumulation and depletion, productivity growth, and labor force growth.

Turning to the central focus of this paper, the nesting for electricity generation in MIRAGE is shown in Fig. 2. Each leaf of the tree corresponds to the supply of a given electricity sector. The nesting is made of two layers, to represent the better substitutability among fossil electricity sectors.

In the standard MIRAGE, the intermittency of renewable energy sources is not modeled. All renewable electricity sectors, including both non-intermittent hydro power and VRE sources such as solar and wind, are aggregated in a single sector. This approach is based on the assumption that, for macroeconomic assessment purposes, the integration of total renewables into the electricity mix is of primary importance, while distinctions among different renewable sources are considered less critical. However, in light of the arguments presented in the introduction, this assumption is to be relaxed. We will illustrate how amending the model in such direction helps in better representing the consequences of an energy shock.

Different from GTAP-Power documented in Peters (2016), where firms demand individual technologies as opposed to an aggregate national electricity, MIRAGE assumes that firms demand electricity as a single aggregate commodity. The national power producer provides electricity to firms and households. This is based on the reality that end consumers do not select the technology used to generate their electricity, instead, they receive electricity as a whole from a mix of sources. Electricity as such can also be traded internationally.

3.2 Base and peak load nesting

The base and peak load nesting that we introduce in the standard version of MIRAGE is represented in Fig. 3. Electricity generation is divided between base and peak load production, following the same kind of structure that can be found in Peters (2016). A Leontief production has been chosen to account for (almost) no storage capacities of

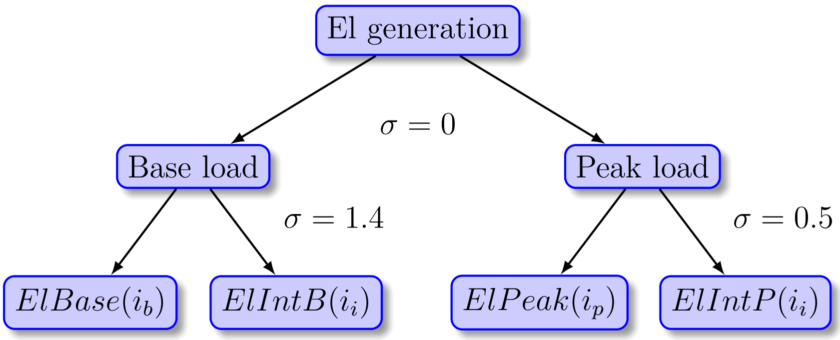

Figure 3: Base and peak load production function for electricity generation

electricity.[10] Then, the nesting[11] tries to model the merit order curve:

- Base load production comes from pure base load electricity $ElBase_{i_b rt}$, and base intermittent electricity $ElIntB_{i_i rt}$, where r and t denote respectively region and time. Pure base load electricity is composed of sectors $i_b \in E_{BL}$ which are always considered as base load sectors. By default, it includes coal, nuclear, and base load hydroelectricity. Coal and nuclear are always at the very bottom of the merit order curve, due to their low variable costs. Renewables also have low variable costs, but they are either intermittent (e.g., wind and solar) or in limited availability (e.g., hydro). For this reason, hydroelectricity is split between base and peak load hydroelectricity, while intermittent electricity sectors indexed by $i_i \in E_{Int}$ are distributed between a base load production $ElIntB_{i_i rt}$ and a peak load production $ElIntP_{i_i rt}$. More explanations on this distribution are given below.
- Peak load production comes from pure peak load electricity $ElPeak_{i_p rt}$, and peak intermittent electricity $ElIntP_{i_i rt}$. By default, pure peak load sectors $i_p \in E_{PL}$ are gas, oil, and peak load hydroelectricity. Gas and oil are the last plants to be called on the merit order curve, because of their relatively high variable costs. Peak renewable electricity activities are the counterpart of base load renewable electricity discussed above.

Distribution of intermittent renewables

Intermittent renewables are not easy to model, because they share a very special place in the merit order curve. Indeed, their variable cost is zero, putting them at the bottom of the curve, while their intermittency modifies the curve at each passing day. Thus, intermittent renewables can be considered either as base load energies, when their usage substitutes "pure" base load energies, or peak load energies, in the opposite case. For instance, if

[10]This elasticity can be increased to simulate scenarios where storage capacities become important enough to allow substitution between base load and peak production.

[11]The elasticities of substitution inside each nest follow from Peters (2016).

renewables produce electricity only during peaking hours, they could be considered as peak load energies in the nesting.[12]

In our model, intermittent electricity production[13] addresses both the demand for base and peak load intermittent electricity. More precisely, each intermittent electricity sector i_i gets a base load contribution $ElIntB_{i_irt}$ and a peak load contribution $ElIntP_{i_irt}$. It is assumed that intermittent electricity is produced randomly without any correlation to electricity demand. Thus, the proportion of supply that is allocated to base load electricity is a fixed parameter r_r^{ElB} that depends on the region r. This ratio is calibrated by evaluating the ratio of all base load electricity production—except intermittent renewables—to total electricity generation; then, intermittent renewables are distributed according to this ratio in order to mimic their uncorrelated production:

$$ElIntB_{i_irt} = r_r^{ElB} Y_{i_irt}\,, \quad ElIntP_{i_irt} = (1 - r_r^{ElB}) Y_{i_irt}\,, \quad \text{for } i_i \in E_{Int}\,. \tag{7}$$

Prices are chosen such as to ensure that the previous equations hold with the conservation of total value, i.e.

$$\begin{aligned} P_{i_irt}^{ElIntB} &= P_{rt}^{ElB} \left(\frac{a_{i_ir}^{ElIntB} ElB_{rt}}{r_r^{ElB} Y_{i_irt}} \right)^{1/\sigma^{ElB}}, \\ P_{i_irt}^{ElIntP} &= \frac{(1 + tax_{i_irt}^{P}) P_{i_irt}^{Y} - r_r^{ElB} P_{i_irt}^{ElIntB}}{1 - r_r^{ElB}}\,, \end{aligned} \tag{8}$$

where $tax_{i_irt}^P$ is the production tax and σ^{ElB} the elasticity of substitution in the base load electricity nest.

With this allocation of intermittent renewables between base and peak load, we expect to better capture the complexity of substituting energy sources in the electricity sector. This question is of major importance when studying for example energy transition scenarios, where sometimes the intermittency of renewables is not correctly taken into account, thus underestimating the complementarities of the different energy sources.

This concludes the implementation of the base-peak structure in a full CGE model such as Mirage. In the following, we will test this new feature in the same kind of simulation scenario as we experimented with our toy model: a cut on European gas imports from Russia.

[12] Other CGE models with a base-peak nesting, such as GTAP-Power, choose to hard-code the base or peak nature of a VRE, thus removing the peculiar nature of intermittent sources. As an example, in GTAP-Power, wind electricity belongs to base energies, while solar electricity belongs to peak energies. In our model, we want to better represent the intermittency nature of these energy sources, because we believe it to be of crucial importance for energy or carbon emission scenarios.

[13] In most cases this concerns wind and solar, but it is possible to assign any sector to this category in the aggregation procedure.

4 Application to Russian gas cuts

To test the new feature in Mirage, we apply it to the case of Russian gas cuts for Germany and the EU in 2022. This scenario is particularly relevant as it involves a significant and sudden reduction in gas supply, which can illustrate the amplification of the shock enabled by the base-peak feature. Moreover, this scenario is also the one chosen by Bachmann et al. (2024) for their analysis, which allows us to compare our model results with theirs.

4.1 Description of the scenario

Two different simulations will be conducted: one with the original Mirage model and one with the base-peak feature. These two simulations use the same scenario, namely a complete Russian gas cut for Germany and the EU in 2022.[14] From now on, we denote by S0 the simulation with the original Mirage model, and by S1 the simulation with the base-peak feature.

The model, used in its (recursive) dynamic version, is calibrated on 2017, the year of the gtap 11 database. GDP growth is then updated to 2022 using World Bank data. Then, the model is run up to 2040, which is interpreted as the year when a new steady state is achieved. For the baseline, projections data such as GDP or population come from the MaGE model (Fontagné, Perego, et al. 2022). It allows determining the TFP endogenously, which is then imposed exogenously during the simulation itself, thus relaxing the constraint on GDP.

The model is aggregated in 22 regions and 26 sectors.[15] The individualized countries in the region of interest (i.e. Europe) are Germany, France, Russia and the UK. Other aggregate regions in this zone include the rest of the EU, EFTA countries, and the rest of Europe. For the sectors, the aggregation is quite detailed for both industry and energy sectors.

International trade is achieved by requiring regional demand to follow a two-level Armington-type ces function. This tow-level specification allows a home bias: it is easier to switch between imports of different origins than between production and imports. The value of elasticities between importing regions is sourced from Fontagné, Guimbard, et al. (2022).

Protection data for year 2017 and 2022 come from the MAcMap-HS6 database (Guimbard et al. 2012). The baseline also includes the Brexit. However, carbon policies are not implemented, although they could technically be handled by Mirage. Indeed, we wanted our simulation to be as closed as possible to the framework of Bachmann et al. (2024);

[14]In this regard, this application differs from traditional general equilibrium simulations, which compare different scenarios to the same baseline within the same model; here, the scenario is the same, but the baseline will be different, due to the two versions of the same model being different.

[15]See Tables 5 and 6 in the Appendix for details.

incorporating a carbon price in the EU would have created too much of a difference, by dampening the results of the simulation, since part of the gas substitution would have taken place in the baseline.

The scenario itself is quite simple: it consists in imposing large iceberg trade costs for gas between Russia and EU countries, starting from 2022 and continuing in subsequent years, in order to eliminate nearly all gas trade. Because we are in a framework with CES functions, we cannot reduce gas imports to a true zero; however, the value is so small that it is equivalent in practice. It should also be emphasized that this scenario does not correspond to the actual situation. Indeed, gas pipelines have been cut between Germany and Russia since 2022, but LNG continues to be exported by the latter. Moreover, several European countries, especially in the East, have pursued their gas imports through pipelines. Finally, sanctions have been imposed between European countries and Russia, which are not accounted for here. The choice of this scenario rather than reality is twofold: first, it allows for a cleaner energy shock through gas supply, which is very convenient for testing the new feature of the model; second, it sticks to the scenario of Bachmann et al. (2024) for comparison purposes.

4.2 Results

To obtain the impact of the Russian gas cut, the simulation is compared to the baseline, which acts as a counterfactual scenario. Such exercise is not intended to provide short-run simulations. Several reasons prevent this kind of interpretation, such as:

- The "large" value of the elasticities of substitution, particularly for trade, which are rather calibrated for the medium run.
- The absence of friction in the allocation of factors. Except for capital, which is dynamically adjusted each year and can only be moved with depreciation and investment, other factors are perfectly mobile across sectors within each region of the world.
- The absence of uncertainty in the model, which is often a major economic driver in the short run.
- The use of real prices instead of nominal prices. Thus, Neo-Keynesian effects cannot be accounted for.

Therefore, the results presented here should be understood as the medium-run economic impact, or alternatively as a lower bound of the impact on the economy.

4.2.1 Impact on gas consumption

The first thing to examine is the variation of gas consumption, both globally and by sectors. For all EU countries, imports of gas from Russia drop by more than 97 % in both

Table 2: Impact of the simulations on the volume of total gas demand (%)
Variation in 2040 compared to baseline

Region	Original model (S0)	Base-peak nesting (S1)
Germany	−28.1	−20.2
France	−8.0	−5.5
Rest of European Union 27	−12.9	−8.0

Source: Authors calculation

simulations, as a consequence of the prohibitive trade cost imposed in 2022. For its part, Russia sees its bilateral exports of gas being partially redirected towards other trading partners, even though the volume of total gas exports from Russia drop by at least 27 %.

Table 2 shows the impact of the simulations on total gas demand for European countries. For Germany, the volume of total gas demand decreases by 20.2 % in S1 (base-peak simulation) against 28.1 % in S0 (original model). The difference between both simulations is already interesting to interpret: gas was much easier to substitute with other inputs in absence of the base-peak feature, which authorizes cutting more imports.[16] For reference, total gas supply decreased by 17 % between 2021 and 2023 in Germany (source: IEA). This is by no means a benchmark for our simulation, due to the different temporality, among many other identification issues.[17] We expect a gas supply shock to lead to a lower impact on the volume of total demand in the short run, because substitution between trading partners or energy sources is more likely to be a bottleneck. Nevertheless, it gives an order of magnitude—and a lower bound—for the expected decrease in total gas demand in the short run. In their paper, Bachmann et al. (2024) consider as one of their central hypotheses a shock on gas supply equal to roughly −30 %. This number, which was obtained by assuming a conservative case where only 50 % of the gas coming from Russia could be substituted, is aligned with the first column of Table 2. On the other hand, the new version of the model is closer to the value measured by the IEA between 2021 and 2023.

4.2.2 Impact on GDP and welfare

The impact on GDP and welfare is shown in Fig. 4. For Germany, the base-peak nesting increases GDP losses, albeit quite moderately: the variation in GDP goes from −0.61 % (S0) to −0.71 % (S1), hence a 16 % increase. The demand of gas volume being less affected in S1 than in S0, this increase is driven by the valuation effect, caused by the large increase

[16] We discuss the change in imports in Section 4.2.4, but we recall that domestic production of gas is anecdotical.

[17] Total gas supply was more or less constant between 2017 and 2021 in Germany, so taking the variation between 2021 and 2023 is not entirely far-fetched. However, we reiterate that this number should be considered with great caution.

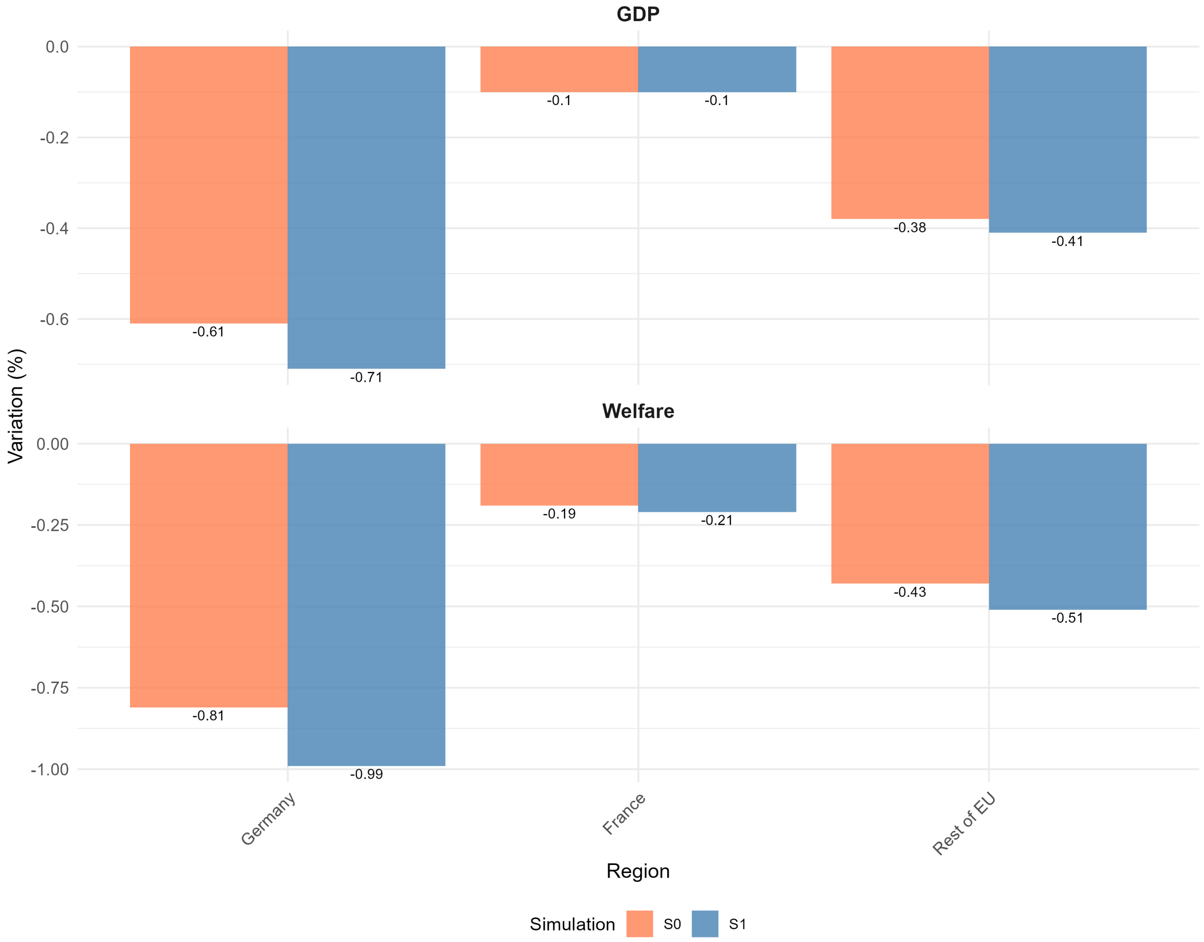

Figure 4: Impact of the simulations on GDP and welfare
Variation in 2040 compared to baseline
Source: Authors calculation

in gas prices. For France, the impact is much more limited, at −0.10 % in both scenarios, as could be expected from its production structure, with less chemical industry or gas usage for electricity generation. The rest of the EU countries lies somewhere in between, with a GDP loss between −0.38 % (S0) and −0.41 % (S1).

Together with GDP, we also turn our attention to welfare loss. This indicator is relevant for such an energy shock, because gas is also an important good for final consumers, not just as an intermediate input. Moreover, because European countries must internationally substitute a large part of their gas imports, they also suffer a loss in their terms of trade which is more captured by welfare than by GDP. For Germany, welfare losses are indeed more substantial: the impact is either −0.81 % (S0) or −0.99 % (S1). This is also the case for France (with about −0.20 %) and the rest of the EU countries (from −0.43 % to −0.51 %).

Bachmann et al. (2024) found different results for national income losses, depending on the methodology they used (see Section 2 for a recap on their framework). With a Baqaee–Farhi model, which is basically a CGE model Taylor-expanded at second order (Baqaee and Farhi 2024), the loss is relatively low, between 0.2 and 0.3 %, both for GDP and GNE. In their framework, gas is not disaggregated from electricity and water supply, which can explain why the result we find is at least twice bigger. The authors also conducted a back-of-the-envelope calculation with a 30 % shock on gas supply. In their preferred scenario, the GNE loss reaches 0.72 %, which is interestingly close to our result. This resemblance could be misleading though. In order to obtain such an impact on GDP, they are forced to consider that 30 % of gas supply would be cut and not substituted by other countries.[18] Had total gas imports been decreased in such a way, the base-peak version of our model would have depicted a higher blow to the economy, due to the structure of its production function—in other words, the base-peak structure predicts a 0.71 % loss of GDP when total gas demand is "only" decreased by 20.2 %.

4.2.3 Impact on sectoral production

Here comes the real value that a multi-sector multi-country general equilibrium model provides: the detailed impact on production and value added, sector by sector, displayed in Table 3. Because variations between the simulation and the baseline do not indicate the size of the sector in the economy, their contribution to the variation of total value added can be very different; as an example, a 1 % variation in agriculture for Germany would have a low impact, compared to services or even industry.

Let us first focus on variations in sectoral output for Germany. As could be expected, the most impacted aggregated sectors are energy and industry: for energy and mining, the production varies from −1.52 % (S0) to −3.86 %, while for industry, it goes from −0.76 % (S0) to −0.83 % (S1). The base-peak feature introduces a more pronounced difference in the aggregate energy and mining sector rather than in the industry sector; nothing unexpected, since the electricity sector is at the heart of this modification. In details, chemistry, electricity, and gas production represent the sectors with the most visible impact. For chemistry, the difference between the two scenarios is very limited: the production varies from −11.0 % for S0 to −12.8 % for S1. Gas is an important intermediate input for chemistry, hence the importance of the shock on output; moreover, since electricity is not as important, this also explains the small difference between both simulations. For electricity, on the contrary, the impact is more than twice as large with the base-peak nesting: it goes from −2.4 % for S0 to −5.6 % for S1. This difference is understandable when examining the electricity generation sectors. For S0, substitution plays its role between the different sources: while the gas electricity sector endures a huge production

[18] Moreover, their calibrated parameters are higher than those found with GTAP values. Again, Section 2 explains the difference and computes their toy model with our set of parameters.

Table 3: Impact of the simulations on sectoral output (%)
Variation in 2040 compared to baseline

	Base-peak nesting (S1)		Original model (S0)	
Sector	Germany	France	Germany	France
Agriculture and agroindustry	-0.62	-0.12	-0.56	-0.11
Forestry	0.02	-0.01	-0.01	-0.02
Coal	-4.53	-1.34	3.25	0.24
Oil	0.01	-0.04	-0.02	0.03
Gas	26.18	18.69	21.72	15.30
Refined oil	-0.97	-0.03	-0.96	-0.20
Mineral and mining	-2.71	-0.82	-2.38	-0.76
Electricity	-5.56	-0.03	-2.43	0.09
Electricity coal	-9.64	-0.42	6.84	4.45
Electricity gas	-9.23	-1.03	-42.20	-11.32
Electricity nuclear	-10.07	-0.50	3.82	1.52
Electricity oil	8.04	3.84	7.08	4.06
Electricity renewables	0.76	1.73	3.76	1.55
Elec. transmission and distribution	-5.99	0.14	-2.57	0.16
Electronic and optical products	1.11	-0.07	0.83	-0.06
Machinery and electric products	0.82	-0.15	0.63	-0.12
Metals	-1.06	-0.20	-0.67	-0.30
Other manufacture	-1.00	0.03	-0.78	-0.03
Chemistry	-12.76	-0.43	-11.00	-0.54
Pharmacy	2.22	0.45	1.58	0.34
Textile	-1.03	-0.49	-1.02	-0.47
Transportation equipment	1.81	0.54	1.36	0.31
Vehicles	1.77	-1.14	1.32	-0.94
Business services	-0.14	-0.03	-0.17	-0.04
Other services	-0.45	-0.06	-0.39	-0.06
Domestic transportation	-0.44	-0.11	-0.36	-0.11
International transportation	-0.22	-0.07	-0.31	-0.09
Agriculture	-0.60	-0.12	-0.54	-0.11
Energy and Mining	-3.86	0.06	-1.52	0.13
Industry	-0.83	-0.13	-0.76	-0.18
Services	-0.30	-0.05	-0.28	-0.05

Source: Authors calculation

decrease of −42 %, other sectors boost their production, so that total electricity generation is only hampered by 2.4 %. For S1, because gas is a peak electricity source, substitution can only occur with other peak load energies, hence the 8 % increase of oil electricity. Due to their intermittency, only part of renewables production can be devoted to peak production, so the increase in production is slighter in S1 (0.8 %) than in S0 (3.8 %). On the other hand, pure base load energies suffer from the complementarity, with around the same decrease of 10 % in their production as for gas electricity.

Other sectors are impacted more lightly, even though they might weigh heavier in the economy overall. The vehicles and pharmacy sectors contribute positively to the variation in production, in both scenarios, due to the reallocation of factors among sectors that are less dependent on gas or electricity usage—an outcome of the general equilibrium structure of the model.

Finally, although they are not as impacted as the industry, services also represent a substantial loss of GDP, due to their important weight in the economy. Either because of their consumption of gas as an intermediate input (e.g. for heating) or because of a general equilibrium effect, their production is negatively impacted in both scenarios, with almost the same value of −0.3 %. Again, apart from the general equilibrium effect, we indeed expect the base-peak feature not to make any difference in services production.

4.2.4 Discussion on the Armington function

In many trade models, substitution between imports from different origins is captured by an Armington CES function, which takes imports from region s as inputs, and gives import demand as output. This is the case in our exercise as well. Import demand is then used in a second-level Armington function, together with demand for domestic goods, to obtain total demand for good i. The main drawback of this specification, as usual with CES, is that values are conserved in the process, not volumes—which can be a problem in the case at hand.

Let us take an example to illustrate this issue. Total imports of gas for a given region can be computed by summing the volumes of imports from each of its trading partners. The resulting impact of the simulations on such indicator is displayed in Table 4. Should volumes be conserved, this table should coincide with the variation of total gas demand shown in Table 2, because domestic gas production is nearly inexistent. If we take Germany as an example, total gas imports decrease by around 5 % in S1, while total gas demand decreases by around 20 %. This discrepancy exists because total demand is computed as the output of a non-physical Armington function, which is just an artifact used to model import diversification.

This is a serious issue, at least because it is unclear which indicator best describes the real situation. Should we track physical produced quantities, and say that gas consumption decreases by 5 %? Or should we focus on total demand CES volumes, as done in this work, which are then used in production processes or final consumption, and may better represent the kind of shortage that occurs in the country? This can also have consequences for the size of the shock: Germany endures a shock on the volume of total gas demand equal to −20 %, but to reach this target, it must import tons of gas from countries other

Table 4: Impact of the simulations on the volume of total gas imports (%)
Variation in 2040 compared to baseline

Importing region	Original model (S0)	Base-peak nesting (S1)
Germany	−14.60	−5.21
France	−9.92	−7.37
Rest of European Union 27	−10.90	−5.01

Source: Authors calculation

than Russia, so that the volume of total gas imports only drop by 5 %.[19] Therefore, there is a revenue flow to other countries that might be higher than what corresponds to a −20 % decrease of gas consumption—or if we approach the problem the other way around, the impact on the economy would be lower with a smaller impact on total gas demand.

This issue is more fundamental than the simulation we study here, and rather concerns the Armington structure used in most trade models. This is why we do not tackle it in this work. We simply indicate that the impact on gas consumption is more subtle than what appears in our results.

5 Conclusion

The issue of securing energy supplies, particularly electricity, is now at the forefront of economic policymakers' agendas. Their decisions must be informed by economic modelling, but this raises difficult challenges. There are many sources of electricity generation, some of which are notoriously intermittent, while electricity is difficult to store and demand fluctuates with significant peaks, requiring the use of the full range of production solutions. Different production technologies vary in terms of the relative share of fixed and variable costs in overall generation costs, and combining them also requires the deployment of complex interconnection grids. It is challenging to represent such complexity in multisectoral and global economic models, while technical-economic models, more suited to these issues, would fail to satisfactorily account for interactions between countries and sectors. Of particular interest are indeed the cascading effects of a limited sectoral shock originating in a particular country, leading to a significant macroeconomic impact. In this paper, we examined a simple solution, considering two types of electricity that are not substitutable, depending on whether they are demanded and produced during peak hours or not.

After providing an insight into our reasoning using a toy model, we introduced the same

[19] This is caused by the huge size of Russia in gas imports at calibration year. Because the factor share of Russia is so large compared to other countries, other "intermediate inputs" of the Armington must increase substantially to compensate for only a fraction.

base-peak structure into a multisectoral general equilibrium model of the global economy and compared the macroeconomic impact of a shock to Russian gas depending on whether or not the base-peak structure was considered. This approach made two contributions. First, on a theoretical level, we showed that a simple calculation of cascading effects based on a first-order approximation of this effect (following Hulten's theorem) is inadequate for large shocks and low elasticities of substitution. Complementing the results of Baqaee and Farhi (2019) on second-order effects and shock amplification in networks, we have shown that the validity of the Taylor expansion for approximating the impact of a shock is limited if the shock is large and substitution is limited. Third-order effects then come into play, under conditions that we have identified. Secondly, with regard to taking these difficulties into account in an applied general equilibrium model, we have shown that the base-peak structure more accurately reproduces the observed impact of the stylized shock of the disruption of Russian gas supplies.

What are the ultimate implications of this stylized exercise? In terms of applied modelling, we have shown that it is possible to find a middle ground between an eco-energy model and a multinational, multisectoral general equilibrium model, provided that we accept a simplified representation of electricity demand and the low degree of substitution between production assets mobilized during peak hours and at off-peak times. In terms of economic policy, our exercise highlights the levers that can be activated to better respond to an energy shock such as the one examined here. These are supply flexibility on the one hand, and demand smoothing on the other. With regard to the first lever, storage technologies and grid interconnections naturally alleviate the constraint. As for the second lever, dynamic pricing in line with demand intensity, or contracts providing for the disconnection of large consumers, are solutions that are widely explored by utilities. Finally, we must emphasize the illustrative nature of our exercise. Several extensions should be introduced to better represent the mechanisms at work: electricity generation from renewable energies is considered here as a whole, whereas the constraints on mobilization may differ, for example between hydroelectric power and wind turbines. The constraint represented by the availability of a decentralized and interconnected grid is not considered. The price of electricity in a given country and for a given year is uniform (except for taxes and carbon pricing). The dynamic model is based on an annual time step, which fails to adequately reflect changes at a higher frequency. Finally, we have highlighted the difficulties raised by the use of CES functions. These various points open up a number of avenues for future research.

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Appendix

A Taylor expansion of Bachmann's toy model

Bachmann's toy model consists in a single CES function, where final good Y is produced from gas G and other inputs X. The factor share is denoted α, while the elasticity of substitution is σ. By normalizing the equilibrium prices to 1, the factor share corresponds to the ratio of gas expenditures over GDP:

$$\frac{G_0}{Y_0} = \alpha \,, \quad \frac{X_0}{Y_0} = 1 - \alpha \,. \tag{A.1}$$

After a shock $\Delta \log G$ on gas supply, the variation of GDP can be written

$$\Delta \log Y|_0 = \frac{\partial \log Y}{\partial \log G}|_0 \Delta \log G + \frac{1}{2}\frac{\partial^2 \log Y}{(\partial \log G)^2}|_0 (\Delta \log G)^2 + \frac{1}{6}\frac{\partial^3 \log Y}{(\partial \log G)^3}|_0 (\Delta \log G)^3 + \mathcal{O}((\Delta \log G)^4) \,, \tag{A.2}$$

which is simply the Taylor expansion of the function

$$Y(G, X) = \left(\alpha^{\frac{1}{\sigma}} G^{\frac{\sigma-1}{\sigma}} + (1-\alpha)^{\frac{1}{\sigma}} X^{\frac{\sigma-1}{\sigma}}\right)^{\frac{\sigma}{\sigma-1}} \,. \tag{A.3}$$

Computing the derivative of this function is detailed below.

First-order derivative

$$\begin{aligned}
\frac{\partial \log Y}{\partial \log G} &= \frac{\sigma}{\sigma-1} \frac{\partial \log \left(\alpha^{\frac{1}{\sigma}} G^{\frac{\sigma-1}{\sigma}} + (1-\alpha)^{\frac{1}{\sigma}} X^{\frac{\sigma-1}{\sigma}}\right)}{\partial \log G} \\
&= \frac{\sigma}{\sigma-1} \frac{\sigma-1}{\sigma} \frac{\alpha^{\frac{1}{\sigma}} G^{-\frac{1}{\sigma}}}{\alpha^{\frac{1}{\sigma}} G^{\frac{\sigma-1}{\sigma}} + (1-\alpha)^{\frac{1}{\sigma}} X^{\frac{\sigma-1}{\sigma}}} G \frac{\partial G}{\partial G} \\
&= \frac{\alpha^{\frac{1}{\sigma}} G^{\frac{\sigma-1}{\sigma}}}{\alpha^{\frac{1}{\sigma}} G^{\frac{\sigma-1}{\sigma}} + (1-\alpha)^{\frac{1}{\sigma}} X^{\frac{\sigma-1}{\sigma}}} \\
&= \alpha^{\frac{1}{\sigma}} \left(\frac{G}{Y}\right)^{\frac{\sigma-1}{\sigma}} \,.
\end{aligned} \tag{A.4}$$

Second-order derivative

$$\begin{aligned}
\frac{\partial^2 \log Y}{(\partial \log G)^2} &= \frac{\partial}{\partial \log G}\left(\alpha^{\frac{1}{\sigma}} \left(\frac{G}{Y}\right)^{\frac{\sigma-1}{\sigma}}\right) \\
&= \alpha^{\frac{1}{\sigma}} \frac{\sigma-1}{\sigma} \left(\frac{G}{Y}\right)^{-\frac{1}{\sigma}} \frac{\partial}{\partial \log G}\left(\frac{G}{Y}\right) \\
&= \alpha^{\frac{1}{\sigma}} \frac{\sigma-1}{\sigma} \left(\frac{G}{Y}\right)^{-\frac{1}{\sigma}} \frac{GY - GY\alpha^{\frac{1}{\sigma}} (G/Y)^{\frac{\sigma-1}{\sigma}}}{Y^2} \\
&= \frac{\sigma-1}{\sigma} \alpha^{\frac{1}{\sigma}} \left(\frac{G}{Y}\right)^{\frac{\sigma-1}{\sigma}} \left(1 - \alpha^{\frac{1}{\sigma}} \left(\frac{G}{Y}\right)^{\frac{\sigma-1}{\sigma}}\right) \,,
\end{aligned} \tag{A.5}$$

where the third line comes from

$$\frac{\partial G}{\partial \log G} = G\,, \quad \frac{\partial Y}{\partial \log G} = Y \frac{\partial \log Y}{\partial \log G} = Y \alpha^{\frac{1}{\sigma}} (G/Y)^{\frac{\sigma-1}{\sigma}}\,. \tag{A.6}$$

Third-order derivative

$$\begin{aligned} \frac{\partial^3 \log Y}{(\partial \log G)^3} &= \frac{\sigma-1}{\sigma} \frac{\partial}{\partial \log G} \left(\frac{\partial \log Y}{\partial \log G} \left(1 - \frac{\partial \log Y}{\partial \log G} \right) \right) \\ &= \frac{\sigma-1}{\sigma} \frac{\partial^2 \log Y}{(\partial \log G)^2} \left(1 - 2 \frac{\partial \log Y}{\partial \log G} \right). \end{aligned} \tag{A.7}$$

B Fossil electricity specification

As stated in Section 3, in Mirage, all electricity generation sectors—including fossils—follow the standard production function, depicted in Fig. 5. However, this nesting might not be satisfactory for fossil electricity. Indeed, in this standard production function, energy enters in the value added bundle, to better capture its complementarity or substitutability with capital. While this makes sense for non-energy sectors, fossil electricity sectors rather use fossil fuel as an intermediate input that directly enters the production process. In other words, we would like that a shock ΔX of fossil fuel consumption in the electricity sector yields a variation ΔX on its associated electricity generation, instead of being mitigated by other factors of production.

To implement this idea, we extract the fossil fuel input from the previous nesting, and we put it at the same layer as "Value added" and "Intermediate consumption". Because there is a Leontief production at this level, we indeed capture the behaviour we expected from fossil electricity generation. Figure 6 shows an example of this production function applied for the case of gas electricity. The generalization to coal or oil electricity is straightforward: in these sectors, either "Coal" or "Refined oil" is extracted from below (instead of "Gas") and put at the same layer as VA and IC.

C Geographical and sectorial aggregation

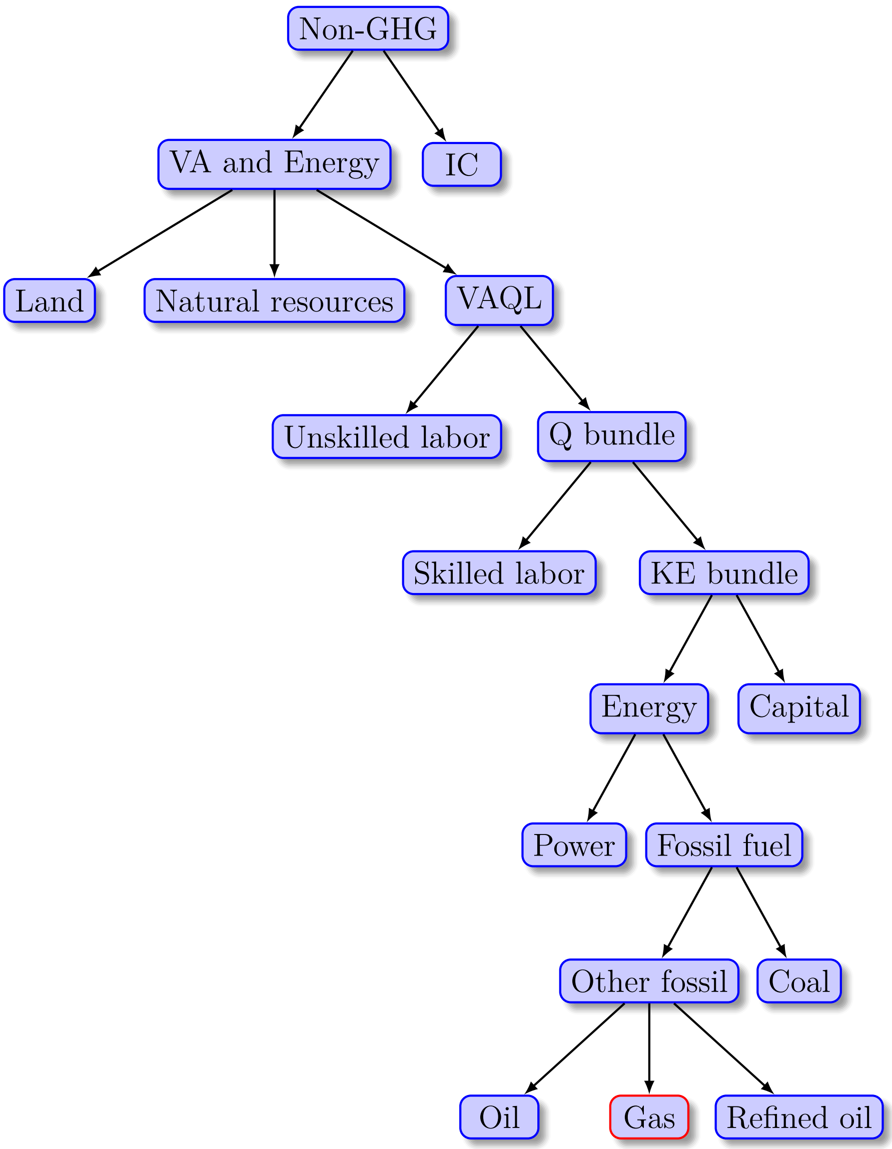

Figure 5: Standard production function in MIRAGE
Gas supply is highlighted in red to illustrate the change with the gas electricity production function (taken as an example) in the new version of the model

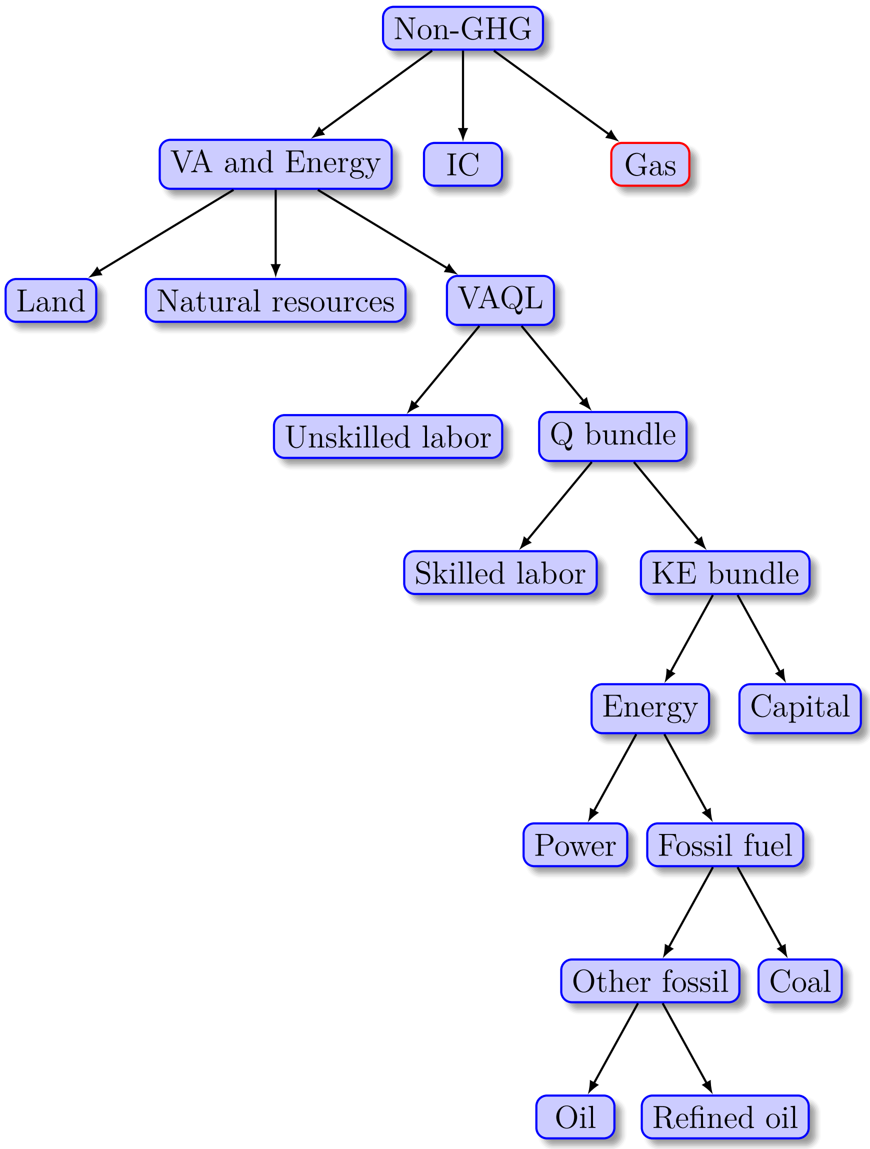

Figure 6: Gas electricity production function in the new version of the model

Table 5: Regional aggregation

MIRAGE Region	GTAP code
ASEAN	BRN, IDN, KHM, LAO, MYS, PHL, SGP, THA, VNM
Australia and New Zealand	AUS, NZL
Brazil	BRA
Canada	CAN
China	CHN
EFTA	CHE, NOR, XEF
France	FRA
Germany	DEU
India	IND
Japan	JPN
Korea	KOR
Mexico	MEX
Middle East and North Africa	ARE, BHR, DZA, EGY, IRN, IRQ, JOR, KWT, LBN, MAR, OMN, PSE, QAT, SAU, SYR, TUN, TUR, XNF, XWS
Rest of America	HTI, XCA, XCB, XNA, XSM, XTW
Rest of Asia	AFG, BGD, HKG, ISR, NPL, PAK, LKA, MNG, TWN, UZB, XEA, XOC, XSA, XSE
Rest of Europe	ALB, ARM, AZE, BLR, GEO, KAZ, KGZ, SRB, TJK, UKR, XEE, XER, XSU
Rest of European Union	AUT, BEL, BGR, CYP, CZE, DNK, ESP, EST, FIN, GRC, HRV, HUN, IRL, ITA, LTU, LUX, LVA, MLT, NLD, POL, PRT, ROU, SVK, SVN, SWE
Rest of Latin America	ARG, BOL, CHL, COL, CRI, DOM, ECU, GTM, JAM, HND, NIC, PAN, PRI, PRY, PER, SLV, TTO, URY, VEN
Russia	RUS
Sub-Saharan Africa	AGO, BEN, BFA, BWA, CAF, CIV, CMR, COD, COG, COM, ETH, GAB, GHA, GIN, GNQ, KEN, MDG, MLI, MOZ, MUS, MWI, NAM, NER, NGA, RWA, SEN, SWZ, TCD, TGO, TZA, UGA, XAC, XCF, XEC, XSC, XWF, ZAF, ZMB, ZWE
United Kingdom	GBR
United States	USA

Table 6: Sectorial aggregation

MIRAGE Sector	GTAP code
Agriculture and agro-industry	pdr, wht, gro, v_f, osd, c_b, pfb, ocr, ctl, oap, rmk, wol, cmt, omt, vol, mil, pcr, sgr, ofd, b_t
Forestry and fishing	frs, fsh
Coal	coa
Oil	oil
Gas	gas, gdt
Mineral and mining	oxt, nmm
Textile	tex, wap, lea
Other manufacture	lum, ppp, rpp, omf
Refined oil	p_c
Chemistry	chm
Pharmacy	bph
Metals	i_s, nfm, fmp
Electronic and optical products	ele, eeq
Machinery	ome
Vehicles	mvh
Transportation equipment	otn
Electricity	ely
Electricity transmission and distribution	TND
Electricity nuclear	NuclearBL
Electricity coal	CoalBL
Electricity gas	GasBL, GasP
Electricity oil	OilBL, OilP
Electricity renewables	WindBL, SolarP, HydroBL, HydroP, OtherBL
Business services	trd, cmn, ofi, ins, rsa, obs
Domestic transportation	otp, whs
Internation transportation	atp, wtp
Other services	wtr, cns, afs, ros, osg, edu, hht, dwe