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Climate Change, Socioeconomic Vulnerability and Climate-Related Economic Losses in the European Union: Evidence from Fixed-Effects Panel Models (2015–2023)

Juan Antonio Torrents Arevalo [1,2,*] and Rosella de Nisco [1]

[1] Department of Management, Polytechnic University of Catalonia, Barcelona-Tech, Building P, Room 209 2nd Plant, 44-50, 08028 Barcelona, Spain; rosella.de.nisco@upc.edu
[2] Department of Economic Analysis, Universidad Nacional de Educación a Distancia (UNED), 08018 Barcelona, Spain
* Correspondence: juanantonio.torrents@upc.edu

Abstract

Climate change represents one of the most significant sustainability challenges facing contemporary societies, generating substantial environmental, economic, and social impacts across multiple spatial scales (This study examines the associations between climate-related economic losses, measured as the logarithm of climate-related losses relative to GDP (Log Loss Ratio), and climatic, environmental, and socioeconomic factors across the 27 European Union Member States over the period 2015–2023. The explanatory variables include annual average temperature, greenhouse-gas emissions, renewable-energy deployment, unemployment, and the At-risk-of-Poverty Rate. A panel-based empirical framework was applied, combining multiple linear regression and mixed-effects models with a country and year fixed-effects specification as the principal robustness check. The baseline and mixed-effects models indicate statistically significant positive associations between the Log Loss Ratio and temperature, greenhouse-gas emissions, renewable-energy deployment, and the At-risk-of-Poverty Rate, while unemployment is not statistically significant. However, the fixed-effects specification provides a more stringent assessment by controlling for time-invariant country-specific characteristics and common year effects. Under this specification, temperature, greenhouse-gas emissions, renewable-energy deployment, and unemployment are no longer statistically significant, whereas the At-risk-of-Poverty Rate remains statistically significant ($p = 0.049$). These findings indicate that some associations identified in the baseline models may partly reflect persistent differences between countries, while socioeconomic vulnerability retains explanatory relevance when country-specific and temporal effects are controlled for. The results should therefore be interpreted as conditional statistical associations rather than causal effects and highlight the importance of integrating socioeconomic vulnerability into climate adaptation and resilience policies.

Keywords: climate-related economic losses; climate change; socioeconomic vulnerability; European Union; fixed-effects panel models; climate adaptation

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1. Introduction

1.1. Research Objectives and Contributions

The main objective of this study is to analyze and demonstrate the impact of climate change on both the economy and society within the European Union, where climate-related effects are more intense and concentrated. Specifically, the research seeks to show that

climate change leads to increasing economic costs and growing social consequences, thereby challenging the sustainability of economic growth when climate impacts are considered.

The study adopts an empirical, quantitative approach based on data from European Union countries covering the period from 2015 to 2023. The methodology includes the following:

- The use of SPSS (Statistical Package for the Social Sciences) for statistical data analysis.
- The application of econometric models to examine and quantify the relationship between climate change and socioeconomic variables.
- The use of additional mathematical models to validate and assess the effects of climate change on economic and social dimensions.

Through these statistical and econometric techniques, the study evaluates the extent to which climate change influences economic costs and social outcomes, confirming that the relationship is asymmetrical and that climate change causes both economic and social impacts.

1.2. Global Climate Change

Recent scientific evidence indicates that climate change is altering both the frequency and intensity of extreme weather events, including heatwaves, droughts, and floods, generating measurable economic impacts through losses of physical capital, labor productivity, and agricultural output, as well as increased macro financial risks. Global temperature anomaly records [1] reveal a clear upward trend in average temperatures, with the distribution of temperature observations shifting towards higher values, indicating a progressively warmer planet. Although interannual fluctuations associated with climatic phenomena such as El Niño and La Niña remain evident, Earth's average surface temperature is currently approximately 1.2 °C higher than it was at the beginning of the twentieth century.

Over the past 485 million years, the Earth's average temperature has varied considerably, ranging from approximately 11 °C to 36 °C [2]. These long-term fluctuations have been closely linked to changes in atmospheric carbon dioxide (CO_2) concentrations, with warmer 'greenhouse' periods dominating much of Earth's geological history. A strong relationship exists between atmospheric CO_2 levels and global temperatures, making greenhouse gas concentrations a key driver of climate conditions over geological timescales. Although life on Earth evolved under a wide range of climatic conditions, human civilization developed during a relatively stable and cooler climatic period, making the current rate of anthropogenic warming particularly challenging for modern societies and economic systems.

The occurrence of climate change is supported by robust statistical evidence [3], and climate change is generally defined as long-term alterations in climatic patterns resulting from both natural variability and anthropogenic influences. However, contemporary climate change is primarily driven by greenhouse gas (GHG) emissions, especially emissions of carbon dioxide (CO_2) and methane, generated by the combustion of fossil fuels and other human activities. Consequently, global mean surface temperature has increased substantially relative to pre-industrial levels, and the 1.5 °C threshold was exceeded for the first time in 2024 [4]. Beyond rising temperatures, climate change contributes to a wide range of environmental and socio-economic impacts, including more frequent and severe heatwaves, increased water scarcity, instability in electricity supply systems, declining agricultural productivity, and biodiversity loss through habitat degradation [5].

In response to these challenges, the Paris Agreement [6] was adopted in 2015 by 193 Parties as a multilateral framework aimed at mitigating climate change through the systematic reduction of greenhouse gas emissions. The Agreement established a long-term

objective of limiting the increase in global average temperature to well below 2 °C above pre-industrial levels by 2100 while pursuing efforts to restrict warming to 1.5 °C.

To achieve these objectives, Parties are required to prepare, communicate, and periodically update their nationally determined contributions (NDCs) [7]. These commitments outline national emissions-reduction targets, policy instruments, and strategic actions for climate change mitigation. NDCs are reviewed and strengthened every five years through a progressive ambition mechanism designed to ensure alignment with the long-term goals of the Paris Agreement and enhance global climate action over time.

However, climate change is not a recent phenomenon, having been identified as a significant scientific concern as early as 1856 [8,9]. Over the subsequent century, advances in climate science led to a more comprehensive understanding of the relationship between anthropogenic greenhouse gas emissions and global warming. Despite increasing scientific evidence and growing public dissemination of these findings, widespread acceptance of the issue was hindered by misinformation, competing political and industrial interests, and the proliferation of conflicting narratives [10]. These factors collectively limited public understanding and delayed the implementation of effective climate change mitigation policies.

In 1972, the Club of Rome's Limits to Growth [11] presented 12 scenarios using system dynamics modelling to explore humanity's trajectory on a finite planet.

Recent research [11,12] suggests that the dynamics of the global socioecological system are converging towards two particularly critical prospective trajectories. The first, the business-as-usual 2 (BAU2) scenario, assumes an expanded availability of non-renewable resources coupled with the continuation of prevailing growth dynamics. Under these conditions, model projections indicate a systemic collapse around 2040, preceded by a deceleration in per capita industrial output beginning in approximately 2015, a sustained increase in mortality rates from 2020 onward, and a subsequent decline in global population levels after 2030.

In contrast, the comprehensive technology (CT) scenario is predicated on exceptionally high rates of technological advancement alongside substantial reductions in pollution intensity. However, empirical evidence indicates that such assumptions significantly exceed historically observed technological and environmental performance trends, thereby constraining the empirical plausibility of this pathway.

Empirical assessments [13,14] demonstrate a closer correspondence between observed historical data and decline-oriented scenarios than with stabilisation trajectories. Accordingly, it is essential to emphasise that the *Limits to Growth* framework does not constitute a deterministic forecasting tool but rather a system dynamic-based exploratory model that elucidates the potential consequences of exponential growth within a finite planetary system. Considering the cumulative evidence over the past five decades, current indicators point to a persistent absence of structural transformations of sufficient magnitude to significantly alter the prevailing global trajectory.

During 2024 [15], approximately 24% of the Earth's surface experienced record-high annual mean temperatures at the local scale, encompassing 32% of terrestrial regions and 21% of oceanic areas. These anomalously warm regions largely coincide with several major population centres. It is estimated that around 3.3 billion individuals—equivalent to 40% of the global population—were exposed to locally record-high annual average temperatures during this year. This includes roughly two-thirds of the population of China, as well as most of the populations of Brazil, Nigeria, Ethiopia, and Mexico, approximately one-third of the population of the United States, and substantial portions of the populations of South and Central America and Eastern Europe. Notably, the decade spanning the last ten years comprises the ten warmest years recorded in the instrumental temperature record.

Furthermore [16], the rapid increase in atmospheric methane (CH_4) observed between 2019 and 2023 during the COVID-19 pandemic was examined using an integrated framework combining satellite observations, ground-based measurements, and atmospheric inversion models. The results indicate that a significant reduction in hydroxyl radicals (OH) during 2020–2021, associated with decreased emissions of NO_x and CO during COVID-19 lockdowns, led to a temporary weakening of atmospheric oxidative capacity, explaining approximately 80% of the interannual variability in CH_4 growth rates. In parallel, an increase in natural methane emissions, primarily from wetlands and inland waters, was identified as driven by enhanced microbial activity under wetter conditions. The prolonged El Niño phase (2020–2023) contributed to expanded inundation areas and increased soil moisture, further amplifying biogenic emissions. Isotopic analysis ($C\text{-}CH_4$) confirmed the predominance of microbial sources over fossil-fuel contributions. Overall, the findings demonstrate that atmospheric methane variability is controlled by both emission fluxes and changes in atmospheric chemical sinks, highlighting the critical need to improve the representation of coupled biogeochemical and atmospheric processes in climate models.

On the other hand [17], the World Meteorological Organization (WMO) report indicates that Earth's climate system has entered an unprecedented state of disequilibrium, primarily driven by the sustained increase in atmospheric greenhouse gas concentrations. The period from 2015 to 2025 represents the warmest decade in the instrumental record, with global mean surface temperatures significantly exceeding pre-industrial baselines. Most of the excess thermal energy has been absorbed by the world's oceans, resulting in pronounced impacts, including sea-level rise, accelerated cryosphere loss, and an increased frequency and intensity of extreme weather events. These findings underscore that climate change is no longer a prospective risk but an ongoing systemic perturbation, with long-term and potentially irreversible consequences that necessitate immediate, evidence-based mitigation and adaptation strategies.

In 2026 [18], the Institute and Faculty of Actuaries indicated that unmitigated climate change constitutes a potential systemic risk capable of triggering a global crisis, conceptualised as 'planetary insolvency' and characterised by severe and cascading impacts, including intensified extreme weather events, substantial economic losses, and widespread societal disruption. Current evidence suggests that the rate of global warming is accelerating and may exceed 2 °C above pre-industrial levels before mid-century, thereby significantly increasing the probability of crossing critical climate tipping points. These findings highlight the urgent need for immediate and coordinated action, integrating rapid greenhouse gas emissions reductions, enhanced adaptive capacity, and the development of innovative strategies aimed at stabilising Earth's climate system.

It is critical [19] to conceptualise climate risk as a complex, multidimensional, and systemic phenomenon, the rigorous assessment of which necessitates the integrated consideration of physical climate drivers, informational dynamics, and policy-related and transition-induced uncertainties. This integrative perspective demonstrates that climate change transcends its characterisation as an environmental issue, emerging instead as a structural and pervasive source of systemic risk for financial markets and the global macroeconomic system, with far-reaching implications for asset pricing, portfolio allocation, and the trajectory of the energy transition. Consequently [20], the development and implementation of more sophisticated, high-resolution, and empirically grounded climate risk metrics are essential to enhance analytical accuracy, improve decision-making under uncertainty, reinforce resilient and sustainable investment frameworks, and inform robust, evidence-based policy interventions aimed at mitigating the escalating and potentially nonlinear impacts of climate change.

It is important to emphasise the role of industrial policy expenditure in supporting climate change mitigation efforts [21]. The OECD report indicates that public spending on industrial policy increased moderately by approximately 16% between 2019 and 2023, a rise that remains more limited than is often suggested in public discourse. Furthermore, the persistence of existing policy instruments reflects a considerable degree of structural inertia, as most measures currently in place were already established prior to this period. Importantly, the allocation of resources tends to be directed towards sectors experiencing structural decline rather than towards more competitive or emerging industries. Consequently, the report underscores the critical need for systematic monitoring, evaluation, and adaptive policy adjustment to enhance the effectiveness and strategic alignment of industrial policy frameworks.

1.3. European Union Climate Change

In Europe [22–25], the interplay between physical risks and transition risks (decarbonization policies, carbon pricing, and trade adjustments) has shaped a complex economic landscape since 2013, exacerbated by events such as the 2021 floods and the 2022 heatwaves.

In 2023 [26], imported fossil fuels covered 58% of the EU's primary energy demand, roughly the same proportion as before the energy crisis. This leaves the EU considerably more dependent on fossil fuel imports than are other major economies, such as China (24%) and India (37%). Only Japan (84%) and South Korea (80%) have higher levels of dependence.

Recent evidence [27] indicates an acceleration of global warming, with record temperatures in 2023–2024 particularly affecting the Northern Hemisphere. This trend contributes to amplified regional warming, as Europe is among the fastest-warming regions globally. Ocean surface warming and intensified marine heatwaves are especially evident in the Mediterranean, leading to biodiversity loss and ecosystem disruption. Additionally, terrestrial carbon sinks are weakening because of increasing disturbances such as wildfires, thereby reducing ecosystem resilience. On the other hand, loops between climate change and biodiversity decline further exacerbate environmental degradation. Groundwater depletion is accelerating, particularly in southern Europe, affecting water security and agriculture. These processes collectively generate growing socioeconomic impacts, including reduced labour productivity and increased climate-related risks.

Following the ideas proposed [28], the catastrophic floods that occurred in Valencia in October 2024—characterised by record-breaking extreme rainfall of up to 771.8 mm within 16 h and resulting in more than 230 fatalities—were substantially amplified by anthropogenic climate change. This human-induced forcing significantly intensified the event by enhancing both the magnitude and the spatial extent of precipitation, thereby exacerbating the overall flood hazard and associated impacts. Furthermore [29], forest disturbances across Europe are projected to approximately double by the end of the 21st century under scenarios of continued greenhouse gas emissions. In particular, the area affected by wildfires could nearly triple relative to the 2001–2020 baseline period, highlighting a marked intensification of fire regimes. The Mediterranean region emerges as the most vulnerable hotspot, with up to 90% of its forested areas potentially exposed to heightened risks of both wildfires and biotic disturbances, such as pest outbreaks. Collectively, this body of evidence demonstrates that anthropogenic climate change acts as a significant driver of multiple interacting disturbance processes, fundamentally altering the structure, functioning, and resilience of European forest ecosystems while amplifying their environmental, economic, and societal impacts.

The spatial heterogeneity of CO_2 emissions across European regions [30] reveals a structurally fragmented climate landscape that is not adequately captured by national-

level aggregates. A joint analysis of per capita emissions and economic output [31] (GDP per capita) identifies four distinct regional typologies: (a) high-income, low-emission 'green leaders'; (b) high-income, carbon-intensive regions; (c) low-income, low-emission peripheries; and (d) low-income, carbon-intensive regions. Particularly noteworthy is the latter group, comprising approximately 50 regions—predominantly located in Central and Eastern Europe—that exhibit a dual constraint of limited economic capacity and elevated carbon intensity. This configuration [32] places them at a structural disadvantage in the context of decarbonisation pathways and highlights the inherent tensions between climate mitigation objectives and cohesion policy goals.

Furthermore, these findings underscore that emission patterns are more strongly driven by regional industrial structures and energy system legacies than by income levels alone. Consequently, the observed 'green divide' [33] within Europe reflects deep-rooted structural asymmetries rather than transitional imbalances. From a policy perspective, this implies that uniform decarbonisation strategies may exacerbate regional inequalities unless complemented by targeted, place-based interventions. Therefore, achieving an equitable and effective low-carbon transition requires differentiated policy frameworks that integrate climate objectives with regional development strategies, ensuring that vulnerable regions are not disproportionately burdened by the costs of decarbonisation.

The European Union [34] is actively promoting the deployment of synthetic fuels, specifically renewable fuels of non-biological origin (RFNBOs), as a key pathway for decarbonisation, particularly in hard-to-electrify sectors such as aviation and heavy industry. These fuels, produced from renewable hydrogen and captured CO_2, have the potential to achieve greenhouse gas emission reductions exceeding 70% compared with conventional fossil fuels. Consequently, their development is being accelerated through regulatory frameworks such as the Renewable Energy Directive (RED III), which establishes binding targets for the transport and industrial sectors. Despite significant technological progress—reflected in the advancement of production pathways and the implementation of pilot and early commercial-scale projects—current RFNBO production levels remain limited, highlighting the need for further scaling and investment.

However, previous research [35] has demonstrated that increasing legal complexity in European Union climate policy significantly undermines implementation effectiveness. More complex legislation—characterized characterised by greater length, higher levels of detail, and extensive interconnections among provisions—has been shown to reduce implementation performance [36], even in member states with strong administrative capacity. Overall, these findings emphasise the importance of balancing regulatory ambition with practical feasibility to ensure effective and robust climate policy outcomes.

Finally, it is essential to highlight the need for the European Union [37] to harmonise climate risk assessments and adopt common climate scenarios to support coherent adaptation planning. In addition, establishing a clear long-term vision for climate resilience—supported by measurable targets and integrated policy frameworks—is crucial for effective governance. Equally important is the promotion of a just and equitable adaptation approach, which accounts for regional disparities and ensures the mobilisation of both public and private investments to address the growing impacts of climate change.

1.4. European Union Cities

In urban environments [38], this phenomenon is further exacerbated by the urban heat island (UHI) effect, whereby local temperatures may exceed those of adjacent rural areas by approximately 5–15 °C.

Between 2013 and 2024, mean annual temperatures exhibited a consistent upward trend across nearly all European capitals. The most pronounced increases were recorded in

southern European cities [39], particularly Madrid and Rome, highlighting a clear regional gradient in warming intensity.

Precipitation regimes have also undergone significant changes characterised by heightened variability. Western Europe has experienced a rise in the frequency and intensity of extreme precipitation events, whereas southern and eastern regions have been increasingly affected by prolonged drought conditions. These changes [40] have contributed to a marked escalation in the occurrence of hydrometeorological hazards, including flooding and wildfires.

Moreover, heatwaves have increased in frequency, duration, and intensity throughout the study period. Major metropolitan areas [41], such as Paris and Berlin, have reported record-breaking temperature extremes, underscoring the growing vulnerability of urban systems to climate-related stressors.

The urban heat island (UHI) effect is associated with several adverse biophysical and anthropogenic processes. These include (a) [42] the high thermal absorptivity and low albedo of impervious surfaces, such as asphalt, which enhance solar radiation uptake and heat storage; (b) [43] the alteration of urban morphology, whereby dense building configurations impede atmospheric circulation and reduce natural ventilation; (c) [44] the limited presence of vegetative cover, resulting in decreased evapotranspiration and diminished cooling capacity; and (d) [45] additional heat fluxes associated with anthropogenic activities, including transportation, industry, and energy consumption.

Collectively, these factors contribute to elevated urban temperatures. Evidence from multiple European cities suggests that projected climate change scenarios [46] are likely to significantly amplify the intensity and frequency of urban heat stress conditions.

Between 2013 and 2016, air temperatures increased progressively, accompanied by the emergence of the first major extreme heat events [47]. This trend intensified during the 2017–2019 period, which was characterised by severe drought conditions across central and western Europe, along with record-breaking heatwaves in 2018 and 2019 [48]. Subsequently, the 2020–2022 interval exhibited further climatic intensification, with numerous cities registering all-time-high temperature records, alongside a marked rise in the frequency and severity of wildfires, increasing water stress, and a significant escalation in the occurrence of tropical nights. Most recently, the period from 2023 to 2025 has been distinguished by a pronounced acceleration of extreme climatic phenomena, including unprecedented temperature anomalies, widespread flooding events, torrential precipitation episodes, and recurrent record-breaking heat extremes, highlighting an evident amplification of climate variability and associated impacts.

From a scientific perspective, an analysis of major European cities reveals consistent patterns of climate change impacts characterised by rising temperatures, altered precipitation regimes, and increasing stress on urban systems and water resources [49]. In Madrid, these impacts include a growing number of days exceeding 35 °C, longer-lasting heatwaves, reduced water availability, and increased heat-related summer mortality. Barcelona is experiencing progressive warming of the Mediterranean Sea, more frequent episodes of torrential rainfall and urban flooding, as well as an increase in tropical nights and overall thermal stress. Paris has faced more frequent heatwaves since 2018, an intensified urban heat island effect, and a rising risk of Seine flooding associated with extreme precipitation events [50]. In Berlin, recurrent droughts, declining soil moisture, and intense rainfall episodes that overwhelm urban drainage systems are becoming more common. Amsterdam is increasingly vulnerable to both fluvial and coastal flooding and more frequent extreme rainfall events, necessitating strengthened water management infrastructure. Brussels shows a clear rise in intense precipitation, more frequent urban flooding, and significantly warmer summers compared with historical averages. In Rome, prolonged heatwaves, seasonal

water scarcity, and increased energy demand for cooling are key concerns [51]. Athens stands out as one of the cities most affected by extreme heat, with heightened risks of peri-urban wildfires and extended drought periods. Vienna is experiencing more frequent heatwaves, increased flood risk from intense rainfall, and heightened thermal stress in densely built environments. Finally, Warsaw demonstrates growing climate variability, with alternating droughts and periods of extreme rainfall, rising average temperatures, and increasing pressure on urban water resources. Collectively [52], these trends highlight the intensification of climate-related risks across European urban environments and the urgent need for integrated adaptation strategies.

2. Economics and Social Consequences in the European Union

Since 2013, when the European Union adopted its first climate adaptation strategy, there has been a clear increase in the economic costs associated with climate-related events [53]. Over the past decade [54,55], average annual economic losses have been around €26 billion, while approximately 25% of all losses recorded since 1980 were concentrated between 2021 and 2024, highlighting a recent acceleration of the problem. In addition, the period from 2020 to 2023 recorded average losses of about €44.5 billion per year, more than double the levels seen during the 2010s. This impact is particularly significant in cities, where most of the population, infrastructure, and economic assets are concentrated.

The economic impacts [56] of climate change are substantially larger than previously estimated. A 1 °C increase in global temperature may lead to a reduction in world GDP exceeding 20% in the long run. Global rather than local temperature measures more effectively capture the role of extreme climatic events, such as heatwaves and storms. These empirical findings [57] are then incorporated into a neoclassical growth model, through which it is estimated that welfare losses could exceed 30% under business-as-usual warming scenarios. Furthermore, the social cost of carbon is projected to surpass $1.200 per tonne.

Historically [58], increases in global GDP have been closely associated with rising carbon emissions, suggesting a structural dependence of economic expansion on environmentally intensive activities.

Despite international climate commitments [59], current trends indicate that global temperature targets, particularly the 1.5 °C threshold, are increasingly unlikely to be met. This is compounded by evidence that several planetary boundaries have already been exceeded, raising concerns about the long-term sustainability of current economic systems.

There are three main economic perspectives [60,61]: green growth, which emphasises technological solutions; green Keynesianism, which advocates state-led investment; and post-growth approaches, which question the compatibility of continuous growth with ecological limits.

Climate change entails significant long-term economic costs [62], such as reduced GDP and increased social and financial risks. Greenhouse gas emissions and global warming have negative effects on economic growth, making it lower and more volatile, and on social well-being.

Despite considerable geographical and climatic differences, major European Union cities exhibit several common economic impacts associated with climate change. Increasing temperatures and more frequent heatwaves [63] have led to higher healthcare expenditures due to the growing incidence of heat-related illnesses and mortality among vulnerable populations. Simultaneously, local governments, such as those of Barcelona and Madrid, have been required to allocate substantial financial resources to the development of climate-resilient infrastructure, including flood protection systems, green urban spaces, and adaptive water management networks. Extreme temperature events in Berlin [64] have also been associated with reductions in labor productivity, particularly in sectors characterized by

outdoor activities and physically demanding tasks. Furthermore, in Rome [65], rising cooling demands have significantly increased energy consumption and operational costs for households, businesses, and public institutions. Climate-related hazards, such as floods, storms, and extreme precipitation events, have generated extensive damage to urban infrastructure, resulting in considerable repair and maintenance expenditures. Finally [66], sectors highly dependent on climatic conditions, notably tourism and agriculture, have experienced economic losses due to changes in environmental conditions, resource availability, and seasonal patterns. Collectively, these impacts illustrate the growing economic vulnerability of European urban systems to climate change and highlight the need for comprehensive adaptation strategies.

Climate change is increasingly recognised as a critical determinant of population health, particularly in urban environments where climatic, environmental, and sociodemographic risk factors converge. Europe [67] is experiencing a faster rate of warming than the global average, with mean surface temperatures having risen approximately 1 °C above global levels since pre-industrial times. This accelerated warming has translated into more frequent and intense heatwaves, altered disease patterns, and rising environmental health risks.

Heatwaves constitute the most immediate and severe climate-related health hazard in European cities [68]. Recent epidemiological evidence indicates that the summer of 2022—the hottest on record in Europe—resulted in approximately 61,672 heat-related deaths across the continent. The burden was disproportionately concentrated in Southern and Western Europe, with countries such as Italy, Spain, and Greece exhibiting the highest mortality rates.

Urban populations are particularly vulnerable due to the urban heat island effect, which amplifies exposure to extreme temperatures [69]. Heat-related morbidity includes heatstroke, dehydration, and exacerbation of preexisting cardiovascular and respiratory diseases. Mortality risk is significantly elevated among older adults, children, and individuals with chronic conditions.

Recent estimates attribute approximately 206,000 deaths annually in Europe to long-term exposure to $PM_{2.5}$ alone, alongside significant morbidity linked to nitrogen dioxide (NO_2) and ozone (O_3). These pollutants are strongly associated with the following [70]:

- Increased incidence and severity of asthma and chronic obstructive pulmonary disease (COPD);
- Higher rates of hospital admissions for respiratory conditions;
- Elevated risk of cardiovascular disease and lung cancer;

Urban areas with high traffic density and limited green infrastructure—such as Milan and Barcelona—experience particularly high exposure levels, exacerbating health inequalities.

In addition to physical health effects, climate change has significant implications for mental health. Both direct exposure to extreme weather events and indirect psychological stressors contribute to a growing burden of mental health disorders.

Eco-anxiety, defined as chronic fear or distress associated with environmental change, is increasingly prevalent across Europe [71]. A large cross-national study found that approximately 42.8% of Europeans reported high levels of concern about climate change, with significant variation across countries.

Furthermore, climate-related worry has been associated with an increased risk of anxiety disorders, as well as reduced well-being and life satisfaction [72]. Vulnerable populations may also experience heightened social isolation and reduced quality of life due to environmental degradation and extreme heat.

Major European cities—including Madrid, Paris, Rome, Athens, Barcelona, Milan, and Lisbon—are particularly exposed to climate-related health risks. These urban centres share several vulnerability factors:

- High population density;
- Aging demographics;
- Significant air pollution levels;
- Elevated urban temperatures.

The coexistence of these factors amplifies the risk of adverse health outcomes and places additional strain on health systems. Moreover, intra-urban disparities mean that populations living in lower-socioeconomic-status areas with high traffic exposure and limited green space face disproportionate risks.

This theoretical framework is particularly relevant for understanding the social consequences of climate change in major European cities during the period 2013–2014, when unequal impacts on the urban population were already evident [73]. Phenomena such as more intense heatwaves, worsened pollution episodes, and extreme weather events disproportionately affected the most vulnerable groups, such as older adults, low-income communities, and neighborhoods with less access to green infrastructure. In cities [74] such as Paris, Madrid, and London, these impacts translated into increased heat-related mortality, public health problems, and strain on urban services, as well as inequalities in access to adaptation resources, such as adequate housing and heating and cooling systems. Thus, the dynamics observed in European cities [75] clearly reflect the principles of climate justice, demonstrating that even within developed countries, profound inequities persist in the distribution of risks and capacities to respond to climate change. This reinforces the need for inclusive urban policies that integrate social equity into mitigation and adaptation strategies and move towards a more resilient and equitable urban development model.

However, when temperature is analysed at the city level, its impact on life expectancy appears to be context-dependent, varying according to local adaptation to heat [76]. A study modelling the relationship between temperature and mortality across 854 European cities demonstrates the need for substantial changes in urban design; for instance, an ambient temperature of 30 °C results in higher mortality in Manchester than in Madrid. This discrepancy reflects the fact that human populations and built environments are not equally adapted to climatic conditions that fall outside their historical expectations.

This relationship is examined using [77] with four key variables—average temperature, mortality risk increment, population size, and geographical region—and reveals a strong positive correlation. Cities in Southern Europe, which are culturally and architecturally better adapted to high temperatures, tend to exhibit lower mortality risks at equivalent temperature levels. Nevertheless, notable deviations from this pattern are observed. For example, Barcelona and Rome display higher mortality rates than would be expected based solely on their Mediterranean locations. Factors such as humidity and specific urban planning models provide partial explanations for these anomalies. Indeed, projections by Masselot indicate that Barcelona could experience an additional 246,000 heat-related deaths by 2099, representing the highest cumulative figure among European cities.

A study conducted by researchers at University College London [78] on the 2022 London heatwave provides further quantitative evidence: approximately 38% of heat-attributable mortality can be directly attributed to the urban heat island effect rather than to ambient temperature alone. This result indicates that heat-related mortality is not solely determined by regional climatic conditions but is significantly mediated by urban form and infrastructure, which can intensify thermal exposure beyond baseline environmental levels.

Furthermore, the study [79] examines heatwaves in the Iberian Peninsula under different climate scenarios. The results indicate that their intensity is projected to increase significantly, with average increases of up to 144% during the second half of the century. Moreover, these events are expected to become more geographically widespread and more frequent, affecting a larger proportion of the population and territory. This trend is closely

linked to global warming and shifts in regional atmospheric circulation patterns. Overall, the study concludes that heatwaves will constitute an increasingly critical climate risk for public health, energy systems, and environmental sustainability.

Finally, previous research has shown that [80] the economic impact of temperature-related mortality associated with urban heat islands (UHIs) in European cities has been shown to significantly increase heat-related mortality, particularly in densely populated urban areas. The monetary valuation of these additional deaths highlights substantial economic losses linked to rising temperatures. Although UHI effects may contribute to a reduction in cold-related mortality, their overall impact remains strongly negative because of increased heat exposure. Furthermore, notable spatial disparities are observed, with Southern European cities facing disproportionately higher risks and associated costs. These findings underscore the critical importance of implementing effective urban adaptation strategies to mitigate both the economic and public health impacts of increasing heat.

3. Materials and Methods

3.1. Research Design and Analytical Framework

This study adopts a quantitative longitudinal research design based on panel data covering the 27 member states of the European Union during the period 2015–2023. The panel structure allows for the simultaneous analysis of cross-sectional differences between countries and temporal changes associated with climate change, environmental performance and socioeconomic conditions.

The dataset therefore has a relatively large cross-sectional dimension ($N = 27$) and a short temporal dimension ($T = 9$). Accordingly, the empirical analysis is designed to examine cross-sectional and short-run longitudinal associations rather than long-run macroeconomic dynamics. The study does not seek to estimate unit-root processes, cointegrating relationships, or other long-term dynamic properties that cannot be robustly assessed with the available time dimension.

The primary empirical analysis is based on a mixed-effects panel model designed to account for unobserved country-level heterogeneity and temporal dependence. Multiple linear regression is used as a baseline specification to examine the associations between climate-related economic losses and the selected explanatory variables.

The methodological approach combines descriptive statistics, econometric panel data modelling and mixed-effects regression techniques. The integration of these complementary approaches allows the identification of both structural relationships among socioeconomic variables and temporal dynamics associated with climate variability.

The research framework was developed to ensure methodological transparency and reproducibility by explicitly defining the study population, data sources, variable construction, econometric specifications, estimation procedures, and statistical validation techniques.

3.2. Study Area

This research focused on the European Union (EU-27), using the most recent consolidated data available. On 1 January 2024, the EU had an estimated population of 449.2 million inhabitants and a geographical area of approximately 4 million square kilometres [81]. The European Union remains one of the world's largest economic blocs, accounting for roughly 14–15% of global GDP. Following the recovery from the COVID-19 pandemic and subsequent economic disruptions, the EU labour market reached record levels of resilience, with the unemployment rate falling to 5.9% in 2024—the lowest level recorded since the beginning of the harmonised Eurostat time series in 2009. Population growth in recent years has been mainly driven by positive net migration, while economic activity has continued to be supported by a strong single market and high employment levels.

In 2019, the European Commission launched the European Green Deal, a comprehensive growth strategy aimed at transforming the European Union into a climate-neutral economy by 2050. The policy promotes investment and innovation in low-carbon technologies, renewable energy, energy efficiency, and sustainable production systems [82]. During the period from 2015 to 2023, the European Union experienced major economic and geopolitical disruptions, including the COVID-19 pandemic and the consequences of the war in Ukraine. Nevertheless [83], greenhouse gas emissions continued their long-term downward trend while the European economy gradually recovered and adapted to these challenges. In 2023, total greenhouse gas emissions in the EU were approximately 3.4 billion tonnes of CO_2 equivalent, significantly below 2015 levels, reflecting progress towards the EU's climate objectives. Therefore, the 2015–2023 period provides a relevant framework for analysing the relationship between greenhouse gas emissions and economic growth under both normal economic conditions and periods of significant external shocks.

3.3. Data Sources and Variables Construction

The empirical analysis was conducted using a country-year dataset covering the 27 Member States of the European Union and the period 2015–2023. The initial balanced panel consisted of 243 country-year observations (27 countries × 9 years). Annual national average temperature data were obtained from the Copernicus Climate Change Service and linked to each country-year observation. Descriptive statistics are reported for all available observations, while econometric estimations use the final analytical sample of 241 observations.

The analytical dataset included the logarithm of climate-related economic losses normalised by gross domestic product (Log Loss Ratio), which was used as the dependent variable in all econometric specifications as the main outcome variable. The explanatory variables included annual average temperature, domestic net greenhouse gas emissions, the share of renewable energy in gross final energy consumption, unemployment rate and the at-risk-of-poverty rate. These variables were selected to capture climatic conditions, environmental pressure, energy transition and socioeconomic vulnerability across EU member states.

The data were obtained from Eurostat and the Copernicus Climate Change Service in June 2026 [84,85]. The exact definitions, units of measurement, sources, transformations, and analytical roles of all variables are reported in Table 1.

Table 1. Variables.

Variable	Analytical Role	Unit	Source	Transformation
Log Loss Ratio	Dependent variable	Losses/GDP	Eurostat	Natural logarithm
Temperature	Climatic explanatory variable	°C	Copernicus	None
Domestic net greenhouse gas emissions	Explanatory variable	Million tonnes CO_2e	Eurostat	Natural logarithm
Share of renewable energy	Explanatory variable	%	Eurostat	Natural logarithm
Unemployment rate	Control variable	%	Eurostat	None
At-risk-of-poverty rate	Control variable	%	Eurostat	None

The initial dataset contained 243 country-year observations. Two observations containing incomplete information were excluded using listwise deletion, resulting in a final analytical sample of 241 observations. The dependent variable was defined as the logarithm of climate-related losses normalised by GDP (Log Loss Ratio = ln (climate-related losses/GDP)) Logarithmic transformations were also applied to the loss ratio, greenhouse gas emissions and renewable energy variables to reduce skewness and improve linearity.

3.4. Processing and Model Validation

Prior to statistical analysis, all variables were subjected to a standardised data-processing procedure to ensure consistency, comparability, and reproducibility. Data were collected from the Eurostat and Copernicus Climate Change Service (C3S) databases for the period 2015–2023. The initial dataset contained 243 observations corresponding to 27 European Union member states observed over nine annual periods.

Data cleaning involved three stages. First, all variables were inspected for missing values, inconsistencies, and potential recording errors. Observations containing incomplete information for any of the variables included in the econometric models were removed using listwise deletion. After this procedure, the final analytical dataset consisted of 241 valid observations.

Second, logarithmic transformations were applied to the loss ratio, greenhouse gas emissions, and renewable energy variables. For the Log Loss Ratio, observations with zero climate-related losses were checked prior to the logarithmic transformation because the natural logarithm of zero is undefined. No zero-loss observations were included in the final analytical sample; therefore, no adjustment or replacement of zero values was required before calculating the natural logarithm.

These transformations reduced skewness, minimised the influence of extreme observations, and improved the linearity of relationships among variables.

Third, descriptive analyses and graphical inspections were conducted to identify outliers and abnormal observations. Extreme values were retained when supported by officially reported statistics because they represented actual climate-related events and economic conditions rather than measurement errors.

To enhance reproducibility, all statistical analyses were performed using IBM SPSS Statistics (Version 30). The econometric procedures followed a predefined workflow consisting of descriptive statistics, correlation analysis, multiple linear regression and mixed-effects panel estimation.

Several diagnostic procedures were conducted to evaluate the validity and reliability of the estimated models. Multicollinearity was assessed using variance inflation factors (VIFs) and tolerance statistics. All VIF values remained below the commonly accepted threshold of 10, while tolerance values exceeded 0.10, indicating the absence of severe multicollinearity among the explanatory variables. The goodness of fit of the regression model was evaluated using the coefficient of determination (R^2), adjusted R^2, analysis of variance (ANOVA), Akaike information criterion (AIC), and Bayesian information (BIC). Taking together, these diagnostic indicators provided evidence of an acceptable model fit and did not reveal major specification problems. Residual diagnostics were performed by examining standardised residuals and predicted values. Residual distributions exhibited no substantial departures from normality, and no systematic patterns suggesting severe heteroscedasticity were observed.

For the mixed-effects panel model, year was incorporated as a fixed effect, while country-specific random effects were included to account for unobserved heterogeneity across EU member states. In addition, repeated yearly observations within countries were modelled using a diagonal residual covariance structure. This specification allows for the

estimation of temporal effects while controlling for country-level differences that remain constant over time.

The primary empirical specification was estimated using a mixed-effects panel model:

$$LogLossRatio_{it} = \beta_0 + \beta_1 Temperature_{it} + \beta_2 LogEmissions_{it} + \beta_3 LogRenewal_{it} + \beta_4 Unemployment_{it} + \beta_5 Poverty_{it} + \gamma_t + u_i + \varepsilon_{it} \quad (1)$$

where Log Loss Ratio_it represents the logarithm of climate-related economic losses relative to GDP for country i in year t; Temperature it represents annual temperature; Log Emissions it represents logarithmically transformed greenhouse gas emissions; Log Renewal it represents logarithmically transformed renewable-energy share; Unemployment it and Poverty it represent the unemployment and at-risk-of-poverty rates, respectively; γt represents year fixed effects; ui captures the country-specific random intercept; and εit represents the residual error term.

The mixed-effects specification was selected as the primary model because it explicitly accounts for the longitudinal structure of the data, incorporates year-specific effects, and allows for unobserved heterogeneity between EU Member States through country-specific random intercepts.

3.5. Methods

This study employs an integrated quantitative framework to analyse the relationship between climate-related economic losses normalised by GDP, climatic conditions, environmental indicators, energy-transition variables and socioeconomic conditions across the 27 European Union member states during the period 2015–2023. The methodological approach combines descriptive statistics, econometric modelling and mixed-effects panel analysis. This combination allows for the identification of the main factors associated with climate-related losses while simultaneously examining temporal patterns and climate variability.

The analysis was conducted in four stages. First, descriptive statistics were used to characterise the distribution and variability of all variables included in the dataset. Second, a baseline multiple linear regression model was estimated to examine the associations between the Log Loss Ratio and the selected explanatory variables. Third, a mixed-effects panel model was estimated as the primary empirical specification, incorporating year fixed effects and country-specific random effects to account for temporal variation and unobserved heterogeneity across EU member states. Fourth, robustness analyses were conducted by comparing the results obtained from the baseline regression and the mixed-effects specification.

3.5.1. Descriptive Statistical Analysis

Descriptive statistics were calculated using all available observations for each variable. The initial balanced panel comprised 243 country-year observations (27 countries × 9 years). Due to two incomplete observations, 241 complete country-year observations were available for the multivariable econometric analyses after listwise deletion. Consequently, the number of observations reported in the descriptive statistics varies across variables according to data availability, whereas the econometric models were estimated using the complete-case sample of 241 observations.

Table 2 presents the descriptive statistics for the variables included in the empirical analysis. The results reveal substantial heterogeneity across European Union Member States during the period 2015–2023. The dependent variable, Log Loss Ratio, exhibits considerable variability, indicating significant differences in the relative economic burden associated with climate-related losses across countries.

Table 2. Descriptive statistics for selected variables.

Variable	Range	Minimum	Maximum	Average	Standard Deviation	Variance	*N*
Log loss ratio	4.666	−9.492	−4.825	−6.959	0.967	0.935	243
Temperature	18.6	2.5	21.1	11.31	4.1	16.91	243
Log Emissions	7.460	2.860	10.320	7,013	1.596	2.549	241
Log Renewal	2.5887	1.6068	4.1955	3.0557	0.5276	0.278	243
Unemployment rate	23.0	2.0	25.0	7.2292	3.772	14.228	243
At-risk-of-Poverty Rate	16.0	8.6	25.4	16.54	3.854	14.858	243

Annual average temperature ranges from 2.5 °C to 21.1 °C, with a mean value of 11.31 °C and a standard deviation of 4.11 °C, reflecting the considerable climatic diversity of the European Union. Greenhouse-gas emissions also display substantial variability, suggesting important differences in environmental performance among Member States.

The share of renewable energy exhibits moderate dispersion, while unemployment and at-risk-of-poverty rates show notable cross-country differences, highlighting heterogeneous socioeconomic conditions across the European Union. The Log Loss Ratio also presents substantial variation, indicating important differences in the relative economic burden associated with climate-related losses. Overall, the descriptive statistics reveal sufficient variability in all variables to support subsequent econometric estimation and mixed-effects panel analysis.

3.5.2. Correlation Matrix

Table 3 shows the Pearson correlation coefficients and their respective levels of statistical significance.

Table 3. Pearson Correlation.

Variable	Log Loss Rate	Temperature	Log Emissions	Log Renewal	Unemployment Rate	At-Risk-Off Poverty Rate
Log loss ratio	1.000	0.202 **	0.090	0.078	0.117	0.192 **
Temperature	0.202 **	1.000	−0.004	−0.443 ***	0.229 ***	0.100
Log Emissions	0.090	−0.004	1.000	−0.147 *	0.099	−0.001
Log Renewal	0.078	−0.443 ***	−0.147 *	1.000	0.054	0.111
Unemployment rate	0.117	0.229 ***	0.099	0.054	1.000	0.346 ***
At-risk-of-Poverty Rate	0.192 **	0.100	−0.001	0.111	0.346 ***	1.000

Notes: * $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$.

Table 3 presents the Pearson correlation coefficients among the variables included in the econometric analysis. The results indicate that the Log Loss Ratio is positively associated with temperature ($r = 0.202$, $p = 0.002$) and the At-risk-of-Poverty Rate ($r = 0.192$, $p = 0.003$). These findings suggest that countries experiencing higher temperatures and greater socioeconomic vulnerability tend to exhibit higher climate-related losses relative to GDP.

By contrast, the correlations between the Log Loss Ratio and greenhouse-gas emissions ($r = 0.090$, $p = 0.160$), renewable-energy deployment ($r = 0.078$, $p = 0.227$), and unemployment rates ($r = 0.117$, $p = 0.068$) are not statistically significant at conventional significance levels.

The strongest correlation among the explanatory variables is observed between unemployment and At-risk-of-Poverty Rates ($r \approx 0.35$, $p < 0.001$), reflecting the close relationship

between labour-market conditions and socioeconomic vulnerability. Overall, the correlation matrix does not indicate severe multicollinearity problems and supports the use of multivariable econometric models in the subsequent analysis.

3.5.3. Multiple Linear Regression

As a baseline specification, a multiple linear regression model was estimated to examine the associations between the Log Loss Ratio and the selected explanatory variables. This model serves as a robustness check and provides a benchmark for comparison with the mixed-effects panel model, which constitutes the primary empirical specification of the study.

The model can be expressed as

$$LogLossRatio_{it} = \beta_0 + \beta_1 Temperature_{it} + \beta_2 LogEmissions_{it} + \beta_3 LogRenewal_{it} + \beta_4 Unemployment_{it} + \beta_5 Poverty_{it} + \varepsilon_{it} \quad (2)$$

Logarithmic transformations were employed to reduce skewness and heteroscedasticity in the regression analysis. Such transformations are commonly used in environmental and economic research because they improve distributional properties, facilitate the interpretation of coefficients, and reduce the influence of extreme observations [86,87]. Moreover, logarithmic transformations help linearise multiplicative relationships and often produce more stable parameter estimates than models based on raw data.

3.5.4. Mixed-Effects Panel Model

The mixed-effects panel model constitutes the primary empirical specification of this study. By accounting for unobserved country-level heterogeneity and temporal variation, this approach provides the principal framework for evaluating the associations between climate-related losses and the selected climatic, environmental, and socioeconomic variables. The results are therefore interpreted primarily based on this specification, while the multiple linear regression model is retained as a robustness check.

Given the panel structure of the dataset, consisting of repeated annual observations for the 27 European Union Member States during the period 2015–2023, a mixed-effects model was estimated to account for both cross-sectional heterogeneity and temporal dependence. Unlike conventional regression models, mixed-effects specifications allow for the inclusion of random effects that capture unobserved country-specific characteristics that remain relatively stable over time, such as institutional quality, geographical conditions, economic structure, and long-term exposure to climate-related risks.

In this study, countries were specified as random effects, while year was incorporated as a fixed effect. The explanatory variables included annual average temperature, greenhouse gas emissions, renewable energy deployment, unemployment rate, and the at-risk-of-poverty rate. In addition, repeated yearly observations within countries were modelled using a diagonal residual covariance structure. This specification improves the reliability of parameter estimates and provides a robust framework for assessing the determinants of climate-related losses across European Union member states.

The mixed-effects panel model estimated in this study can be expressed as

$$\begin{aligned} LogLossRatio_{it} &= \beta_0 + \beta_1 Temperature_{it} + \beta_2 LogEmissions_{it} \\ &+ \beta_3 LogRenewal_{it} + \beta_4 Unemployment_{it} + \beta_5 Poverty_{it} + \gamma_t \\ &+ u_i + \varepsilon_{it} \end{aligned} \quad (3)$$

where

- $LogLossRatio_{it}$ *represents climate-related losses normalised by GDP;*
- $Temperature_{it}$ *denotes annual average temperature;*
- $LogEmissions_{it}$ *represents greenhouse-gas emissions;*

- $LogRenewal_{it}$ *denotes renewable-energy deployment;*
- $Unemployment_{it}$ *represents the unemployment rate;*
- $Poverty_{it}$ *denotes the at-risk-of-poverty rate;*
- γ_t *represents year fixed effects;*
- u_i *captures country-specific random effects;*
- ε_{it} *denotes the idiosyncratic error term.*

3.5.5. Software

All statistical analyses were conducted using IBM SPSS Statistics. Data preprocessing, descriptive statistics, econometric estimation, graphical analyses, and statistical diagnostics were carried out within the same analytical environment to ensure consistency and reproducibility. All procedures followed standard econometric practices commonly applied in empirical studies analysing panel data and climate-related socioeconomic indicators.

4. Results

4.1. Multiple Linear Regression

The estimated OLS equation is

$$Log\ Loss\ Ratio = -10.023 + 0.073\ Temperature + 0.100\ Log\ Emissions + 0.296\ Log\ Renewal - 0.002\ Unemployment - 0.040\ Poverty + \varepsilon \quad (4)$$

Table 4 presents the overall fit indicators for the multiple linear regression model.

Table 4. Parameters of Linear Regression.

Parameter	Figure
R	0.346
R^2	0.120
Correct R^2	0.101
Statistical changes; R^2	0.120
Statistical changes in F	6.457
Changes Statistics df1	5
Changes Statistics df2	237
Sig.F Change	<0.001
Akaike Information Criterion	−36,279
Amemiya Prediction Criterion	0.925
Mallows' Cp	6.000
Schwarz Bayesian Criterion	−15.320
Durbin-Watson	1.772

The F-statistic of 6.457 is statistically significant ($p < 0.001$), indicating that the explanatory variables jointly contribute to explaining differences in the Log Loss Ratio across European Union Member States. The estimated model accounts for approximately 12.0% of the observed variation in climate-related losses normalised by GDP ($R^2 = 0.120$). Although the explanatory power of the model is moderate, the results suggest that climatic, environmental, and socioeconomic factors are associated with climate-related losses within the study sample. The ANOVA results reported in Table 5 confirm the statistical significance of the regression model.

Table 5. Analysis of Variance (ANOVA) for Multiple Linear Regression (5 predictors).

Variable	Sum of Squares	*df*	Mean Square	*F*	Sig
Regression	27.137	5	5.427	6.457	<0.001
Residual	199–215	237	0.841		
Total	226.351	242			

Dependent Variable: Log Loss Ratio. Predictors: Constant, log emissions, Unemployment rate, log Renewal, At-risk-of-poverty rate, temperature.

Table 6 presents the estimated coefficients of the regression model.

Table 6. Coefficients.

Variable	Unstandardised Coefficients	Standardised Coefficients	*T*	Sig
Constant	*B* Std. Error	Beta		
	−10.023 0.595		−16.856	<0.001
Temperature	0.073 0.017	0.312	4.265	<0.001
Log Emissions	0.100 0.039	0.165	2.547	0.011
Log Renewal	0.296 0.128	0.162	2.310	0.022
Unemployment	−0.002 0.017	−0.009	−0.133	0.894
Poverty	0.040 0.016	0.159	2.425	0.016

Table 6 presents the estimated coefficients of the OLS regression model. Temperature exhibits a positive and statistically significant association with the Log Loss Ratio (B = 0.073; $p < 0.001$), indicating that countries with higher average temperatures tend to exhibit higher climate-related losses relative to GDP. Greenhouse-gas emissions are also positively associated with the dependent variable (B = 0.100; $p = 0.011$), while renewable-energy deployment shows a positive and statistically significant relationship (B = 0.296; $p = 0.022$). The At-risk-of-Poverty Rate is positively and significantly associated with the Log Loss Ratio (B = 0.040; $p = 0.016$), suggesting that higher levels of socioeconomic vulnerability are associated with greater climate-related losses. By contrast, the unemployment rate does not reach statistical significance ($p = 0.894$) and therefore does not appear to be systematically associated with climate-related losses within the estimated specification.

Overall, the results indicate that climatic conditions, environmental pressures, renewable-energy deployment, and socioeconomic vulnerability are associated with climate-related losses across European Union Member States.

Table 7 presents the multicollinearity indicators.

Table 7. Collinearity Statistics.

Variable	Tolerance	VIF
Temperature	0.695	1.438
Log Emissions	0.887	1.128
Log Renewal	0.758	1.319
Unemployment	0.828	1.208
Poverty	0.862	1.160

The collinearity diagnostics do not indicate severe multicollinearity. All variance inflation factors (VIFs) remain below the commonly accepted threshold of 10, and all tolerance values exceed 0.10. Accordingly, the explanatory variables can be considered sufficiently independent to support reliable coefficient estimation.

4.2. Mixed-Effects Panel Model

The estimated mixed-effects panel model can be expressed as

$$LogLossRatio_{it} = 141.934 - 0.076Year_{it} + 0.091Temperature_{it} + 0.115LogEmissions_{it} + 0.453LogRenewal_{it} - 0.024Unemployment_{it} + 0.038Poverty_{it} + u_i + \varepsilon_{it} \quad (5)$$

where γt represents year fixed effects, ui denotes the country-specific random effect, and εit represents the idiosyncratic error term.

To account for the longitudinal structure of the dataset and control for unobserved heterogeneity among European Union member states, a mixed-effects panel model was estimated with countries specified as random effects and year specified as a fixed effect. This specification constitutes the primary empirical model of the study and provides a more appropriate framework for analysing panel data than conventional cross-sectional regression models.

Table 8 presents the Type III fixed effects tests.

Table 8. Type III fixed effects tests.

Source	gl of Numerator	gl of Denominator	*F*	Sig
Intercept	1	17.367	7.367	0.014
Year	1	169.533	8.446	0.004
Temperature	1	220.051	25.564	<0.001
Log Emissions	1	233.288	8.776	0.003
Log Renewal	1	209.659	11.132	0.001
Unemployment rate	1	191.648	1.768	0.185
At-risk-of-Poverty Rate	1	233.288	5.531	0.020

Depend variable: Log Loss Ratio.

The Type III tests of fixed effects indicate that temperature represents the strongest climatic predictor of the Log Loss Ratio ($F = 25.564$; $p < 0.001$). Renewable-energy deployment also remains statistically significant within the mixed-effects specification ($F = 11.132$; $p = 0.001$), while greenhouse-gas emissions exhibit a positive and statistically significant association with climate-related losses ($F = 8.776$; $p = 0.003$).

Year effects are statistically significant ($F = 8.446$; $p = 0.004$), indicating the presence of temporal variation in climate-related losses during the study period. The At-risk-of-Poverty Rate is also statistically significant ($F = 5.531$; $p = 0.020$), suggesting that socioeconomic vulnerability contributes to explaining variations in climate-related losses across European Union Member States.

By contrast, the unemployment rate does not reach statistical significance ($p = 0.185$), indicating a limited contribution to explaining differences in the Log Loss Ratio within the estimated specification.

Table 9 presents the estimates of the model coefficients.

Table 9. Fixed Effects Estimates of the Mixed-Effects Model.

Variable	Coefficient	Standard Error	*T*-Value	*p*-Value
Intercept	141.934	52,293	2.714	0.014
Year	−0.076	0.026	−2.906	0.004
Temperature	0.091	0.018	5.056	<0.001
Log Emissions	0.115	0.039	2.962	0.003
Log Renewal	0.453	0.136	3.336	0.001
Unemployment rate	−0.024	0.018	−1.329	0.185
At-risk-of-Poverty Rate	0.038	0.016	2.352	0.020

Log Loss Ratio.

Model fit statistics: Restricted Log-Likelihood = 667.90 AIC = 687.90; AICC = 688.88 CAIC = 732.54 BIC = 722.54.

Model fit statistics indicate an acceptable adjustment of the mixed-effects specification. The restricted log-likelihood was 667.90, while the Akaike Information Criterion (AIC), corrected Akaike Information Criterion (AICC), Consistent Akaike Information Criterion (CAIC), and Bayesian Information Criterion (BIC) were 687.90, 688.88, 732.54, and 722.54, respectively. The results are consistent across the OLS and mixed-effects specifications and temperature is significantly associated with the Log Loss Ratio (B = 0.091; $p < 0.001$). Greenhouse-gas emissions also remain positively associated with climate-related losses normalized by GDP (B = 0.115; $p = 0.003$), while renewable-energy deployment exhibits a positive and statistically significant relationship with the dependent variable (B = 0.453; $p = 0.001$). The At-risk-of-Poverty Rate is positively and significantly associated with the Log Loss Ratio (B = 0.038; $p = 0.020$), suggesting that greater socioeconomic vulnerability is linked to higher climate-related losses across European Union Member States. In contrast, the unemployment rate does not reach statistical significance ($p = 0.185$). The year coefficient is negative and statistically significant (B = −0.076; $p = 0.004$), indicating a modest downward temporal trend in climate-related losses after controlling country-level heterogeneity and the remaining explanatory variables.

The OLS and mixed-effects specifications yield broadly comparable results for the main explanatory variables. However, this similarity should be interpreted cautiously, as both models are estimated using the same observations and variables, and OLS does not explicitly account for within-country dependence. Therefore, the similarity between the two specifications is not considered sufficient evidence of robustness. To provide a more stringent robustness assessment, a country and year fixed-effects model was additionally estimated, controlling for time-invariant country-specific characteristics and common temporal effects.

4.3. Country and Year Fixed-Effects Model

As an additional robustness check, a specification including both country and year fixed effects was estimated following the reviewer's recommendation. The results are reported in Table 10.

Table 10. Robustness Analysis: Country and Year Fixed-Effects Model.

Source	Type III Sum of Squares	df	Mean Square	F	*p*-Value
Temperature	0.033	1	0.033	0.589	0.444
Country	180.677	26	6.949	124.211	<0.001
Year	0.376	8	0.047	0.841	0.568
Log Emissions	0.028	1	0.028	0.494	0.483
Log Renewal	0.138	1	0.138	2.473	0.117
At-risk-of-Poverty Rate	0.219	1	0.219	3.909	0.049
Unemployment Rate	0.022	1	0.022	0.399	0.528

Dependent variable: Log Loss Ratio.

As an additional robustness check, a specification including both country and year fixed effects was estimated following the reviewer's recommendation. The results indicate that the At-risk-of-Poverty Rate remains statistically significant after controlling for country-specific and temporal effects (F = 3.909; $p = 0.049$). By contrast, temperature, greenhouse-gas emissions, renewable-energy deployment, and unemployment do not remain statistically significant within the fixed-effects framework.

The country and year fixed-effects model provides the main robustness assessment of the empirical results. By controlling for time-invariant country-specific characteristics

and common year effects, this specification provides a more stringent test of whether the observed associations remain when identification relies primarily on within-country changes over time. The results differ from those obtained under the OLS and mixed-effects specifications. Temperature, greenhouse-gas emissions, and renewable-energy deployment are no longer statistically significant, whereas the At-risk-of-Poverty Rate remains statistically significant ($p = 0.049$).

The loss of statistical significance for temperature, greenhouse-gas emissions, and renewable-energy deployment suggests that part of the associations identified in the baseline models may reflect persistent differences between countries rather than changes occurring within countries over time. Once these time-invariant country characteristics and common temporal effects are controlled for, the evidence for these relationships becomes weaker. By contrast, the persistence of the association between poverty and climate-related losses indicates that socioeconomic vulnerability retains explanatory relevance even after accounting for country-specific and year-specific effects. These findings therefore support a cautious interpretation of the baseline estimates and indicate that not all observed associations are equally robust across alternative model specifications.

The highly significant country effects ($F = 124.211$; $p < 0.001$) suggest that a substantial proportion of the variation in climate-related losses is associated with structural differences across European Union Member States. These results indicate that some of the associations identified in the baseline OLS and mixed-effects specifications may partly reflect persistent country-specific characteristics.

Nevertheless, the fixed-effects estimates continue to highlight the relevance of socioeconomic vulnerability, as measured by the At-risk-of-Poverty Rate.

5. Discussion and Policy Implications

5.1. Interpretation of the Main Findings

The empirical results provide evidence that climatic, environmental, and socioeconomic factors are associated with climate-related economic losses across European Union Member States, although the strength and statistical significance of these associations depend on the econometric specification. The baseline OLS and mixed-effects models identify significant associations between the Log Loss Ratio and temperature, greenhouse-gas emissions, renewable-energy deployment, and the At-risk-of-Poverty Rate. However, the country and year fixed-effects specification provides a more stringent assessment by controlling for time-invariant country-specific characteristics and common temporal effects.

Under the fixed-effects specification, temperature, greenhouse-gas emissions, and renewable-energy deployment are no longer statistically significant, whereas the At-risk-of-Poverty Rate remains statistically significant. This difference suggests that part of the associations identified in the baseline models may reflect persistent structural differences between European Union Member States rather than changes occurring within countries over time. The findings therefore support a cautious interpretation of the baseline estimates and indicate that the relationships between climate-related losses and the explanatory variables are not equally robust across specifications.

The highly significant country effects further indicate that substantial differences exist across Member States in the level of climate-related economic losses. These differences may reflect persistent characteristics related to economic structure, geographical exposure, infrastructure, institutional conditions, or adaptive capacity. Although these mechanisms are not directly estimated in the present study, their relevance is consistent with the importance of accounting for country-specific heterogeneity when analysing climate-related losses.

5.2. Socioeconomic Vulnerability and Climate-Related Losses

Among the explanatory variables considered, socioeconomic vulnerability emerges as the most consistent factor across the alternative specifications. The At-risk-of-Poverty Rate remains statistically significant in the country and year fixed-effects model ($p = 0.049$), whereas the other substantive explanatory variables do not. This result suggests that changes in socioeconomic vulnerability are associated with changes in the relative magnitude of climate-related economic losses, even after controlling for time-invariant country characteristics and common temporal effects.

This finding highlights the relevance of socioeconomic conditions in understanding the distribution of climate-related economic losses. Countries and populations characterised by greater socioeconomic vulnerability may have fewer resources available to absorb, recover from, and adapt to climate-related shocks. Nevertheless, the observational design of the study does not allow this relationship to be interpreted as causal. The result should therefore be understood as evidence of a persistent statistical association between socioeconomic vulnerability and climate-related losses.

From a policy perspective, this finding suggests that climate adaptation strategies should not focus exclusively on physical or environmental exposure. Measures aimed at reducing socioeconomic vulnerability may also form an important component of climate resilience strategies. Policies supporting vulnerable households, improving access to essential services, strengthening social protection, and reducing disparities in adaptive capacity may contribute to improving resilience to climate-related shocks.

5.3. Environmental and Climate Factors

The positive associations between temperature, greenhouse-gas emissions, and the Log Loss Ratio observed in the baseline and mixed-effects specifications indicate that climatic and environmental conditions are relevant for understanding differences in climate-related losses. However, the loss of statistical significance of these variables under the fixed-effects specification indicates that these relationships may partly reflect persistent differences between countries.

In particular, the temperature coefficient should not be interpreted as evidence of a direct causal effect of higher national temperature on economic losses. Countries differ substantially in their geographical characteristics, exposure to climate hazards, infrastructure, economic structure, and adaptive capacity. Some of these characteristics may be relatively persistent over time and are absorbed by the country fixed effects [88].

Similarly, the positive association between greenhouse-gas emissions and climate-related losses observed in the baseline models should be interpreted cautiously. The present analysis uses total national greenhouse-gas emissions, while the dependent variable is expressed relative to GDP. Alternative measures, such as emissions per capita or carbon intensity, may provide additional information about the relationship between environmental pressures and economic losses.

Renewable-energy deployment also shows a positive association with the Log Loss Ratio in the baseline and mixed-effects models but loses statistical significance under the fixed-effects specification. This result should not be interpreted as evidence that renewable-energy deployment increases climate-related losses. Instead, the association may partly reflect the fact that countries experiencing greater climate-related challenges may simultaneously increase investment in renewable-energy transition policies. Reverse causality therefore remains a possible explanation that cannot be fully addressed within the present empirical specification.

5.4. Policy Implications

The findings have several implications for climate and socioeconomic policy in the European Union. First, the persistence of the association between the At-risk-of-Poverty Rate and climate-related losses under the fixed-effects specification suggests that climate adaptation policies should incorporate socioeconomic vulnerability as an explicit dimension of resilience. Adaptation measures targeted at vulnerable populations may be particularly relevant where limited economic resources constrain the capacity to prepare for and recover from climate-related events.

Second, the results support the continued relevance of mitigation and energy-transition policies, but the estimated coefficients should not be interpreted as causal effects. The associations identified in the baseline models suggest that environmental pressures and climate-related losses are interconnected, while the fixed-effects results indicate that part of this relationship may be explained by persistent differences across countries.

Recent evidence [89] suggests that the economic costs of climate inaction substantially exceed the investments required for mitigation and adaptation. According to a joint study by the Boston Consulting Group, the Cambridge Judge Business School, and the University of Cambridge climate TRACES Lab, allowing global warming to reach approximately 3 °C by 2100 could reduce cumulative global economic output by between 15% and 34%, whereas investments equivalent to 1–2% of cumulative GDP could substantially limit these damages.

Third, renewable-energy deployment is positively associated with the Log Loss Ratio within the estimated specification. This relationship should not be interpreted as evidence that renewable energy increases climate-related losses. Rather, it may indicate that countries facing greater climate-related challenges have simultaneously accelerated investments in renewable-energy transitions, adaptation measures, and broader sustainability policies. Consequently, the observed relationship may partly reflect reverse-causality mechanisms and should therefore be interpreted with caution.

Overall, the findings support an integrated approach combining climate adaptation, mitigation, energy transition, and measures aimed at reducing socioeconomic vulnerability. However, given the observational nature of the analysis and the limited time dimension of the panel, these implications should be interpreted as policy-relevant associations rather than evidence of direct causal effects.

6. Conclusions

This study examined the associations between climate-related economic losses and climatic, environmental, and socioeconomic factors across the 27 European Union Member States over the period 2015–2023. Climate-related losses were measured using the logarithm of climate-related losses relative to GDP, while annual average temperature, greenhouse-gas emissions, renewable-energy deployment, unemployment, and the At-risk-of-Poverty Rate were considered as explanatory variables.

The baseline OLS model identified statistically significant positive associations between the Log Loss Ratio and temperature, greenhouse-gas emissions, renewable-energy deployment, and the At-risk-of-Poverty Rate, whereas unemployment was not statistically significant. The mixed-effects panel model produced broadly similar results, with temperature, greenhouse-gas emissions, renewable-energy deployment, and the At-risk-of-Poverty Rate remaining statistically significant, while unemployment remained non-significant. These results suggest that socioeconomic vulnerability represents the most stable explanatory factor across alternative model specifications.

However, the country and year fixed-effects specification provides a more stringent assessment of the stability of these associations by controlling for time-invariant country-

specific characteristics and common temporal effects. Under this specification, temperature, greenhouse-gas emissions, renewable-energy deployment, and unemployment are no longer statistically significant, whereas the At-risk-of-Poverty Rate remains statistically significant ($p = 0.049$). In addition, the country effects are highly significant ($F = 124.211$; $p < 0.001$), indicating substantial heterogeneity across European Union Member States.

These findings suggest that some of the associations identified in the baseline and mixed-effects models may partly reflect persistent differences between countries rather than relationships that are consistently observed within countries over time. The results therefore highlight the importance of accounting for country-specific heterogeneity when analysing climate-related economic losses. At the same time, the persistence of the association between the At-risk-of-Poverty Rate and the Log Loss Ratio under the fixed-effects specification indicates that socioeconomic vulnerability remains statistically relevant after controlling for country-specific and temporal effects.

From a policy perspective, the findings support an integrated approach to climate resilience that combines climate adaptation with measures addressing socioeconomic vulnerability. The results suggest that adaptation policies should consider not only climatic and environmental conditions but also the socioeconomic capacity of countries and populations to absorb and recover from climate-related shocks. However, the estimated relationships should be interpreted as statistical associations rather than causal effects.

Overall, this study contributes to the empirical literature by showing that the apparent importance of climatic, environmental, and socioeconomic factors depends on the econometric specification employed. While temperature, greenhouse-gas emissions, renewable-energy deployment, and poverty are significant in both the OLS and mixed-effects specifications, the fixed-effects model highlights socioeconomic vulnerability as the most consistently supported explanatory factor. These findings emphasise the importance of accounting for country-specific heterogeneity when evaluating climate-related economic losses across European Union Member States.

7. Limitations and Further Discussion

This study presents several limitations that should be considered when interpreting the findings. First, the analysis is based on a country-year panel covering the 27 Member States of the European Union between 2015 and 2023. Consequently, the results reflect associations at the national level and may not fully capture regional and local heterogeneity within individual countries. Furthermore, the relatively short time dimension of the dataset ($T = 9$) limits our ability to investigate long-run dynamic relationships and causal mechanisms. The estimated models should therefore be interpreted as identifying statistical associations rather than causal effects.

Second, although the analysis incorporates indicators of socioeconomic conditions, only the At-risk-of-Poverty Rate exhibited a statistically significant relationship with climate-related losses. Other dimensions of vulnerability, including institutional capacity, demographic structure, governance quality, adaptive resilience, and social inequality, are not explicitly captured by the available dataset. Future research could incorporate a broader set of socioeconomic and institutional indicators to provide a more comprehensive assessment of climate vulnerability.

Third, the analysis relies on aggregated national indicators and therefore cannot explicitly account for substantial differences in exposure, vulnerability, and adaptation capacity across regions, metropolitan areas, or individual cities within the same country. Future research could extend the temporal coverage of the dataset, incorporate regional or city-level observations, and integrate additional climate-risk indicators, environmental variables, and measures of adaptive capacity. The use of geospatial information, remote-sensing

products, and advanced statistical or machine-learning techniques may also contribute to a more detailed understanding of the determinants of climate-related economic losses across Europe.

Finally, although the mixed-effects panel model accounts for both country-specific heterogeneity and temporal variation, it remains subject to several methodological limitations. The specification assumes that country-level random effects are uncorrelated with the explanatory variables, an assumption that may not be fully justified in practice. In addition, the relatively short time dimension of the panel ($T = 9$) limits the ability to capture long-term dynamics and structural changes. Consequently, the estimated coefficients should be interpreted as conditional associations within the observed sample rather than as evidence of long run or causal relationships.

Moreover, the mixed-effects specification cannot fully eliminate the possibility of omitted-variable bias arising from unobserved factors that vary across countries and over time. Institutional quality, governance structures, adaptive capacity, demographic composition, and regional exposure to climate hazards may also influence climate-related losses but are not explicitly incorporated into the estimated models. Although the country and year fixed-effects specification provides a more stringent robustness assessment, it cannot fully eliminate all sources of omitted-variable bias or reverse causality.

An additional limitation concerns the measurement of greenhouse-gas emissions. The present study employs total national emissions in order to maintain consistency with the harmonised Eurostat indicators used throughout the analysis. However, alternative indicators such as emissions per capita or carbon-intensity measures may capture different dimensions of environmental pressure and could yield different results. Future research should examine whether the relationships identified in this study remain robust when alternative emissions metrics are employed.

Furthermore, the positive association identified between renewable-energy deployment and climate-related losses may partly reflect reverse causality. Countries facing greater climate-related challenges may simultaneously accelerate investments in renewable-energy transition policies and climate adaptation measures. Accordingly, this relationship should be interpreted cautiously and not as evidence of a direct causal effect of renewable-energy deployment on climate-related economic losses.

Finally, the positive association identified between renewable-energy deployment and climate-related losses may partly reflect reverse causality. Countries facing greater climate-related challenges may simultaneously accelerate investments in renewable-energy transition policies. Accordingly, this relationship should be interpreted cautiously and not as evidence of a direct causal effect of renewable-energy deployment on climate-related economic losses.

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References

1. NASA. *National Aeronautics and Space Administration Shifting Distribution of Land Temperature Anomalies, 1964–2024*; NASA: Washington, DC, USA, 2025.
2. Judd, E.A.; Tierney, J.E.; Lunt, D.J.; Montañez, I.P.; Huber, B.T.; Wing, S.L.; Valdes, P.J. A 485-million-year history of Earth's surface temperature. *Science* **2024**, *385*, eadk3705. [CrossRef] [PubMed]
3. Intergovernmental Panel on Climate Change [IPCC]. *Global Warming of 1.5 °C*; Cambridge University Press: Cambridge, UK, 2022; pp. 541–562. [CrossRef]
4. World Meteorological Organization. *WMO Confirms 2024 as Warmest Year on Record at About 1.55 °C Above Pre-Industrial Level*; World Meteorological Organization: Geneva, Switzerland, 2025. Available online: https://wmo.int/news/media-centre/wmo-confirms-2024-warmest-year-record-about-155degc-above-pre-industrial-level (accessed on 12 May 2026).
5. Byers, E.A.; Gidden, M.; Leclère, D.; Balkovič, J.; Burek, P.; Ebi, K.; Greve, P.; Grey, D.; Havlik, P.; Hillers, A.; et al. Global exposure and vulnerability to multi-sector development and climate change hotspots. *Environ. Res. Lett.* **2018**, *13*, 055012. [CrossRef]
6. United Nations. Climate Change. Paris Agreement from the Paris Agreement|UNFCCC. Available online: https://unfccc.int/process-and-meetings/the-paris-agreement (accessed on 31 May 2026).
7. United Nations. Climate Change Nationally Determined Contributions (NDCs)|UNFCCC. Available online: https://unfccc.int/process-and-meetings/the-paris-agreement/nationally-determined-contributions-ndcs (accessed on 31 May 2026).
8. Jackson, R. Eunice Foote, John Tyndall and a question of priority. *Notes Rec.* **2020**, *74*, 105–118. [CrossRef]
9. Foote, E. Circumstances affecting the heat of the sun's rays. *Am. J. Sci. Arts* **1856**, *22*, 382–383.
10. Jones, M.D.H.; Henderson-Sellers, A. History of the greenhouse effect. *Prog. Phys. Geogr.* **1990**, *14*, 1–18. [CrossRef]
11. Meadows, D.H.; Meadows, D.L.; Randers, J.; Behrens, W.W. *The Limits to Growth: A Report for the Club of Rome's Project on the Predicament of Mankind*; Universe Books: Cleveland, OH, USA, 1972.
12. Turner, G.M. A comparison of the Limits to Growth with 30 years of reality. *Glob. Environ. Change* **2008**, *18*, 397–411. [CrossRef]
13. Turner, G.M. *Is Global Collapse Imminent? An Updated Comparison of the Limits to Growth with Historical Data*; Melbourne Sustainable Society Institute: Parkville, Australia, 2014.
14. Herrington, G. Update to limits to growth: Comparing the World3 model with empirical data. *J. Ind. Ecol.* **2021**, *25*, 614–626. [CrossRef]
15. Berkeley Earth. Global Temperature Report for 2024. 2025. Available online: https://berkeleyearth.org/global-temperature-report-for-2024/ (accessed on 30 August 2026).
16. Ciais, P.; Zhu, Y.; Cai, Y.; Lan, X.; Michel, S.E.; Zheng, B.; Zhao, Y.; Hauglustaine, D.A.; Lin, X.; Zhang, Y.; et al. Why Methane Surged in the Atmosphere During the Early 2020s. *Science* **2026**, *391*, eadx8262. [CrossRef] [PubMed]
17. World Meteorological Organization (WMO). *State of the Global Climate 2025*; World Meteorological Organization: Geneva, Switzerland, 2026.
18. Institute and Faculty of Actuaries. Parasol Lost: Recovery Plan Needed: Global Risk Management for Human Prosperity. 2026. Available online: https://actuaries.org.uk (accessed on 30 August 2026).
19. Díaz-Rodríguez, F.; Robles Fernández, M.D. A multi-factor climate risk index (CRI) for fossil fuels and ESG investments: A jar full of CRI-kets. *Sustain. Futures* **2026**, *11*, 101717. [CrossRef]
20. Chang, P.; Fu, D.; Liu, X.; Castruccio, F.S.; Prein, A.F.; Danabasoglu, G.; Wang, X.; Bacmeister, J.; Zhang, Q.; Rosenbloom, N.; et al. Future extreme precipitation amplified by intensified mesoscale moisture convergence. *Nat. Geosci.* **2025**, *19*, 1021–1028. [CrossRef]
21. Dechezleprêtre, A. *OECD Industrial Policy Spending Across 20 Countries: What Governments Actually Fund*; Industrial Policy Spending in OECD Countries: Recent Trends and Insights; OECD: Paris, France, 2026.
22. Bednar-Friedl, B.; Biesbroek, R.; Schmidt, D.N.; Alexander, P.; Børsheim, K.Y.; Carnicer, J.; Georgopoulou, E.; Haasnoot, M.; Le Cozannet, G.; Lionello, P.; et al. Europe. In *Climate Change 2022: Impacts, Adaptation, and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*; Pörtner, H.-O., Roberts, D.C., Tignor, M., Poloczanska, E.S., Mintenbeck, K., Alegría, A., Craig, M., Langsdorf, S., Löschke, S., Möller, V., et al., Eds.; Cambridge University Press: Cambridge, UK, 2022; pp. 1817–1927. [CrossRef]
23. European Environment Agency (EEA). *Economic Losses from Weather- and Climate-Related Extremes in Europe*; European Environment Agency: Copenhagen, Denmark, 2024. Available online: https://www.eea.europa.eu/en/analysis/indicators/economic-losses-from-climate-related (accessed on 30 August 2026).
24. Burke, M.; Hsiang, S.; Miguel, E. Global non-linear effect of temperature on economic production. *Nature* **2015**, *527*, 235–239. [CrossRef] [PubMed]
25. Kotz, M.; Levermann, A.; Wenz, L. The economic commitment of climate change. *Nature* **2023**, *628*, 551–557. [CrossRef] [PubMed]
26. International Energy Agency. Europe. 2023. Available online: https://www.iea.org/regions/europe (accessed on 7 June 2026).
27. Future Earth; The Earth League; World Climate Research Programme. *10 New Insights in Climate Science 2025/2026*; Future Earth: Stockholm, Sweden, 2025.

28. Calvo-Sancho, C.; Díaz-Fernández, J.; González-Alemán, J.J.; Halifa-Marín, A.; Miglietta, M.M.; Azorin-Molina, C.; Prein, A.F.; Montoro-Mendoza, A.; Bolgiani, P.; Morata, A.; et al. Human-induced climate change amplification on storm dynamics in Valencia's 2024 catastrophic flash flood. *Nat. Commun.* **2026**, *17*, 1492. [CrossRef] [PubMed]
29. Grünig, M.; Rammer, W.; Senf, C.; Albrich, K.; André, F.; Augustynczik, A.L.D.; Baumann, M.; Bohn, F.J.; Bouwman, M.; Bugmann, H.; et al. Climate change will increase forest disturbances in Europe throughout the 21st century. *Science* **2026**, *391*, eadx6329. [CrossRef] [PubMed]
30. Bourdin, S.; Perrot, A. Breaking free from the regional carbon trap: Analysing the persistence of CO_2 emissions in EU regions. *Camb. J. Reg. Econ. Soc.* **2026**, *19*, 49–67. [CrossRef]
31. Martín-Ortega, J.L.; González-Sánchez, M. Sectoral composition of GDP and greenhouse gas emissions: An empirical analysis in EU27. *Environ. Dev. Sustain.* **2025**, *27*, 3899–3926.
32. Vagnini, C.; Vieira, L.C.; Longo, M.; Mura, M. Regional drivers of industrial decarbonization: A spatial econometric analysis of 238 EU regions between 2008 and 2020. *Reg. Stud.* **2024**, *59*, 2380369. [CrossRef]
33. Bettarelli, L.; Yarveisi, K. Climate change policies and emissions in European regions: Disentangling sources of heterogeneity. *Reg. Stud. Reg. Sci.* **2023**, *10*, 722–741. [CrossRef]
34. Buffi, M.; Motola, V.; Rejtharova, J.; Hurtig, O.; Scarlat, N.; Mountraki, A.; Georgakaki, A.; Salvucci, R.; Schade, B.; Rózsai, M.; et al. *Renewable Fuels of Non-Biological Origin in the European Union: 2025 Status Report on Technology Development, Trends, Value Chains and Markets*; Publications Office of the European Union: Luxembourg, 2026.
35. Hurka, S.; Steinebach, Y. Legal complexity undermines effective climate policy implementation. *Clim. Policy* **2026**. [CrossRef]
36. Haag, M.; Hurka, S.; Kaplaner, C. Policy complexity and implementation performance in the European Union. *Regul. Gov.* **2025**, *19*, 656–674. [CrossRef]
37. European Scientific Advisory Board on Climate Change (ESABCC). *Strengthening Resilience to Climate Change—Recommendations for an Effective EU Adaptation Policy Framework*; Publications Office of the European Union: Luxembourg, 2026; ISBN 978-92-9480-744-1. [CrossRef]
38. Copernicus Climate Change Service (C3S). Demonstrating Heat Stress in European Cities. 2021. Available online: https://climate.copernicus.eu (accessed on 30 August 2026).
39. Schwingshackl, C.; Daloz, A.S.; Iles, C.; Aunan, K.; Sillmann, J. High-resolution projections of ambient heat for major European cities using different heat metrics. *Nat. Hazards Earth Syst. Sci.* **2024**, *24*, 331–354. [CrossRef]
40. Steensen, B.M.; Myhre, G.; Hodnebrog, Ø.; Fischer, E. Future increase in European compound events where droughts end in heavy precipitation. *npj Clim. Atmos. Sci.* **2025**, *8*, 267. [CrossRef]
41. Rousi, E.; Kornhuber, K.; Beobide-Arsuaga, G.; Luo, F.; Coumou, D. Accelerated western European heatwave trends linked to more-persistent double jets over Eurasia. *Nat. Commun.* **2022**, *13*, 3851. [CrossRef] [PubMed]
42. Mohajerani, A.; Bakaric, J.; Jeffrey-Bailey, T. The urban heat island effect, its causes, and mitigation, with reference to the thermal properties of asphalt concrete. *J. Environ. Manag.* **2017**, *197*, 522–538. [CrossRef] [PubMed]
43. Zhao, Y.; Zhang, W.; Mei, S.; Liang, J.; Zeng, L.; Hang, J.; Buccolieri, R. Integrated impacts of anthropogenic heat locations and building configurations on urban wind-thermal environments and pollutant exposure in two-dimensional street canyons. *City Environ. Interact.* **2025**, *28*, 100251. [CrossRef]
44. Paschalis, A.; Chakraborty, T.; Fatichi, S.; Meili, N.; Manoli, G. Urban forests as main regulator of the evaporative cooling effect in cities. *AGU Adv.* **2021**, *2*, e2020AV000303. [CrossRef]
45. Lu, Y.; Shao, Z.; Lu, H. Quantification of anthropogenic heat and simulation of its effects on environment and climate: A comprehensive review. *Renew. Sustain. Energy Rev.* **2024**, *204*, 114802. [CrossRef]
46. Katavoutas, G.; Founda, D.; Varotsos, K.V.; Giannakopoulos, C. Climate change impacts on thermal stress in four climatically diverse European cities. *Int. J. Biometeorol.* **2022**, *66*, 2339–2355. [CrossRef] [PubMed]
47. Copernicus Climate Change Service. European State of the Climate: Striking East-West Contrast and Widespread Flooding—Europe's Warmest Year. 2025. Available online: https://climate.copernicus.eu/european-state-climate-striking-east-west-contrast-and-widespread-flooding-europes-warmest-year (accessed on 30 August 2026).
48. Buras, A.; Rammig, A.; Zang, C.S. Quantifying impacts of the 2018 drought on European ecosystems in comparison to 2003. *Biogeosciences* **2020**, *17*, 1655–1672. [CrossRef]
49. European Environment Agency. *Urban Adaptation in Europe: What Works?* EEA Report No. 14/2023; Publications Office of the European Union: Luxembourg, 2024. Available online: https://www.eea.europa.eu/en/analysis/publications/urban-adaptation-in-europe-what-works (accessed on 30 August 2026).
50. Laino, E.; Iglesias, G. Extreme climate change hazards and impacts on European coastal cities: A review. *Renew. Sustain. Energy Rev.* **2023**, *184*, 113587. [CrossRef]
51. Lauwaet, D.; Berckmans, J.; Hooyberghs, H.; Wouters, H.; Driesen, G.; Lefebre, F.; De Ridder, K. High resolution modelling of the urban heat island of 100 European cities. *Urban Clim.* **2024**, *55*, 101850. [CrossRef]

52. Copernicus Climate Change Service (C3S); World Meteorological Organization (WMO). *European State of the Climate 2024*; World Meteorological Organization: Geneva, Switzerland, 2025. Available online: https://climate.copernicus.eu/european-state-climate (accessed on 1 August 2026).
53. European Environment Agency. Economic Losses from Weather- and Climate-Related Extremes in Europe. 2025. Available online: https://www.eea.europa.eu (accessed on 30 August 2026).
54. Feyen, L.; Ciscar Martinez, J.; Gosling, S.; Ibarreta Ruiz, D.; Soria Ramirez, A.; Dosio, A.; Naumann, G.; Russo, S.; Formetta, G.; Forzieri, G.; et al. *Climate Change Impacts and Adaptation in Europe*; European Commission, Joint Research Centre (JRC): Brussels, Belgium, 2020. Available online: https://publications.jrc.ec.europa.eu (accessed on 30 August 2026).
55. World Bank. *Unlivable: How Cities in Europe and Central Asia Can Survive and Thrive in a Hotter Future*; World Bank Group: Washington, DC, USA, 2025. Available online: https://www.worldbank.org (accessed on 30 August 2026).
56. Bilal, A.; Känzig, D.R. *The Macroeconomic Impact of Climate Change: Global vs. Local Temperature*; Working Paper No. 32450; National Bureau of Economic Research: Cambridge, MA, USA, 2026. [CrossRef]
57. IPCC. *Climate Change 2023: Synthesis Report*; Intergovernmental Panel on Climate Change: Geneva, Switzerland, 2023.
58. Hickel, J.; Kallis, G. Is Green Growth Possible? *New Political Econ.* **2020**, *25*, 469–486. [CrossRef]
59. International Energy Agency. *World Energy Outlook 2023*; IEA: Paris, France, 2023.
60. Jackson, T. *Prosperity Without Growth: Foundations for the Economy of Tomorrow*, 2nd ed.; Routledge: Oxfordshire, UK, 2017.
61. The Guardian. Economic growth is still heating the planet. Is there any way out? *Climate crisis|The Guardian*, 9 February 2026.
62. Andrés, J.; Doménech, R. Cambio climático y crecimiento económico. *Revista de Geoeconomía*. 2020. Available online: https://www.uv.es/rdomenec/AD_Cambio_Climatico_y_Crecimiento%20Economico_Dic2019_vf.pdf (accessed on 15 July 2026).
63. European Climate and Health Observatory. *Heat and Health*; European Environment Agency: Copenhagen, Denmark, 2024.
64. International Labor Organization. *Working on a Warmer Planet: The Impact of Heat Stress on Labour Productivity*; ILO: Geneva, Switzerland, 2019.
65. Estrada, F.; Lupi, V.; Botzen, W.; Tol, R.S.J. Urban and Non-Urban Contributions to the Social Cost of Carbon. *Nat. Commun.* **2025**, *16*, 4193. [CrossRef] [PubMed]
66. Tol, R.S.J. A Meta-Analysis of the Total Economic Impact of Climate Change. *Energy Policy* **2022**, *185*, 113922. [CrossRef]
67. European Environment Agency. Harm to Human Health from Air Pollution in Europe: Burden of Disease Status, 2025 (Briefing No. 12/2025). 2025. Available online: https://www.eea.europa.eu/en/analysis/publications/harm-to-human-health-from-air-pollution-burden-of-disease-status-2025 (accessed on 30 August 2026).
68. Ballester, J.; Quijal-Zamorano, M.; Méndez Turrubiates, R.F.; Pegenaute, F.; Herrmann, F.R.; Robine, J.M.; Basagaña, X.; Tonne, C.; Antó, J.M.; Achebak, H. Heat-related mortality in Europe during the summer of 2022. *Nat. Med.* **2023**, *29*, 1857–1866. [CrossRef] [PubMed]
69. van Daalen, K.R.; Romanello, M.; Rocklöv, J.; Semenza, J.C.; Tonne, C.; Markandya, A.; Dasandi, N.; Jankin, S.; Achebak, H.; Ballester, J.; et al. The 2022 Europe report of the Lancet Countdown on health and climate change: Towards a climate resilient future. *Lancet Public Health* **2022**, *7*, E942–E965. [CrossRef] [PubMed]
70. Soares, J.; Plass, D.; Kienzler, S.; González Ortiz, A.; Gsella, A.; Horálek, J. *Assessing the Environmental Burden of Disease Related to Air Pollution in Europe in 2023*; (Eionet Report–ETC HE 2025/8); European Topic Centre on Human Health and the Environment: Cornwall, UK, 2025. [CrossRef]
71. Niedzwiedz, C.; Katikireddi, S.V. Determinants of eco-anxiety: Cross-national study of 52,219 participants from 25 European countries. *Eur. J. Public Health* **2023**, *33*, ckad160.069. [CrossRef]
72. Collery, A.; Niedzwiedz, C.L. Climate change worry and the association with future depression and anxiety: Cross-national analysis of 11 European countries. *BMJ Ment. Health* **2025**, *28*, e301318. [CrossRef] [PubMed]
73. Islam, M.S. Rethinking Climate Justice: Insights from Environmental Sociology. *Climate* **2024**, *12*, 203. [CrossRef]
74. Leone, M.; D'Ippoliti, D.; De Sario, M.; Analitis, A.; Menne, B.; Katsouyanni, K.; De' Donato, F.K.; Basagana, X.; Salah, A.B.; Casimiro, E.; et al. A time series study on the effects of heat on mortality and evaluation of heterogeneity into European and Eastern-Southern Mediterranean cities: Results of EU CIRCE project. *Environ. Health* **2013**, *12*, 55. [CrossRef] [PubMed] [PubMed Central]
75. Paniello-Castillo, B.; Chen, Z.Y.; Shartova, N.; Méndez Turrubiates, R.F.; Beltrán, N.; Peyrusse, F.; Achebak, H.; Raffetti, E.; Ballester, J. Socio-economic factors impact vulnerability to and burden of heat- and cold-related mortality in Europe. *Nat. Health* **2026**, *1*, 647–656. [CrossRef]
76. Masselot, P.; Mistry, M.; Vanoli, J.; Schneider, R.; Iungman, T.; Garcia-Leon, D.; Ciscar, J.C.; Feyen, L.; Orru, H.; Urban, A.; et al. Excess mortality attributed to heat and cold: A health impact assessment study in 854 cities in Europe. *Lancet Planet. Health* **2023**, *7*, e271–e281. [CrossRef] [PubMed]
77. The Economist. Where will Europe's Heatwave Be Most Deadly? 2026. Available online: https://www.economist.com/graphic-detail/2026/06/25/where-will-europes-heatwave-be-most-deadly (accessed on 30 August 2026).

78. Simpson, C.H.; Brousse, O.; Heaviside, C. Estimated mortality attributable to the urban heat island during the record-breaking 2022 heatwave in London. *Environ. Res. Lett.* **2024**, *19*, 094047. [CrossRef] [PubMed]
79. Díaz-Poso, A.; Lorenzo, N.; Martí, A.; Royé, D. Heat and cold wave intensity and spatial extent on the Iberian Peninsula: Future climate projections (2050–2095). *Clim. Dyn.* **2025**, *63*, 222. [CrossRef]
80. Huang, W.T.K.; Masselot, P.; Bou-Zeid, E.; Fatichi, S.; Paschalis, A.; Sun, T.; Manoli, G. Economic valuation of temperature-related mortality attributed to urban heat islands in European cities. *Nat. Commun.* **2023**, *14*, 7438. [CrossRef] [PubMed]
81. European Union. Key Facts and Figures on the European Union. 2024. Available online: https://european-union.europa.eu/principles-countries-history/facts-and-figures-european-union_en (accessed on 30 August 2026).
82. European Commission. European Climate Action Progress Report 2024. Publications Office of the European Union, 2024. Available online: https://climate.ec.europa.eu (accessed on 30 August 2026).
83. European Environment Agency. Trends and Projections in Europe 2024: Tracking Progress Towards Europe's Climate and Energy Targets. EEA Report. European Environment Agency. 2024. Available online: https://www.eea.europa.eu/publications/trends-and-projections-in-europe-2024 (accessed on 30 August 2026).
84. Eurostat Database. *Climate Related Economic Losses, Domestic Net Greenhouse Gas Emissions, Investments in Climate Change Mitigation, GDP, Share of Renewable Energy in Gross Final Energy Consumption by Sector %*; Database-Eurostat (europa.eu): Luxembourg, 2025.
85. Copernicus Climate Change Service (C3S). ERA5 Reanalysis Dataset. European Centre for Medium-Range Weather Forecasts (ECMWF). Available online: https://climate.copernicus.eu/climate-reanalysis (accessed on 15 July 2026).
86. Wooldridge, J.M. *Introductory Econometrics: A Modern Approach*, 7th ed.; Cengage Learning: Boston, MA, USA, 2020.
87. Greene, W.H. *Econometric Analysis*, 8th ed.; Pearson: London, UK, 2018.
88. Nasa Goddard Institute for Space Studies (GISS). Global Annual Mean Surface Air Temperature Change (GISTEMP v4). 2026. Available online: https://data.giss.nasa.gov/gistemp/graphs_v4/ (accessed on 30 August 2026).
89. Benayad, A.; Hagenauer, A.; Holm, L.; Jones, E.R.; Kämmerer, S.; Maher, H.; Mohaddes, K.; Santamarta, S.; Zawadzki, A. *Too Hot to Think Straight, Too Cold to Panic: Landing the Economic Case for Climate Action with Decision Makers*; Boston Consulting Group (BCG): Boston, MA, USA; Cambridge Judge Business School: Cambridge, UK; University of Cambridge clima TRACES Lab.: Cambridge, UK, 2025.

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