# The Impact of the Russia-Ukraine War on Renewable Energy *

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**Abstract**

Global adoption of renewable energy has increased rapidly since the early 2000s, driven partly by learning-by-doing mechanisms. Despite this progress, the world remains below what is needed to reach net-zero by 2030. This paper examines how the Russia-Ukraine war accelerated Europe's clean energy transition. The European Union relied heavily on Russian natural gas for electricity generation, and the war disrupted this relationship, creating a supply shock. Countries experienced this shock at varying intensities depending on their pre-war import exposure to Russian gas. We exploit variation in pre-war Russian gas dependency and find that more dependent countries transitioned faster post-war compared to less-exposed counterparts. We develop a model featuring learning-by-doing and heterogeneous fossil-fuel dependency to rationalize these findings. Preliminary results show economies accelerate their renewable transition approximately four periods after a permanent supply shock, while highly exposed countries do so up to eight periods earlier due to higher electricity prices, lower fossil-fuel investment returns, and learning-by-doing amplification. Low-exposure countries show minimal response. Crucially, this acceleration only sustains when the shock is permanent, suggesting that learning-by-doing alone cannot generate lasting effects from temporary disruptions.

*Keywords*: Clean growth, Renewable Energy.

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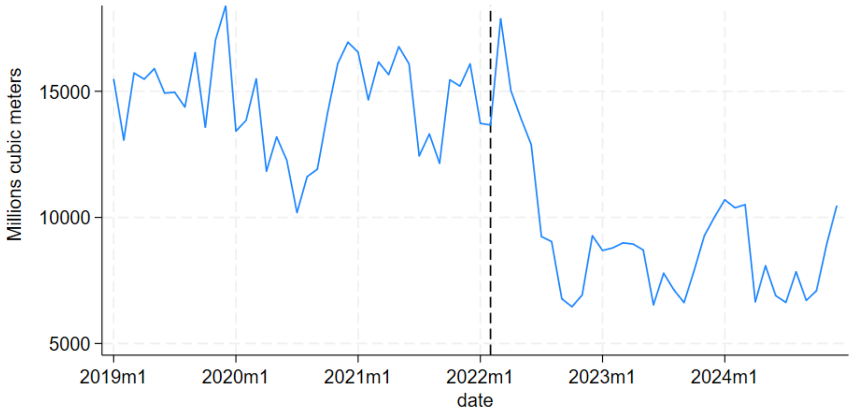
# 1 Introduction

The clean energy transition is a cornerstone of global climate change policy. The IPCC has warned of the climate risks associated with crossing the 1.5° warming limit (IPCC, 2018). In order to reduce the risk of surpassing this threshold, significant abatement needs to occur in the near term, including transitioning the economy from fossil fuels to renewable energy sources to meet net zero goals. Transition in the electricity sector to renewable sources has made notable progress, with the share of electricity worldwide coming from renewable sources increasing from 18% in 2000 to 34.5% in 2025 (Bojek and International Energy Agency, 2025). This is largely due to the reductions in the cost of renewable technologies, and while many factors have contributed to this declining cost, the virtuous cycle of the "learning-by-doing" mechanism has been an important driver of this progress, where cumulative deployment lead to steady reductions in renewable technology costs (Newbery, 2018; Roser, 2020; Rubin et al., 2015). However, while the learning-by-doing mechanism has contributed to the progress, current transition rates are not nearly enough to meet the target goals for 2030. According to the International Renewable Energy Agency (2024), current policies only deliver half of the clean growth needed to meet 2030 targets, with the COP28 even calling for a tripling global renewable electricity capacity to meet net-zero goals. Alongside falling short of installed capacity trajectories, annual investment in clean power is also far from its targets, with a 60% increase needed from 2024 levels between 2025 and 2030 to reach net-zero by 2050 (Cheung et al., 2025).

These deployment and investment shortfalls are occuring against a backdrop of rising concerns over energy security. Most notably, the Russian invasion of Ukraine in February 2022 disrupted Europe's heavy reliance on Russian natural gas, triggering a supply shock with pipeline gas deliveries falling by 75% from June to September, shown in Figure 1, which also contains liquefied natural gas deliveries. In response, the European Commission proposed the RePowerEU plan, as part of the Versailles declaration in March 2022, to reduce Europe's reliance on Russian fossil fuels using a two pillar approach comprising of both diversifying gas sources and expanding the use of renewables and electrification to "fast forward" the clean transition (European Commission, 2022). This paper investigates whether this gas supply disruption acted as a catalyst for accelerating the clean energy transition, triggering self-reinforcing dynamics via the learning-by-doing mechanism, particularly in countries' with a high pre-war exposure to Russian natural gas.

We begin with an empirical approach in which our identification strategy exploits cross-country variation in the exposure of electricity production to Russian natural gas imports before the onset of the war. We use a difference-in-difference specification to identify the impact of the trade shock, defined as a change in Russian natural gas imports relative to pre-war gas consumption. We find that countries with a higher import exposure

Figure 1: Total Exports from Russia to the EU (Pipeline and LNG)




*Notes:* We use pipeline and liquefied natural gas data from Eurostat's *Imports of natural gas by partner country*. We extract monthly pipeline and liquefied natural gas imports from Russia to EU countries, measured in million cubic metres. This chart illustrates total exports of Russian gas in millions of cubic meters to the European Union, via both delivery methods. The line depicts the start of the war in February 2022.

to Russian gas increased their renewable energy use significantly more after the invasion relative to their less-exposed counterparts.

In order to rationalize our findings, the paper develops a small open economy model with electricity sector, a fossil-fuel manager who makes sourcing decisions to meet the country's fossil-fuel demands, and learning-by-doing to both explore the mechanisms through which energy shocks affect the pace of transition and quantify how post-war clean transition rates could vary across countries with different import exposure to Russian gas. With all these ingredients, the model captures the interaction between production, household investment decisions, and the energy sector. Electricity can be generated by fossil capital that uses fossil-fuel inputs, or renewable capital, with the relative cost of fossil inputs determined by world energy prices and a CES aggregator of sources that captures differences in exposure. Households allocate resources between consumption and investment across three types of capital: production, fossil-fuel electricity capital, and renewable-electricity capital. They face adjustment costs and benefit from learning-by-doing in renewable capital accumulation that drives down the cost of investment in renewables over time. This framework captures two key forces relevant to the European energy crisis. First, fossil fuel scarcity increases energy prices and raises the return to renewable capital. Second, higher renewable investment feeds back into productivity through learning-by-doing.

To discipline the model, we conduct a preliminary calibration that adopts parameter values commonly used in the macro-energy and climate-economics literatures. At the current state of this paper, these choices are not intended to deliver a fully targeted quantitative fit. Rather, they provide a baseline from which to study the model mechanisms. Production parameters follow standard values for capital and energy shares, adjustment-cost parameters are chosen to generate smooth investment dynamics, and the learning-by-doing process for renewables follows estimates from recent empirical work. While this calibration allows us to present the qualitative transition dynamics implied by the model, it is intentionally parsimonious and does not aim to match specific countries moment-by-moment at this stage.

Model simulations reveal how these forces interact in shaping the transition path. Starting with a baseline economy that has medium exposure to Russian gas, we impose a permanent disruption in Russian supply. The productivity of fossil-fuel electricity capital declines, leading to permanently lower returns to investment. At the same time, the shock to electricity supply drives up the price of electricity. These combined forces increase the returns to renewable electricity capital and drives investment towards renewables. The resulting uptick in renewable capacity is further amplified by a persistent uptick in the learning-by-doing term, which makes the cost of investing renewable capital cheaper over time. Taken together, all of these forces accelerate the clean energy transition by four model periods. In contrast, a temporary supply shock in a moderately-exposed country produces similar but short-lived effects, with almost no impact on long-run transition dynamics once fossil fuel supply is restored.

Next, the model reproduces the strong heterogeneity across countries that we observe in the data. Countries with higher import-exposure experience larger accelerations as the supply shock results in a greater energy price spike, thus driving higher returns to renewable capital investment and increasing uptake. Under a temporary shock, they take longer to return back to the baseline equilibrium, as the initial uptick in renewable capital is larger than for moderately-dependent countries, amplified by the learning-by-doing response. For low-exposure countries, there is almost no change in their clean-energy transitions.

Together, the empirical evidence and model-based mechanism experiments suggest that energy security shocks can meaningfully accelerate the clean energy transition, namely in countries with substantial dependence on imported fossil fuels and only when the disruption is sufficiently persistent to trigger learning-driven investment dynamics.

**Related Literature**

This paper contributes to two strands of literature. The first strand embeds transitions into economic growth frameworks. One set of papers center directed technical change as the driver of clean growth (Acemoglu et al., 2012, 2016; Aghion et al., 2016), while in contrast, Arkolakis and Walsh (2024) emphasize learning-by-doing externalities where renewable energy adoption proliferates without the help of policies due to the self-reinforcing nature of accumulated renewable capital deployment which drives down costs. Partial-equilibrium models of the electricity market have similarly characterized learning-by-doing as a key market failure (Fischer et al., 2021). Our work builds on this learning-by-doing framework, investigating whether a supply shock can interact with learning-by-doing externalities and accelerate a transition or if the income effect dominates, slowing down progress. Similar to Tahvonen and Salo (2001), who theoretically characterize the clean energy transition along the path of development, where rising extraction costs of fossil fuel drive economies back to renewable energy, we study if the supply shock to fossil fuel imports which drives up cost can have a similar effect. This analysis contributes to a strand of literature investigating the immediate economic effects of the Russia-Ukraine war using multi-sector models to quantify the impact on GDP of an embargo on Russian fuel imports (Bachmann et al., 2022; Baqaee et al., 2022). Our analysis focuses on the long-run impacts on the energy system and economic outcomes.

To complement our theoretical framework, we provide empirical evidence of the impact of the Russia shock on renewable energy adoption by applying quasi-experimental methods from the trade shock literature pioneered by Autor et al. (2013), who use predetermined exposure to create variation for identifying causal effects. Our method is in the spirit of (Adamopoulos and Leibovici, 2024), who apply this empirical strategy using a difference-in-difference approach to the Ukraine-Russia war in the context of food insecurity. We adopt their approach to the European energy market and construct country-level exposure measures based on pre-war Russian gas dependence and use difference-in-differences to test whether highly-exposed countries show differentially faster renewable growth post-2022.

# 2 Empirical Evidence

In this section, we provide empirical evidence on whether the Russia–Ukraine war accelerated the renewable energy transition in Europe. Our strategy builds on cross-country variation in dependence on Russian natural gas to examine how the disruption affected energy composition after 2022.

## 2.1 Data

Our empirical analysis relies on data from Eurostat and the International Energy Agency (IEA). From Eurostat, we obtain data that contains the monthly natural gas imports from Russia and Ukraine for 27 European Union countries from January 2019 to January 2025, as well as monthly domestic production, exports, and consumption of natural gas for each country. The import data and consumption data is used to construct our trade shock measure, which is the change in Russian and Ukraine imports relative to pre-war natural gas consumption, capturing the magnitude of natural gas disruption faced by each country following the onset of the war. The domestic production data is used to construct our pre-war exposure variable, which combined with IEA data will capture each country's pre-war dependence on natural gas imports and thus their exposure to the trade shock. From the IEA, we obtain monthly electricity data on the composition of electricity sources within a country. This dataset breaks down the generation from renewable sources, such as solar, hydro, wind, and geothermal, and from non-renewable sources such as coal, peat, manufactured gasses, oil, and natural gas. We use this dataset to construct our outcome variables of renewable energy share of electricity as well as renewable energy production in GWh.

## 2.2 Empirical Strategy

Our identification strategy exploits cross-country variation in pre-war natural gas import exposure to evaluate how renewable energy responded after the trade shock that is the Russian invasion of Ukraine, following the approach of Adamopoulos and Leibovici (2024). Specifically, we estimate a difference-in-differences specification of the form:

$$\Delta\text{Renewable Energy}_{it} = \beta \cdot (\text{NG Import Exposure}_{i0} \times \text{Trade Shock Size}_{it}) + \gamma_i + \lambda_t + u_{it} \tag{1}$$

where $i$ indexes countries and $t$ denotes months following the trade shock, with $t = 0$ set to be January 2022. We include country time fixed effects $\gamma_i$ and time fixed effects $\lambda_t$. The coefficient $\beta$ in this regression measures whether countries with electricity sectors more exposed to natural gas imports from Russia experience differential clean energy adoption following the trade shock. Because the trade shock is negative, a negative estimate means that more-exposed countries move in the opposite direction of the shock, so they increase their renewable energy adoption. In contrast, a positive estimate indicates that greater exposure slows the clean transition.

The trade shock is defined as the change in imports of Russian natural gas by a country $i$ scaled by their baseline natural gas consumption in the period before the war:

$$\text{Trade Shock Size}_{it} = \frac{\Delta\text{Russian Imports}_{it}}{\text{NG Consumption}_{i0}} \tag{2}$$

Natural gas import exposure is measured as the product of the baseline share of electricity generation from natural gas and the share of domestic natural gas consumption not covered by domestic production:

$$\text{NG Import Exposure}_{i0} = \text{NG Electricity Share}_{i0} \times \Big(1 - \text{Own Production Share of NG Consumption}_{i0}\Big) \quad (3)$$

This captures the vulnerability of a country's electricity sector to the trade shock. Electricity sectors with a high dependence on both natural gas for electricity generation and import dependence will be more vulnerable to trade shocks.

Table 1 reports our regression results for the effects of the Russian natural gas shock on the level of renewable energy of a country, controlling for region and time fixed effects. The coefficient on the exposure weighted trade shock is negative, suggesting that countries with electricity sectors highly reliant on imported natural gas from Russia increase renewable energy generation when experiencing import reductions post-war.

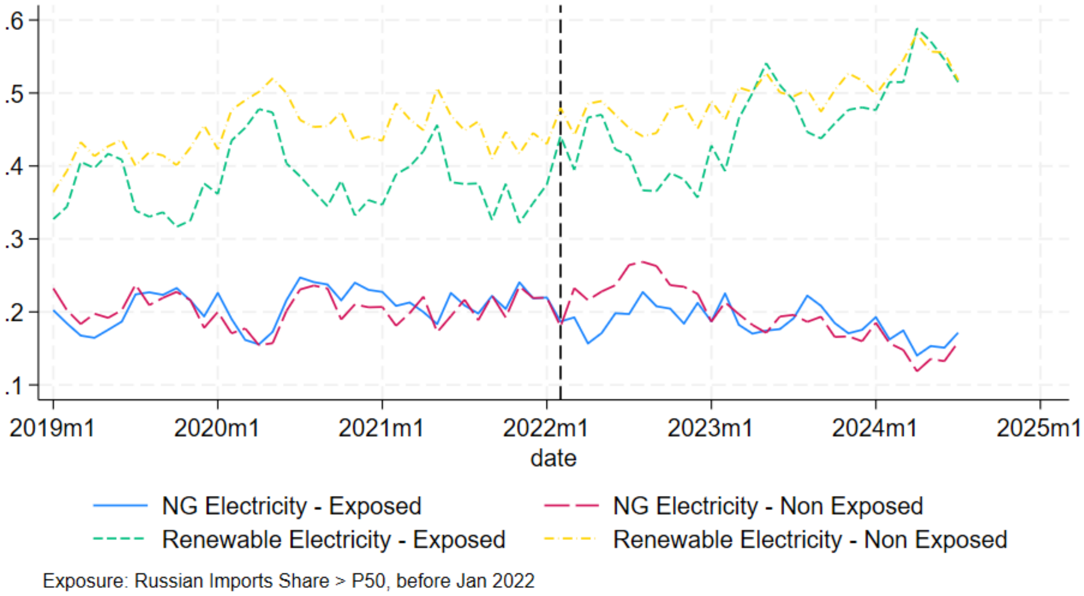
Table 1: Regression Results for Renewable Electricity

| | **Log Renewable Energy (GWh )** |
|---|---|
| **Exposure Weighted Trade Shock** | $-0.242^{***}$ |
| | (0.0792) |
| Constant | 0.00334 |
| | (0.00401) |
| Observations | 2,428 |
| R-squared | 0.007 |

*Notes:* Robust standard errors in parentheses.
$^{***}p < 0.01$, $^{**}p < 0.05$, $^{*}p < 0.1$.

In addition, for each country we calculate the share of their imports they source from Russia and split it along the median value, classifying them into the exposed versus non-exposed groups. Figure 2 shows the share of electricity arising from renewable and natural gas for these two groups. Before the onset of the war, exposed and non-exposed regions had similar levels of natural gas shares in electricity generation. After January 2022, both groups reduce gas usage similarly as the energy crisis in Europe included not just a supply shock but also a spike in the Dutch TTF. However, non-exposed and exposed regions differ in their renewable energy uptake after the war. Before the war, countries with a high degree of exposure to Russian imports used less renewable energy than their non-exposed counterparts, with some cyclical component to it where the gap closes in the first of the year reflecting increased wind and solar electricity generation. After the war, renewable electricity generation for exposed countries begins trending upwards, driven by increased solar output as can be seen by Figure 3 which disaggregates the renewable electricity generation into hydro, solar, and wind. This pattern indicates that although all countries reduced gas-usage irrespective of import exposure, only regions with high Russian import dependence substituted toward renewables.

Figure 2: Share of Electricity Source out of Total Electricity Production

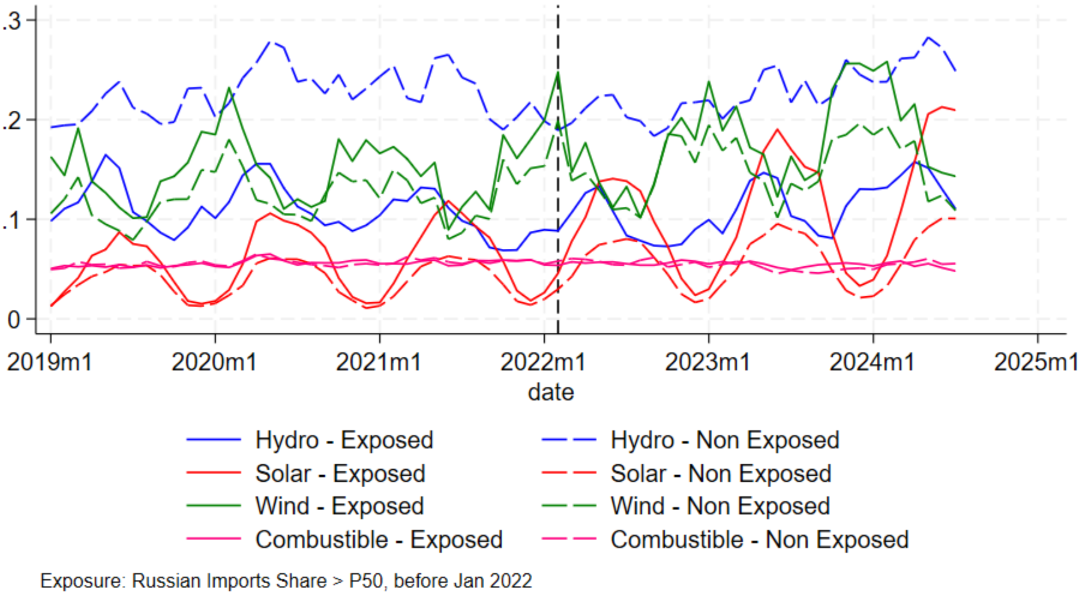



*Notes:* Monthly electricity generation shares for natural gas and renewables, plotted separately for countries above and below the median pre-war exposure to Russian gas imports. Data are from the International Energy Agency (IEA), *Monthly Electricity Statistics*.

The disaggregated figure also reveals a large change in the amount of wind power coming online in the winter of January 2024. While exposed countries generally had more wind generation than their counterparts, this differential widens dramatically in 2024. Solar generation also shows a similar pattern, with the difference between exposed and unexposed countries becoming larger and larger after the war. Hydro, in contrast, shows little difference.

Overall, the empirical results show that the reaction to the war was not the same across countries. Regions with higher dependence on Russian natural gas increased their use of renewable energy more after 2022, while less exposed countries showed little or no change. The figures and regression results indicate that the shock may have encouraged a faster transition in some countries, especially through solar and wind energy. These findings suggest that energy security concerns can play an important role in the clean energy transition.

Figure 3: Share of Electricity Source - Disaggregation




*Notes:* The figure shows the monthly share of electricity generation from hydro, solar, wind, and combustible sources for countries with high and low pre-war exposure to Russian natural gas (above/below the median import share prior to January 2022). Data are from the IEA *Monthly Electricity Statistics*.

# 3 Model

There is a small open economy which consists of a representative household, a representative firm producing a final good, an energy sector using both renewable and fossil technologies, with clean and dirty electricity producers providing each, and lastly a fossil fuel import manager. Production relies on three types of capital: production capital $K_t^P$, fossil electricity capital $K_t^F$, and renewable electricity capital $K_t^R$.

## Final Goods Producers

The representative firm produces output using production capital $K_t^P$ that it rents from households at rate $r_t^P$, labour $L_t$ which is paid wage $w_t$, and electricity $E_t$ costing $p_t^E$ using the following Cobb-Douglas technology:

$$Y_t = \left(K_t^P\right)^\alpha L_t^{1-\alpha-\eta} E_t^\eta \tag{4}$$

with factor prices determined by their marginal products. $\alpha$ denotes the share of output attributed to production capital and $\eta$ being the share attributed to the energy sector. The remainder falls to labour.

## Electricity Generation

Electricity $E_t$ used by the final good firm is produced from both renewable and dirty sources, in a zero-profit and perfectly competitive manner, and treated as perfect substitutes:

$$E_t = E_t^R + E_t^F. \tag{5}$$

where $E_t^R$ is the amount of electricity generated from clean sources and $E_t^F$ is the electricity generated using fossil fuel capital and fossil fuel imports, making it dirty.

More specifically, renewable electricity generation is linear in renewable capital where $\theta$ is renewable power potential, following the specification of Arkolakis and Walsh (2024):

$$E_t^R = \theta K_t^R \tag{6}$$

Dirty electricity generation combines fossil fuel capital $K_t^F$ with a fossil fuel input $X_t$ that is dirty using the following technology:

$$E_t^F = \left(K_t^F\right)^{\alpha_F} X_t^{1-\alpha_F} \tag{7}$$

## Electricity Producers' Problems

The dirty electricity producer will then choose how much $K_t^F$ to rent from households at the rental rate $r_t^F$ and the amount of $X_t$ to purchase from the fossil fuel manager at price $P_t^X$ (which will arise from the fossil fuel import manager's problem) to maximize profits:

$$\max_{K_t^F, X_t} \; p_t^E \left(K_t^F\right)^{\alpha_F} X_t^{1-\alpha_F} - r_t^F K_t^F - P_t^X X_t \tag{8}$$

leading to standard first-order conditions for capital demand and fossil fuel input demand.

The renewable electricity producer similarly chooses how much $K_t^R$ to rent from households at rate $r_t^R$ to maximize

$$\max_{K_t^R} \; p_t^E \theta K_t^R - r_t^R K_t^R \tag{9}$$

The renewable electricity producer's problem determines the rental price houeshold's receive:

$$r_t^R = p_t^E \theta \tag{10}$$

Importantly, this implies that the returns to investing in renewable capital increase with the price of electricity.

## Fossil Fuel Manager

Fossil fuel inputs $X_t$ are sourced from either Russian or non-Russian sources. The import manager minimizes the cost of delivering the $X_t$ demanded by the dirty electricity producer using inputs $F_{R,t}$, Russian fuel which costs $p_{R,t}$, and $F_{NR,t}$, non-Russian fuel costing $p_{NR,t}$:

$$\min_{F_{R,t}, F_{NR,t}} \; p_{R,t} F_{R,t} + p_{NR,t} F_{NR,t} \quad \text{s.t.} \quad \left[\omega_R F_{R,t}^{\gamma} + (1-\omega_R) F_{NR,t}^{\gamma}\right]^{\frac{1}{\gamma}} = X_t \tag{11}$$

The Russian and non-Russian fuel is combined using a CES aggregator that contains a Russian fuel bias term $\omega_R$ which captures that some countries will prefer Russian gas arising from factors such as geographic proximity, existing infrastructure and contractual relationships, or political ties. A higher $\omega_R$ reflects greater dependence, and thus a greater share of the composite fuel arising from Russian sources.

This set-up yields that the price for the fossil fuel import is:

$$P_t^X = \left(\omega_R^{\frac{1}{1-\gamma}} p_{R,t}^{\frac{\gamma}{\gamma-1}} + (1-\omega_R)^{\frac{1}{1-\gamma}} P_{NR,t}^{\frac{\gamma}{\gamma-1}}\right)^{\frac{\gamma-1}{\gamma}} \tag{12}$$

This structure implies that the price of the fossil fuel import is a CES index of the prices of Russian and non-Russian fuel, each weighted by the country-specific parameter. A country with a higher dependence on Russian fuel will then have its price index for the fossil fuel imports place greater weight on the price of Russian fuel. The shock to Russian natural gas imports will involve shutting off Russian fuel completely ($F_{R,t} = 0$).

## Households

The representative household is an infinitely-lived agent who maximizes their present discounted value of lifetime utility by choosing how much to consume of the final good and how much to invest in each type of capital every period:

$$\max_{\{c_t, I_t^k\}} \sum_{t=0}^{\infty} \beta^t \ln(c_t) \tag{13}$$

subject to the budget constraint

$$c_t + \sum_{k \in \{R,F,P\}} g(I_t^k) = w_t L_t + r_t^P K_t^P + r_t^R K_t^R + r_t^F K_t^F \tag{14}$$

where $\beta$ is the standard intertemporal discount factor, and households earn income from renting out all types of capital.

Investment is subject to convex adjustment costs to prevent abrupt jumps in capital stocks.

$$g(I_t^k) = I_t^k + \frac{\phi}{2}\left(\frac{I_t^k}{K_t^k}\right)^2 K_t^k \quad \text{where} \quad k \in \{R, F, P\} \tag{15}$$

The term $\phi$ governs the degree of adjustment frictions, with higher values penalizing investment that is large relative to current capital stock. Adjustment costs will ensure smoother investment paths.

The law of motion for each type of capital is defined as follows:

$$K_{t+1}^F = (1-\delta)K_t^F + I_t^F \tag{16}$$
$$K_{t+1}^P = (1-\delta)K_t^P + I_t^P \tag{17}$$
$$K_{t+1}^R = (1-\delta)K_t^R + Q_t^R \tag{18}$$

where $\delta$ is a common depreciation term. For fossil fuel and production capital, the law of motion is standard and capital stock tomorrow depends on the amount of the final good that was invested $I_t^K$. Renewable capital is subject to learning-by-doing, modelled following the approach of Arkolakis and Walsh (2024):

$$Q_t^R = \left[\sum_{i=1}^{\infty} \mu^i Q_{t-i}\right]^{\gamma_R} I_t^R \tag{19}$$

where $\mu < 1$ controls how quickly past installation experience decays and $\gamma_R$ captures how strongly past deployment improves the efficiency of building new renewable capital. This formulation captures that the productivity of renewable investment grows with the history of global installations. This provides a simple way to represent learning-by-doing, where accumulated deployment gradually reduces the effective cost of expanding renewable energy.

Solving the household's problems lead to the following Euler equations for an interior solution for production and fossil fuel capital, where $k \in \{F, P\}$

$$\frac{1}{c_t}\left[1+\phi\left(\frac{K_{t+1}^k-(1-\delta)K_t^k}{K_t^k}\right)\right]=\frac{\beta}{c_{t+1}}\left\{r_{t+1}^k+1-\delta+\frac{\phi}{2}\left[\left(\frac{K_{t+2}^k}{K_{t+1}^k}\right)^2-(1-\delta)^2\right]\right\} \tag{20}$$

The left-hand side captures the current period marginal utility cost of investing in one unit of fossil or production capital for tomorrow. The investment incurs an adjustment cost so that the effective cost of installing an extra unit of capital exceeds one unit of consumption when capital stock is growing. The right-hand side represents the discounted marginal utility benefit in the next period from investing the additional unit of capital. This includes the rental returns from production or fossil fuel capital, subject to depreciation, with the last term capturing the benefits of lowering future adjustment costs.

The Euler equation for renewable capital captures the same trade-off, but is augmented by the learning-by-doing term.

$$\frac{1}{c_t}\frac{\left[1+\phi\left(\frac{K_{t+1}^R-(1-\delta)K_t^R}{K_t^R}\right)\right]}{\left(\sum_{i=1}^{t}\mu^iQ_{t-i}\right)^{\gamma_R}}=\frac{\beta}{c_{t+1}}\left\{r_{t+1}^R+\frac{(1-\delta)+\frac{\phi}{2}\left[\left(\frac{K_{t+2}^R}{K_{t+1}^R}\right)^2-(1-\delta)^2\right]}{\left(\sum_{i=1}^{t+1}\mu^iQ_{t+1-i}\right)^{\gamma_R}}\right\} \tag{21}$$

Learning-by-doing affects both the marginal cost and benefit of investing in renewables. On the cost side (LHS), the accumulated learning stock reduces the effective cost of adding one more unit of renewable capital because experience makes installation more efficient. On the benefit side (RHS), the net-of-depreciation value of renewable capital and the effect of today's capital on next period's adjustment costs are both divided by next period's learning stock. This reflects that increased renewable investment today makes future installation less costly, thus increasing the continuation value of renewable capital and amplifying the incentives to invest in renewables overtime.

The Euler equations described above hold with equality when $I_t^k \geq 0$ for $k \in \{F, P, R\}$ in the interior case. However, these equalities may not hold if the optimal choice of investment leads to a corner solution in any of the capital investment decisions. In these cases, the Euler no longer holds with equality for the investment decision of that particular capital type.

**Definition 1** (Equilibrium). *An equilibrium is a sequence of prices* $\{w_t,\ r_t^P,\ r_t^R,\ r_t^F,\ p_t^E,\ P_t^X\}$ *and allocations* $\{c_t,\ K_{t+1}^P,\ K_{t+1}^R,\ K_{t+1}^F,\ F_{R,t},\ F_{NR,t},\ E_t\}$ *such that, given initial capital stocks* $\{K_0^P, K_0^R, K_0^F\}$ *and exogenous Russian and non-Russian fuel prices* $\{p_{R,t}, p_{NR,t}\}$, *the following conditions hold for all* $t$*:*

1. *The allocations* $\{c_t, K_{t+1}^P, K_{t+1}^R, K_{t+1}^F\}$ *solve the representative household's intertemporal optimization problem and satisfy the associated Euler equations, including the no-arbitrage conditions across the three capital types.*

2. *Given* $\{K_t^P, L_t, E_t\}$, *the factor prices* $\{w_t, r_t^P, p_t^E\}$ *are consistent with the final-good firm's profit-maximizing first-order conditions.*

3. *The renewable and fossil electricity producers choose* $\{K_t^R\}$ *and* $\{K_t^F, X_t\}$ *to satisfy their profit-maximizing first-order conditions.*

4. *The inputs* $\{F_{R,t}, F_{NR,t}\}$ *ensure the fossil fuel manager is minimizing the cost of delivering* $X_t$ *and*

$$P_t^X = \left(\omega_R^{\frac{1}{1-\gamma}} p_{R,t}^{\frac{\gamma}{\gamma-1}} + (1-\omega_R)^{\frac{1}{1-\gamma}} p_{NR,t}^{\frac{\gamma}{\gamma-1}}\right)^{\frac{\gamma-1}{\gamma}}$$

5. *Market clearing conditions hold:*

   - Electricity market:
$$E_t = \theta K_t^R + (K_t^F)^{\alpha_F} X_t^{1-\alpha_F}$$

   - Final-good market:
$$Y_t = c_t + g(I_t^P) + g(I_t^R) + g(I_t^F) + P_t^X X_t$$

   - Labour market:
$$L_t = 1$$

   - Fuel aggregator:
$$X_t = \left[\omega_R F_{R,t}^{\gamma} + (1-\omega_R) F_{NR,t}^{\gamma}\right]^{1/\gamma}$$

   - Capital markets clear for all three capital types

# 4 Calibration

In this preliminary calibration exercise, we choose a set of parameter values that are standard in the literature and suitable for illustrating the qualitative mechanisms of the model. In future versions of this paper, we will calibrate the model to target European countries in the next stage of this paper.

## Preferences and Technology

We set the production technology parameters to the standard $\alpha = 0.3$ and $\eta = 0.04$, as in Golosov et al. (2014). We follow Arkolakis and Walsh (2024) and set fossil fuel capital share of dirty electricity output to 0.7. We adopt their values of the learning-by-doing process, with a depreciation rate of 1% and choose a $\gamma_r = 0.25$, on the high-end of the range presented. The productivity of renewable electricity generation is governed by $\theta$ which we set to be 1.9. We calibrate this, along with the initial capital stock conditions for renewable and fossil-fuel capital stocks, such that initial renewable energy share of electricity generation matches that of the countries we plan to target in our final calibration exercise.

## Adjustment Costs

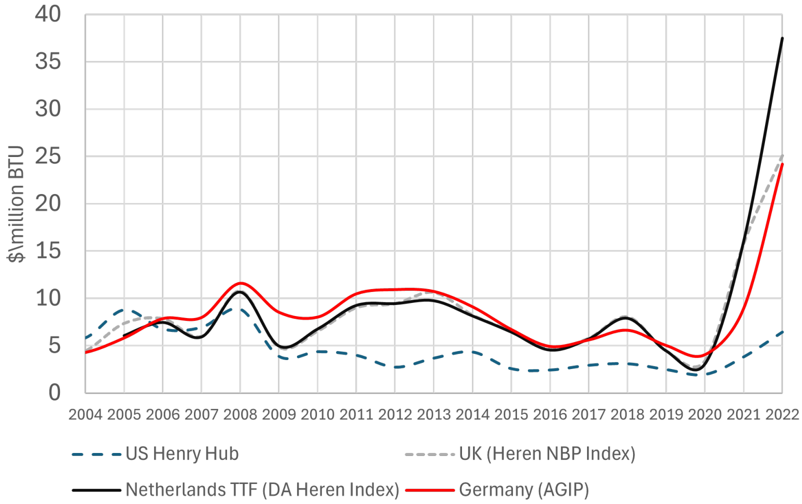
Households face convex adjustment costs when investing in physical, fossil, and renewable capital. The adjustment cost parameter is set to $\phi = 0.15$, which ensures smooth investment paths without inducing excessive inertia. This is a moderate value since this is less than the $\phi = 0.21$ in David and Venkateswaran (2019) for the U.S. We plan on running robustness checks to assess the importance of this parameter in driving transition dynamics.

## Fossil Fuel Imports and Exposure

Imported fossil fuel inputs are aggregated using a CES structure that combines Russian and non-Russian sources. The parameter $\omega_R = 0.55$ governs the initial weight placed on Russian fossil fuels in the composite fuel input. This value is chosen to represent an economy with substantial dependence on Russian imports, in line with several EU member states before 2022. The elasticity of substitution between Russian and non-Russian fuels is set to $\gamma = 0.5$. This is to capture that these fuels are imperfect substitutes.

The fossil fuel manager faces exogenous prices for Russian and non-Russian inputs. In our preliminary calibration, we set these prices equal to each other to capture the co-movement observed in the Dutch TTF and Russian gas as reflected in German contract prices, shown in Figure 4. In the counterfactual experiments, we restrict the supply of Russian fossil-fuel, which increases the price of total imports.

Figure 4: Natural Gas Prices




*Source:* Energy Institute, *Statistical Review of World Energy*, Energy Charting Tool. Prices shown: Henry Hub (U.S.), NBP (U.K.), TTF (Netherlands), and Germany (AGIP), in USD per million BTU.

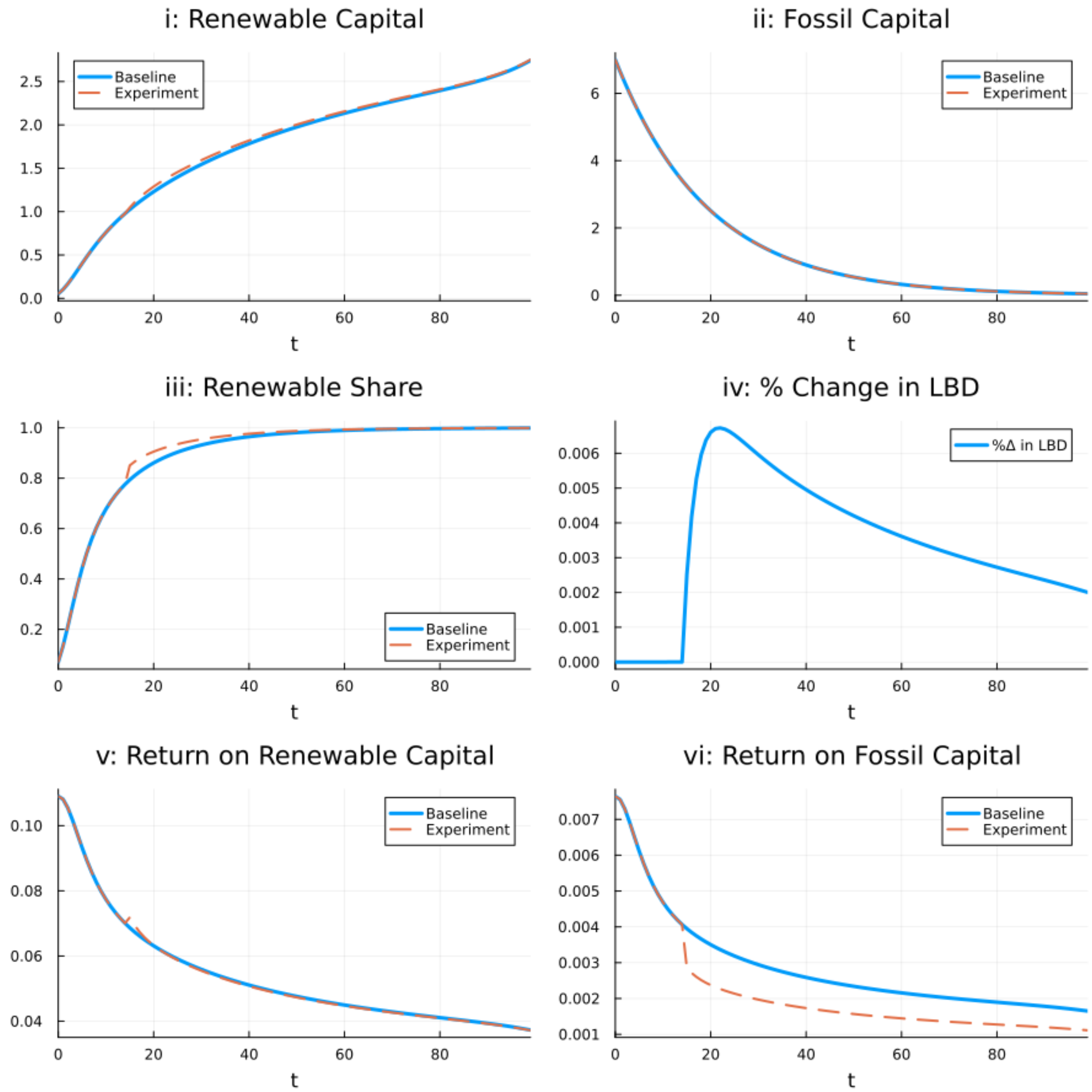
# 5 Experiments

In this section, we present a series of illustrative mechanism experiments. These simulations are not a full calibration. Rather, they highlight the model's qualitative implications and help interpret the empirical results. We compare the baseline scenario with a set of counterfactual experiments in which the supply of Russian fossil fuels is fully restricted. This experiment is designed to mimic the consequences of the Russian invasion of Ukraine, during which most European countries severed trade links with Russia and lost access to its fossil energy resources. We consider two types of shocks. The first is a permanent shock, in which the restriction on Russian fossil fuel supply remains in place for the entire simulation horizon. The second is a temporary shock, in which the restriction lasts for only five periods before access to Russian resources is restored. The figures here presented depicts the transition paths toward steady-state, starting at an initial scenario which resembles some pre-energy transition economies.

## 5.1 Permanent supply shock

Figure 5 presents six panels that contain model outcomes in the baseline and experiment equilibrium. It depicts renewable capital, fossil fuel capital, renewable energy share of electricity, percentage change in learning-by-doing compared to the benchmark equilibrium, return on renewable energy capital, and return on fossil fuel capital. Each panel, except the fourth, displays two lines: a solid blue line representing the baseline scenario and a dashed red line representing the counterfactual. In this case, the counterfactual corresponds to a permanent Russian fossil fuel supply shock.

Figure 5: Model Results - Permanent Shock




*Notes*: We depict here the evolution over time of renewable and fossil fuel capital for electricity generation purposes, the renewable share of electricity generation, the percentage change in the learning-by-doing term, the rate of return on investing in renewable and fossil fuel capital. The blue line depicts the baseline equilibrium with no shocks. The red lines are how the variables evolve under a permanent shock.

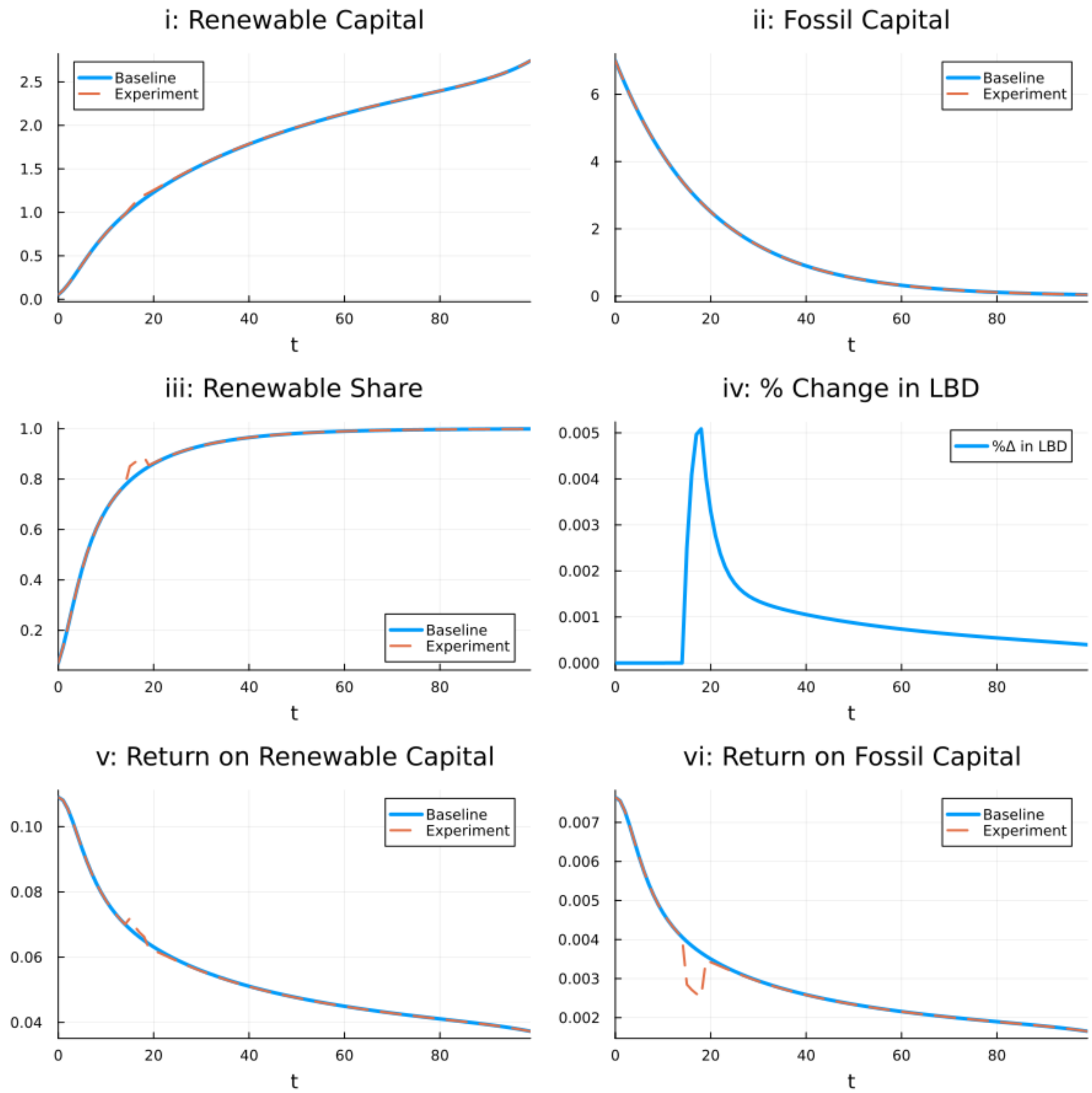
We begin by analyzing the baseline results, represented by the blue lines. Renewable capital, the capital used to produce renewable energy, grows rapidly over time, while fossil capital steadily declines. This decline in fossil capital reflects pure depreciation, indicating that investment in this sector is essentially zero. These dynamics are consistent with the bottom two panels, which show that although the returns to both renewable and fossil capital decrease over time, the level of returns to renewable capital remains substantially higher than that of fossil capital. The decline in returns is driven by falling energy prices as more renewable capacity comes online. However, learning-by-doing enables continuous accumulation of renewable capital despite the reduction in its marginal return. As a result, there is a rapid shift in the energy mix absent any intervention. The share of renewable energy rises from 7% at the beginning of the simulation to 85% by period 20, as shown in the third panel.

We now turn to the first counterfactual experiment, in which the supply of Russian fossil fuels is permanently shut down at period 15. This exercise allows us to examine how a persistent fossil energy shock alters the dynamics of capital accumulation and the renewable transition relative to the baseline. The most immediate effect appears in the returns to fossil capital: the shock causes a sharp decline in these returns, which, together with the reduction in fossil fuel use, leads to a drop in fossil energy production, even though the fossil capital stock itself continues to follow its depreciation-driven path. The drop in returns occurs because when the fossil fuel input becomes more scarce, this decreases the productivity of fossil fuel capital, lowering its marginal product and consequently, its rental rate. Secondly, the return to investing in renewable capital rises temporarily. The shock to electricity supply as a result of the fossil fuel input shock drives energy prices up. Because the return to renewable capital is proportional to the energy price, the shock immediately increases the profitability of investing in renewables. As renewable uptake increases, return rates fall back to the baseline equilibrium but the temporary boost in the profitability of renewable capital is reinforced by the learning-by-doing mechanism, which remains elevated much long after the onset of the shock. Together, these forces accelerate the transition by roughly four years, as the renewable share of electricity generation jumps from 77% in period 15 to 85% in period 16, reaching the level that the baseline scenario would only attain by period 20.

## 5.2 Temporary supply shock

We next examine the temporary shock scenario, in which the restriction on Russian fossil fuel supply is introduced at period 15 and lifted in period 20. This allows us to isolate the effects of a short-lived disruption in Russian fossil fuel imports on investment incentives and the renewable transition. In this case, the effects on the variables move in the same direction as in the permanent shock, but they recede once the shock is lifted. Panel 6 of Figure 6 shows that the returns to fossil capital decline only temporarily. Returns to investing in renewable capital also temporarily rise, with the increase in energy prices driving the small uptick in renewable capital adoption. This accumulation triggers *some* momentum via learning-by-doing, as can be seen in Panel 4, but it is much smaller in scale relative to the impact under a permanent supply shock. Since the increase in learning-by-doing is brief and fades quickly after the shock, there are no strongly persistent effects on renewable capital accumulation or on the long-term energy transition path. The renewable energy share of electricity generation is higher relative to the baseline from periods 15 to 20, but this is almost entirely driven by lower dirty electricity generation and fades away once the shock does.

Figure 6: Model Results - Temporary shock




*Notes*: We depict here the evolution over time of renewable and fossil fuel capital for electricity generation purposes, the renewable share of electricity generation, the percentage change in the learning-by-doing term, the rate of return on investing in renewable and fossil fuel capital. The blue line depicts the baseline equilibrium with no shocks. The red lines are how the variables evolve under a temporary shock.

## 5.3 Permanent and temporary supply shocks in highly-exposed countries

Panel (a) in Figure 7 illustrates how a permanent shock affects a country that is highly exposed to Russian fossil fuel imports. In this scenario, the exposure parameter is increased to $\omega_R = 0.7$ from the baseline value of $\omega_R = 0.55$. A highly-exposed country reduces fossil-fuel inputs more sharply, and experiences a greater energy price spike and larger fall in returns to investing in fossil fuel capital. Higher energy prices make the returns to investing in renewable capital higher, and the increased renewable capital accumulation is further amplified by the larger response in the learning-by-doing term. Additionally, return rates to renewable capital are lower during this time, driven by a faster transition that more rapidly increases renewable electricity supply. The transition in this economy accelerates by roughly eight periods compared to the baseline. The relative change in $G$ is about three times larger than in the benchmark case of $\omega_R = 0.55$. Overall, the effects on both $r_t^R$ and $r_t^F$ are amplified, leading to a sharper increase in renewable capital investment.

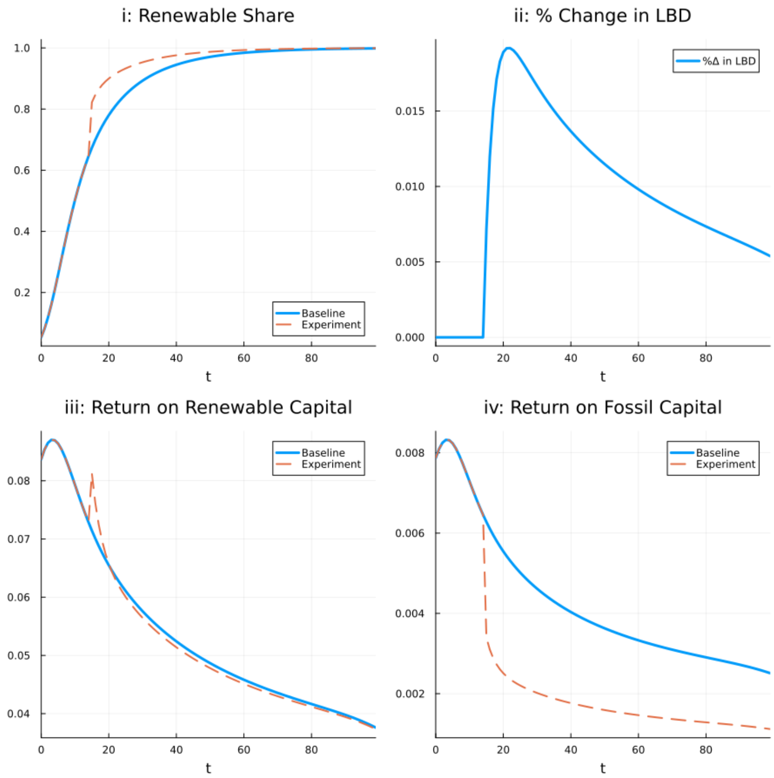
For a temporary shock, a highly-exposed country takes longer to return to its path under the baseline equilibrium with no shocks. In the case of the benchmark model, the effects on investment returns for renewable and fossil fuel capital reset back to their original paths once the shock disappeared. For highly-exposed countries, this is no longer the case. First, returns on fossil fuel capital investments remain lower than the baseline for almost 10 periods after the shock dissipates. Similarly, while returns on renewable capital experience a boost during the supply shock, after it ends, returns are actually lower compared to the baseline. This is driven by a temporary period of lower energy prices made possible by the increased uptake in renewable electricity generation in those periods, further amplified by a stronger learning-by-doing boost than what we had in the $\omega_R = 0.55$ economy.

## 5.4 Permanent and temporary supply shocks in low-exposure countries

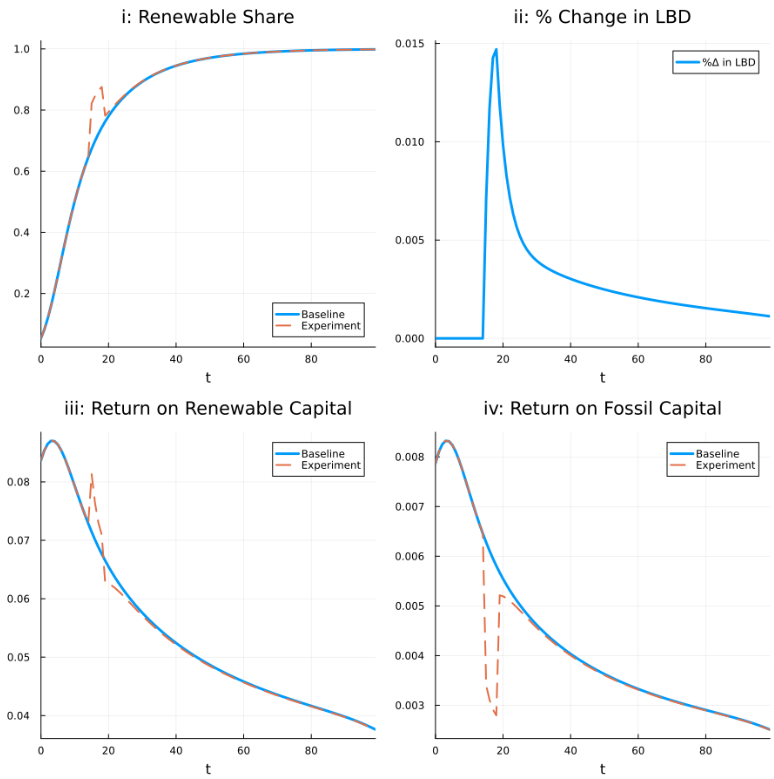
Lastly, Figure 8 replicates the experiment for a country with low exposure to Russian fossil fuel imports, setting $\omega_R = 0.1$. In this case, both Panel (a) and Panel (b) show that neither the permanent nor the temporary shock produces any noticeable effects on the variables of interest as we would expect. This is under the assumption that the price of non-Russian gas remained the same after the shock. However, it is worth noting that even in low-exposure countries, there is a small increase in the learning-by-doing mechanism, that is more pronounced in the case of a permanent shock.

Figure 7: Model Results - High exposure economy

(a) Permanent Shock



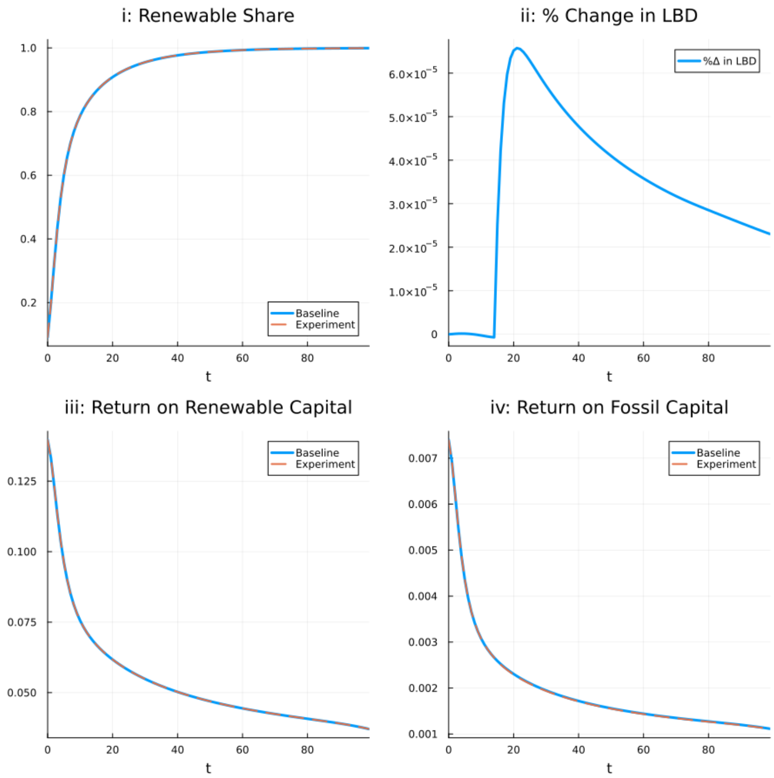

(b) Temporary Shock



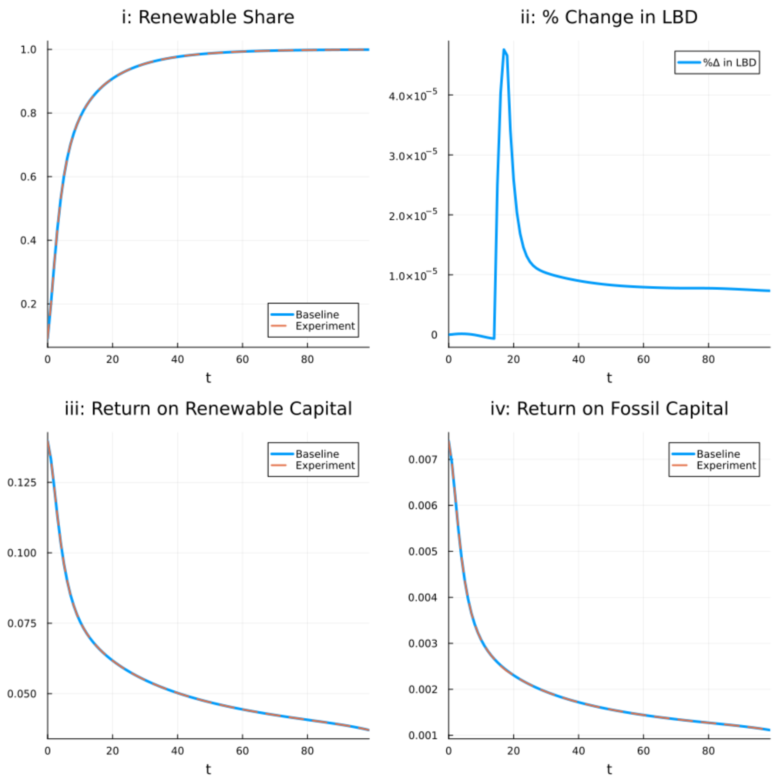

*Notes*: We depict here the evolution over time of the relevant variables under a temporary or permanent shock for a highly dependent country. The blue line depicts the baseline equilibrium with no shocks. The red lines are how the variables evolve under a permanent or temporary shock.

Figure 8: Model Results - Low exposure economy

(a) Permanent Shock




(b) Temporary Shock




*Notes*: We depict here the evolution over time of the relevant variables under a temporary or permanent shock for a low-dependency country. The blue line depicts the baseline equilibrium with no shocks. The red lines are how the variables evolve under a permanent or temporary shock.

In summary, the experiments highlight the critical role of both shock persistence and exposure intensity in shaping the renewable transition. Permanent disruptions in fossil fuel supply accelerate the transition by several periods, as higher energy prices and learning-by-doing jointly drive investment toward renewable capital. In contrast, temporary shocks generate only short-lived adjustments, with their effects dissipating once fossil supply is restored. The results also reveal strong heterogeneity across countries: economies that are highly exposed to Russian fossil fuel imports experience a faster and more pronounced transition, whereas low-exposure economies are virtually unaffected. Overall, the model suggests that energy security shocks can serve as catalysts for structural change, but their long-term impact depends on both the duration of the disruption and the degree of dependence on fossil imports.

# 6 Conclusion

This paper documents the impact of the Russia-Ukraine war on the pace of the clean electricity transition for countries in Europe that were dependent on Russian natural gas. The empirical results show that European countries with greater pre-war exposure to imported Russian gas increased their renewable electricity generation more after the shock than their less-exposed counterparts. Using a difference-in-differences strategy that exploits cross-country variation in natural gas import exposure, we find that the trade shock induced by the war led highly exposed countries to substitute away from gas-fired electricity toward renewables, especially wind and solar. Less exposed countries reduced gas use as well but renewable deployment did not occur as rapidly. These results suggest that energy security shocks can interact with initial energy mixes and trade relations to shape the trajectory of the clean energy transition.

To understand the mechanisms driving these findings, we develop a small open economy model with an electricity sector, imported fossil fuels, and learning-by-doing in renewable capital. A permanent disruption to Russian fossil fuel supply results in both reduced productivity of fossil-fuel electricity capital and increased energy prices. The resulting declines in returns to investing in fossil-fuel electricity capital and simultaneous increase in returns on renewable capital result in higher renewable investment. This creates momentum in the learning-by-doing process, accelerating the renewable transition by several periods, especially for countries with high import exposure. In contrast, a temporary disruption generates temporary effects. Once gas access is restored, the economy returns to its baseline path. So while the empirical results suggest that highly exposed countries did increase renewable electricity generation, the model experiments suggest that energy security shocks can catalyse faster adoption, but only when dependence is high and the disruption is persistent enough. This has important implications for policy.

Policies that encourage dependence on any particular fossil fuel supplier, whether through infrastructure choices or long-term contract, can not only have implications for energy security during a crisis but also the pace of a clean energy transition.

The Russia–Ukraine war is an extreme but informative episode that reveals how geopolitical shocks can either accelerate or impede progress toward net-zero targets. By combining empirical evidence with a dynamic general equilibrium model featuring learning-by-doing, this paper takes a first step toward identifying when such shocks can be harnessed to accelerate the clean energy transition, and when their effects are too weak or temporary to leave a lasting mark.

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