SILESIAN UNIVERSITY OF TECHNOLOGY PUBLISHING HOUSE

SCIENTIFIC PAPERS OF SILESIAN UNIVERSITY OF TECHNOLOGY 2025
ORGANIZATION AND MANAGEMENT SERIES NO. 241

SYSTEMIC FINANCIAL RISK OF THE POLISH ENERGY SECTOR UNDER MARKET, CLIMATE TRANSITION AND PHYSICAL STRESS

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Purpose: The purpose of this investigation is to develop and apply an framework that combines market, transition, and physical climate risks into a single systemic-risk measure in order to assess how these interacting shocks affect the financial vulnerability of energy sector.

Design/methodology/approach: To assess financial systemic risk, we used the extended SRISK framework and the GJR-DCC-GARCH model for four Polish systemically important energy companies. The analysis, covering the period 2009-2023, includes market, climate transition, and physical risk factors.

Findings: Investigation indicate that the market and climate-related risk is gaining prominence, especially when viewed against the backdrop of recent disruptions such as the COVID-19 pandemic and Russia's invasion of Ukraine.

Research limitations/implications: A key limitation of this study is its reliance on simplified proxies for transition and physical risks and on publicly available market data, which may not fully capture the operational complexities or evolving dynamics of the energy sector. Future research could incorporate more granular firm-level information and additional climate variables.

Practical implications: This study incorporates multiple external drivers of systemic risk, with particular emphasis on the growing influence of climate-related factors on the energy sector.

Social implications: The proposed framework enables the identification of systemic vulnerabilities—including those arising from climate change—thereby supporting policymakers in enhancing the resilience of the energy system to a wide range of potential shocks.

Originality/value: This research is the first to jointly integrate market risk, transition climate risk, and physical climate risk into a unified assessment of systemic financial risk for the energy sector.

Keywords: systemic risk, energy sector, climate transition risk, climate physical risk.

JEL Classification: Q40, Q54, G20, C53.

http://dx.doi.org/10.29119/1641-3466.2025.241.28

1. Introduction

Systemic risk refers to a situation in which a disturbance in a single company or a shock affecting part of a sector disrupts the functioning of the entire system, potentially causing widespread dysfunction. In the G-10 report published a quarter of a century ago, systemic financial risk is defined as "the risk that an event will trigger a loss of economic value or confidence in, and attendant increases in uncertainty about, a substantial portion of the system" (G-10, 2001). As this shows, awareness of systemic risk has existed for a long time. However, the last decade—shaped by ongoing globalization and the occurrence of major shock events in the global economy, such as the Covid-19 lockdowns—has brought a marked increase in interest in this area, particularly within the financial sector, where concerns were already visible after The Global Financial Crisis (subprime crisis) of 2007-2009.

Systemic financial risk can arise from several sources, including interconnectedness and contagion, common risk exposures, procyclicality and feedback loops, and macro-shocks or external stressors. While the first three factors are typical for the financial sector, the fourth also applies to the energy sector. Market stress—such as a significant decline in a broad market index—often leads to reductions in the capitalization of energy companies, and thus diminishes the economic value of their equity.

In the energy sector, external stressors also include those related to climate change, which has become one of the leading sources of systemic uncertainty, shaping both operational conditions and long-term strategic planning. Companies now face two interconnected forms of climate risk: transition risk, arising from regulatory pressure, technological shifts, and the move toward low-emission energy production; and physical risk, resulting from rising temperatures and increasing weather anomalies.

These risks no longer operate independently. Regulatory changes may amplify the effects of extreme weather, while physical disruptions can intensify the economic consequences of decarbonization policies. For energy producers—particularly those still dependent on fossil fuels—the combined impact can significantly affect market value and financial stability.

This study proposes a simplified framework that integrates market risk with climate-related transition and physical risks into a single measure (Dziwok, Szczepaniak, 2025a). The framework is adapted from the systemic risk measure SRISK, originally developed for the financial sector. The method is applied to the largest Polish energy companies, capturing how market and climate-related shocks may influence the stability of this strategically important segment of the Polish economy, and to the author's knowledge, this is the first study of its kind concerning the energy sector. The study adopts the working hypothesis that integrating market, transition, and physical climate risks provides a comprehensive framework for assessing systemic financial risk within the energy sector.

The central problem of this study is to evaluate how market, transition, and physical climate shocks jointly affect systemic financial vulnerability in the Polish energy sector. To address this, the SRISK framework is applied because it directly measures expected capital shortfall under extreme stress, making it well suited for systemic-risk analysis. However, standard SRISK considers only market risk. Therefore, to reflect the nature of the problem, we extend the methodology by incorporating climate-transition and climate-physical factors. The GJR-DCC-GARCH model is used to estimate time-varying betas and correlations between market and climate shocks, capturing the dynamic interactions that are essential to understanding systemic vulnerabilities. This methodological combination directly addresses the research aim of assessing multi-dimensional, interacting sources of systemic risk.

Using publicly available data, local proxy models for transition shocks were constructed based on a portfolio of stranded assets relevant to Poland's energy mix, while physical shocks were modeled using national temperature anomalies (Dziwok, Szczepaniak, 2025b). The objective is to provide a practical tool for assessing how market and climate risks accumulate within major Polish energy companies and how these risks jointly shape the sector's overall vulnerability.

The paper is organized as follows. Section 2 outlines the methodological framework. Section 3 describes empirical analysis of the Polish energy sector using proposed measure. Section 4 concludes the paper.

2. Methods

Research on market and climate-related risk has expanded rapidly as regulators, investors, and companies increasingly recognize that climate change can destabilize entire markets. Regulatory bodies such as the NGFS, ECB, and the Basel Committee on Banking Supervision (BCBS) have emphasized the need for climate stress testing (Basel Committee on Banking Supervision, 2022), while academic research has examined both transition and physical risks from multiple perspectives.

Most studies analyze these two forms of risk separately (Albanese et al., 2024; Bua et al., 2024; Zhou, Ma, 2025): transition risk arises from policy changes, technological innovation, and shifting demand for carbon-intensive products, whereas physical risk stems from extreme weather events and long-term environmental degradation.

However, recent work highlights the importance of integrating these perspectives, arguing that their interaction more accurately reflects real-world dynamics. Methods originally developed for financial institutions, such as SRISK (Brownlees, Engle, 2017), and CoVaR / ΔCoVaR (Adrian, Brunnermeier, 2016), have increasingly been adapted to climate-related research questions (Lu et al., 2025). This study follows that trend but applies these concepts directly to energy companies, which are central to Poland's climate-transition challenge.

The proposed approach builds on the SRISK framework, where a firm's vulnerability increases when it loses value under extreme conditions. In this context, rather than interpreting the output in terms of regulatory capital requirements, we treat it as an expected capital shortfall under combined market and climate-related stress.

Following the standard factor model approach, for the energy company i's stock return at day t:

$$r_{i,t} = \beta_{i,t}^{m} \cdot r_{i,t}^{m} + \beta_{i,t}^{tr} \cdot r_{i,t}^{tr} + \beta_{i,t}^{ph} \cdot r_{i,t}^{ph} \tag{1}$$

where:

$r_{i,t}^{m}$ denotes market return,

$r_{i,t}^{tr}$ change of the climate transition risk factor,

$r_{i,t}^{ph}$ change of the climate physical risk factor,

$\beta_{i,t}^{m}$, $\beta_{i,t}^{tr}$, $\beta_{i,t}^{ph}$ are an indicators of sensitivity respectively to market, climate transition and physical changes.

The capital shortfall $CS_{i,t}$ of the companies i at day t is defined as:

$$CS_{i,t} = \overbrace{k\left(L_{i,t} + MC_{i,t}\right)}^{\text{required capital}} - \overbrace{MC_{i,t}}^{\text{current capital}} \tag{2}$$

where:

k is a capital adequacy ratio,

$L_{i,t}$ is value of the total liabilities,

$MC_{i,t}$ is the company market capitalization. For the i -th company the SRISK measure estimates the capital shortfall may face in the event of a shock over a specified time horizon h:

$$SRISK_{i,t} = \mathbb{E}\left[CS_{i,t+h} \middle| systemic\ event\right] \tag{3}$$

where $h = 6$ months. Finally:

$$SRISK_{i,t} = kL_{i,t} - (1-k)MC_{i,t} \exp\left(\beta_{i,t}^{m} \log(1-\theta^{m})\right) \tag{4}$$

where θ^{m} describe a level of market shock (Brownlees, Engle, 2017). For the system s:

$$SRISK_{s,t} = \sum_{i=1}^{N} SRISK_{i,t} \tag{5}$$

Extending this idea and following (Dziwok, Szczepaniak, 2025a, 2025b), the article proposes a measure of the systemic risk of energy companies $M|TrC|PhC|SRISK_{i,t}$:

$$M|TrC|PhC|SRISK_{i,t} = \\ kL_{i,t} - (1-k)MC_{i,t} \exp\left(\beta_{i,t}^{m} \log(1-\theta^{m}) + \beta_{i,t}^{tr} \log(1-\theta^{tr}) + \beta_{i,t}^{ph} \log(1-\theta^{ph})\right) \tag{6}$$

where:
k is for the energy companies equity-to-asset ratio equal to 0.45,
θ^{tr} is a level of climate transition shock (measured through returns of a tailored stranded-asset portfolio, based on WIG-Mining and WIG-Fuels relative to the broad WIG index),
θ^{ph} is a level of climate physical shock (represented by deviations of Poland's 12-month rolling temperature from its 30-year climatological norm).

Time-varying betas are estimated using a multivariate GJR-DCC-GARCH approach (Glosten et al.,1993; Engle, 2002), allowing for changing correlations between market conditions and climate factors - an important feature, given that extreme events tend to occur jointly (Dziwok, Szczepaniak, 2025a; Jung et al., 2025), see Appendix.

3. Results

The empirical analysis focuses on the four largest Polish publicly listed energy companies: PGE, ENEA, ENERGA, and TAURON, see Appendix. The sample period spans 2009-2023, covering multiple regulatory cycles, episodes of macro-financial turbulence, and shifts in the European climate-policy landscape. This long horizon ensures that the estimated sensitivities capture both structural changes within the sector and shorter-term fluctuations in market conditions.

Market data for all listed companies and benchmark indices are obtained from LSEG, ensuring consistency in pricing, return construction, and data frequency. These data form the basis for estimating systematic exposures under financial and climate-related stress. Complementing the financial data, temperature records are sourced from IMiGW, the national meteorological institute, which provides high-quality, long-term observations. Monthly temperature anomalies are calculated relative to long-term climatological normals, enabling the identification of periods of acute physical stress.

Stress measures are defined along three distinct dimensions: market, transition, and physical:

- market stress is captured using tail events in the broad WIG index, where the 1% lower tail of monthly returns identifies episodes of severe market disruption.
- transition stress is represented by the performance of a stranded-asset portfolio—also evaluated at the 1% lower tail—intended to proxy regulatory shocks, accelerated decarbonization pressures, and shifts in investor sentiment toward carbon-intensive assets.

- physical stress is measured using the 1% upper tail of positive temperature deviations, reflecting extreme heat events that may affect production efficiency, electricity demand, and operational continuity.

Combining these elements, the study estimates company-specific betas for each stress category, providing a granular view of how individual firms respond to different forms of market and climate-related risk. These betas are subsequently aggregated into a total market-and-climate risk indicator that captures each company's joint exposure to market turmoil, transition pressures, and physical hazards. This integrated measure forms the empirical foundation for assessing heterogeneity in market and climate-risk sensitivities across the Polish energy sector and for evaluating how these sensitivities evolve over time.

Across the sample, companies with a traditional fuel-based profile (e.g., coal-dependent generators) exhibit greater sensitivity to transition shocks. Firms with stronger exposure to renewable technologies show milder reactions to stranded-asset risk but remain affected by physical temperature anomalies, which influence electricity demand, generation costs, and operational reliability.

The combined market-and-climate risk measure is consistently higher than any single risk component estimated in isolation. Periods such as The Global Financial Crisis, Eurozone Debt Crisis, the COVID-19 pandemic, and the post-2022 energy-security shock illustrate how climate-related risks interact with broader market volatility (see Figure 1). Sensitivity to transition shocks increased notably during debates on European energy policy, while sensitivity to physical risk rose in years with pronounced temperature anomalies.

Interestingly, during the energy-security crisis triggered by the war in Ukraine, the sector's exposure to transition risk temporarily declined as markets placed greater value on energy security and fossil-fuel capacity. In contrast, physical risk remained elevated due to persistent temperature anomalies.

4. Conclusions

Poland's energy companies are increasingly exposed to a complex set of market and climate-related risks whose interactions cannot be fully understood when examined separately. Transition shocks arising from decarbonization policies and regulatory tightening intersect with physical risks associated with rising temperatures and more frequent weather anomalies. Within the energy sector, these forces often act simultaneously, amplifying financial vulnerabilities, altering operating conditions, and reshaping long-term strategic prospects. As a result, an integrated analytical approach is required to capture the interconnected nature of these pressures.

To address this challenge, the study adapts systemic-risk measurement tools—traditionally applied in the financial sector—to the context of the energy industry. By combining these methods with Polish market data and detailed meteorological records, the analysis provides a transparent and accessible framework for evaluating market and climate-related threats. This methodological approach makes it possible to assess how firms respond to different forms of stress, whether triggered by abrupt policy changes or extreme environmental conditions.

The problem addressed in this study concerned the need to evaluate how market dynamics, transition risk, and physical climate shocks jointly influence systemic financial vulnerability within the energy sector. This requires a methodological framework capable of capturing both firm-level exposure to extreme market conditions and the dynamic interactions between multiple risk factors over time. The extended SRISK framework is employed because it directly measures expected capital shortfall during periods of systemic distress and is therefore uniquely suited to analysing the potential contribution of individual firms to system-wide fragility. However, accurately estimating SRISK under climate-related stress necessitates modelling time-varying betas and correlations between market, transition, and physical climate variables. For this reason, the GJR-DCC-GARCH model is integrated into the analysis, as it accommodates asymmetric volatility responses and evolving correlation structures that are characteristic of climate-driven financial shocks. By combining these two approaches, the methodology aligns closely with the research problem: it enables the quantification of systemic risk under heterogeneous and non-linear climate stress scenarios while reflecting the dynamic transmission channels through which climate factors interact with financial markets. This integrated modelling strategy thus provides a coherent and empirically grounded response to the study's core objective of assessing multidimensional systemic risk in a climate-constrained environment.

The empirical results reveal several important patterns. First, exposure to climate risk is heterogeneous across the WIG-Energy companies, reflecting differences in generation portfolios, balance-sheet structures, and strategic investment decisions. Second, transition and physical shocks propagate through distinct channels: policy-driven disruptions primarily affect asset valuations, expected cash flows, and regulatory compliance costs, while physical shocks influence operating performance, infrastructure resilience, and demand fluctuations. Third, when these shocks occur jointly, the resulting vulnerabilities exceed the impact of either risk factor in isolation, highlighting the importance of interaction effects.

This study contributes novel insights into the systemic financial risk of the Polish energy sector by demonstrating that market, transition, and physical climate shocks interact to amplify firm-level and sector-wide vulnerabilities. Unlike previous research that examines these risks in isolation, the integrated SRISK–GJR-DCC-GARCH framework developed here quantifies the combined impact of multiple stressors, capturing dynamic correlations and asymmetric volatility responses over time. The findings reveal heterogeneity in risk exposure across energy companies, with traditional fossil-fuel-based firms exhibiting heightened sensitivity to transition shocks, while all firms remain vulnerable to extreme physical events. These results underscore the importance of considering the joint effects of policy-driven and environmental stressors in financial risk assessment. Methodologically, the study illustrates the feasibility of adapting systemic-risk measures from the financial sector to assess climate-related vulnerabilities in non-financial industries. Practically, the analysis provides policymakers and corporate managers with a tool to identify systemic weaknesses and prioritize resilience-building strategies, highlighting that neglecting the interaction between market and climate risks may lead to substantial underestimation of potential capital shortfalls. Overall, the research advances understanding of multidimensional risk propagation in energy markets and emphasizes the necessity of integrated approaches in both academic inquiry and risk management practice.

The significance of this research lies in its advancement of systemic-risk analysis by incorporating transition and physical climate shocks into a unified framework traditionally applied only to financial market stress. By adapting and extending the SRISK methodology through the integration of a GJR-DCC-GARCH model, the study provides the first empirical evidence on how heterogeneous climate-related shocks interact with market dynamics to shape systemic vulnerability within the Polish energy sector. This contributes to the broader field by bridging the methodological gap between climate finance, systemic-risk modelling, and energy economics, offering a replicable approach that can be applied to other sectors and national contexts. The findings have implications not only for academic discourse but also for regulatory practice, as they demonstrate the necessity of incorporating climate-sensitive parameters in macroprudential stress testing. Moreover, the insights obtained can inform the development of more accurate risk-monitoring tools, enhance the design of climate-related financial disclosures, and support policy initiatives aimed at managing transition pathways. The modelling strategy and empirical results may be further used to evaluate sectoral resilience under alternative climate scenarios, identify systemically important entities, and guide investment strategies that account for climate-market interdependencies. Collectively, the research broadens the analytical foundations for understanding climate-induced systemic risk and establishes a methodological blueprint for future studies seeking to quantify climate–market interactions in complex economic systems.

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Appendix

The beta coefficients for market risk $\beta_{i,t}^{m}$, transition climate risk $\beta_{i,t}^{tr}$, and physical climate risk $\beta_{i,t}^{ph}$ are derived as follows:

$$\begin{bmatrix} \beta_{i,t}^{m} \\ \beta_{i,t}^{tr} \\ \beta_{i,t}^{ph} \end{bmatrix} = \begin{bmatrix} \sigma_{m,t}^{2} & \sigma_{m,t}\sigma_{tr,t}\rho_{m,tr,t} & \sigma_{m,t}\sigma_{ph,t}\rho_{m,ph,t} \\ \sigma_{m,t}\sigma_{tr,t}\rho_{m,tr,t} & \sigma_{tr,t}^{2} & \sigma_{tr,t}\sigma_{ph,t}\rho_{tr,ph,t} \\ \sigma_{m,t}\sigma_{ph,t}\rho_{m,ph,t} & \sigma_{tr,t}\sigma_{ph,t}\rho_{tr,ph,t} & \sigma_{ph,t}^{2} \end{bmatrix}^{-1} \cdot \begin{bmatrix} \sigma_{i,t}\sigma_{m,t}\rho_{i,m,t} \\ \sigma_{i,t}\sigma_{tr,t}\rho_{i,tr,t} \\ \sigma_{i,t}\sigma_{ph,t}\rho_{i,ph,t} \end{bmatrix} \tag{7}$$

where:

$\sigma_{m,t}^{2}$, $\sigma_{tr,t}^{2}$, $\sigma_{ph,t}^{2}$ are conditional variance,

$\rho_{m,tr,t}$, $\rho_{m,ph,t}$, $\rho_{tr,ph,t}$, $\rho_{i,m,t}$, $\rho_{i,tr,t}$, $\rho_{i,ph,t}$ are conditional correlations.

The GJR-GARCH model for the conditional variance take the form:

$$\sigma_{i,t}^{2} = \omega_{\mathrm{V}i} + \alpha_{\mathrm{Vi}} r_{i,t-1}^{2} + \gamma_{\mathrm{Vi}} r_{i,t-1}^{2} I_{i,t-1}^{-} + \beta_{\mathrm{Vi}} \sigma_{i,t-1}^{2} \tag{8}$$

$$\sigma_{m,t}^{2} = \omega_{\mathrm{V}m} + \alpha_{\mathrm{Vm}} r_{m,t-1}^{2} + \gamma_{\mathrm{Vm}} r_{m,t-1}^{2} I_{m,t-1}^{-} + \beta_{\mathrm{Vm}} \sigma_{m,t-1}^{2} \tag{9}$$

$$\sigma_{tr,t}^{2} = \omega_{\mathrm{V}tr} + \alpha_{\mathrm{V}tr} r_{tr,t-1}^{2} + \gamma_{\mathrm{V}tr} r_{tr,t-1}^{2} I_{tr,t-1}^{-} + \beta_{\mathrm{V}tr} \sigma_{tr,t-1}^{2} \tag{10}$$

$$\sigma_{ph,t}^{2} = \omega_{\mathrm{V}ph} + \alpha_{\mathrm{V}ph} r_{ph,t-1}^{2} + \gamma_{\mathrm{V}ph} r_{ph,t-1}^{2} I_{ph,t-1}^{+} + \beta_{\mathrm{V}ph} \sigma_{ph,t-1}^{2} \tag{11}$$

where $I_{i,t}^{-} = 1$ if $r_{i,t} < 0$, $I_{m,t}^{-} = 1$ if $r_{m,t} < 0$, $I_{tr,t}^{-} = 1$ if $r_{tr,t} < 0$, $I_{ph,t}^{+} = 1$ if $r_{ph,t} > 0$, and 0 otherwise.

The conditional correlation of the volatility-adjusted returns

$$\varepsilon_{i,t} = r_{i,t}/\sigma_{i,t} \tag{12}$$

$$\varepsilon_{m,t} = r_{m,t}/\sigma_{m,t} \tag{13}$$

$$\varepsilon_{tr,t} = r_{tr,t}/\sigma_{tr,t} \tag{14}$$

$$\varepsilon_{ph,t} = r_{ph,t}/\sigma_{ph,t} \tag{15}$$

is

$$\mathrm{Cor}(\varepsilon_{\mathrm{i,t}}) = diag(Q_{i,m,tr,ph,t})^{-1/2} Q_{i,m,tr,ph,t} diag(Q_{i,m,tr,ph,t})^{-1/2} \tag{16}$$

where the DCC model specifies the dynamics of the pseudo-correlation matrix $Q_{i,m,tr,ph,t}$ as

$$Q_{i,m,tr,ph,t} = (1 - \alpha_{\mathrm{Ci}} - \beta_{\mathrm{Ci}}) S_i + \alpha_{\mathrm{Ci}} \begin{bmatrix} \varepsilon_{i,t} \\ \varepsilon_{m,t} \\ \varepsilon_{tr,t} \\ \varepsilon_{ph,t} \end{bmatrix} \begin{bmatrix} \varepsilon_{i,t} \\ \varepsilon_{m,t} \\ \varepsilon_{tr,t} \\ \varepsilon_{ph,t} \end{bmatrix}' + \beta_{\mathrm{Ci}} Q_{i,m,tr,ph,t-1} \tag{17}$$

with the unconditional correlation of adjusted returns S_i.

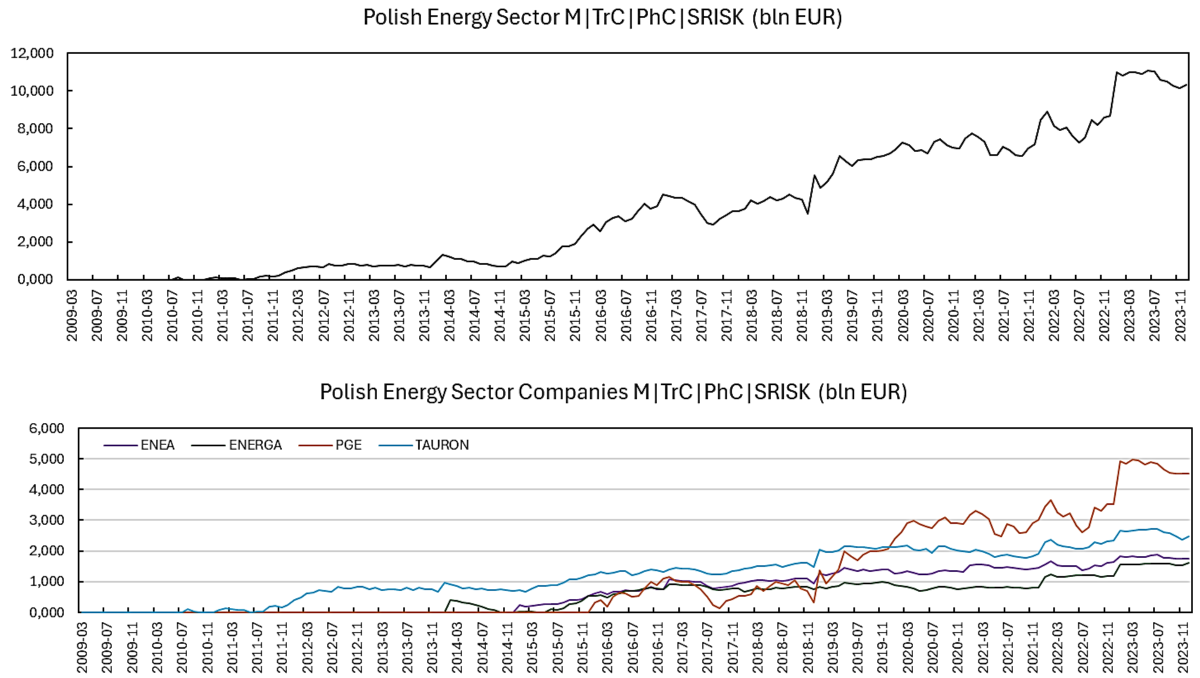

Figure 1. Systemic financial risk of The Polish Energy Sector and The Polish Energy Companies.

Source: Own elaboration.

Table 1.
Descriptive statistics

Company and risk factor	**Obs.**	**Mean**	**Std. dev.**	**Minimum**	**Maximum**
ENEA	178	-0.0006	0.1030	-0.2635	0.3006
ENERGA	119	-0.0052	0.0818	-0.2496	0.2167
PGE	167	-0.0065	0.1055	-0.3268	0.3993
TAURON	161	-0.0012	0.1113	-0.3027	0.5475
Market index WIG	178	0.0067	0.0540	-0.2292	0.1729
Stranded asset portfolio index	178	0.0004	0.0917	-0.2952	0.2586
Temperature anomaly index	178	0.0009	0.0665	-0.3061	0.1702

Source: Own elaboration.

Table 2.
GJR-GARCH estimation parameters

Company	α_{Vi}	α_{Vi} **SE**	γ_{Vi}	γ_{Vi} **SE**	β_{Vi}	β_{Vi} **SE**
ENEA	0.000002	0.005168	0.090563	0.001267	0.951035	0.006328
ENERGA	0.034350	0.004738	0.117323	0.007002	0.854697	0.002482
PGE	0.000002	0.003670	0.123712	0.007177	0.930830	0.001856
TAURON	0.264270	0.308196	0.000002	6.620957	0.478521	0.680511

Source: Own elaboration.

Table 3.
DCC-GARCH estimation parameters

Company	α_{Ci}	α_{Ci} **SE**	β_{Ci}	β_{Ci} **SE**
ENEA	0.000002	0.000030	0.000049	6.159022
ENERGA	0.000002	0.000000	0.000036	1.020475
PGE	0.000002	0.001719	0.000057	9.170844
TAURON	0.000002	0.002263	0.081686	7.806210

Source: Own elaboration.