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Energy price shocks, fossil fuel dependence, and carbon emissions (CO_2): A multi-stage transmission framework analysis

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ABSTRACT

This paper investigates how energy price shocks are transmitted through energy consumption and fuel composition into carbon emissions, and how G7 carbon outcomes relate to global temperature dynamics, over the period 1991–2024. Using a balanced panel of 238 country-year observations for Canada, France, Germany, Italy, Japan, the United Kingdom and the United States, the analysis estimates a four-stage transmission chain: (i) energy price shocks to primary energy supply; (ii) energy price shocks to fossil fuel consumption; (iii) energy consumption composition to total CO_2 emissions; and (iv) aggregate G7 emissions to global temperature anomaly. Country fixed-effects models with Driscoll–Kraay standard errors are used for the panel stages, while Newey–West autocorrelation- and heteroskedasticity-consistent standard errors are used for the aggregate climate-stage time-series models. The results indicate that Brent oil price shocks are positively associated with G7 primary energy supply and, more weakly, with fossil fuel consumption, whereas natural gas and coal price shocks show no robust direct effects in the baseline panel. The carbon channel is considerably stronger: fossil fuel consumption and coal consumption are robust positive drivers of CO_2 emissions, while the renewable energy share significantly reduces emissions, particularly in the coal-channel and per-capita specifications. The aggregate climate stage shows that global temperature anomaly is highly persistent and trend-driven; once lagged temperature or a deterministic trend is included, contemporaneous G7 emissions lose explanatory power. The paper therefore frames its contribution as identifying a transmission mechanism – energy price shocks shape energy use, which in turn shapes emissions–rather than claiming a direct energy-price-to-

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temperature effect, and concludes that G7 decarbonisation, although necessary, is insufficient to explain global climate outcomes on its own.

Keywords: Energy price shocks, Fossil fuel consumption, CO_2 emissions, Renewable energy, Climate change, G7 economies; Driscoll–Kraay standard errors, Energy transition.
Article type: Perspective.

INTRODUCTION

Energy price shocks have repeatedly disrupted advanced economies over the past three decades, from the Asian crisis-era oil price reversals of the late 1990s, through the commodity super-cycle of the 2000s, to the COVID-19 demand collapse of 2020. Each episode has reshaped the level and composition of energy consumption, with consequences for fossil fuel use, electricity generation, industrial activity and, ultimately, carbon emissions. Understanding how price shocks propagate through energy systems and emissions is therefore central to both energy economics and climate policy. The Group of Seven (G7) economies – Canada, France, Germany, Italy, Japan, the United Kingdom and the United States – are a particularly informative laboratory for this question: they are advanced, high-income, energy - intensive systems that have historically accounted for a large share of cumulative global emissions, and they have also led some of the most ambitious decarbonisation policy commitments in recent years. Despite a substantial literature on each individual link in the chain – energy prices and energy demand, fossil fuel use and emissions, renewables and emissions mitigation, as well as emissions and temperature – relatively few studies present these stages within a single, internally consistent framework. The dominant approach has been to estimate isolated bilateral relationships, often with mixed empirical findings depending on country coverage, sample period and identification strategy. As a result, conclusions about how energy price shocks ultimately affect environmental outcomes are frequently drawn implicitly rather than estimated explicitly, and the climate-stage step is sometimes presented as if a direct contemporaneous link from national emissions to global temperature were estimable from a panel regression. The latter inference is methodologically fragile because the global temperature anomaly is a single global series that does not vary across countries within a given year, and because climate outcomes reflect cumulative and worldwide emissions over decadal horizons. This paper addresses these gaps by estimating a four-stage transmission framework for the G7 economies over 1991 – 2024, and by treating the climate stage explicitly as aggregate time-series evidence rather than as a country-level panel effect. The conceptual chain is: energy price shocks → energy consumption and fuel composition → CO_2 emissions → aggregate climate-stage implications. Energy price shocks are measured for Brent oil, natural gas and coal as annual log-price differences, and an aggregate Energy Price Shock Index is constructed as the average of the three. Energy consumption is captured by primary energy supply, fossil fuel consumption, coal consumption and the renewable energy share. Carbon outcomes are measured by total CO_2 emissions and CO_2 emissions per capita. The climate-stage variable is the global temperature anomaly. The empirical strategy uses country fixed-effects models with Driscoll – Kraay standard errors, which are robust to heteroskedasticity, serial correlation and cross-sectional dependence across the seven economies; the climate stage uses time-series regressions with Newey – West autocorrelation- and heteroskedasticity-consistent standard errors. Four research questions guide the analysis. First, do energy price shocks – measured by Brent, natural gas, coal and the aggregate index – affect primary energy supply and fossil fuel consumption in G7 economies? Second, do fossil fuel and coal consumption increase CO_2 emissions, and does the renewable share mitigate these emissions? Third, are these results robust to alternative shock specifications, lagged shocks, per-capita emissions, and crisis controls for 2008 – 2009, 2020 and 2022 – 2023? Fourth, can contemporaneous G7 emissions explain global temperature anomaly, or is the climate stage dominated by persistence and a long - run trend? The paper makes four contributions. Theoretically, it offers a transmission - channel framing of the energy–carbon–climate nexus that links three commonly separated empirical literatures within a single coherent framework. Empirically, it provides updated G7 panel evidence over 1991 – 2024 that explicitly disentangles oil, gas and coal shocks from each other and from an aggregate index. Methodologically, it adopts a Driscoll – Kraay/Newey – West design tailored to the cross-sectional dependence of advanced economies and to the time-series character of global climate variables. From a policy perspective, the analysis emphasises that managing energy price shocks, accelerating coal phase-out and expanding renewables are necessary domestic instruments, but that climate stabilisation requires globally coordinated decarbonisation because temperature outcomes reflect cumulative worldwide emissions rather than current G7 emissions alone. The remainder of the paper is organised as follows. Section 2 reviews the literature and develops the testable hypotheses. Section 3 describes the data and variables. Section 4 presents the methodology. Section 5 reports the empirical results across the four stages. Section 6 discusses the findings and Section 7 derives policy implications. Section 8 concludes, while Section 9 outlines limitations and avenues for future research.

Literature review and hypothesis development

This section organises the literature around four sub - themes that mirror the four stages of the transmission framework: energy price shocks and energy demand; fossil fuel dependence and CO_2 emissions; renewable energy and emissions mitigation; and the linkage between energy price shocks, carbon emissions and climate outcomes. The aim is not to provide an exhaustive survey but to position the present analysis with respect to the most directly relevant strands of work and to derive five testable hypotheses.

Energy price shocks and energy demand

The relationship between energy prices and aggregate energy demand has a long - standing tradition in energy economics, starting from the Hamilton (1983) characterisation of oil price shocks as macroeconomically important and the subsequent debate about whether the propagation of these shocks is symmetric, asymmetric or non-linear. Subsequent work by Kilian (2009) and Kilian & Park (2009) emphasised the importance of distinguishing between supply - driven and demand-driven oil price shocks, while later contributions extended the logic to natural gas and coal markets, where geographic segmentation, contractual rigidity and varying degrees of substitutability complicate the demand response. In advanced economies, the price elasticity of aggregate energy demand is typically estimated to be small in the short run because much of the energy capital stock – buildings, vehicles, industrial equipment and power plants – is fixed and adjusts only over long horizons. As a consequence, contemporaneous responses of primary energy supply and fossil fuel consumption to annual price shocks are usually modest in magnitude, with sign and significance varying across estimators, time periods and shock measures. Several studies further document that oil price shocks tend to dominate aggregate demand responses since oil markets are globally integrated and oil prices are widely treated as benchmarks for energy-related expectations, whereas natural gas and coal markets are more regional. These features motivate the inclusion of separate Brent, gas and coal shocks in the present panel, alongside an aggregate index, in order to test whether the oil channel is empirically more visible than the gas and coal channels in the G7.

Fossil fuel dependence and CO_2 emissions

The second strand of literature concerns the link between fossil fuel use and CO_2 emissions. The Environmental Kuznets Curve (EKC) literature, surveyed for example by Stern (2017), documents heterogeneous evidence regarding the relationship between income, energy consumption and emissions, with results sensitive to country group, period and functional form. A more robust finding is that, conditional on the level of energy consumption, the carbon intensity of the energy mix – the share of coal, oil and gas in primary supply – is a decisive determinant of emissions outcomes. Coal, in particular, is widely identified as the most carbon-intensive fossil fuel per unit of energy delivered, so that coal consumption tends to translate disproportionately into CO_2 emissions. For G7 economies, this fuel-composition logic is particularly relevant because the post - 1990 decarbonisation trajectory has involved both efficiency improvements and a structural shift away from coal in countries such as the United Kingdom, France and Italy, while the role of coal in Germany and Japan has remained more contested. Empirical studies on G7 emissions therefore frequently find that coal consumption and total fossil fuel consumption are dominant proximate drivers of emissions, while controls for energy intensity, structural change and policy variables play conditioning roles. The present study contributes by separately modelling a fossil-fuel channel and a coal channel as parallel specifications, allowing the relative importance of overall fossil dependence and coal in particular to be assessed using identical estimators.

Renewable energy transition and emissions mitigation

The third strand of literature concerns the role of renewable energy in mitigating CO_2 emissions. A growing body of work, including reviews and meta-analyses by Apergis and Payne (2014, to be verified) and subsequent contributions, finds that the share of renewables in primary energy or electricity is generally associated with lower emissions in advanced economies, although the magnitude varies with measurement, sample and the inclusion of structural controls. The mitigation channel operates through both substitution–renewable generation displaces fossil generation– and complementarity with energy efficiency improvements and electrification of end - uses. For G7 economies, the policy mix has involved feed-in tariffs, renewable portfolio standards, carbon pricing instruments and direct investment in renewable capacity over the sample period. Yet the empirical effect of the renewable share on emissions is sometimes attenuated when the level of fossil fuel consumption is also included as a regressor, because the renewable share is partially a residual of the fossil share. A practical implication is that the marginal effect of renewables on emissions should be larger and more precisely estimated when the carbon-intensive component of the fossil mix–coal–is explicitly controlled for, or when emissions are scaled by population to remove level effects. This logic motivates the parallel coal-channel and CO_2- per-capita specifications in the present study.

Energy shocks, carbon emissions and climate outcomes

The fourth strand of literature relates to the connection between energy markets, carbon emissions and climate outcomes. Climate science establishes that temperature change is driven by cumulative anthropogenic emissions of CO_2 and other greenhouse gases over decadal horizons, with the global temperature anomaly responding to global rather than national emissions. National decarbonisation, however ambitious, contributes to climate outcomes through its share of cumulative global emissions and through possible spillovers to global energy markets and technology costs. This implies that contemporaneous national emissions are unlikely to identify a structural climate effect in a panel setting in which the temperature anomaly is a single global series. From an econometric standpoint, a related concern is that aggregate emissions and global temperature both display strong trends and persistence over recent decades, so that simple bivariate correlations between national emissions and temperature can yield misleading signs – including spurious negative associations when national emissions decline while global temperature continues to rise. The literature consequently treats temperature dynamics with autoregressive specifications and deterministic trends, and uses heteroskedasticity- and autocorrelation-consistent standard errors. The present paper follows this practice by estimating climate-stage models on aggregate G7 time-series data with Newey – West (1987) standard errors, and by interpreting the climate stage as aggregate evidence on the limits of national climate accounting rather than as a causal climate model. Building on the foregoing literature, the paper formulates five testable hypotheses. H1: Energy price shocks – particularly Brent oil shocks and the aggregate Energy Price Shock Index–are significantly associated with primary energy supply and fossil fuel consumption in G7 economies. H2: Fossil fuel consumption is positively associated with CO_2 emissions in G7 economies. H3: Coal consumption has a positive effect on CO_2 emissions, conditional on the renewable share. H4: The renewable energy share reduces CO_2 emissions, particularly when coal consumption is controlled for or emissions are expressed in per-capita terms. H5: Global temperature anomaly is more strongly explained by persistence and a long - run trend than by contemporaneous G7 CO_2 emissions alone.

Data and variables

The empirical dataset is constructed as an annual country-level panel for the G7 economies – Canada, France, Germany, Italy, Japan, the United Kingdom and the United States – for 1991–2024. Information on energy use and fuel structure, namely primary energy supply, fossil fuel consumption, coal consumption and the share of renewables in primary energy, was compiled from the Energy Institute Statistical Review of World Energy and the Our World in Data Energy database. The carbon-emission indicators, covering total CO_2 emissions and CO_2 emissions per capita, were sourced from the Our World in Data CO_2 and Greenhouse Gas Emissions database. International energy-price series for Brent crude oil, natural gas and thermal coal were obtained from the World Bank Commodity Price Data (Pink Sheet) and the IMF Primary Commodity Price System. The corresponding price-shock variables are measured as year-to-year log changes in each price series. The composite Energy Price Shock Index is then calculated as the arithmetic mean of the Brent, gas and coal shock variables. The global temperature anomaly series is taken from NASA GISS Surface Temperature Analysis (GISTEMP v4) and the Berkeley Earth temperature dataset. All series are converted to annual frequency and aligned by country and year. Since the shock variables require one lagged price observation, the usable estimation period starts in 1991 and ends in 2024, producing 238 G7 country-year observations and 34 annual aggregate observations for the climate-stage analysis.

Table 1. Data sources and variable construction.

Variable group	Variables	Data source
Energy price shocks	Brent oil price shock, natural gas price shock, coal price shock, Energy Price Shock Index	World Bank Commodity Price Data; IMF Primary Commodity Price System
Energy consumption	Primary energy supply, fossil fuel consumption, coal consumption	Energy Institute Statistical Review of World Energy; Our World in Data Energy database
Renewable energy	Renewable energy share	Energy Institute Statistical Review of World Energy; Our World in Data Energy database
Carbon emissions	Total CO_2 emissions, CO_2 emissions per capita	Our World in Data CO_2 and Greenhouse Gas Emissions database
Climate variable	Global temperature anomaly	NASA GISTEMP v4; Berkeley Earth
Sample coverage	Canada, France, Germany, Italy, Japan, United Kingdom, United States; 1991–2024	Author's compilation

Notes: Energy price shocks are calculated as year-to-year log changes in Brent crude oil, natural gas and thermal coal prices. The Energy Price Shock Index is computed as the arithmetic mean of the three price-shock variables. All series are harmonised at annual frequency and matched by country and year.

Energy price shocks are constructed as the first difference of log prices,

$$Shock_t^j = \ln(Price_t^j) - \ln(Price_{t-1}^j),\ j \in \{Brent,\ Gas,\ Coal\} \qquad \textbf{(1)}$$

So that a positive value of Shock_t corresponds to a percentage increase in the price of fuel j between years t − 1 and t. The aggregate Energy Price Shock Index (EnergyShockIndex) is computed as the simple average of BrentShock, GasShock and CoalShock. Because the shock construction requires the previous year's price, observations for 1990 are dropped and the regression sample begins in 1991. The balanced panel therefore spans seven countries and 34 years, yielding 7 × 34 = 238 country-year observations, while the climate-stage time-series dataset contains 34 annual observations on aggregate G7 emissions, aggregate fossil fuel and coal consumption, the average renewables share, the energy shock index and the global temperature anomaly. Table 2 reports definitions and descriptive statistics for the core variables. The shock variables have means close to but slightly above zero, reflecting the long-run upward drift of nominal commodity prices over the sample, with substantial dispersion (standard deviations between 0.26 and 0.35 in log-difference units) and ranges that include episodes of steep declines and increases. Energy quantities show wide dispersion across G7 economies, reflecting differences in size: primary energy supply ranges from 5.6 to 96.9 EJ and CO_2 emissions from 264.2 to 6,126.9 Mt. The renewable energy share averages 6.1 per cent of primary supply with a standard deviation of 4.5 percentage points, while CO_2 emissions per capita average 10.76 t with substantial heterogeneity across countries. The global temperature anomaly averages 0.66 °C above the reference period over the sample, with values rising from approximately 0.22 °C in the early 1990s to 1.28 °C by 2024.

Methodology

The empirical strategy proceeds in four stages corresponding to the conceptual transmission chain CO_2. The four stages are estimated separately, in keeping with the transmission-channel framing, rather than within a single simultaneous-equations system, to keep the empirical model transparent and to allow stage-specific robustness checks.

Stages 1 and 2: Energy price shocks and energy use

Stage 1 models primary energy supply as a function of the three energy price shocks. Stage 2 replaces the dependent variable with fossil fuel consumption. Both stages share the same regressor set, allowing a direct comparison of how oil, gas and coal shocks transmit into total energy supply versus the fossil-fuel component of supply. The two stages are specified as:

$$PrimaryEnergySupply_{it} = \alpha_i + \beta_1 BrentShock_t + \beta_2 GasShock_t + \beta_3 CoalShock_t + \varepsilon_{it} \quad \textbf{(2)}$$

$$FossilFuelConsumption_{it} = \alpha_i + \gamma_1 BrentShock_t + \gamma_2 GasShock_t + \gamma_3 CoalShock_t + u_{it} \quad \textbf{(3)}$$

where the index it denotes country i in year t, α_i is a country fixed effect that absorbs all time-invariant country characteristics (size, geography, industrial structure and long-standing energy policy regimes), and ε_{it} is the disturbance. Year fixed effects are deliberately not included in these specifications because BrentShock, GasShock and CoalShock are common annual variables that vary only over time and are repeated across countries; including year dummies would absorb precisely the variation of interest. Country fixed effects are retained because they remove the substantial cross-country variation in the levels of energy supply and fossil consumption.

Table 2. Variable definitions and descriptive statistics, G7 panel, 1991-2024 (n = 238).

Variable	n	Mean	SD	Min	Max	Skew	Kurt
BrentShock	238	0.0372	0.2601	−0.5867	0.5403	−0.336	−0.330
GasShock	238	0.0093	0.3294	−0.8794	0.6689	−0.464	0.691
CoalShock	238	0.0363	0.3514	−0.6912	0.9156	0.667	0.501
EnergyShockIndex	238	0.0276	0.2736	−0.5896	0.6352	−0.085	0.311
PrimaryEnergySupply (EJ)	238	23.0622	28.1035	5.600	96.947	1.955	1.997
FossilFuelConsumption (EJ)	238	19.3711	24.6134	4.121	84.888	1.945	1.979
CoalConsumption (EJ)	238	4.1419	6.1438	0.101	22.849	2.076	3.002
RenewablesShare (%)	238	6.0613	4.4999	0.258	15.232	0.677	−0.985
CO_2 Emissions (Mt)	238	1337.36	1736.25	264.16	6126.90	1.954	2.060
CO_2 per capita (t)	238	10.7600	4.6573	3.969	21.398	0.720	−0.619
Global Temp Anomaly (°C)	238	0.6609	0.2560	0.220	1.280	0.369	−0.353

Notes. The shock variables are constructed as annual log-difference returns. Energy quantities are in exajoules (EJ); CO_2 emissions in megatonnes (Mt) and tonnes per capita (t); the renewable share is in percentage points of primary energy supply. Source: author's computations from internationally recognised public energy, emissions, commodity-price and climate datasets, as documented in the project data note.

Stage 3: Energy consumption and CO_2 emissions

Stage 3 models CO_2 emissions as a function of energy consumption composition. Two parallel specifications are estimated. The first uses fossil fuel consumption as the principal energy variable, alongside the renewable energy share:

$$CO_2Emissions_{it} = \alpha_i + \delta_1 FossilFuelConsumption_{it} + \delta_2 RenewablesShare_{it} + v_{it} \quad \textbf{(4)}$$

The second replaces fossil fuel consumption with coal consumption, isolating the most carbon-intensive component of the fuel mix:

$$CO_2Emissions_{it} = \alpha_i + \theta_1 CoalConsumption_{it} + \theta_2 RenewablesShare_{it} + w_{it} \quad \textbf{(5)}$$

Primary energy supply and fossil fuel consumption are not entered jointly because their pairwise correlation in the panel exceeds 0.99, generating severe multicollinearity (see Appendix Table A1). Coal consumption and fossil fuel consumption are also highly correlated (≈ 0.96), but they are entered in separate specifications rather than jointly. The renewable share is entered in both specifications to test whether the marginal mitigation effect of renewables is more cleanly identified once the carbon-intensive coal component is controlled for.

Stage 4: Aggregate climate-stage evidence

Stage 4 examines whether aggregate G7 CO_2 emissions explain the global temperature anomaly. Because GlobalTemperatureAnomaly_C is global and identical across G7 countries within each year, it cannot be modelled as a country-level panel: the within-year cross-sectional variance is mechanically zero. Instead, aggregate G7 emissions are constructed as

$$G7\ CO_{2t} = \textstyle\sum_i CO_2\ Emissions_{it} \quad \textbf{(6)}$$

and the climate stage is estimated as a set of time-series regressions on 34 annual observations:

$$Temp_t = \mu_0 + \mu_1 G7CO_{2t} + \eta_t \quad \textbf{(7)}$$

$$Temp_t = \lambda_0 + \lambda_1 Temp_{t-1} + \lambda_2 G7CO_{2,t-1} + \zeta_t \quad \textbf{(8)}$$

$$Temp_t = \phi_0 + \phi_1 G7CO_{2t} + \phi_2 Trend_t + \xi_t \quad \textbf{(9)}$$

Specifications C1 and C2 examine the contemporaneous and one-year-lagged association between aggregate G7 emissions and global temperature anomaly. Specification C4 introduces a one-period lag of the dependent variable to capture the strong persistence of the temperature series. Specification C5 introduces a deterministic time trend, which approximates the cumulative-emissions component of climate dynamics. The interpretation of these specifications is descriptive rather than causal: the goal is to assess whether the time-series association between G7 emissions and global temperature is robust to standard time-series controls, and to highlight the cumulative and global nature of climate outcomes.

Standard errors and robustness design

All four panel specifications are estimated by country fixed effects with Driscoll and Kraay (1998) standard errors. The Driscoll – Kraay correction is appropriate because G7 economies are exposed to common global shocks – oil-price movements, business-cycle fluctuations, financial crises and pandemic episodes – which generate cross-sectional dependence across the seven panels. Driscoll – Kraay standard errors are simultaneously robust to heteroskedasticity, serial correlation and cross - sectional dependence, and have been shown to perform well in panels with a moderate cross - section dimension. Hausman (1978) tests are reported in Appendix Table A2 as a model-selection diagnostic; they prefer fixed effects in the carbon-channel models (Models 3 and 4) and random effects in the energy - demand models (Models 1 and 2), but the fixed-effects estimator is retained throughout for consistency and for its desirable cross-sectional-dependence properties. The Newey and West (1987) estimator is used for the climate-stage time-series regressions, with a lag truncation parameter selected following standard rules of thumb for annual data. To probe the robustness of the baseline findings, four families of robustness checks are estimated. First, the three separate shocks are replaced with the aggregate Energy Price Shock Index. Second, lagged shocks ($BrentShock_{t-1}$, $GasShock_{t-1}$, $CoalShock_{t-1}$, $EnergyShockIndex_{t-1}$) are used in place of contemporaneous shocks to allow for delayed responses. Third, CO_2 emissions per capita is used as the dependent variable in place of total CO_2 emissions, removing population - scale effects. Fourth, three crisis dummies – Crisis2008 = 1 for 2008 – 2009, COVID2020 = 1 for 2020, and EnergyCrisis2022 = 1 for 2022–2023–are added to all four stages to capture exceptional macroeconomic episodes. Selected robustness specifications are reported in Table 3 of the main text, while the full robustness table is reproduced in Appendix Table A3.

Empirical Results

This section reports the empirical results across the four stages of the transmission framework. Section 5.1 summarises the descriptive statistics and correlation structure. Section 5.2 reports the baseline fixed-effects Driscoll – Kraay panel estimates. Section 5.3 presents the selected robustness checks. Section 5.4 turns to the aggregate climate - stage time-series evidence.

Descriptive statistics and correlation structure

Table 1 documents the distribution of the 11 core variables in the balanced panel. The shock variables are centred close to zero in log-difference units, with substantial dispersion: BrentShock has a mean of 0.0372 and a range from −0.587 to 0.540, GasShock has a mean of 0.0093 and a range from −0.879 to 0.669, and CoalShock has a mean of 0.0363 and a range from −0.691 to 0.916. The aggregate EnergyShockIndex has a mean of 0.0276 and a range from −0.590 to 0.635. These statistics confirm that the sample contains both severe price collapses (notably 2008–2009, 2014–2016 and 2020) and pronounced price surges (notably 2008, 2011 and 2022). Energy quantities show pronounced cross-country heterogeneity. Mean primary energy supply is 23.06 EJ, with a maximum value of 96.95 EJ (corresponding to the United States in late sample years) and a minimum of 5.60 EJ. Fossil fuel consumption averages 19.37 EJ and coal consumption averages 4.14 EJ. The renewable share averages 6.06 per cent over the period, with a maximum of 15.23 per cent reflecting the most renewable-intensive country - year. Total CO_2 emissions average 1,337.4 Mt and CO_2 per capita averages 10.76 t. The global temperature anomaly averages 0.66 °C across the sample. The pairwise correlation matrix (Appendix Table A1) reveals three patterns that motivate the modelling choices. First, the three shock variables are highly correlated with each other (0.60–0.69 in pairwise terms) and very highly correlated with the EnergyShockIndex (0.87–0.87), reflecting the constructed nature of the index. Second, primary energy supply, fossil fuel consumption, coal consumption and total CO_2 emissions are correlated at very high levels (≥ 0.94), confirming that they should not be entered jointly as regressors in the same specification. Third, the renewable share is negatively correlated with CO_2 emissions (−0.26) and positively correlated with global temperature anomaly (0.52). The latter correlation is driven by common time trends–rising renewable shares and rising global temperature–and should not be interpreted causally; the climate-stage analysis explicitly addresses this concern using a deterministic trend.

Baseline panel regression results

Table 3 presents the baseline fixed-effects estimates with Driscoll–Kraay standard errors for Models 1 to 4. Model 1 regresses primary energy supply on the three contemporaneous shocks. The Brent oil shock enters with a positive and statistically significant coefficient of 2.006 ($p = 0.039$), indicating that a one-unit increase in the log-difference Brent shock is associated with a 2.0 EJ increase in average G7 primary energy supply within the same year, conditional on country fixed effects. The gas and coal shock coefficients are statistically insignificant and small. This is consistent with the interpretation that oil-price movements provide the clearest contemporaneous global energy-demand signal in advanced economies, while gas and coal shocks operate through more segmented and lagged channels. Model 2 replaces the dependent variable with fossil fuel consumption and yields a similar but weaker pattern. The Brent shock coefficient is 1.602 with $p = 0.086$, providing marginal evidence at the 10 per cent level, while gas and coal shocks remain insignificant. The fact that the Brent coefficient is smaller in Model 2 than in Model 1 reflects the substitution into non-fossil energy sources triggered by sustained oil-price increases, which dampens the response of fossil fuel consumption relative to total primary supply. Model 3 turns to the carbon-emissions channel using fossil fuel consumption as the energy regressor. The fossil fuel coefficient is 85.99 ($p < 0.001$), implying that an additional EJ of fossil fuel consumption is associated with approximately 86 Mt of additional CO_2 emissions in the average G7 country-year. The renewable share enters with a small negative coefficient (−2.49) that is not statistically distinguishable from zero in this specification. The lack of significance for the renewable share in Model 3 is intuitive: once fossil fuel consumption is conditioned on, the residual variation in the renewable share is mostly composition rather than scale, and total emissions reflect mostly the scale of fossil use. Model 4 replaces fossil fuel consumption with coal consumption and yields the strongest carbon-channel evidence. The coal-consumption coefficient is 65.33 ($p < 0.001$), so that one additional EJ of coal consumption is associated with approximately 65 Mt of CO_2 emissions, which is substantially above the implied marginal emission factor of average fossil consumption and consistent with the higher carbon intensity of coal relative to oil and gas. The renewable share now enters with a coefficient of −14.15 ($p < 0.001$), indicating that a one-percentage-point increase in the renewable share is associated with approximately 14 Mt fewer CO_2 emissions in the average G7 country-year. This reversal in the role of the renewable share – statistically insignificant in Model 3 but strongly significant in Model 4 – provides clear support for hypothesis H4: the marginal mitigation effect of renewables is sharply identified once the most carbon-intensive component of the fuel mix is explicitly controlled for. Taken together, the baseline results provide consistent support for hypotheses H1 (oil-shock channel), H2 (fossil-emission link) and H3–H4 (coal and renewable-share effects).

Robustness checks

Table 4 reports a selected set of robustness checks; the full robustness table is reproduced in Appendix Table A3. Four observations stand out. First, replacing the three shocks with the aggregate EnergyShockIndex preserves the qualitative pattern: the index has a positive and significant coefficient of 1.228 ($p = 0.072$) in the primary energy supply equation and a positive but weaker coefficient of 1.173 ($p = 0.105$) in the fossil fuel consumption equation under Driscoll–Kraay standard errors. The result is therefore supportive of the energy-demand channel but not decisive at conventional thresholds in the fossil-fuel specification. Second, the lagged - shock specifications confirm the dominance of the Brent channel. Lagged BrentShock retains a positive and significant coefficient of 2.006 ($p = 0.039$) for primary energy supply and a marginally significant coefficient of 1.602 ($p = 0.086$) for fossil fuel consumption. The lagged gas and coal shocks remain insignificant. The persistence of the Brent effect at one-year lag indicates that oil shocks operate not only contemporaneously but also with delayed transmission, plausibly reflecting the time it takes for households and firms to adjust energy use in response to sustained price changes. Third, the per-capita robustness models substantially strengthen the role of the renewable share. When CO_2 emissions per capita is the dependent variable, fossil fuel consumption enters positively (0.203, $p = 0.060$) and the renewable share enters negatively and very precisely (−0.344, $p < 0.001$). In the parallel coal-channel per-capita specification, the coal-consumption coefficient is 0.399 ($p < 0.001$) and the renewable-share coefficient is −0.323 ($p < 0.001$), with the latter t-statistic exceeding 34 in absolute value. These results provide unambiguous support for H4 and indicate that the mitigation contribution of renewables is most cleanly visible in emissions intensity rather than in total emissions.

Table 3. Baseline fixed-effects panel estimates with Driscoll-Kraay standard errors, G7 economies, 1991-2024.

Regressor	**(1) Primary Energy Supply (EJ)**	**(2) Fossil Fuel Cons. (EJ)**	**(3) CO_2 Emissions (Mt) - Fossil channel**	**(4) CO_2 Emissions (Mt) - Coal channel**
BrentShock	2.006**	1.602*	–	–
	(0.967)	(0.929)		
GasShock	−0.183	0.210	–	–
	(0.666)	(0.655)		
CoalShock	−0.211	−0.332	–	–
	(0.601)	(0.641)		
FossilFuelConsumption (EJ)	–	–	85.989***	–
			(11.042)	
CoalConsumption (EJ)	–	–	–	65.329***
				(8.044)
RenewablesShare (%)	–	–	−2.485	−14.145***
			(3.624)	(1.276)
Country fixed effects	Yes	Yes	Yes	Yes
Year fixed effects	No	No	No	No
Standard errors	DK	DK	DK	DK
Observations	238	238	238	238
Countries	7	7	7	7

Notes. Coefficients reported above standard errors in parentheses. *** $p < 0.01$, ** $p < 0.05$, * $p < 0.10$. All models are estimated with country fixed effects; year fixed effects are not included in Models 1 and 2 because the shock regressors vary only over time. Models 3 and 4 use total $\mathrm{CO_2}$ emissions (Mt) as the dependent variable. Standard errors are Driscoll–Kraay (DK) heteroskedasticity-, autocorrelation- and cross-sectional-dependence-consistent. Sample: 7 countries × 34 years = 238 observations.

Fourth, the crisis-control specifications reveal that the COVID-2020 dummy and the 2022–2023 EnergyCrisis dummy are large, negative and highly significant determinants of primary energy supply (−1.895 and −1.429 respectively, both $p < 0.001$) and fossil fuel consumption (−2.200 and −1.700, both $p < 0.001$). The 2008–2009 crisis dummy enters more weakly. Crucially, the carbon-channel coefficients on fossil fuel consumption and coal consumption remain large, positive and highly significant after these crisis controls, and the negative coefficient on the renewable share is preserved in the coal-channel specification (−13.29, $p < 0.001$). The robustness evidence therefore supports hypotheses H1 to H4 and confirms that the principal results are not driven by isolated crisis episodes.

Climate-stage aggregate evidence

Table 5 reports the climate-stage Newey – West time-series regressions on the 34 aggregate annual observations. Specification C1 regresses the global temperature anomaly on contemporaneous aggregate G7 emissions and yields a negative and significant coefficient (-2.34×10^{-4}, $p < 0.001$). Specification C2 uses the one-year lag of aggregate emissions and yields a similar negative and significant coefficient (-2.19×10^{-4}, $p < 0.001$). At face value, these bivariate associations might be read as evidence that higher G7 emissions are followed by lower global temperatures – an interpretation that is implausible on physical grounds. The correct interpretation is that aggregate G7 emissions declined after the mid - 2000s while global temperature continued to rise; the two series move in opposite directions in the late part of the sample, generating a mechanical negative correlation that is descriptive rather than causal. Fig. 4 illustrates this divergence by plotting standardised G7 emissions and the global temperature anomaly on a common scale. Specifications C4 and C5 are designed to remove this misleading association by conditioning on the persistence and trend of the temperature series. Specification C4 includes the one-period lag of the temperature anomaly. The lagged-temperature coefficient is 0.920 with $p < 0.001$, indicating very strong persistence in the global temperature series and an autoregressive root close to unity.

Table 4. Selected robustness checks, fixed-effects panel with Driscoll-Kraay standard errors.

Specification	**Regressor of interest**	**Coef.**	**SE**	**t**	**p**	**Sig.**
R1.1 Aggregate Index → Primary Supply	EnergyShockIndex	1.228	0.680	1.806	0.072	*
R1.2 Aggregate Index → Fossil Consumption	EnergyShockIndex	1.173	0.720	1.629	0.105	
R2.1 Lagged shocks → Primary Supply	$BrentShock_{t-1}$	2.006	0.967	2.074	0.039	**
R2.2 Lagged shocks → Fossil Consumption	$BrentShock_{t-1}$	1.602	0.929	1.723	0.086	*
R3.1 Fossil → CO_2 per capita	FossilFuelConsumption	0.203	0.107	1.892	0.060	*
	RenewablesShare	−0.344	0.032	−10.671	< 0.001	***
R3.2 Coal → CO_2 per capita	CoalConsumption	0.399	0.032	12.332	< 0.001	***
	RenewablesShare	−0.323	0.009	−34.580	< 0.001	***
R4.1 Index + Crisis → Primary Supply	COVID2020	−1.895	0.284	−6.678	< 0.001	***
	EnergyCrisis2022	−1.429	0.308	−4.641	< 0.001	***
R4.2 Index + Crisis → Fossil Consumption	COVID2020	−2.200	0.249	−8.834	< 0.001	***
	EnergyCrisis2022	−1.700	0.265	−6.421	< 0.001	***
R4.3 Fossil + Renew + Crisis → CO_2	FossilFuelConsumption	85.331	11.132	7.665	< 0.001	***
	EnergyCrisis2022	−45.338	12.991	−3.490	< 0.001	***
R4.4 Coal + Renew + Crisis → CO_2	CoalConsumption	64.799	8.249	7.856	< 0.001	***
	RenewablesShare	−13.288	1.391	−9.552	< 0.001	***
	COVID2020	−52.283	8.338	−6.270	< 0.001	***

Notes. The table reports selected robustness specifications drawn from the full robustness battery (Appendix Table A3). Aggregate Index models replace the three separate shocks with the EnergyShockIndex; lagged-shock models replace contemporaneous with one-year-lagged shocks; per-capita models replace total $\mathrm{CO_2}$ emissions with $\mathrm{CO_2}$ emissions per capita; and crisis models add Crisis2008 (2008–2009), COVID2020 (2020) and EnergyCrisis2022 (2022–2023). *** $p < 0.01$, ** $p < 0.05$, * $p < 0.10$.

The coefficient on lagged G7 emissions becomes statistically indistinguishable from zero (-2.8×10^{-5}, $p = 0.417$). Specification C5 instead introduces a deterministic time trend; the trend coefficient is 0.0226 ($p < 0.001$), indicating an average annual increase in the global temperature anomaly of about 0.023 °C, while the coefficient on contemporaneous G7 emissions becomes statistically insignificant (-3.1×10^{-5}, $p = 0.307$). Specifications C4 and C5 therefore strongly support hypothesis H5: the global temperature anomaly is dominated by persistence and a long-run trend, and contemporaneous G7 emissions do not retain explanatory power once these features are controlled for. Specification C6, reported as a sensitivity analysis, regresses the temperature anomaly on aggregate G7 fossil fuel and coal consumption. Aggregate fossil consumption enters positively and significantly (0.024, $p < 0.001$) and aggregate coal consumption enters negatively and significantly (−0.057, $p < 0.001$). The negative coefficient on aggregate G7 coal must not be interpreted as evidence that coal cools the planet; rather, it reflects the fact that G7 coal consumption has declined sharply over the sample while global temperature has continued to rise, again producing a descriptive negative association. This further illustrates that any inference about the climate effects of national energy use requires a global, cumulative - emissions framing that is beyond the scope of the present G7 panel. Read together, Sections 5.1 to 5.4 support an integrated interpretation of the four-stage transmission framework. Energy price shocks – particularly Brent oil shocks–are positively associated with G7 primary energy supply and, more weakly, with fossil fuel consumption. The carbon channel is robustly identified: fossil fuel and coal consumption are large and significant drivers of CO_2 emissions, while the renewable share reduces emissions, particularly in the coal-channel and per-capita specifications. The aggregate climate stage shows that, despite a meaningful decline in G7 emissions after the mid-

2000s, the global temperature anomaly continued to rise, and that this divergence is best explained by the cumulative and global character of climate dynamics rather than by current G7 emissions alone.

Figures

The figures referenced in the empirical analysis are reproduced in the accompanying figures package. Fig. 2 plots the trend in aggregate G7 CO_2 emissions over 1991–2024 and shows a clear decline after the mid-2000s. Fig. 3 plots the global temperature anomaly over the same period and documents its persistent upward trend. Fig. 4 reports standardised G7 CO_2 emissions and the global temperature anomaly on a common axis and provides the most informative visual representation of the divergence between national decarbonisation in the G7 and global climate outcomes. Fig. 5 plots aggregate G7 fossil fuel and coal consumption and supports the interpretation of the carbon-channel results in Section 5.2. Fig. 1 (conceptual transmission framework) and the appendix figures (correlation heatmap; G7 CO_2 versus temperature scatter) are reproduced in the accompanying figures file.

Table 5. Climate-stage time-series regressions, aggregate G7, 1991-2024 (Newey-West standard errors).

Regressor	**(C1) Temp ~ G7CO_2**	**(C4) Temp ~ $Temp_{t-1}$+ $G7CO_{2,t-1}$**	**(C5) Temp ~ G7CO_2+ Trend**
Intercept	2.852***	0.342	0.558*
	(0.483)	(0.361)	(0.301)
G7CO_2 (Mt)	-2.34×10^{-4}***	–	-3.1×10^{-5}
	(5.1×10^{-5})		(3.0×10^{-5})
$G7CO_{2,t-1}$	–	-2.8×10^{-5}	–
		(3.4×10^{-5})	
$Temp_{t-1}$	–	0.920***	–
		(0.088)	
Trend	–	–	0.0226***
			(0.0020)
Standard errors	Newey–West	Newey–West	Newey–West
Observations	34	33	34

Notes. Standard errors in parentheses are Newey–West heteroskedasticity- and autocorrelation-consistent. *** $p < 0.01$, ** $p < 0.05$, * $p < 0.10$. Specification C1 is a contemporaneous bivariate regression; C4 augments the model with a one-period lag of the dependent variable; C5 adds a deterministic time trend. The full set of climate-stage specifications (C1–C6) is reproduced in Appendix Table A4. The negative G7 CO_2 coefficients in C1 reflect the descriptive divergence between declining G7 emissions and rising global temperature documented in Figure 4 and should not be interpreted causally.

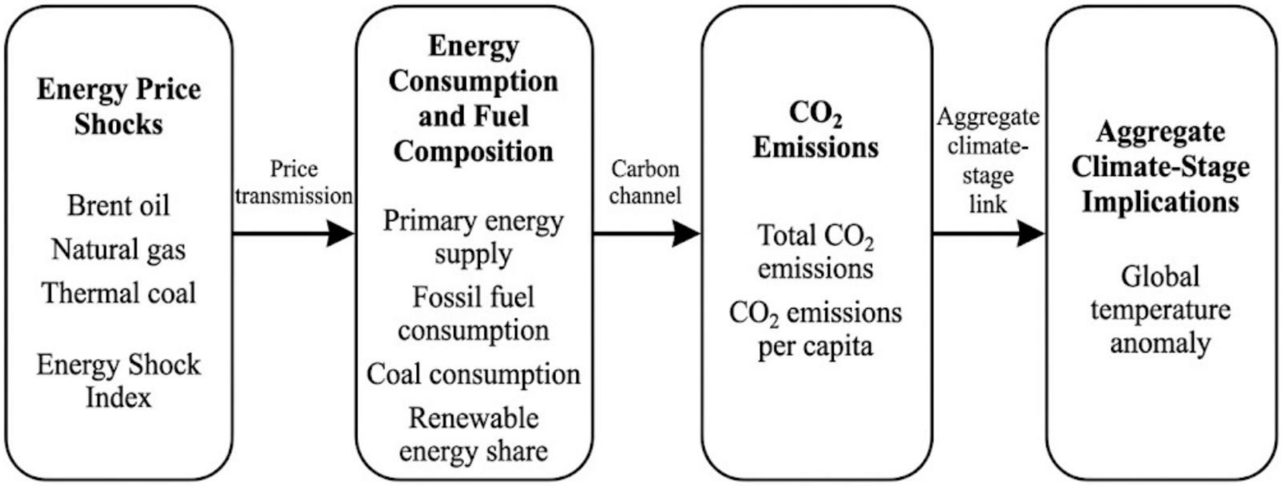

Fig. 1. Conceptual transmission framework. Energy price shocks → energy consumption and fuel composition → CO_2 emissions → aggregate climate-stage implications.

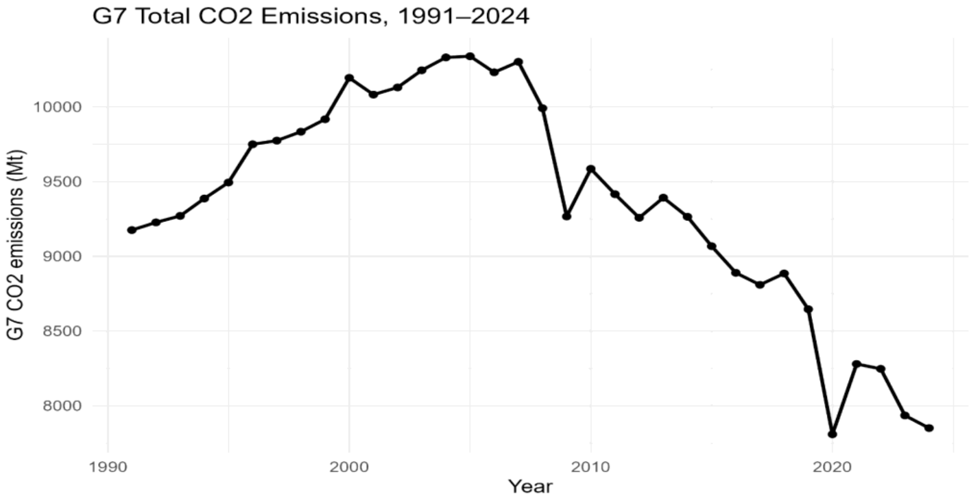

Fig. 2. Aggregate G7 CO_2 emissions, 1991-2024 (Mt).

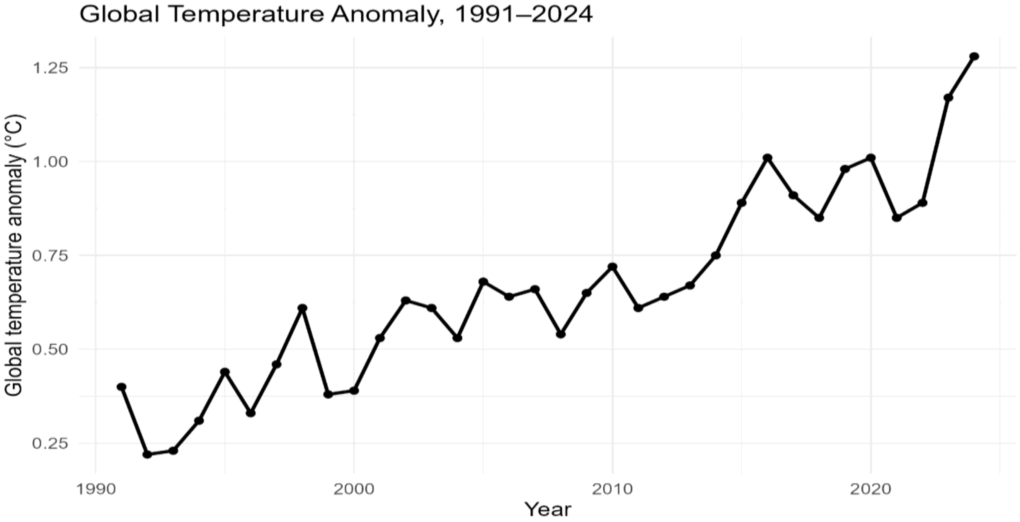

Fig. 3. Global temperature anomaly, 1991-2024 (°C).

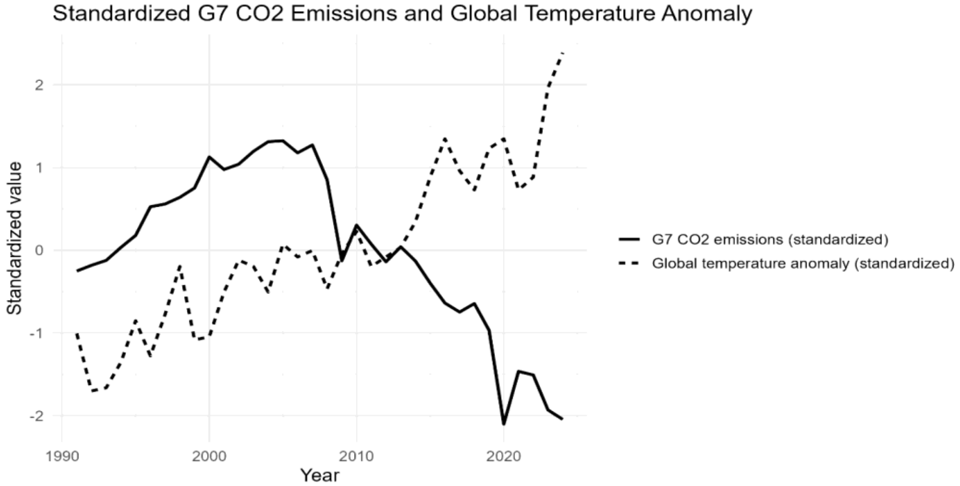

Fig. 4. Standardised G7 CO_2 emissions and global temperature anomaly, 1991-2024.

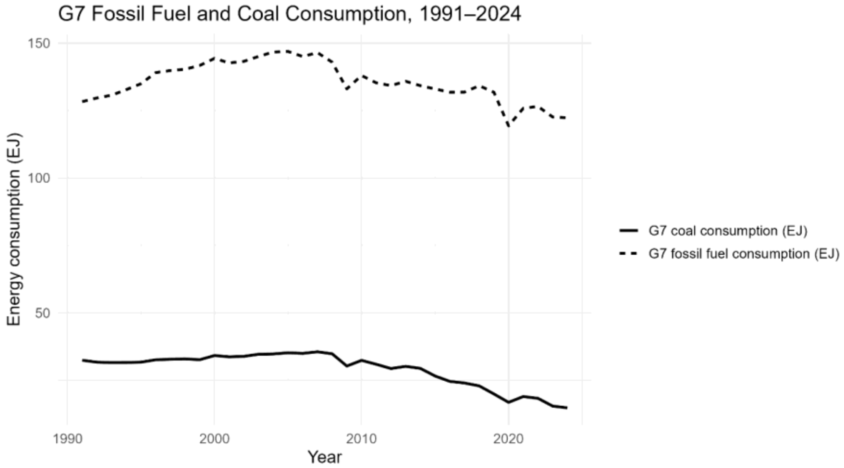

Fig. 5. Aggregate G7 fossil fuel and coal consumption, 1991-2024 (EJ).

DISCUSSION

The empirical pattern that emerges from the four stages can be summarised in five propositions. First, the energy system in advanced economies responds asymmetrically to different price shocks. The Brent oil channel is the most robust contemporaneous and lagged price-shock channel for both primary energy supply and fossil fuel consumption, while gas and coal shocks display no robust direct effect at the panel level over 1991 – 2024. This is consistent with the global integration and benchmarking role of oil markets and with the more segmented nature of natural gas and coal markets in the G7. Second, the carbon intensity of the energy mix is the dominant proximate driver of emissions. Fossil fuel consumption raises CO_2 emissions by approximately 86 Mt per EJ on average, while coal consumption raises emissions by approximately 65 Mt per EJ – a per - EJ effect that, given the substantially smaller share of coal in total energy supply, indicates a much higher carbon intensity per physical unit. The Stage - 3 coal channel therefore identifies a particularly powerful lever for emissions mitigation in G7 countries that retain coal in their fuel mix. Third, the renewable share contributes to emissions mitigation, but the magnitude and statistical precision of the effect depend on the specification. The renewable share is statistically insignificant in the fossil-channel total-emissions model, large and highly significant in the coal-channel total-emissions model (-14.15 Mt per percentage point), and very precisely negative in both per-capita robustness models. This pattern aligns with the substitution interpretation: renewables reduce emissions chiefly to the extent that they displace coal, and the marginal effect is most cleanly identified when the carbon-intensive component is controlled for or when emissions are scaled by population. Fourth, the climate stage reveals a divergence between G7 decarbonisation and global temperature outcomes. G7 emissions declined after the mid - 2000s, accelerating during the COVID-19 pandemic, while the global temperature anomaly continued its upward trajectory. This divergence is consistent with the cumulative-emissions framing of climate dynamics: temperature responds to the stock of cumulative anthropogenic CO_2 emissions, which has continued to rise even as flows from the G7 have moderated. The methodological consequence is that simple bivariate regressions of temperature on national emissions can yield economically meaningless negative coefficients, and the policy consequence is that national decarbonisation in advanced economies, although necessary, is insufficient on its own to stabilise global climate outcomes. Fifth, the COVID-19 and 2022–2023 energy-crisis episodes are visible in the panel as substantial reductions in primary energy supply and fossil fuel consumption. The associated changes in CO_2 emissions are consistent with the underlying carbon channel rather than with a separate crisis effect on emissions intensity, and the principal coefficients on fossil and coal consumption remain robust to crisis controls. This robustness reinforces the view that the four-stage transmission framework captures structural energy-system relationships rather than artefacts of specific crisis episodes. Compared with prior studies that examine each stage in isolation, the integrated framework offered here yields a clearer narrative: energy price shocks affect the system primarily through aggregate energy demand and the fossil-fuel component of supply; these in turn shape emissions through their carbon intensity; renewables mitigate these emissions, especially through the coal channel; and global climate outcomes ultimately respond to cumulative global emissions, with G7 contributions being one input among many. This narrative is consistent with the broader climate-economics literature but is delivered here through a single coherent estimator design with consistent sample, period and standard-error conventions across the four stages.

CONCLUSION

This paper has examined the transmission from energy price shocks to energy consumption, fossil fuel use, CO_2 emissions and aggregate climate-stage outcomes in G7 economies over 1991–2024. Using a balanced panel of 238 country-year observations and 34 aggregate annual observations, country fixed-effects models with Driscoll–Kraay standard errors, and time-series models with Newey–West standard errors, the analysis delivers four main findings. First, Brent oil shocks are positively associated with primary energy supply and, more weakly, with fossil fuel consumption; gas and coal shocks have no robust direct effects in the baseline panel. Second, fossil fuel and coal consumption are large and statistically robust positive drivers of CO_2emissions. Third, the renewable energy share reduces emissions, especially in the coal-channel and per-capita specifications. Fourth, the global temperature anomaly is highly persistent and trend-driven; once these features are controlled for, contemporaneous G7 emissions lose explanatory power. Taken together, these results identify the energy – carbon transmission channel rather than a direct energy-price-to-temperature effect, and indicate that G7 decarbonisation is necessary but insufficient for global climate stabilisation. The integrated multi-stage transmission framework offers an internally consistent narrative for understanding how energy markets, energy structure, emissions and climate dynamics interact in advanced economies.

Limitations and Future Research

The analysis is subject to a number of limitations that should be borne in mind when interpreting the results and that suggest avenues for future research. First, the empirical sample is restricted to the G7 economies. While the G7 represents a coherent group of advanced, energy-intensive economies, the results may not generalise to emerging or developing economies, where the energy mix, the policy environment and the response to price shocks may differ. Extending the sample to OECD or G20 economies, or to comparable advanced-emerging panels, is a natural next step. Second, the analysis uses annual data, which may obscure short-term dynamics in energy-price responses. Quarterly or monthly data would permit a richer characterisation of the lag structure of the energy-demand and fossil-fuel responses to price shocks, although such data are not consistently available for all variables in the present sample.

Third, energy price shocks are common across countries, so year fixed effects cannot be used in the shock-energy specifications without absorbing the variation of interest. Country fixed effects together with Driscoll – Kraay standard errors mitigate but do not fully resolve concerns about unobserved time-varying heterogeneity. Incorporating richer policy variables (e.g., explicit carbon-price series, renewable-policy indices) and instrumenting for shock components are promising extensions. Fourth, the climate-stage analysis is presented as aggregate time-series evidence and should not be interpreted as a full causal climate model. Global temperature is shaped by cumulative global emissions, methane and other greenhouse gases, land-use change, aerosols, ocean–atmosphere dynamics and natural variability, none of which are explicitly modelled in the present time-series specifications. Future work could incorporate cumulative global emissions, multi-gas radiative forcing and structural climate–economy linkages, ideally drawing on integrated assessment models or climate–macro panels with global coverage. Fifth, the analysis does not estimate a simultaneous-equations system across the four stages. While this design choice keeps the empirical model transparent and stage-specific, it abstracts from feedback effects–for example, from energy use to prices, or from climate impacts back to energy demand. Joint estimation in a panel VAR or structural framework, ideally with policy-relevant identification, would complement the present transmission-channel evidence.

REFERENCES

Apergis, N & Payne, JE 2014, Renewable energy, output, CO_2 emissions, and fossil fuel prices in Central America: evidence from a nonlinear panel smooth transition vector error correction model. *Energy Economics*, 42: 226–232.

Berkeley Earth 2024, Global temperature anomaly dataset. Available at: https://berkeleyearth.org.

British Petroleum 2024, Statistical Review of World Energy / Energy Institute Statistical Review. London: Energy Institute.

Driscoll, JC & Kraay, AC 1998, Consistent covariance matrix estimation with spatially dependent panel data. *Review of Economics and Statistics*, 80(4): 549–560.

Hausman, JA 1978, Specification tests in econometrics. *Econometrica*, 46(6): 1251–1271.

International Energy Agency 2023, World Energy Outlook 2023. Paris: IEA.

International Monetary Fund 2024, Primary commodity price database. Washington, DC: International Monetary Fund.

Intergovernmental Panel on Climate Change 2023, AR6 Synthesis Report: Climate Change 2023. Geneva: IPCC.

Kilian, L 2009, Not all oil price shocks are alike: disentangling demand and supply shocks in the crude oil market. *American Economic Review*, 99(3): 1053–1069.

Kilian, L & Park, C 2009, The impact of oil price shocks on the U.S. stock market. *International Economic Review*, 50(4): 1267–1287.

NASA Goddard Institute for Space Studies 2024, GISS Surface Temperature Analysis (GISTEMP v4). New York: NASA GISS. Available at: https://data.giss.nasa.gov/gistemp/.

Newey, WK & West, KD 1987, A simple, positive semi-definite, heteroskedasticity and autocorrelation consistent covariance matrix. *Econometrica*, 55(3): 703–708.

Our World in Data 2024, CO_2 and Greenhouse Gas Emissions. Available at: https://ourworldindata.org/co2-and-greenhouse-gas-emissions.

Our World in Data 2024, Energy: data and statistics. Available at: https://ourworldindata.org/energy.

Pesaran, MH 2006, Estimation and inference in large heterogeneous panels with a multifactor error structure. *Econometrica*, 74(4): 967–1012.

Stern, DI 2017, The environmental Kuznets curve after 25 years. *Journal of Bioeconomics*, 19(1): 7–28.

United Nations Framework Convention on Climate Change 2015, Paris Agreement. Bonn: UNFCCC.

World Bank 2024, Pink Sheet: commodity markets monthly. Washington, DC: World Bank.

Zivot, E & Wang, J 2006, Modeling Financial Time Series with S-PLUS. 2nd edn. New York: Springer.

Berkeley Earth 2024, Global Temperature Anomaly Data. Berkeley Earth.

Energy Institute 2024, Statistical Review of World Energy 2024, London: Energy Institute.

International Monetary Fund 2024, Primary Commodity Price System. Washington, DC: IMF.

NASA Goddard Institute for Space Studies 2024, GISS Surface Temperature Analysis (GISTEMP v4). New York: NASA GISS.

Our World in Data 2024, CO_2 and Greenhouse Gas Emissions Database.

Our World in Data 2024, Energy Data Explorer.

World Bank 2024, Commodity Markets: Pink Sheet Data. Washington, DC: World Bank.

Burkhanov, AU, Iiyos, A, Baxtiyor, T, Sarvinoz, S, Myachina, O, Sattoriy, F & Olimov, K 2025, Role of information systems in achieving Sustainable Development Goals for water conservation in rural Uzbekistan. *Caspian Journal of Environmental Sciences*, 23(5): 1159-1166, DOI: 10.22124/cjes.2025.9357.

Eshkaraev, S *et al.* 2025, Dynamic Stability Analysis and Control of AC/DC Microgrids with Energy Storage Systems for Transient State Mitigation. *Journal of Operation and Automation in Power Engineering* 13. Special Issue.

Pandikumar, S, Bostani, A, Sundaranarayana, D, Fakhriddin, I, Alimjon, D, Ilkhom, U & Juraboyev, A 2025, AIdriven nonlinear optimization for knowledge extraction and pattern analysis in IoT-enabled data mining systems. *Results in Nonlinear Analysis*, 8(3): 36-46.

Abrorov, S 2020, The importance of sukuk in the development of economy: as an example of its impact on the income of the malaysian population. *Journal of Critical Reviews,* 7(02). https://doi.org/10.31838/jcr.07.02.142. DOI: https://doi.org/10.31838/jcr.07.02.142

Meylikulov, S *et al.* 2025, Dynamic Modeling and State Feedback Control for Enhancing Small Signal Stability in Islanded Microgrids with Diesel Generator Frequency Damping. *Journal of Operation and Automation in Power Engineering,* 13: 29-43.

Menglikulov, B Yu *et al.* 2025, Improving the organizational and methodological aspects of the current biological assets audit in livestock. Technological horizons of decarbonization based on environmental innovations. Cham: Springer Nature Switzerland, pp. 185-190, https://doi.org/10.1007/ 978-3-031-82210-0_3

Pandikumar, S, Bostani, A, Sundaranarayana, D, Fakhriddin, I, Alimjon, D, Ilkhom, U & Juraboyev, A 2025, AIdriven nonlinear optimization for knowledge extraction and pattern analysis in IoT-enabled data mining systems. *Results in Nonlinear Analysis*, 8(3): 36-46.

Prabha, KR *et al.* 2026, A multi-layer artificial intelligence–enabled governance framework for integrating information security management, quality management, and strategic human resource analytics: An empirical study on the role of corporate social responsibility in sustainable organizational performance." *Calitatea* 27.210: 418-426.

Indhumathi, R *et al.* 2025, Hybrid quantum–cloud framework for nonlinear clustering optimization and intelligent resource management. *Results in Nonlinear Analysis* 8(3): 26-35.

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Appendix

Table A1. Pairwise correlation matrix of the core variables, G7 panel, 1991-2024.

	Brent Shock	**Gas Shock**	**Coal Shock**	**Energy Shock Index**	**Primary Energy Supply_EJ**	**Fossil Fuel Consumption_EJ**	**Coal Consumption_EJ**	**Renewables Share_pct**	**CO_2 Emissions_Mt**	**CO_2 Per Capita_t**	**Global Temperature Anomaly_C**
Brent Shock	1										
Gas Shock	0.682	1									
Coal Shock	0.65	0.596	1								
Energy Shock Index	0.869	0.873	0.874	1							
Primary Energy Supply_EJ	0.015	0.009	0.008	0.012	1						
Fossil Fuel Consumption_EJ	0.016	0.012	0.008	0.013	0.998	1					
Coal Consumption_EJ	0.026	0.028	0.012	0.025	0.947	0.957	1				
Renewables Share_pct	-0.069	-0.094	-0.008	-0.063	-0.239	-0.242	-0.31	1			
CO2 Emissions_Mt	0.017	0.015	0.008	0.015	0.996	0.999	0.969	-0.255	1		
CO2 PerCapita_t	0.049	0.063	0.013	0.046	0.686	0.696	0.707	0.066	0.701	1	
Global Temperature Anomaly_C	-0.183	-0.279	-0.096	-0.211	-0.01	-0.021	-0.116	0.519	-0.04	-0.254	1

Table A2. Hausman model-selection test results.

Model	**Chi-square**	**df**	***p*-value**	**Preferred model**
Model 1: Primary Energy Supply	0	3	1	Random Effects
Model 2: Fossil Fuel Consumption	0	3	1	Random Effects
Model 3: CO_2 Emissions Fossil	23.994	2	0.000006	Fixed Effects
Model 4: CO_2 Emissions Coal	17.887	2	0.000131	Fixed Effects

Notes: The Hausman test compares fixed-effects and random-effects specifications. Although random effects are preferred in Models 1 and 2, the fixed-effects estimator is retained across all specifications for methodological consistency and to control for unobserved country-specific heterogeneity. Final specifications are estimated with country fixed effects and Driscoll–Kraay standard errors.

Table A3. Robustness checks using fixed effects with Driscoll-Kraay standard errors.

Model	Variable	Estimate	Std_Error	t_value	p_value	Significance
R1.1 EnergyShockIndex -> PrimaryEnergySupply	EnergyShockIndex	1.22831	0.68014	1.80598	0.07223	*
R1.2 EnergyShockIndex -> FossilFuelConsumption	EnergyShockIndex	1.17253	0.71996	1.6286	0.10477	
R1.3 EnergyShockIndex -> RenewablesShare	EnergyShockIndex	-1.03495	1.64208	-0.63027	0.52915	
R1.4 EnergyShockIndex -> CoalConsumption	EnergyShockIndex	0.55253	0.60766	0.90928	0.36415	
R2.1 Lagged shocks -> PrimaryEnergySupply	BrentShock_lag1	2.00613	0.96727	2.07401	0.0392	**
R2.1 Lagged shocks -> PrimaryEnergySupply	GasShock_lag1	-0.18324	0.66607	-0.2751	0.78349	
R2.1 Lagged shocks -> PrimaryEnergySupply	CoalShock_lag1	-0.21118	0.60081	-0.35149	0.72554	
R2.2 Lagged shocks -> FossilFuelConsumption	BrentShock_lag1	1.60152	0.92941	1.72317	0.08621	*
R2.2 Lagged shocks -> FossilFuelConsumption	GasShock_lag1	0.21031	0.65531	0.32093	0.74855	
R2.2 Lagged shocks -> FossilFuelConsumption	CoalShock_lag1	-0.33161	0.64129	-0.5171	0.60559	
R2.3 Lagged EnergyShockIndex -> FossilFuelConsumption	EnergyShockIndex_lag1	1.17253	0.71996	1.6286	0.10477	
R2.4 Lagged EnergyShockIndex -> RenewablesShare	EnergyShockIndex_lag1	-1.03495	1.64208	-0.63027	0.52915	
R3.1 FossilFuelConsumption -> CO_2PerCapita	FossilFuelConsumption_EJ	0.20308	0.10732	1.89238	0.0597	*
R3.1 FossilFuelConsumption -> CO_2PerCapita	RenewablesShare_pct	-0.34379	0.03222	-10.671	0	***
R3.2 CoalConsumption -> CO_2PerCapita	CoalConsumption_EJ	0.39936	0.03238	12.33234	0	***

R3.2 CoalConsumption -> CO_2PerCapita	RenewablesShare_pct	-0.32291	0.00934	-34.5804	0	***
R4.1 EnergyShockIndex + Crisis -> PrimaryEnergySupply	EnergyShockIndex	1.03566	0.64758	1.59928	0.11115	
R4.1 EnergyShockIndex + Crisis -> PrimaryEnergySupply	Crisis2008	0.53166	0.25679	2.07041	0.03955	**
R4.1 EnergyShockIndex + Crisis -> PrimaryEnergySupply	COVID2020	-1.89494	0.28378	-6.67754	0	***
R4.1 EnergyShockIndex + Crisis -> PrimaryEnergySupply	EnergyCrisis2022	-1.42905	0.30793	-4.64081	1.00E-05	***
R4.2 EnergyShockIndex + Crisis -> FossilFuelConsumption	EnergyShockIndex	0.91704	0.65557	1.39884	0.16322	
R4.2 EnergyShockIndex + Crisis -> FossilFuelConsumption	Crisis2008	0.31353	0.23402	1.33978	0.18166	
R4.2 EnergyShockIndex + Crisis -> FossilFuelConsumption	COVID2020	-2.19994	0.24904	-8.83361	0	***
R4.2 EnergyShockIndex + Crisis -> FossilFuelConsumption	EnergyCrisis2022	-1.69986	0.26475	-6.42054	0	***
R4.3 FossilFuel + Renewables + Crisis -> CO_2Emissions	FossilFuelConsumption_EJ	85.33144	11.13224	7.66525	0	***
R4.3 FossilFuel + Renewables + Crisis -> CO_2Emissions	RenewablesShare_pct	-0.9965	3.58971	-0.2776	0.78157	
R4.3 FossilFuel + Renewables + Crisis -> CO_2Emissions	Crisis2008	5.35263	7.61883	0.70255	0.48306	
R4.3 FossilFuel + Renewables + Crisis -> CO_2Emissions	COVID2020	-22.1618	19.29674	-1.14847	0.25199	
R4.3 FossilFuel + Renewables + Crisis -> CO_2Emissions	EnergyCrisis2022	-45.3379	12.99074	-3.49002	0.00058	***
R4.4 Coal + Renewables + Crisis -> CO_2Emissions	CoalConsumption_EJ	64.79919	8.24867	7.85572	0	***
R4.4 Coal + Renewables + Crisis -> CO_2Emissions	RenewablesShare_pct	-13.2879	1.39106	-9.55233	0	***
R4.4 Coal + Renewables + Crisis -> CO_2Emissions	Crisis2008	-7.592	16.35795	-0.46412	0.64301	
R4.4 Coal + Renewables + Crisis -> CO_2Emissions	COVID2020	-52.2826	8.33818	-6.27027	0	***
R4.4 Coal + Renewables + Crisis -> CO_2Emissions	EnergyCrisis2022	-9.10465	8.45728	-1.07655	0.28283	

Notes: The table reports robustness checks estimated using country fixed effects with Driscoll–Kraay standard errors. Robustness specifications include the aggregate EnergyShockIndex, lagged energy-price shocks and crisis-period controls. Significance levels are denoted as follows: * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.

Table A4. Full set of climate-stage specifications (C1-C6).

Variables	**C1 CO_2**	**C2 Lag CO_2**	**C3 CO_2+ Shock**	**C4 TempLag + CO_2Lag**	**C5 CO_2 + Trend**	**C6 Fossil + Coal**
Intercept	2.852***	2.731***	2.812***	0.342	0.558*	−0.905
	-0.434	-0.505	-0.452	-0.404	-0.325	-0.604
G7 CO_2emissions, Mt	−0.000***		−0.000***		−0.000	

	0		0		0	
Lagged G7 CO_2 emissions		−0.000***		−0.000		
		0		0		
Energy Shock Index			−0.049			
			-0.129			
Lagged temperature				0.920***		
				-0.111		
Trend					0.023***	
					-0.002	
G7 fossil fuel consumption, EJ						0.024***
						-0.006
G7 coal consumption, EJ						−0.057***
						-0.007
Observations	34	33	34	33	34	34
R^2	0.445	0.351	0.448	0.803	0.861	0.773

Notes. Standard errors in parentheses are Newey–West heteroskedasticity- and autocorrelation-consistent. *** $p \leq 0.01$, ** $p \leq 0.05$, * $p \leq 0.10$. Specification C1 is a contemporaneous bivariate regression; C4 augments the model with a one-period lag of the dependent variable; C5 adds a deterministic time trend. The negative G7 CO_2 coefficients in C1 reflect descriptive divergence between declining G7 emissions and rising global temperature and should not be interpreted causally.

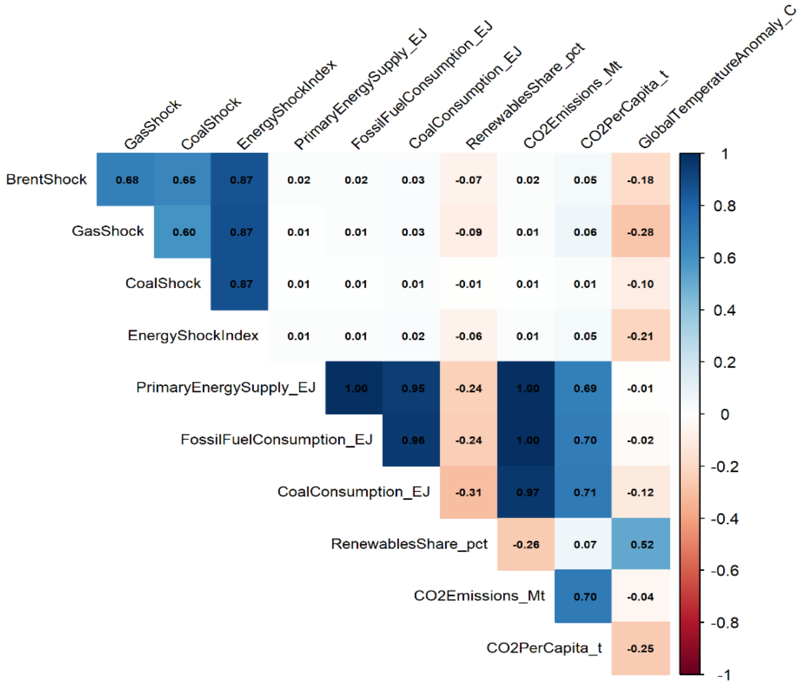

Fig. A1. Correlation heatmap of the main study variables.

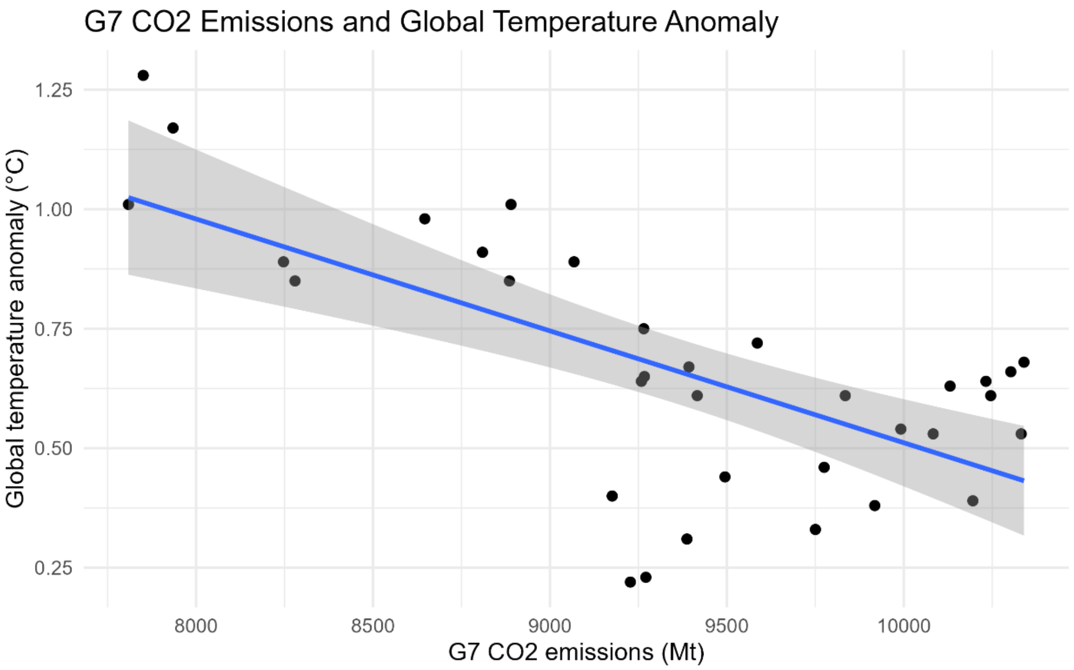

Fig. A2. Scatter plot of G7 CO_2 emissions and global temperature anomaly.