“Market-based climate-policy stringency and European machinery production after Russia’s full-scale invasion of Ukraine: Energy-market stress and energy vulnerability”

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MARKET-BASED CLIMATE-POLICY STRINGENCY AND EUROPEAN MACHINERY PRODUCTION AFTER RUSSIA'S FULL-SCALE INVASION OF UKRAINE: ENERGY-MARKET STRESS AND ENERGY VULNERABILITY

Abstract

Decarbonization has become a challenge for European manufacturing, particularly after Russia's full-scale invasion of Ukraine, amid rising energy costs and tensions between environmental transition and industrial competitiveness. This study assesses whether market-based climate-policy stringency is non-linearly associated with European machinery production, whether this relationship differed during 2022–2023, and whether it varies with electricity-market stress and 2020–2021 baseline energy-use characteristics. The analysis uses a 2017–2023 panel of 24 European countries; the principal C28 models cover 20 countries and 140 observations. Two-way fixed-effects models combine quadratic specifications, post-2022 interactions, electricity-price moderation, baseline energy-use moderators, and wild-cluster bootstrap inference. The contemporaneous C28 industrial-production specification shows statistically significant concavity: the quadratic MBI coefficient is −0.019 (bootstrap $p = 0.047$), with a model-implied turning point of approximately 4.7. The upper-bound marginal effect is −0.0984 ($p < 0.001$), whereas the positive lower-bound effect of 0.0768 is not statistically significant ($p = 0.120$). This pattern is not reproduced when MBI is lagged or when real C28 GVA levels or growth are used as alternative outcomes. Neither the post-2022 interactions ($F = 0.611$, $p = 0.553$) nor the electricity-price interactions ($F = 2.193$, $p = 0.139$) are jointly significant. The natural-gas triple interaction is positive but statistically inconclusive under wild-cluster bootstrap inference ($\beta = 0.242$, $p = 0.057$), while the alternative energy-use moderators are insignificant. The findings support contemporaneous concavity in short-run C28 industrial production and an adverse association at high MBI levels, but not a general non-linear relationship across broader measures of machinery-sector performance.

Keywords climate policy, policy stringency, industrial performance, energy stress, energy vulnerability, machinery manufacturing

JEL Classification Q58, Q48, L64

INTRODUCTION

The operating environment of European industry changed markedly after Russia's full-scale invasion of Ukraine in 2022, as energy insecurity, supply uncertainty, and geopolitical risks intensified. Dependence on imported fossil fuels exposed European producers to sharp energy price movements and heterogeneous effects on investment, manufacturing activity, and competitiveness (Anaya Longaric et al., 2025). The EU response reflected these vulnerabilities: REPowerEU sought to reduce dependence on Russian gas, oil, and coal through lower energy consumption, supply diversification, and faster deployment of clean energy (European

Commission, 2022). At the same time, electricity prices became crucial for energy-intensive manufacturing and industrial competitiveness (Arlia & Hutchinson, 2026), with prolonged high prices also associated with employment losses in energy-intensive industries (Bijnens et al., 2025). Access to affordable energy therefore remains important for reconciling competitiveness with decarbonization (European Commission, n.d.a), while the Clean Industrial Deal similarly integrates energy affordability, industrial modernization, and decarbonization objectives (European Commission, 2025). These developments link climate-regulatory pressures more closely to prevailing energy-market conditions and sector-specific energy-use profiles.

This context raises the question of whether increasingly stringent climate policy has a uniform relationship with manufacturing performance, or whether this association varies with policy intensity and energy market conditions. The OECD Climate Actions and Policies Measurement Framework (CAPMF) enables harmonized cross-country comparison of mitigation policy stringency across sectors and instruments (Nachtigall et al., 2022; OECD, 2025), while recent OECD evidence indicates that the expansion of climate policy action has slowed despite ongoing mitigation needs (OECD, 2024). For the EU, this creates a difficult balance between reducing dependence on Russian fossil fuels, accelerating the clean-energy transition, maintaining affordable energy, and preserving industrial competitiveness (European Commission, 2022; European Commission, n.d.a). Against this background, the study examines whether market-based climate-policy stringency is non-linearly associated with short-run C28 industrial production, whether this relationship differed during 2022–2023 following Russia's full-scale invasion of Ukraine, and whether it varies with electricity-market stress and 2020–2021 baseline energy-use characteristics. Broader real C28 GVA measures are used as alternative outcomes to assess whether the production-index findings extend to wider sectoral economic performance.

1. LITERATURE REVIEW

Research on climate-policy stringency and industrial performance increasingly emphasizes that regulation can both constrain and stimulate competitiveness. Climate policies may raise production costs, intensify trade pressures, and increase carbon leakage risks in energy-intensive manufacturing (Bassi et al., 2009; Antimiani et al., 2016), while ecological modernization theory suggests that regulation can also promote structural transformation and technological upgrading (Jänicke et al., 2000). Recent evidence supports a context-dependent rather than purely linear relationship, as stricter environmental requirements may encourage green innovation and improved environmental performance, depending on technological capacity, energy exposure, and institutional conditions (Belazreg et al., 2026; Faiella & Mistretta, 2022). Financial innovation and information screening can further support green innovation (Yuan et al., 2021), while sustainability outcomes should be considered together with their economic implications (Kubalek et al., 2024). Firm responses may also evolve through feedback between climate-risk exposure and subsequent adjustment, reinforcing heterogeneity in regulatory effects (Pham et al., 2026).

Energy costs are a central channel linking climate policy to manufacturing performance. Energy-price shocks may weaken productivity and influence employment and production decisions through labor–energy complementarities (André et al., 2025; Bretschger & Jo, 2024). In Europe, electricity price shocks have also been associated with inflation and macroeconomic instability, particularly as Russia's full-scale invasion of Ukraine intensified energy market disruption (Vasylieva et al., 2025; Snieska & Navickas, 2026). Carbon-price shocks can further increase electricity costs and contribute to employment reallocation (Bijnens et al., 2026). These effects vary with firms' technological characteristics and energy intensity (Sahu et al., 2022). Evidence from newer EU member states also links manufacturing sustainability to electricity prices and renewable energy development (Simionescu & Radulescu, 2025), while financial conditions can amplify or moderate the effects of energy prices and climate policy uncertainty on investment (Shahbaz et al., 2024). The evidence indicates that the industrial consequences of climate-policy pressure depend strongly on energy exposure, technological capacity, and the ability to finance adaptation.

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A non-linear relationship is plausible because firms may respond differently as regulatory pressure increases. Moderate climate-policy stringency can encourage efficiency gains, technological renewal, and green innovation, whereas higher compliance and transition costs may eventually offset these benefits. Evidence from cap-and-trade systems illustrates this trade-off: market-based regulation improves energy efficiency while also affecting firm value (Pal et al., 2024). Green total factor productivity likewise depends on technological, environmental, and spatial conditions, and its determinants vary across the performance distribution (Thapliyal et al., 2025; Wang et al., 2020). Energy intensity can condition firms' exposure to climate-policy uncertainty (Islam, 2026), while digitalization may reduce this sensitivity by lowering energy intensity (Hao et al., 2025). Energy-efficiency improvements, audits, process optimization, cogeneration, storage, waste-heat recovery, and digital monitoring can further strengthen technological progress and competitiveness (Cantore et al., 2016; Honcharuk et al., 2025; Rashid et al., 2026; Tomczyk et al., 2025). This evidence supports the possibility of an inverted-U pattern in which moderate policy pressure promotes adaptation, while sufficiently high policy-related costs weaken industrial performance.

The effect of climate-policy pressure also depends on the wider European energy-security environment. Energy-tax exemptions may protect short-run competitiveness but weaken incentives for efficiency improvements (Locmelis & Blumberga, 2019), while differences in national energy-tax regimes create heterogeneous regulatory burdens across EU countries (Sineviciene & Miliauskaite, 2025). Competitiveness is additionally shaped by embodied energy in supply chains and broader regional energy vulnerability (Bordigoni et al., 2012; Chiaradia et al., 2026). The 2022 energy crisis highlighted the importance of electricity prices, renewable energy penetration, and institutional resilience for macroeconomic stability (Vasylieva et al., 2026a; Vasylieva et al., 2026b), while Russia's full-scale invasion of Ukraine intensified energy and macroeconomic pressures across Europe (Koilo, 2023; Zozulinskyy, 2024). Geopolitical and energy-security risks also affect sustainable finance and realized renewable-energy investment (Hakmi et al., 2026; Zozulinskyy & Bilan, 2026). At the firm level, resilience therefore depends on the capacity to adapt operational practices, supply chains, and resource allocation to major external shocks (Sitnicka & Serhiienko, 2025). Climate-policy stringency should thus be assessed jointly with energy-security conditions rather than as an isolated regulatory factor.

A growing literature examines how regulatory pressure can support adaptation and productive transformation rather than act solely as a constraint. Competitiveness losses and carbon-leakage risks may be mitigated through compensation, innovation support, and sector-specific measures (Antimiani et al., 2016; Fragkos et al., 2021), while public and fiscal support can facilitate renewable-energy deployment where institutional and economic conditions are favorable (Raboshuk et al., 2025; Sitnicki et al., 2026; Mikhno et al., 2026). This reinforces the interdependence of energy security and environmental sustainability (Nihal et al., 2024; Georgescu et al., 2025). Technological adaptation can strengthen resilience to energy shocks, including through green hydrogen (Leuratti et al., 2024), new investment and technology adoption (Riaz et al., 2026), and improved monitoring and forecasting in resilient energy systems (Wojciechowski et al., 2025). Regulation may also strengthen environmental accountability (To & Tran, 2025), while transition outcomes depend on governance, sectoral policy, and financing (Makarenko et al., 2025). Excessive compliance burdens may generate unintended behavioral responses (Lyeonov et al., 2025). In contrast, financial risks can restrict decarbonization investment, and Industry 4.0 technologies may reshape the relationship between environmental constraints and productivity (Melnyk et al., 2025). Climate-policy effects therefore depend on regulatory stringency together with technological, financial, and energy-management capacity.

Despite this growing body of evidence, European machinery manufacturing remains insufficiently studied within an integrated, sector-specific framework. Existing research commonly examines energy-price shocks, regulation, energy efficiency, innovation, and macroeconomic resilience separately, often focusing on highly energy-intensive industries or aggregate outcomes (Bassi et al., 2009; Faiella &

Mistretta, 2022). However, potential gains from innovation and rising compliance costs imply that linear specifications may conceal non-linear responses, while firm characteristics and climate-risk exposure generate substantial heterogeneity (Pham et al., 2026). Differences in electricity prices, energy taxation, and energy intensity further support the explicit incorporation of energy vulnerability (Locmelis & Blumberga, 2019; Sahu et al., 2022; André et al., 2025). Manufacturing responses also depend jointly on electricity market conditions, renewable energy development, and financial uncertainty (Simionescu & Radulescu, 2025; Shahbaz et al., 2024). These issues became particularly salient after 2022, when geopolitical risk associated with Russia's full-scale invasion of Ukraine and broader macroeconomic instability intensified pressures on industrial competitiveness (Vasylieva et al., 2026b; Shanyazov et al., 2026). Evidence that green productivity determinants vary across the performance distribution further supports approaches that capture heterogeneous responses (Wang et al., 2020).

The literature points to two opposing effects of market-based climate policy stringency: stronger regulation may stimulate efficiency, technological upgrading, and innovation, but may also raise adjustment and compliance costs, especially for energy-exposed manufacturers. This suggests the need to consider both non-linearity and energy-related heterogeneity. Accordingly, this study aims to examine whether climate-policy stringency is non-linearly associated with short-run C28 industrial production, whether this relationship varies with post-2022 and electricity-market conditions, and whether the findings extend to broader GVA-based measures of sectoral performance.

Based on this framework, we test four hypotheses:

H1: *An inverted-U relationship exists between market-based climate policy stringency and short-run C28 industrial production.*

H2a: *A non-linear MBI–production relationship differs in 2022–2023 relative to 2017–2021, with adverse associations emerging at a lower model-implied MBI level.*

H2b: *Higher wholesale electricity-price stress is associated with a less favorable MBI–production relationship and a lower model-implied turning point.*

H3: *At the sample-mean level of MBI, the post-2022 change in the local MBI–production slope becomes more adverse as 2020–2021 baseline reliance on natural gas increases.*

2. METHOD

The empirical design uses a balanced annual panel of European countries for 2017–2023, with country-year observations and machinery manufacturing defined as NACE Rev. 2 division C28. The initial 24-country panel reflects the availability of a consistent OECD CAPMF Industry MBI series and the feasibility of matching these economies with the relevant Eurostat and IEA data. Because not all outcome and energy-use variables are available for every country, estimation samples vary by specification. The results, therefore, apply to European economies with sufficient comparable data rather than to all European countries. Regulatory pressure is measured using the OECD Climate Actions and Policies Measurement Framework, with the Industry Market-Based Instruments aggregate as the main explanatory variable (OECD, 2025). MBI is appropriate because it captures climate policy instruments operating through prices, costs, and financial incentives and exhibits sufficient cross-country and within-country variation for panel estimation.

The database combines sectoral, macroeconomic, and energy-market indicators from Eurostat and the International Energy Agency. Eurostat provides the C28 industrial production index, real gross value added, HICP inflation, real GDP growth, and sectoral energy consumption data (European Commission, n.d.b), while wholesale electricity prices are taken from the IEA Real-Time Electricity Tracker and expressed annually in EUR/MWh (IEA, n.d.). C28 energy use is measured in terajoules and disaggregated into natural gas, solid fossil fuels, oil and petroleum products, renewables and biofuels, and electricity. Because detailed energy data become substantially more complete only after 2020, pooled 2020–2021 observations are used to construct H3 baseline energy-use indicators. These measures pro-

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vide a short pre-2022 reference profile rather than a definitive long-run structural baseline, since 2020 was affected by the COVID-19 shock and 2021 had already experienced substantial energy price pressures. The post-2022 indicator therefore distinguishes the 2022–2023 period of exceptional energy-market and geopolitical stress following Russia's full-scale invasion of Ukraine, while annual electricity prices capture observed variation in energy-market stress rather than war exposure itself.

The official C28 Industrial Production Index (2021 = 100) is the principal dependent variable. Baseline IPI regressions are restricted to the 20 countries with an official Eurostat C28 series, yielding up to 140 country-year observations. Two alternative outcome measures are used for robustness.

First, real C28 gross value added is measured in chain-linked 2020 million euros and entered in logarithmic form. Second, annual real C28 GVA growth is calculated from log differences as:

$$\Delta \ln\left(RealGVA_{it}\right) = \ln\left(RealGVA_{it}\right) - \ln\left(RealGVA_{i,t-1}\right). \quad (1)$$

This transformation captures the annual percentage-like change in real sectoral output and is used as an alternative dependent variable to assess whether the results obtained for short-run industrial production also extend to broader changes in real sectoral economic performance.

The baseline H1–H2 specifications are estimated on 20 countries with complete official C28 industrial production data, yielding up to 140 country-year observations. The H3 vulnerability models also require complete 2020–2021 C28 energy consumption data to construct 2020–2021 baseline natural-gas reliance measures, thereby reducing the main H3 sample to 17 countries and 119 observations. Table A2 summarizes the estimation-sample structure and annual availability of the C28 energy variables.

2.1. Non-linear policy effect

The first hypothesis is examined using a non-linear two-way fixed-effects model. The baseline specifications use contemporaneous MBI in order to preserve the complete 2017–2023 observation window. Since climate-policy effects may materialize with a delay, otherwise equivalent specifications using one-year-lagged MBI are estimated separately as temporal robustness tests for the 2018–2023 period. MBI is mean-centered before constructing the quadratic term to reduce the mechanical multicollinearity between the linear and squared policy terms:

$$MBI_{it}^{c} = MBI_{it} - \overline{MBI}. \quad (2)$$

The baseline two-way fixed-effects specification is:

$$\ln\left(IPI_{it}\right) = \beta_1 MBI_{i,t}^{c} + \beta_2\left(MBI_{i,t}^{c}\right)^2 + \gamma' X_{it} + \alpha_i + \lambda_t + \varepsilon_{it}, \quad (3)$$

where IPI_{it} denotes the official C28 Industrial Production Index for country i in year t. X_{it} is the vector of time-varying controls, denotes country fixed effects, and λ_t denotes year fixed effects. Country fixed effects absorb time-invariant structural differences between national machinery industries, while year fixed effects account for shocks common to all countries. The one-year-lagged robustness specification replaces $MBI_{i,t}^{c}$ and $\left(MBI_{i,t}^{c}\right)^2$ with $MBI_{i,t-1}^{c}$ and $\left(MBI_{i,t-1}^{c}\right)^2$, respectively.

Evidence of an inverted-U relationship requires more than a negative and statistically significant quadratic coefficient. Accordingly, the analysis evaluates the boundary-slope conditions by calculating the marginal effect of MBI at the lower and upper bounds of its observed distribution:

$$\frac{\partial \ln IPI_{it}}{\partial MBI_{it}} = \beta_1 + 2\beta_2 MBI_{it}^{c}. \quad (4)$$

Moreover, the analysis estimates the implied turning point in the original MBI scale as:

$$MBI^{*} = \overline{MBI} - \frac{\beta_1}{2\beta_2}. \quad (5)$$

The 95% confidence interval of the turning point is also evaluated. An inverted-U interpretation is considered empirically supported only when the estimated turning point lies within the observed MBI range and the marginal slope is positive at the lower bound and negative at the upper bound, with the corresponding boundary tests providing statistical support. Where only the negative curvature and upper-bound slope are statistically established, the results are interpreted more cautiously as evidence of concavity and an upper-range adverse association rather than a fully validated inverted-U relationship.

The resulting value is interpreted as a model-implied feature of the fitted quadratic relationship rather than as a regulatory threshold or policy cutoff.

2.2. Post-2022 period, following Russia's full-scale invasion of Ukraine, energy and geopolitical shock

The second hypothesis tests whether the non-linear relationship between market-based climate-policy stringency and C28 production differed during 2022–2023 following Russia's full-scale invasion of Ukraine. The post-2022 indicator is treated as a period-comparison measure rather than as a measure of either the onset of the European energy-price disruption or the causal effect of the invasion, since energy prices had already risen substantially in 2021 and the invasion further intensified energy insecurity, supply disruption, and price pressures in 2022. Accordingly, the specification compares the MBI–production relationship in 2022–2023 with that observed in 2017–2021. Because the standalone post-2022 effect is absorbed by year fixed effects, the analysis focuses on interactions between the post-2022 indicator and country-varying policy stringency:

$$\begin{aligned}\ln\left(IPI_{it}\right) &= \beta_1 MBI^c_{i,t-1} + \beta_2\left(MBI^c_{i,t-1}\right)^2 \\ &+\beta_3\left(MBI^c_{i,t-1}\cdot Post2022_t\right) \\ &+\beta_4\left(\left(MBI^c_{i,t-1}\right)^2\cdot Post2022_t\right) \\ &+\gamma' X_{it} + \alpha_i + \lambda_t + \varepsilon_{it}.\end{aligned} \tag{6}$$

The implied pre-2022 threshold is:

$$MBI^*_{pre} = \overline{MBI} - \frac{\beta_1}{2\beta_2}, \tag{7}$$

whereas in the post-2022 period, following Russia's full-scale invasion of Ukraine, the threshold is:

$$MBI^*_{post} = \overline{MBI} - \frac{\beta_1+\beta_3}{2\left(\beta_2+\beta_4\right)} \tag{8}$$

A finding that

$$MBI^*_{post} < MBI^*_{pre} \tag{9}$$

would indicate that adverse production associations emerge at a lower level of market-based climate policy stringency following the 2022 shock.

Because energy-market stress was already developing before 2022 and varied substantially across countries and years, the binary post-2022 specification is complemented by a continuous measure based on annual wholesale electricity prices. This specification captures observed variation in energy-market stress without imposing 2022 as the onset of the energy-price disruption. It allows the regulatory threshold to vary with prevailing electricity-market conditions. Electricity prices are centered before the interaction terms are constructed. The conditional specification is:

$$\begin{aligned}\ln\left(IPI_{it}\right) &= \beta_1 MBI^c_{i,t-1} + \beta_2\left(MBI^c_{i,t-1}\right)^2 \\ &+\beta_3\left(MBI^c_{i,t-1}\cdot EP^c_{it}\right) + \beta_4\left(\left(MBI^c_{i,t-1}\right)^2\cdot EP^c_{it}\right) \\ &+\delta EP^c_{it} + \gamma' X_{it} + \alpha_i + \lambda_t + \varepsilon_{it},\end{aligned} \tag{10}$$

where EP^c_{it} denotes the centered wholesale electricity price. The corresponding policy threshold, conditional on electricity-market conditions, is:

$$MBI^{*(EP)} = \overline{MBI} - \frac{\beta_1+\beta_3 EP^c_{it}}{2\left(\beta_2+\beta_4 EP^c_{it}\right)}. \tag{11}$$

This specification allows us to determine whether the level of policy stringency at which production effects become adverse shifts under more severe energy-price conditions.

Although energy-price pressures were already evident in 2021, 2022 marked a qualitatively different energy-security regime, characterized by Russia's full-scale invasion of Ukraine, sharp reductions in Russian pipeline-gas deliveries, accelerated

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EU efforts to reduce dependence on Russian fossil fuels, and substantially greater supply-security uncertainty.

2.3. 2020–2021 baseline energy-use characteristics

The third hypothesis (H3) proposes that, at the sample-mean level of MBI, the post-2022 change in the local MBI–production slope becomes more adverse as 2020–2021 baseline natural-gas reliance increases. Annual energy-use observations after 2022 are not used to construct the moderator because they may already reflect firms' responses to changing energy-market conditions. Instead, country-specific baseline measures are constructed from pooled 2020–2021 observations. Pooling the two years reduces reliance on a single annual observation; however, the measures should not be interpreted as unambiguous long-run structural characteristics, since 2020 was affected by the COVID-19 shock and 2021 already reflected substantial energy price pressures. They are therefore treated as short pre-2022 baseline indicators.

2020–2021 baseline C28 energy intensity is defined as:

$$PreEnergyIntensity_i = \frac{TotalEnergy_{i,2020} + TotalEnergy_{i,2021}}{RealGVA_{i,2020} + RealGVA_{i,2021}}. \quad (12)$$

Moreover, it is expressed in terajoules per million euros of real C28 gross value added. Next, 2020–2021 baseline natural-gas reliance is calculated as:

$$PreGasShare_i = \frac{Gas_{i,2020} + Gas_{i,2021}}{TotalEnergy_{i,2020} + TotalEnergy_{i,2021}}. \quad (13)$$

A broader fossil-fuel exposure measure is constructed as:

$$PreFossilShare_i = \frac{Solid_{i,2020} + Solid_{i,2021} + Gas_{i,2020} + Gas_{i,2021} + Oil_{i,2020} + Oil_{i,2021}}{TotalEnergy_{i,2020} + TotalEnergy_{i,2021}}. \quad (14)$$

The share of natural gas in C28 final energy consumption is used as the principal baseline for energy use. It captures the relative importance of natural gas in the sector's 2020–2021 energy mix but does not identify the geographic origin of gas supplies or direct exposure to Russian gas imports. It is therefore interpreted as a baseline energy-use characteristic rather than as a source-specific geopolitical vulnerability measure. Energy intensity and the broader 2020–2021 baseline share of fossil fuels are used as alternative measures of vulnerability.

The moderation mechanism is evaluated through a triple-interaction specification:

$$\begin{aligned}\ln\left(IPI_{it}\right) &= \beta_1 MBI^c_{i,t-1} + \beta_2\left(MBI^c_{i,t-1}\right)^2 \\ &+\theta_1\left(MBI^c_{i,t-1}\cdot Post2022_t\right) \\ &+\theta_2\left(PreGasShare^c_i\cdot Post2022_t\right) \\ &+\theta_3\left(MBI^c_{i,t-1}\cdot PreGasShare^c_i\right) \\ &+\theta_4\left(MBI^c_{i,t-1}\cdot PreGasShare^c_i\cdot Post2022_t\right) \\ &+\gamma' X_{it} + \alpha_i + \lambda_t + \varepsilon_{it},\end{aligned} \quad (15)$$

where

$$PreGasShare^c_i = PreGasShare_i - \overline{PreGasShare}. \quad (16)$$

The H3 specification retains the quadratic MBI term to account for the underlying concavity identified in H1, but does not interact the quadratic component with the baseline energy-use moderator. Accordingly, H3 is interpreted as a test of the moderation of the local MBI slope rather than of the full non-linear MBI–production relationship. Conditional marginal effects are therefore evaluated at the sample-mean level of MBI (MBIc = 0). The specification does not test whether baseline energy-use characteristics alter the curvature of the relationship or generate moderator-specific turning points.

The principal coefficient of interest is the MBI×2020–2021 baseline natural-gas reliance × post-2022 interaction. A negative coefficient would indicate that, around the sample-mean level of MBI, the post-2022 local MBI–production slope becomes more adverse as 2020–2021 baseline natural-gas reliance increases.

2.4. Controls, robustness, and statistical inference

The empirical models are intentionally parsimonious to avoid controlling for variables that may themselves lie on the pathway between climate policy and industrial output. Real GDP growth is used as the main indicator of the macroeconomic cycle, while HICP inflation enters only in extended specifications. Sectoral turnover, employment, labor productivity, the number of enterprises, and value added at factor cost are excluded because they may respond to climate-policy changes. Wholesale electricity prices are likewise not treated as a standard H1 control. However, they are reserved for H2, where they capture observed energy-market stress and test whether the MBI–production relationship varies across price conditions.

All specifications include country and year fixed effects, with country-clustered standard errors used as the principal inference procedure. Given the limited number of country clusters, the main non-linear and interaction coefficients are also assessed using wild-cluster bootstrap inference. H3 is further examined through leave-one-country-out influence diagnostics and an alternative real-GVA specification with wild-cluster bootstrap inference. Driscoll–Kraay standard errors are used only as an auxiliary robustness check because of the short time dimension of the panel. The estimates are therefore interpreted as conditional associations rather than fully identified causal effects, since fixed effects cannot eliminate all risks of reverse causality, time-varying omitted factors, or endogenous policy responses.

Additional descriptive diagnostics, country-level baseline energy-use measures, alternative outcome specifications, leave-one-country-out influence diagnostics, and alternative H3 moderator models (Tables S1–S13) are reported in the Online Supplementary Material deposited on Zenodo (Kuzior et al., 2026).

3. RESULTS

3.1. Descriptive statistics and preliminary patterns

Table A1 summarizes the core variables used in the empirical analysis. The official C28 industrial production sample contains 140 country-year observations from 20 countries, with a mean index value of 99.3, a standard deviation of 11.0, and a range of 51.9–139.0. The OECD market-based policy stringency measure is available for all 24 countries and ranges from 1.83 to 7.25, while in the 20-country H1 sample, it ranges from 2.70 to 7.25. This variation supports testing for non-linearity rather than imposing a purely linear relationship. Real C28 GVA also varies substantially across countries, reinforcing the use of country fixed effects to focus on within-country changes rather than differences in sector size.

The annual patterns reported in Table S1 (Kuzior et al., 2026) show that energy-market stress was already increasing before Russia's full-scale invasion of Ukraine and intensified sharply in 2022. Average wholesale electricity prices rose from EUR 33.7/MWh in 2020 to EUR 103/MWh in 2021 and EUR 228/MWh in 2022, before falling to EUR 95.3/MWh in 2023. Inflation similarly increased from 2.98% in 2021 to 11.1% in 2022, while GDP growth slowed from 6.52% to 3.48%. By contrast, mean MBI declined from 5.30 in 2021 to 5.04 in 2022 and 4.86 in 2023. This supports interpreting post-2022 as a period-comparison indicator, while electricity prices provide a continuous measure of energy-market stress. Table S2 (Kuzior et al., 2026) further confirms sufficient within-country MBI variation for two-way fixed-effects estimation.

The correlations in Table S3 (Kuzior et al., 2026) are descriptive rather than causal. The unconditional association between MBI and C28 production is weak ($r = 0.103$), consistent with a non-linear relationship. Electricity prices, inflation, and government bond yields show stronger contemporaneous correlations, including 0.760 between electricity prices and inflation and 0.558 between inflation and bond yields. These patterns support a parsimonious baseline specification and treating electricity prices as an H2 energy-market stress moderator rather than an additional H1 control.

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3.2. H1: Non-linear effect of market-based climate-policy stringency

Table 1 reports two-way fixed-effects estimates that link market-based climate policy stringency to C28 manufacturing output. The linear specification in Model (1) produces a small, negative, and insignificant centered MBI coefficient (β = −0.016, SE = 0.033), providing no evidence of a simple monotonic relationship. Once curvature is introduced, the squared MBI term becomes negative and significant (Model 2: β = −0.019, SE = 0.008). This result remains virtually unchanged after adding real GDP growth (Model 3: β = −0.019, SE = 0.008) and inflation (Model 4: β = −0.020, SE = 0.008), while neither control is individually significant. The estimated concavity is therefore not explained by contemporaneous GDP growth or inflation.

Model fit also improves when the quadratic term is introduced: within-R^2 rises from 0.006 to about 0.047 and overall R^2 from 0.504 to 0.525, reaching 0.063 and 0.532, respectively, in the most extensive specification. However, a negative quadratic coefficient alone does not establish the inverted-U relationship proposed in H1. Because the centered linear term is slightly negative, the implied maximum lies below the sample mean. The analysis therefore estimates the model-implied turning point, its confidence interval, and the marginal slopes at the lower and upper bounds of the observed MBI range. H1 is supported only if the turning point lies within the data range and the slope is positive at low MBI and negative at high MBI.

As reported in Table 2, the shape diagnostics support concavity more clearly than a fully established inverted-U relationship. In the preferred Model 3, the model-implied turning point is approximately MBI = 4.7 (exact estimate 4.694; 95% CI: 2.819–6.569), within the observed H1 range of 2.70–7.25. However, the wide confidence interval indicates considerable uncertainty around its precise location, so it should be interpreted as a feature of the fitted contemporaneous relationship rather than as a regulatory threshold.

The boundary tests provide only partial support for H1. At MBI = 7.25, the marginal effect is negative and highly significant ($t = -4.122$, one-sided $p < 0.001$), indicating a less favorable production association at high policy stringency. At MBI = 2.70, the marginal effect is positive but insignificant ($t = 1.215$, one-sided $p = 0.120$). Thus, the two boundary conditions required for a conventional inverted-U are not jointly satisfied. The results therefore indicate statistically supported concavity, a model-implied turning point of about 4.7, and a significant adverse association at high MBI levels, but do not establish that greater policy stringency significantly increases C28 production at the lower end of the observed range.

Table 1. Market-based climate-policy stringency and C28 industrial production

Variables	(1) Linear	(2) Quadratic	(3) Quadratic + GDP	(4) Extended
MBI, centered	−0.016 (0.033)	−0.014 (0.030)	−0.014 (0.030)	−0.015 (0.031)
MBI^2, centered		−0.019* (0.008)	−0.019* (0.008)	−0.020* (0.008)
Real GDP growth			−0.0003 (0.004)	0.002 (0.003)
HICP inflation				0.007 (0.005)
Country fixed effects	Yes	Yes	Yes	Yes
Year fixed effects	Yes	Yes	Yes	Yes
Observations	140	140	140	140
Countries	20	20	20	20
R^2	0.504	0.525	0.525	0.532
Within R^2	0.006	0.047	0.047	0.063

Note: The dependent variable is the natural logarithm of the official C28 Industrial Production Index. MBI denotes the OECD Industry Market-Based Instruments index and is mean-centered before constructing the quadratic term. Standard errors clustered at the country level are reported in parentheses. All specifications include country and year fixed effects. Model (3) is the preferred parsimonious specification for H1. * $p < 0.05$.

Table 2. Turning point and boundary-slope tests of the inverted-U conditions for the relationship between industry MBI and C28 industrial production

Test	Estimate	SE / 95% CI	p-value	Interpretation
Model-implied turning point	4.7	[2.819; 6.569]	–	Within observed range; wide 95% CI
Lower-bound slope, MBI = 2.70	0.0768	0.0632	0.120	Positive, not significant
Upper-bound slope, MBI = 7.25	–0.0984	0.0239	<0.001	Negative and significant

Note: The turning point is a model-implied feature of the fitted quadratic specification and should not be interpreted as a regulatory threshold or universal policy cutoff.

The H1 evidence supports a concave response pattern rather than a fully confirmed inverted-U. Market-based climate-policy stringency is non-linearly associated with C28 industrial production, with a model-implied turning point of approximately 4.7. The marginal effect is significantly negative at the upper end of the MBI range, whereas the positive lower-bound effect is not statistically significant. H1 therefore receives only partial support: the data identify significant curvature and an adverse upper-range association, but not all conditions required for a conventional inverted-U.

Wild-cluster bootstrap inference confirms the robustness of the quadratic term. Using 9,999 Rademacher replications clustered by country, the squared MBI coefficient remains negative and significant (β = −0.019, p = 0.047; 95% CI [−0.034, −0.001]), while the centered linear effect remains insignificant (β = −0.014, p = 0.784; 95% CI [−0.093, 0.032]). Thus, the result is not dependent on conventional clustered asymptotics despite the limited number of country clusters (G = 20). However, the one-year-lagged specification reported in Table S4 (Kuzior et al., 2026) does not reproduce the non-linear pattern: both linear and quadratic MBI terms are negligible and insignificant. The identified curvature should therefore be interpreted as a contemporaneous rather than a persistent delayed association.

The alternative-outcome models reported in Tables S5–S6 (Kuzior et al., 2026) likewise do not reproduce the non-linearity. For both real C28 GVA levels and annual GVA growth, the linear and quadratic MBI terms remain statistically insignificant; only real GDP growth is positively associated with GVA growth in the controlled specification (β = 0.509, p < 0.05). Because country coverage differs across outcomes, these contrasts cannot be attributed solely to the dependent variable. Overall, the H1 evidence is therefore specific primarily to short-run C28 industrial production and should not be generalized to broader measures of machinery-sector economic performance.

3.3. H2: Post-2022 period, following Russia's full-scale invasion of Ukraine, change in the MBI–production relationship

The post-2022 specification in Table 3 tests whether the MBI–C28 production relationship differed between 2017–2021 and 2022–2023 following Russia's full-scale invasion of Ukraine. It is interpreted as a period comparison rather than a causal pre- and post-shock design. For 2017–2021, the squared MBI coefficient remains strongly negative across specifications (–0.026 to −0.028, p<0.001), indicating pronounced concavity. However, neither the post-2022 interaction with the linear MBI term nor that with the quadratic term is statistically significant. In the preferred GDP-adjusted model, the interaction coefficients are 0.011 (SE = 0.035) and 0.018 (SE = 0.017), respectively. Thus, the evidence does not show that either the slope or curvature changed during 2022–2023.

Accordingly, H2a is not statistically supported in the available sample. The post-2022 interactions are jointly insignificant (F = 0.611, p = 0.553). Although the model-implied turning point declines descriptively from approximately 4.56 in 2017–2021 to 4.12 in 2022–2023, this 0.44-point difference is not evidence of a statistically established change. H2b therefore complements the period comparison by using annual wholesale electricity prices as a continuous measure of energy-market stress across countries and years.

Additional robustness checks reinforce the conclusion that the binary post-2022 specification does not identify a statistically significant struc-

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Table 3. Post-2022 period, following Russia's full-scale invasion of Ukraine, changes in the non-linear relationship between industry MBI and C28 industrial production

Variables	(1) Post-2022 interaction	(2) + GDP growth	(3) + GDP growth & inflation
MBI, centered	−0.026 (0.041)	−0.026 (0.041)	−0.028 (0.042)
MBI², centered	−0.026*** (0.005)	−0.026*** (0.005)	−0.028*** (0.005)
MBI × post-2022	0.011 (0.035)	0.011 (0.035)	0.020 (0.035)
MBI² × post-2022	0.018 (0.017)	0.018 (0.017)	0.012 (0.015)
Real GDP growth		−0.0006 (0.003)	0.001 (0.003)
HICP inflation			0.008 (0.005)
Country fixed effects	Yes	Yes	Yes
Year fixed effects	Yes	Yes	Yes
Observations	140	140	140
Countries	20	20	20
R^2	0.538	0.538	0.545
Within R^2	0.074	0.074	0.088
Model-implied turning point, 2017–2021		4.56	
Model-implied turning point, 2022–2023		4.12	
Descriptive turning-point difference		−0.44	
Joint Wald test of post-2022 interactions		(F=0.611;p=0.553)	

Note: The dependent variable is the natural logarithm of the official C28 Industrial Production Index. MBI is mean-centered before constructing the quadratic and interaction terms. Post-2022 equals one for 2022–2023 and zero otherwise; its stand-alone effect is absorbed by year fixed effects. Standard errors clustered at the country level are reported in parentheses. Turning-point estimates and the Wald test are based on Model (2), the preferred parsimonious specification. *** p < 0.001.

tural change in the MBI–C28 production relationship. The wild-cluster bootstrap indicates that neither the post-2022 linear interaction (β = 0.011, bootstrap p = 0.834; 95% CI [−0.074, 0.112]) nor the quadratic interaction (β = 0.018, bootstrap p = 0.290; 95% CI [−0.017, 0.080]) differs significantly from zero, while the joint country-clustered Wald test likewise fails to reject the null of no post-2022 change (p = 0.553). Consistent with these results, the combined post-2022 coefficients are also statistically insignificant: the post-2022 linear component equals −0.015 (SE = 0.024, t = −0.638, p = 0.531), whereas the corresponding quadratic component is −0.008 (SE = 0.016, t = −0.503, p = 0.621). Thus, although the estimated threshold declines numerically from 4.56 before 2022 to 4.12 in 2022–2023, this shift is not accompanied by statistically significant changes in either the slope or curvature of the relationship. The turning-point difference should therefore be interpreted as descriptive rather than as evidence of a statistically established post-2022 structural change.

3.4. H2b: Electricity-price stress as a continuous moderator

To complement the binary period comparison, Table 4 uses annual wholesale electricity prices as a continuous measure of energy-market stress. The quadratic MBI coefficient remains negative and significant across specifications (–0.018 to −0.020, p < 0.01), confirming that the contemporaneous concavity identified in H1 persists after accounting for electricity-market conditions. However, the direct effect of electricity prices and its interactions with both the linear and quadratic MBI terms are not statistically significant. Most importantly, the two interaction terms are jointly insignificant (F = 2.193, p = 0.139), providing no statistically detectable evidence that electricity-market stress systematically alters the slope or curvature of the MBI–production relationship.

The fitted turning point varies descriptively from approximately 4.72 at the 25th percentile of electricity prices (EUR 39.99/MWh), to 4.69 at the median (EUR 53.95/MWh), and 4.50 at the 75th percentile (EUR 103.14/MWh). Because the interaction terms are not statistically significant, these differences should be interpreted only as descriptive conditional variation. H2b is therefore not statistically supported in the available sample.

3.5. H3: 2020–2021 baseline energy-use characteristics and post-2022 period, following Russia's full-scale invasion of Ukraine, heterogeneity

The 2020–2021 baseline natural-gas reliance measure varies substantially across countries, from 1.9% in Finland and 2.1% in Sweden to 45.6% in Romania and 53.9% in Belgium (Table S7 (Kuzior et al., 2026)). Within the 17-country H3 sample, the mean is 26.8%, the median is 30.3%, and the standard deviation is 15.4 percentage points, providing sufficient cross-sectional variation for moderation analysis. However, the measure should be interpreted as a short baseline indicator rather than a pure long-run measure of structural vulnerability.

Table 5 does not support H3. Before 2022, the interaction between MBI and baseline natural-gas reliance was negative and marginally significant ($\beta = -0.214$, $p < 0.10$). In contrast, the triple interaction MBI×PreGasShare×Post2022 is positive and marginally significant ($\beta = 0.242$ in the preferred model, $p < 0.10$). The combined post-2022 moderation is therefore approximately 0.028, indicating that the earlier negative moderation is largely offset rather than intensified. The direct gas-reliance × post-2022 effect is insignificant, and the quadratic MBI term is weak in the reduced H3 sample.

Table 4. Electricity-price stress and the non-linear relationship between industry MBI and C28 industrial production

Variables	(1) Electricity-price interaction	(2) + GDP growth	(3) + GDP growth & inflation
MBI, centered	−0.018 (0.031)	−0.017 (0.031)	−0.017 (0.032)
MBI², centered	−0.018** (0.006)	−0.018** (0.006)	−0.020** (0.006)
Electricity price, centered	−0.00006 (0.0003)	−0.00007 (0.0003)	−0.0001 (0.0002)
MBI × electricity price	0.00009 (0.0002)	0.00009 (0.0002)	0.0001 (0.0002)
MBI² × electricity price	0.0003 (0.0002)	0.0003 (0.0002)	0.0002 (0.0002)
Real GDP growth		0.001 (0.003)	0.002 (0.003)
HICP inflation			0.005 (0.005)
Country fixed effects	Yes	Yes	Yes
Year fixed effects	Yes	Yes	Yes
Observations	140	140	140
Countries	20	20	20
(R^2)	0.565	0.565	0.568
Within (R^2)	0.127	0.128	0.133
Joint Wald test of MBI × EP interactions		(F=2.193; p=0.139)	

Panel B. Model-implied MBI turning points conditional on wholesale electricity prices, Model (2)

Electricity-price condition	Price, EUR/MWh	Model-implied MBI turning point
25th percentile	39.99	4.72
Median	53.95	4.69
75th percentile	103.14	4.50

Note: The dependent variable is the natural logarithm of the official C28 Industrial Production Index. MBI and wholesale electricity prices are mean-centered before constructing quadratic and interaction terms. Standard errors clustered at the country level are reported in parentheses. All specifications include country and year fixed effects. Turning points in Panel B are calculated from Model (2). Because the interaction terms are not jointly significant, these conditional turning points are interpreted descriptively rather than as statistically established differences. ** p < 0.01.

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Table 5. 2020–2021 baseline natural-gas reliance and post-2022 heterogeneity in the relationship between market-based policy stringency and C28 industrial production

Variables	(1) Natural gas reliance	(2) + GDP growth	(3) + GDP growth & inflation
MBI, centered	0.029 (0.020)	0.027 (0.020)	0.026 (0.018)
MBI², centered	−0.011 (0.010)	−0.012 (0.010)	−0.016† (0.009)
MBI × post-2022	−0.032 (0.024)	−0.030 (0.024)	−0.021 (0.023)
2020–2021 baseline gas share × post-2022	0.024 (0.118)	0.019 (0.118)	−0.037 (0.119)
MBI × 2020–2021 baseline gas share	−0.215† (0.118)	−0.214† (0.118)	−0.182 (0.107)
MBI × 2020–2021 baseline gas share × post-2022	0.240† (0.121)	0.242† (0.120)	0.197† (0.111)
Real GDP growth		−0.002 (0.004)	0.0002 (0.003)
HICP inflation			0.008† (0.004)
Country fixed effects	Yes	Yes	Yes
Year fixed effects	Yes	Yes	Yes
Observations	119	119	119
Countries	17	17	17
(R^2)	0.747	0.748	0.764
Within (R^2)	0.271	0.275	0.321

Note: The dependent variable is the natural logarithm of the official C28 Industrial Production Index. MBI and 2020–2021 baseline natural-gas reliance are mean-centered before constructing interaction terms. Post-2022 equals one in 2022–2023 and zero otherwise; its standalone effect is absorbed by year fixed effects, while country fixed effects absorb the standalone baseline gas-share effect. Standard errors clustered at the country level are reported in parentheses. † $p < 0.1$.

Thus, around the sample-mean level of MBI, there is no statistically conclusive evidence that greater baseline natural-gas reliance makes the post-2022 local MBI–production slope more adverse; if anything, the point estimate runs in the opposite direction, although the 17-country sample and marginal significance require cautious interpretation.

The conditional marginal-effects analysis in Table B1 further clarifies H3. These are local effects evaluated at the sample-mean level of MBI and should not be interpreted as tests of changes in curvature or the turning point. Before 2022, MBI is positively associated with C28 production only at low baseline natural-gas reliance: at the 25th percentile (16.8%), the marginal effect is 0.0485 (p = 0.029; 95% CI [0.0055, 0.0915]), whereas effects at the median (30.3%) and 75th percentile (36.0%) are insignificant. In 2022–2023, marginal effects are close to zero and insignificant at all three levels. The post-2022 change is numerically most negative at low gas reliance (−0.0545, p = 0.075) and becomes smaller at the median (−0.0219, p = 0.356) and upper quartile (−0.0082, p = 0.737), contrary to the amplification predicted by H3.

Wild-cluster bootstrap inference confirms the positive direction of the triple interaction, but not conventional 5% significance. The coefficient on MBI × baseline natural-gas reliance × post-2022 is 0.242 (p = 0.057; 95% CI [−0.007, 0.708]). Thus, around the sample-mean level of MBI, there is no statistically conclusive evidence that greater baseline natural-gas reliance makes the post-2022 local MBI–production slope more adverse. If anything, the point estimates indicate weaker rather than stronger adverse moderation as gas reliance increases, although statistical precision is limited.

Alternative 2020–2021 energy-use moderators do not reproduce the natural-gas pattern. The MBI × energy intensity × post-2022 interaction is insignificant in the preferred model (β = 0.008, SE = 0.029), as is the corresponding fossil-fuel interaction (β = 0.094, SE = 0.189). Country-level values of the alternative baseline energy-use measures are reported in Tables S8–S9, while the corresponding moderation specifications are reported in Tables S12–S13 in the Online Supplementary Material (Kuzior et al., 2026).

The real-GVA specification (Table S10) provides directionally consistent but statistically inconclusive complementary evidence. The triple interaction remains positive under conventional clustered inference (β = 0.440, SE = 0.198, $p < 0.05$), but wild-cluster bootstrap inference yields $p = 0.071$ and a 95% CI of [−0.045, 1.013]. The point estimate again runs opposite to H3, suggesting attenuation rather than amplification as baseline natural-gas reliance increases. However, the result is not statistically conclusive, and the broader GVA country coverage means that differences from the IPI specification may reflect both the alternative outcome and sample composition.

The leave-one-country-out analysis (Table S11) is treated strictly as an influence diagnostic. Across all 17 re-estimations, the triple-interaction coefficient remains positive, ranging from 0.182 to 0.470, with a median of 0.243; excluding Belgium yields β = 0.230. Because these samples overlap extensively, their p-values are not independent robustness replications. Together with the bootstrap and alternative-moderator results, the H3 evidence is therefore best characterized as directionally stable but statistically inconclusive and opposite to the hypothesized direction.

H1 receives partial support, while H2 and H3 are not statistically supported in the available sample. H1 is characterized by significant contemporaneous concavity and a negative upper-range association. However, the positive lower-bound slope is insignificant, and the pattern is not reproduced with lagged MBI or broader GVA outcomes. Neither the post-2022 nor the electricity-price interactions provide statistically detectable evidence that energy-market conditions amplified the MBI–production relationship. H3 likewise provides no statistically conclusive evidence that greater reliance on natural gas in 2020–2021 makes the post-2022 local MBI–production slope more adverse.

4. DISCUSSION

The first set of findings supports contemporaneous concavity in the relationship between market-based climate-policy stringency and the official C28 Industrial Production Index, rather than a general non-linear relationship with machinery-sector performance. The quadratic MBI coefficient is negative and significant (β = −0.019, bootstrap $p = 0.047$), with a model-implied turning point of about 4.7, although its wide 95% CI (2.819–6.569) precludes interpreting this value as a precise threshold. The upper-bound marginal effect is strongly negative (−0.0984, $p < 0.001$), whereas the positive lower-bound effect is insignificant (0.0768, $p = 0.120$). This pattern is consistent with arguments that environmental regulation may initially encourage efficiency, innovation, and technological upgrading, while higher compliance and transition costs can eventually offset these gains (Jänicke et al., 2000; Faiella & Mistretta, 2022; Belazreg et al., 2026). It also accords with evidence that market-based regulation can generate both efficiency benefits and competitiveness costs (Pal et al., 2024) and that regulatory effects differ across firms and performance conditions (Wang et al., 2020; Pham et al., 2026). However, the pattern is not reproduced with lagged MBI or broader GVA outcomes, suggesting a short-run production association rather than a general long-run effect (Bassi et al., 2009; Antimiani et al., 2016). Given that the H1 bootstrap result is close to the 5% threshold and H3 is also marginal, interpretation emphasizes effect direction, confidence intervals, and cross-specification consistency rather than isolated p-values.

The post-2022 results should be interpreted as evidence on the 2022–2023 energy market and geopolitical environment rather than as estimates of the causal effect of Russia's full-scale invasion of Ukraine. Previous studies show that energy-price shocks can weaken productivity, affect employment and investment, and contribute to inflation and macroeconomic instability (André et al., 2025; Bretschger & Jo, 2024; Vasylieva et al., 2025), while manufacturing responses also depend on renewable-energy development, financial conditions and climate-policy uncertainty (Shahbaz et al., 2024; Simionescu & Radulescu, 2025). In this study, however, neither the post-2022 interactions ($F = 0.611$, $p = 0.553$) nor the electricity-price interactions ($F = 2.193$, $p = 0.139$) are jointly significant. The model-implied turning point declines descriptively from about 4.56 to 4.12 between 2017–2021 and 2022–2023 and from about 4.72 to 4.50 between the 25th and 75th percentiles of electricity prices. However, these movements do

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not constitute statistical evidence of moderation. H2 is therefore not statistically supported in the available sample, complementing earlier research on the 2022 energy crisis and geopolitical disruption (Koilo, 2023; Vasylieva et al., 2026a; Vasylieva et al., 2026b).

The H3 results likewise do not support the expectation that greater reliance on natural gas in 2020–2021 makes the post-2022 local MBI–production slope more adverse. This differs from literature suggesting greater sensitivity among more energy-exposed firms to carbon costs, energy prices, and regulatory pressure (Locmelis & Blumberga, 2019; Sahu et al., 2022; Islam, 2026) and from research linking fossil-fuel dependence and geopolitical risk to investment and resilience (Hakmi et al., 2026; Zozulinskyy & Bilan, 2026). The natural-gas triple interaction is positive (β = 0.242) but statistically inconclusive under wild-cluster bootstrap inference (p = 0.057; 95% CI [–0.007, 0.708]); the real-GVA interaction is similarly positive but inconclusive (β = 0.440, p = 0.071; 95% CI [–0.045, 1.013]), while alternative energy-intensity and fossil-fuel moderators do not reproduce the pattern. The evidence is therefore directionally stable but statistically inconclusive and opposite to H3. One possible explanation is that more gas-reliant industries faced stronger incentives for fuel substitution, efficiency improvements, and supply diversification (Cantore et al., 2016; Leuratti et al., 2024; Rashid et al., 2026), although this mechanism is not identified directly. The result should not be generalized to broader energy vulnerability, and the 2020–2021 baseline itself should not be treated as a pure long-run structural measure.

CONCLUSION

This study examines how market-based climate-policy stringency is associated with European machinery manufacturing, focusing on whether the relationship is non-linear, whether it differs under post-2022 energy-market conditions, and whether 2020–2021 baseline energy-use characteristics modify it. The broader question is whether stronger market-based climate regulation can coexist with industrial competitiveness or whether adverse production associations emerge at higher levels of policy and energy pressure. Regulatory stringency is therefore analyzed jointly with prevailing energy market conditions and sectoral energy use characteristics.

The empirical analysis uses a 2017–2023 panel of 24 European economies, while the principal C28 Industrial Production Index models cover 20 countries and 140 observations. Climate-policy stringency is measured by the OECD CAPMF Industry Market-Based Instruments index and combined with Eurostat and IEA data on production, real GVA, macroeconomic conditions, electricity prices, and sectoral energy use. Estimation relies on non-linear two-way fixed-effects models, post-2022 and electricity-price interactions, and H3 moderation models based on natural-gas reliance and alternative energy-use indicators. Robustness is assessed using clustered and wild-cluster bootstrap inference, alternative outcomes, lagged MBI specifications, and leave-one-country-out influence diagnostics.

The evidence provides partial, outcome-specific support for H1. The preferred C28 industrial-production model shows significant contemporaneous concavity (quadratic MBI = –0.019; bootstrap p = 0.047) and a negative upper-bound effect (–0.0984, p < 0.001), whereas the lower-bound effect is insignificant and the pattern is not reproduced for lagged MBI or GVA outcomes. H1 therefore applies primarily to short-run C28 industrial production rather than to broader machinery-sector performance. H2 is not statistically supported in the available sample: neither the post-2022 interactions (F = 0.611, p = 0.553) nor the electricity-price interactions (F = 2.193, p = 0.139) are jointly significant, and the lower model-implied turning points remain descriptive only. H3 is also unsupported. The natural-gas triple interaction is positive but statistically inconclusive (β = 0.242, bootstrap p = 0.057), while alternative energy-use moderators are insignificant. The leave-one-country-out analysis indicates sign stability only as an influence diagnostic. The H3 estimates run opposite to the hypothesized amplification mechanism but do not establish significant attenuation.

From a policy perspective, the findings caution against assuming a uniform relationship between market-based climate-policy stringency and short-run industrial production. The concavity identified for the C28 Industrial Production Index and the negative marginal association at high MBI values suggest that comparatively high policy stringency may coincide with less favorable short-run production outcomes. However, the model-implied turning point should be viewed only as a feature of the fitted relationship, not as a universal regulatory target or policy cutoff. The analysis also finds no statistically detectable evidence that the MBI–production association became systematically more adverse during 2022–2023, despite the exceptional energy-market and geopolitical conditions following Russia's full-scale invasion of Ukraine.

These results support caution against one-size-fits-all interpretations of climate-policy stringency. Broader policy responses may therefore need to consider affordable low-carbon energy, energy-efficiency investment, technological renewal, and differences in sectoral adaptive capacity. However, these mechanisms are not tested directly in the present models. The H3 findings further indicate that baseline natural-gas reliance alone does not adequately capture post-2022 adjustment, highlighting the importance of technological readiness, energy-sourcing flexibility, and broader adaptive capacity when assessing industrial energy vulnerability.

The findings should be interpreted with several limitations in mind. First, the 2017–2023 panel contains only two post-2022 years, limiting inference about persistent structural change, while the main H3 sample is restricted to 17 countries and 119 observations. Second, despite country and year fixed effects, macroeconomic controls, and few-cluster robustness procedures, the estimates remain conditional associations and may still reflect reverse causality, omitted time-varying factors, or endogenous policy responses. The post-2022 specification should therefore be interpreted as a period comparison rather than a causal pre-/post-shock design and does not isolate the effect of Russia's full-scale invasion of Ukraine. The 2020–2021 baseline energy measures also warrant caution, as 2020 was affected by COVID-19 and 2021 already experienced substantial energy price pressures. They may therefore reflect persistent sectoral characteristics alongside crisis-specific conditions rather than pure long-run vulnerability. Moreover, the aggregate MBI measure obscures differences across individual policy instruments. In contrast, the natural-gas moderator captures sectoral gas reliance rather than direct exposure to Russian gas, import routes, storage, or substitution capacity. H3 further tests moderation only of the local MBI slope at the sample mean and does not identify changes in curvature or turning points. The broader GVA samples also differ from the corresponding IPI samples, so these specifications provide complementary, rather than strictly common-sample, robustness evidence. Finally, results close to conventional significance thresholds should be interpreted cautiously, given the number of related specifications and interaction tests. Future research should extend the post-2022 horizon, use more disaggregated, firm-level data, distinguish among individual policy instruments, apply stronger causal designs, and combine sectoral energy-use indicators with measures of Russian gas dependence, pipeline exposure, LNG access, storage capacity, and supply diversification.

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APPENDIX A. Descriptive statistics and data diagnostics

Table A1. Descriptive statistics of the principal variables

Variable	N	Mean	SD	Min	Median	Max
C28 industrial production index, 2021 = 100	140	99.30	11.00	51.90	100.00	139.00
C28 real gross value added, EUR million	168	9,985.00	21,896.00	89.50	2,957.00	112,146.00
Industry market-based instruments (MBI)	168	4.93	1.23	1.83	4.95	7.25
Wholesale electricity price, EUR/MWh	168	85.90	68.00	9.22	52.90	314.00
Real GDP growth, %	168	2.16	3.72	–10.90	2.50	12.60
HICP inflation, %	168	3.98	4.06	–1.30	2.50	19.40
Long-term government bond yield, %	168	1.66	1.70	–0.51	1.15	7.57

Note: The official C28 industrial production index is available for 20 countries; the remaining variables cover the full 24-country panel.

Table A2. Estimation-sample structure and energy-data coverage

Panel A. Estimation-sample structure			
Sample/specification	**Countries**	**Potential observations**	**Main restriction**
Full panel	24	168	2017–2023
H1–H2 official C28 IPI sample	20	140	Official C28 IPI required
H3 main specification: official IPI + 2020–2021 baseline natural-gas reliance	17	119	Official C28 IPI and complete 2020–2021 total-energy and natural-gas data
H3 robustness: official IPI + 2020–2021 baseline energy intensity	17	119	Official C28 IPI and complete 2020–2021 total-energy data
H3 robustness: official IPI + 2020–2021 baseline fossil-fuel share	16	112	Official C28 IPI and complete 2020–2021 total-energy, natural-gas, solid-fossil-fuel and oil data
H3 alternative outcome: real C28 GVA + 2020–2021 baseline natural-gas reliance	21	147	Real C28 GVA and complete 2020–2021 total-energy and natural-gas data
2020–2021 natural-gas coverage	21	–	Complete total-energy and natural-gas data in both 2020 and 2021
2020–2021 energy-intensity coverage	21	–	Complete total-energy and real C28 GVA data in both 2020 and 2021
2020–2021 fossil-fuel coverage	20	–	Complete total-energy, solid-fossil-fuel, natural-gas and oil data in both 2020 and 2021

Panel B. The annual availability of the C28 energy variables					
Year	**Countries**	**Total energy available**	**Natural gas available**	**Total energy missing**	**Natural gas missing**
2017	24	6	8	18	16
2018	24	6	8	18	16
2019	24	8	10	16	14
2020	24	21	23	3	1
2021	24	21	23	3	1
2022	24	20	24	4	0
2023	24	20	23	4	1

Panel C. Summary statistics of 2020–2021 baseline C28 energy intensity	
Statistic	**Value**
Countries with available measure	21
Mean	1.803
Standard deviation	1.771
Minimum	0.530
25th percentile	0.716
Median	1.561
75th percentile	2.148
Maximum	8.644

Note: The baseline panel covers 24 countries over 2017–2023. The main H1–H2 sample is restricted to countries with an official Eurostat C28 Industrial Production Index. H3 samples vary according to the availability of the 2020–2021 baseline energy-use moderators. Baseline measures are constructed from pooled 2020–2021 observations and are not imputed where the required energy components are unavailable. The H3 alternative-outcome specification using real C28 GVA has broader country coverage because real C28 GVA is available for countries lacking an official C28 IPI series. Baseline energy intensity equals pooled final energy consumption in NACE C28 during 2020–2021 divided by pooled real C28 GVA over the same period. Three countries lack complete total-energy observations. The H3 IPI regression sample also excludes four countries without an official C28 IPI series, resulting in 17 countries and 119 observations. Estonia's high energy-intensity value is included in the broader descriptive sample but does not enter the H3 IPI regression.

APPENDIX B. Empirical results and robustness analysis

Table B1. Conditional marginal effects of industry MBI by 2020–2021 baseline natural-gas reliance and post-2022 period

Panel A. Marginal effect of MBI on C28 industrial production

Gas-reliance level	Gas share	Period	Marginal effect	SE	t-statistic	p-value	95% CI
25th percentile	0.168	Pre-2022	0.0485	0.0203	2.392	0.029	[0.0055, 0.0915]
25th percentile	0.168	2022–2023	−0.0060	0.0238	−0.251	0.805	[−0.0565, 0.0446]
Median	0.303	Pre-2022	0.0197	0.0210	0.935	0.364	[−0.0249, 0.0643]
Median	0.303	2022–2023	−0.0023	0.0269	−0.084	0.934	[−0.0593, 0.0548]
75th percentile	0.360	Pre-2022	0.0075	0.0247	0.303	0.766	[−0.0448, 0.0597]
75th percentile	0.360	2022–2023	−0.0007	0.0313	−0.022	0.983	[−0.0670, 0.0656]

Panel B. Change in the marginal MBI effect after 2022

Gas-reliance level	Gas share	Post-2022 change	SE	t-statistic	p-value	95% CI
25th percentile	0.168	−0.0545†	0.0287	−1.901	0.075	[−0.1153, 0.0063]
Median	0.303	−0.0219	0.0231	−0.950	0.356	[−0.0708, 0.0270]
75th percentile	0.360	−0.0082	0.0238	−0.342	0.737	[−0.0587, 0.0424]

Panel C. Wild-cluster bootstrap test of the triple interaction

Term	Estimate	Bootstrap statistic	Bootstrap p-value	95% bootstrap CI
MBI × 2020–2021 baseline gas share × Post-2022	0.242†	1.847	0.057	[−0.007, 0.708]

Note: Conditional marginal effects are derived from the preferred H3 specification, including real GDP growth, country fixed effects, and year fixed effects. MBI and 2020–2021 baseline natural-gas reliance are mean-centered. Marginal effects are evaluated at the 25th, median, and 75th percentiles of the country-level 2020–2021 baseline gas-share distribution. Wild-cluster bootstrap inference uses 9,999 Rademacher replications clustered by country across 17 clusters. Because the specification contains a quadratic MBI term, the reported conditional marginal effects are evaluated at the sample-mean MBI (MBIc = 0).
† $p < 0.10$.

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