econPOL
POLICY REPORT

55
2025

April
Vol. 9

The Macroeconomic Impact of Different Decarbonization Paths and Strategies

Simone Borghesi and Jacopo Cammeo

CESifo ifo INSTITUTE

EconPol Europe is CESifo's economic policy platform. With key support from the ifo Institute, it seeks to leverage CESifo's globe-spanning network of more than 2,000 high-ranked economists – 14 of whom have won the Nobel Prize – and ifo's decades-deep research expertise to provide well-founded advice to European policymakers and to facilitate informed decisions. Drawing on the wide range of specializations of its members, EconPol's mission is to contribute to the crafting of evidence-based, effective economic policy in the face of the rapidly evolving challenges faced by the European economies and their global partners.

EconPol POLICY REPORT
A publication of the CESifo Research Network

Publisher and distributor: CESifo GmbH
Poschingerstr. 5, 81679 Munich, Germany
Telephone +49 89 9224-0, Email office@cesifo.de
Shipping not included
Editor of this issue: Clemens Fuest, Cornelia Geißler

EconPol Europe: www.econpol.eu

The Macroeconomic Impact of Different Decarbonization Paths and Strategies

Simone Borghesi (European University Institute and University of Siena) and Jacopo Cammeo (European University Institute)

Abstract

The severe upheavals caused by anthropogenic climate change have led to an increasing global effort to mitigate the negative effects of global warming. In this, the European Union has taken the lead in pioneering initiatives to achieve carbon neutrality as a continent by 2050. The climate policies put in place follow a deep decarbonization approach, aiming at a quick response to the climate crisis through the pursuit of stringent goals. These numerous and ambitious policies have led to some encouraging results, but they look challenging for their potential impact on the socio-economic system.

The existing literature and the work of relevant research centers on environmental economics find that the paradigm shift should not lead to significant effects on macroeconomic variables such as GDP, inflation, employment, investment, and industrial production. However, it is clear that the qualitative transformation required to move from a fossil fuel-based society to a net-zero carbon one is not painless. At least in the short term, stringent climate policies may take on the contours of a real shock, with potentially unfavorable and, above all, unfair macroeconomic repercussions. If not properly guided, the phasing out of fossil fuels and the extension of carbon markets to new sectors not previously covered by the mechanism might impact the most vulnerable segments of the population, squeezing economic development, negatively affecting employment, and undermining consumption.

To avoid the adverse effects of decarbonization, Europe has several mechanisms at its disposal, such as the Just Transition Mechanism, the redistribution of EU ETS2 revenues to the Social Climate Fund, and plans for clean industrial production and green technologies. However, further efforts will be needed to mitigate the impact of the net-zero strategy on citizens' purchasing power, avoid stranded assets, sustain green conversion efforts of the industrial system, and support the development of new technologies such as carbon capture, utilization, and storage.

The new European Commission will have to deal with a complex macroeconomic situation already geared toward stringent but fair climate policies. The hope is to meet the planned timetable without compromising the socio-economic system, respecting the motto "leave no one behind" and at the same time coming close to the stringent goals of the Paris Agreement.

Executive Summary

Political entities at the European level largely support the decarbonization of the economic system, as shown by the broad consensus within EU institutions that has led to the ratification of advanced environmental regulations in the past five years.

This journey comes from afar and starts from the widely shared global understanding that only a joint effort can lead to implementing strategies and mechanisms for global warming adaptation and mitigation. In pursuing this effort, Europe is not alone; other major economies have embarked on the road to decarbonization, albeit at different speeds. Instead, the EU is the first continent to set a goal of moving to a net-zero paradigm by 2050. Its first move is a symbolic demonstration of the role taken by the EU in the ongoing transition, as well as a potential virtuous example for other continents to follow. Nevertheless, there is widespread emerging concern that the ambitious goal of making Europe carbon-neutral by 2050 could adversely impact the continent's macroeconomy. In other words, as many observers argue, policies should consider the climate and transitional risks.

Undeniably, climate change's physical impacts have repercussions on GDP, as temperature increases have been shown to harm economic growth and inflation (Bilal and Känzig 2024). The effects of transitioning to decarbonization are also significant, as they impact macroeconomic variables: paradigm shifts can lead to a GDP decrease caused by costs of new technologies and disruption of existing industries, just as extra costs of new climate policies can impact inflation.

The European parliamentary elections of June 2024 could represent a turning point for European Union climate policies. European citizens have elected their representatives in a context of growing skepticism and protests toward the decisions of Brussels and Strasbourg on environmental matters. After proposing the complex EU Green Deal and implementing various initiatives in support of the plan, European institutions will now have to deal with the social acceptability of climate policies, namely the acceptance by citizens of more stringent climate measures.
The major challenge is represented by the goal set by the first von der Leyen Commission to make Europe a carbon-neutral continent by 2050. Such an

ambitious aim carries significant socio-economic consequences, provoking resistance from some critical productive sectors.

One significant macroeconomic concern revolves around the impact on GDP growth. Decarbonization often entails substantial investments in renewable energy infrastructure, energy efficiency measures, and transitioning away from carbon-intensive industries (Claeys et al. 2024). While these investments are crucial for long-term sustainability, they may initially strain economic growth due to the redirection of resources away from other sectors. Additionally, industries reliant on fossil fuels, such as traditional manufacturing and energy production, may experience declines because of the low degree of substitutability of their products, leading to short-term economic disruptions and job losses.

The net-zero strategy also holds significant potential for reshaping private consumption patterns and, consequently, impacting macroeconomic dynamics. Transitioning toward a carbon-neutral economy may increase energy-intensive goods and services costs, potentially affecting household budgets. Higher transportation, heating, and electricity prices could reduce disposable income, dampening consumer spending in the long term.

Moreover, the transition could exacerbate inequalities within and among European countries. Regions heavily reliant on carbon-intensive industries may face disproportionate economic challenges, leading to social unrest and political tensions. Without targeted policies to support affected communities and workers through retraining programs and investment in new economic sectors, the decarbonization process risks widening socio-economic disparities. Quantifying and assessing these effects is necessary to propose increasingly effective and efficient policies, but conducting an evaluation is often complex. Theoretical models, like Integrated Assessment Models or Dynamic Stochastic General Equilibrium models, provide different results in terms of timeframe and expected outcomes. However, as it will emerge from the report, there exists a large consensus in the literature on the fact that, if properly guided, the decarbonization process will not cause disruptions that could compromise the macroeconomic development of the continent. The problem concerns the distributional effects of climate policies: their impact on low-income consumers and SMEs. That is why, of the two most plausible scenarios presented in the literature (1.5°C scenario and Below 2°C scenario), some authors suggest aiming directly for the less ambitious one to implement policies under the banner of realism and pragmatism.

This report synthesizes scenario analyses performed by renowned European and global institutions and research centers. The main findings from existing macroeconomic simulations on the impact of different decarbonization paths and strategies are:

- Stringent decarbonization measures may reduce Euro Area GDP growth from 0.15 to 0.25 percentage points annually (IMF 2022).
- GDP is expected to contract by roughly 1.2% by 2030, with an annual decline in growth of roughly one-eighth of a percentage point. Most notably, at its lowest point, investments fall by around 2.5%, while overall consumption is cut down by about 0.7% (Coenen et al. 2024).
- Pursuing an ambitious 1.5°C scenario, aligned with the Paris Agreement, could result in higher GDP losses compared to a Below 2°C reference scenario, ranging from -0.9% to -6.2% cumulatively from 2020 to 2050, depending on different carbon revenue recycling strategies (Kriegler et al. 2023).
- Indeed, reinvesting carbon tax revenues into reducing labor taxes and social contributions may alleviate these losses, potentially reducing GDP declines by 30% to 70% (Kriegler et al. 2023).
- According to simulations, inflation will increase by 0.2 percentage points if the carbon tax is raised to EUR 140/tCO_2 on a timeline that corresponds with the European Green Deal (Coenen et al. 2024).
- At the global level, a carbon tax of 14.2 times the current fossil fuel price is required to meet the target of the Paris Agreement, but this would lead to severe economic impacts, including unemployment peaking at 17.6% between 2024 and 2028 (baseline: 4.4%) and company bankruptcies increasing from 7.9 to 13.4 annually (Lamperti et al. 2022).
- Instead, industrial regulations and green technology subsidies as part of a policy mix bring more solid outcomes. A ban on new fossil fuel power plants by 2041, combined with green subsidies, will keep global warming below 1.9°C by 2100 while imposing only a modest fiscal impact (Lamperti et al. 2022).
- Transitioning to a low-carbon economy could generate approximately 1.2 to 1.7 million new jobs in Europe in energy sectors aligned with this transition by 2050 while losing about 300,000 jobs in fossil fuel sectors (Kriegler et al. 2023).

- However, results may change across countries, due to the sectoral composition and international trade position of the economies.[1] In particular, job losses are expected to be significant for some geographies and sectors, which may increase economic inequities. For example, an increase in energy prices by 10% will likely determine a 17.9% growth in the employment of technicians and a 13.1% reduction in manual jobs (Marin and Vona 2018).
- Net-zero strategies may impact exports, potentially due to the expansion of the Carbon Border Adjustment Mechanism aimed at reducing carbon leakage (European Commission 2024b).
- The extent of international policy coordination can significantly influence economic outcomes, with greater cooperation generally leading to better performance (Vrontisi et al. 2020).

The analyzed models reveal differing approaches to decarbonization, highlighting trade-offs between rapid and gradual strategies. While fast decarbonization aims to avert severe climate impacts through renewable energy growth, gradual approaches emphasize economic stability and adaptability.

Based on these findings, we discuss eight different aspects of the net-zero process: impact on GDP; impact on employment; carbon pricing and its impact on low-income consumers; phasing out of fossil fuels and promoting renewable energies; effects on capital markets and stranded assets; supporting competitiveness in the EU decarbonization path; investing in research and development (R&D) for carbon capture technologies; and reinforcing international collaboration on climate policies.

While the impact on GDP is significant, it may be partially offset by investment; the effect on employability is complex, especially for workers currently employed in discontinued sectors. For them to participate in and benefit from the green transition, it must be inclusive. Ensuring the fulfilment of the EU's economic and climatic objectives will need concerted measures in the areas of reskilling, lowering labor market inequality, and aiding vulnerable regions.
Research frequently does not take equity into proper account. Advocates of both drastic and gradual carbon neutrality concur that redistributing income from carbon pricing will lessen the distributional effects. Carbon markets like the EU

[1] See, for instance, Aubert et al. (2019) and Lehtonen et al. (2022) for a discussion of the expected impact of the transition on the agrifood sector in France and Finland, respectively.

ETS can successfully lower emissions by raising the cost of high-carbon options and providing support for technological improvements. The EU ETS has effectively targeted major polluters, but its expansion needs to be carefully managed to address changing climate issues.

Phasing out fossil fuel subsidies and promoting renewable energies can accelerate the transition to a low-carbon economy by redirecting financial resources toward sustainable energy sources, reducing reliance on fossil fuels, and fostering innovation in renewable technologies. The cost of solar and wind PV has significantly decreased over the past ten years – by more than 80% in recent years (Fragkos et al. 2021). By 2050, solar and wind power is expected to produce over 70% of the world's electricity. The demand for fossil fuels is predicted to decline sharply, with natural gas forecast to fall by 55%, coal by 90%, and oil by 75% (IEA 2021).

Phasing out fossil fuels could determine some assets becoming stranded (Saygin et al. 2019). In contrast to the 1.5°C scenario, which requires rapid action to mitigate climate change and presents immediate risk from stranded assets, the pathway Below 2°C is more gradual but still challenging.

Supporting competitiveness with specific comprehensive industrial initiatives – such as the Just Transition Mechanism and the Net-Zero Industry Act – ensures that industries remain competitive while transitioning to cleaner production methods, fostering economic growth and job creation in sustainable sectors.

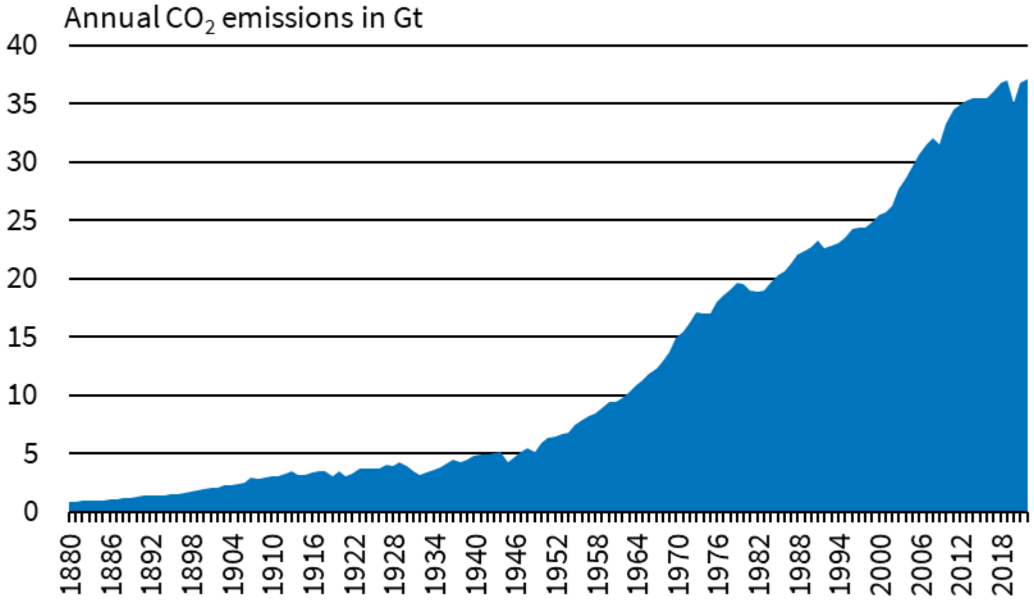
In addition, investing in research and development for carbon capture technologies facilitates the removal of CO_2 from the atmosphere, aiding in the mitigation of greenhouse gas emissions and advancing the transition to a carbon-neutral future.

Last, enhancing international cooperation to align decarbonization efforts globally strengthens collective efforts to combat climate change, enabling the sharing of best practices, technologies, and resources to achieve global emission reduction goals and mitigate the impacts of climate change on a worldwide scale. The linking of emissions trading schemes is a valuable example of future collaborations between Europe and other jurisdictions. As such it can be a first step on the way to setting up a climate club of like-minded jurisdictions. The crucial task that the European Commission will have to face in the future will be to uphold the targets set by the European Union while simultaneously refining existing policies to mitigate adverse impacts on the socio-economic development of Member States and, ultimately, safeguarding the welfare of European citizens.

1 Introduction

Over the last century, climate change has emerged as a critical issue due to an unusual upsurge in global temperatures (Figure 1) and the ever-increasing intensity and frequency of extreme weather events such as heat waves, heavy precipitation, and tropical cyclones (IPCC 2023). The widespread concern is underpinned by scientific consensus that recent global warming is primarily driven by human activities since the Industrial Revolution, notably through increased CO_2 and other greenhouse gas (GHG) emissions from fossil fuels, deforestation, urbanization, and agriculture.

Figure 1: Global CO_2 Emissions from Energy Combustion and Industrial Processes in Gt (1880–2022)



Source: International Energy Agency (2023). © ifo Institute

By integrating more complex climate models with empirical data, Waidelich et al. (2024) quantify the additional economic damages arising from shifts in precipitation patterns, temperature variability, and extreme weather events. They reveal that at **a 3°C rise in global temperatures above pre-industrial levels, economic losses could peak at an aggregated 10% of global GDP by 2050**, with the most severe impacts felt in lower-income, tropical regions. These results are in line with those of other studies. For example, Van der Wijst et al.

(2023) estimate that, in a scenario of global warming well below 2°C, worldwide climate change damages would amount to an aggregated 2% of GDP and 10–12% of GDP with respect to the scenario in which global warming is 3°C. As part of an integrated approach, including worldwide temperature shocks, Bilal and Känzig (2024) forecasted that a 1°C increase in temperature at the world level would be so damaging as to bring about a 12% decline in world GDP. Thus, the nonlinear impacts of climate change on gross output and capital, including potential tipping points, may exert sufficient pressure on the global economy to drive it toward a debt-deflationary trajectory, possibly resulting in enforced economic degrowth in the latter half of the 21st century (Bovari et al. 2020). Moreover, this phenomenon has significant distributional effects as it affects vulnerable populations in poorer countries to a greater extent (Tol 2021).

At the global institutional level, Article 4 of the **Paris Agreement**, influenced by the IPCC's 5th Assessment Report and the UNFCCC's Structured Expert Dialogue, sets a goal for achieving a balance between human-induced GHG emissions and their removal by the latter half of the 21st century. Despite the term "net zero" not being explicitly mentioned in the 2015 Paris Agreement, it aligns with Article 2's aim to limit global warming to below 2°C, preferably to 1.5°C, above pre-industrial levels. Similar commitments to decarbonize by 2050 were taken from the largest economies in the world, like India, China, the United States, Brazil, Nigeria, and South Africa, covering about 90% of global GHG emissions.

According to Fankhauser et al. (2022), there are seven critical attributes for a credible net-zero framework. These include front-loaded emission reductions, a comprehensive approach to emission reductions, cautious use of carbon dioxide removal, effective regulation of carbon offsets, an equitable transition to net zero, alignment with broader socio-ecological objectives, and the pursuit of new economic opportunities. A proper mix of these elements is needed for fast and credible decarbonization processes. However, in the urgent dialogue on climate change, the strategies to reduce carbon emissions are split into two more general and distinct pathways: fast and slow decarbonization (cf., for instance, Pianta et al. 2021).

Fast decarbonization involves a rapid and large-scale reduction in carbon emissions. This approach is driven by the urgent need to meet the stringent limits set by the Paris Agreement of keeping global warming well below 2°C and pursue efforts to limit it to 1.5°C by 2100. For example, the "carbon law" proposed by Rockström et al. (2017) outlines a pathway for fast global decarbonization, aiming to halve CO_2 emissions each decade until mid-century, at which point net-zero emissions are achieved. This approach necessitates immediate, large-scale carbon removal and a sharp reduction in CO_2 emissions from land use, fundamentally transforming key sectors across countries.

In contrast, slow decarbonization refers to a more gradual shift from fossil fuel use to cleaner energy sources, with policies evolving progressively and allowing technological changes to occur over a longer period. This pathway considers extended timeframes to reach carbon neutrality, prioritizing economic stability and minimizing the disruptive impact on existing systems.

2 Decarbonization Strategies in Europe

2.1 Emissions and GDP

The European Union (EU) has been leading the way toward deep decarbonization in recent years. However, the 27 EU Member States produce only around 7.6% of global CO_2 emissions, accounting for around 5.5% of the world population.

In 2019, around 77% of GHG emissions in Europe were caused by energy consumption across various sectors. Agriculture contributed 10.5% of emissions, while industrial processes and product use accounted for 9.1%; the remaining 3.3% came from waste management (European Environment Agency, 2023).[2]

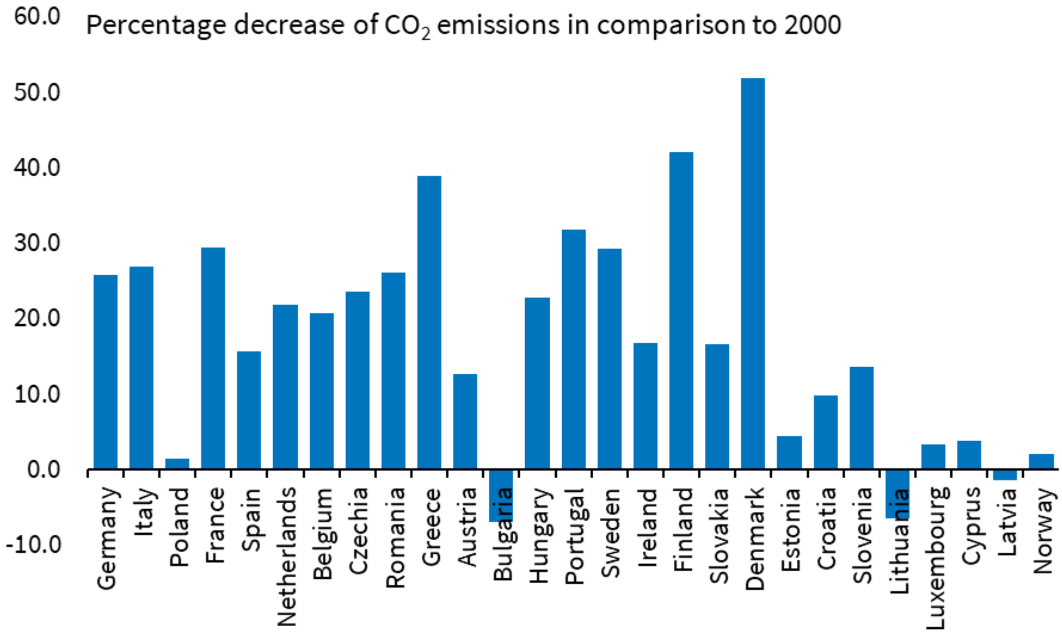
Europe's contribution to pollutants is probably underestimated because the count refers to production-based rather than consumption-based emissions; the latter are much higher, although difficult to quantify (Harris et al. 2020). However, the EU Member States recorded an improvement in their emissions trends, with a 22.6% decrease from 2000 to 2022.

Figure 2, based on data from the Energy Institute Statistical Review of World Energy (2024), shows the percentage decrease trend for each member country. We can see that the negative trend of CO_2 production is common to almost all countries, with differences in magnitude. Northern Europe shows a remarkable decrease, as do the Mediterranean countries. The changes in Eastern Europe are more limited, especially for the Baltic countries.

These differences can be reasonably explained by the diverse political orientations of countries resulting in heterogeneous environmental policies and by exogenous contextual factors such as the global financial crisis of the early 2010s (Karstensen et al. 2018).

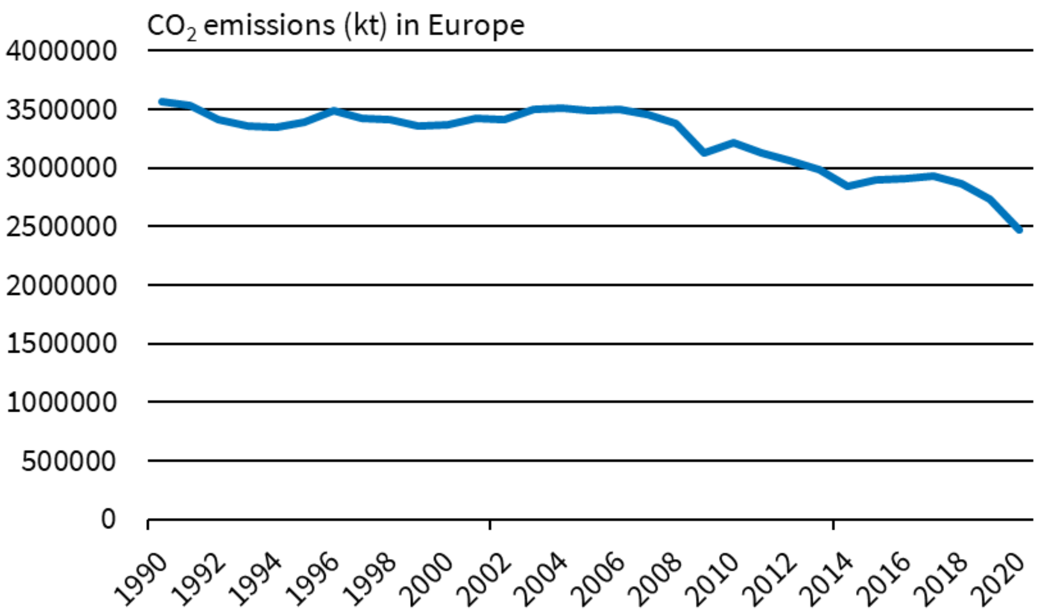
[2] All sectors included land use, land use change, and forestry (LULUCF).

Figure 2: CO_2 Emissions in the European Union by Country



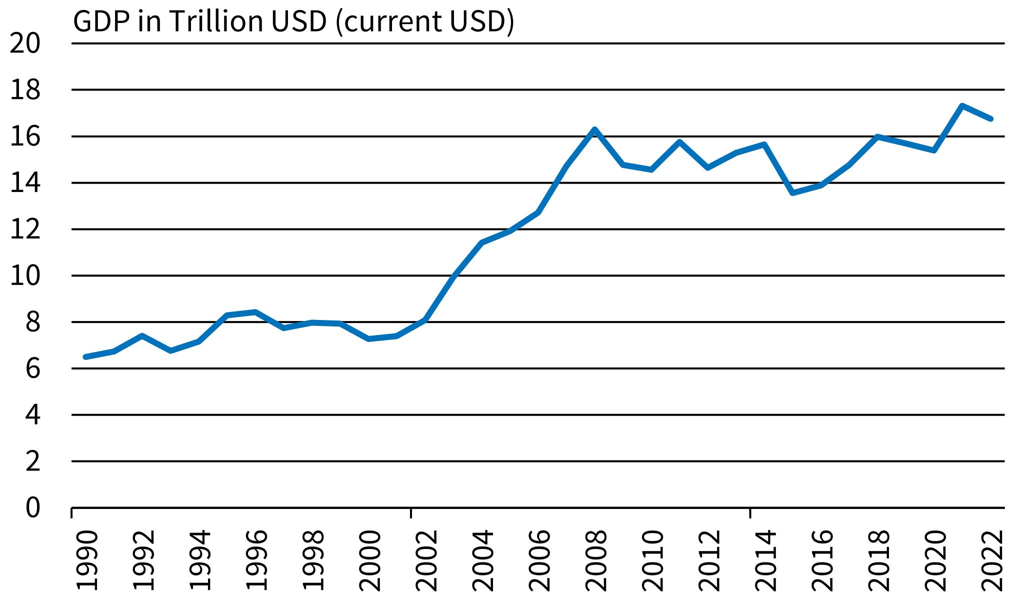
Source: Energy Institute (2024). © ifo Institute

Figure 3: CO_2 Emissions per Capita in the European Union (1990–2020)



Source: World Bank (2024). © ifo Institute

Figure 4: GDP in the European Union (1990–2020)



Source: World Bank (2024). © ifo Institute

Figure 3 and Figure 4 depict the trend of CO_2 emissions and GDP in Europe from 1990 to 2020, and 1990 to 2022 respectively. It shows that the European economy has constantly grown, accompanied by a slight decrease in polluting emissions. In 2020, the pandemic may have impacted the economy and emissions. The diagram suggests that pursuing economic development without increasing pollutants is possible. Indeed, GDP exerts a nonlinear influence on CO_2 emissions, with emissions rising as GDP grows until reaching a certain threshold, after which the effect shifts (Han et al. 2024).

However, the reduction in emissions has been relatively small, and the urgency for action is pressing in light of a significant increase in GHG emissions by 2030 in Europe without technological changes or policy interventions (Giannakis and Zittis 2021).

2.2 European Initiatives

The EU is committed to becoming the first climate-neutral continent by 2050,[3] a core principle of the **European Green Deal** and a mandatory requirement under the **European Climate Law**. The efforts became more concrete through the Fit for 55 (FF55) package introduced in July 2021, aligned with its European Green Deal strategy. The package includes significant proposals such as reforming the **EU Emissions Trading System** (EU ETS), one of the pillars of the EU's decarbonization strategy (European Commission 2023a), and implementing a **Carbon Border Adjustment Mechanism** (CBAM; European Commission 2023b). The EU ETS, the European carbon market established in 2005 that employs a cap-and-trade mechanism for emission allowances within energy-intensive industries and the power generation sector, now encompasses approximately 36% of the EU's greenhouse gas emissions and includes countries like Iceland, Liechtenstein, and Norway (European Commission 2023a). It has facilitated emission reductions over the past 18 years, though the extent is debated. Directive 2023/959 has recently extended the EU ETS with a complementary carbon market (EU ETS2) to cover additional sectors like buildings, transport, and small business emitters.

The EU has also adopted CBAM, intended to minimize carbon leakage (that is, when companies relocate to countries with laxer emission controls), effective October 2023. However, CBAM's compatibility with World Trade Organization rules and its effectiveness in preventing carbon leakage have been questioned. While its definitive impact remains unclear, some studies suggest it could be effective (Bellora and Fontagné 2023), especially if paired with other measures like climate clubs or ETS linkages. Overall, enhanced international cooperation in carbon market regulation is advocated to meet the ambitious targets set by the European Climate Law.

Climate policies must include competitiveness and social justice aspects to be effective and equitable. The transition to a zero-carbon economy has distributional impacts and poses a critical challenge for low-income households with a higher risk of decarbonization. The European institutions intend to

[3] Although Europe is the first continent to propose a comprehensive strategy, the effort toward decarbonization is shared with other geopolitically relevant countries, each with its own plan of action. Recall for example "The Road to Net Zero by 2060" in China, the "Net Zero South Africa 2050," and India's target of net-zero emissions by 2070.

address the negative externalities of the transition, as shown by the **Just Transition Mechanism** (JTM) and its related first pillar, the Just Transition Fund (JTF), an essential component of the European Green Deal, aimed at ensuring a balanced shift toward a green economy. The JTM provides financial and technical support to regions most affected by the transition, ensuring workers and communities adapt to a sustainable future and fostering fairness and solidarity. In addition, a **Social Climate Fund** (SCF) has been officially approved in 2023 by European institutions. The fund is designed to help vulnerable households, micro-enterprises, and transport users mitigate the financial effects of the expanded EU ETS. Set to be part of the EU budget, the SCF will have a funding limit of EUR 86.7 billion and is scheduled to function from 2026 to 2032 (European Commission 2023b). That is quite relevant, since allocating ETS revenues to low-income households could increase the acceptability of carbon pricing and effectively mitigate the transition risks.

Nevertheless, there is a need for unprecedented clean energy technology investments to achieve a net-zero carbon energy system before breaching the Paris Agreement thresholds; with a high probability of overshooting the 1.5°C increase within this decade, immediate policy action is needed to avoid higher mitigation costs and economic damages from delayed action (Panos et al. 2023). In line with the Energy Union governance regulation based on the principle of energy security, EU Member States were required to present their ten-year **National Energy and Climate Plan** (NECP) for the 2021–2030 period to the European Commission (EC) by the close of 2019. These plans detail the energy and climate objectives each Member State aims to achieve to decarbonize its own national energy system.

Additionally, the EU is revitalizing its industrial strategy to reinforce the single market and foster Europe's resilience, emphasizing the development of a robust ecosystem for manufacturing net-zero technology products. This includes the **Innovation Fund**, which boosts the EU's capacity for manufacturing technologies to achieve net-zero emissions.

The **Green Deal Industrial Plan** is set to boost the competitiveness of Europe's net-zero industry and hasten the move toward climate neutrality by enhancing the EU's capacity to produce essential net-zero technologies and products. The plan supports the industrial base for clean tech innovation, focusing on four primary areas – predictable regulatory frameworks, quicker funding access, skill development, and open trade for stable supply chains. On February 6, 2024, a political consensus was achieved between the European Parliament and the Council on the Net-Zero Industry Act, an offshoot of the plan to bolster EU manufacturing of clean technologies. The act is designed to attract investments and improve market conditions for clean tech, targeting an increase in the EU's strategic manufacturing capacity to meet at least 40% of annual deployment needs by 2030 (European Commission 2023c).

In February 2024, the European Commission (EC) proposed its assessment for a 2040 climate target for the EU, advocating for a 90% cut in GHG emissions from 1990 levels. The ambitious target is a critical milestone toward the EU's aim of achieving climate neutrality by 2050. The initiative followed a public consultation process from March to June 2023, inviting input on the EU's climate aspirations for 2040. The recommendation is based on comprehensive assessments and expert advice, marking the beginning of a process to formalize the 2040 climate target.

Together with the assessment, the European Commission (2024a) recommends eight building blocks to solidify the EU's leadership in global climate action, ensuring a sustainable, resilient, and equitable future and achieving the 2040 target:

1. A resilient and decarbonized energy system for our buildings, transport, and industry.
2. An industrial revolution with competitiveness based on research and innovation, circularity, resource efficiency, industrial decarbonization, and clean tech manufacturing at its core.
3. Infrastructure to deliver, transport, and store hydrogen and CO_2.
4. Enhanced emissions reductions in agriculture.
5. Climate policy as an investment policy.
6. Fairness, solidarity, and social policies at the transition's core.
7. EU climate diplomacy and partnerships to encourage global decarbonization.
8. Risk management and resilience.

As shown by these guidelines, the Commission's drive toward effective and rapid decarbonization within the timeframe set by the European Green Deal seems quite evident. The more difficult question is whether the overall European strategy can lead to significant economic setbacks or whether these can be mitigated with appropriate policy instruments.

3 Macroeconomic Models to Assess European Decarbonization Impacts

3.1 Theoretical Models

The following section delves into a descriptive analysis of relevant research efforts highlighting the economic impact of decarbonization strategies. We will then use the results of the study review to focus on specific aspects, such as a) the impact of decarbonization on GDP, b) the impact of decarbonization on employment, c) the impact of decarbonization on low-income consumers, d) the development of the energy sector, e) stranded assets and capital markets, f) industrial competitiveness, g) new technologies, and h) global cooperation.

The two principal theoretical instruments used to perform such analysis are Integrated Assessment Models (IAMs) and Dynamic Stochastic General Equilibrium (DSGE) models (Table 1). These are fundamental tools for analyzing and formulating policies related to economic and environmental challenges, especially in the context of decarbonization (Claeys et al. 2024). IAMs are crucial for understanding the long-term impacts of environmental policies on key economic indicators such as GDP, energy use, and carbon emissions. They simulate the effects of strategies like carbon pricing and renewable energy adoption by incorporating technological, economic, and climatic factors, thus aiding in holistic policy planning for sustainable development (Angeli et al. 2022). Conversely, DSGE models focus on short-term economic fluctuations, typically aligning with business cycles of 5 to 10 years (Claeys et al. 2024). These models aim to predict the economic response to immediate shocks, such as new environmental regulations or changes in energy prices.

IAM models, which offer a long-term view, usually produce more optimistic results than DSGE models regarding the macroeconomic influence of climate legislation.

Table 1: Two Main Macroeconomic Models on Climate

	Integrated Assessment Models (IAMs)	Dynamic Stochastic General Equilibrium (DSGE) Models
Main goal	Jointly assess environmental change and policy impacts, combining physical, economic, and social systems.	Analyze economic phenomena with microeconomic foundations under market equilibrium.
Methodology	Multidisciplinary, often coupling economic, environmental, and sometimes social systems.	The top-down approach is based on equations representing the economy's behavior.
Key applications	Climate change impact assessment, policy analysis, environmental and economic planning.	Macroeconomic policy analysis, forecasting, monetary policy.
Flexibility	Variable, depending on the model; often sector-specific or region-specific with various levels of detail.	Less flexible, assumes rational expectations and often homogeneous agents.
Predictive power	Focused on long-term projections and scenario analysis, with varying degrees of uncertainty.	Aimed at predictive accuracy within the framework of rational expectations.
Stochastic elements	Can include stochastic elements in the representation of uncertainties related to climate and economic responses.	Inherently includes stochastic shocks to the economy.
Typical use cases	Evaluating environmental policies, assessing climate change mitigation and adaptation strategies.	Analyzing economic policies, studying economic cycles.
Time perspective	Mainly long-term, aiming to project decades into the future for policy and environmental change analysis.	Primarily short to medium term, focused on cyclical economic dynamics.

Source: Authors (2024).

The alternative CGE (Computational General Equilibrium) models offer valuable insights too, but they may not be the most suitable for our analysis. CGE models are often designed to analyze static equilibria, making them less effective at capturing the dynamic nature of decarbonization. Additionally, their sectoral aggregation and assumption of perfect information can limit their ability to represent the complexities of the transition process. Therefore, IAMs and DSGE models are likely to be more effective in providing a comprehensive and nuanced understanding of the macroeconomic impacts of decarbonization. Most of the studies we will review in the next section (for a comprehensive overview, see Table 4 at the end of Section 3.3), therefore, use either the IAMs or DSGE models, while static analyses will be mentioned only where useful to provide relevant discussion elements.

3.2 A Review of the Existing Studies

The IAMs are frequently used to analyze temperature trends based on the different decarbonization paths. Due to the vast number of IAMs and their numerous scenarios, only a select few are presented here. These models and scenarios were chosen based on an extensive review of their relevance, robustness, and ability to provide meaningful insights into key aspects of the analysis. Using the MEDEAS-World model, a sophisticated framework designed to assess global economic transitions under the constraints of limited energy resources, Nieto et al. (2020) evaluate three future scenarios: Business as Usual (BAU), Green Growth (GG), and Post-Growth (PG), each depicting different policy and economic pathways up to 2050. The BAU scenario, which follows current economic and energy consumption trends, is insufficient to meet international climate objectives. Similarly, despite emphasizing sustainability and reduced environmental impact, the GG scenario fails to achieve the critical 2°C warming threshold. According to the authors, the PG scenario is the only one to achieve the target. Still, it requires a radical shift from traditional growth-driven policies toward those focusing on efficiency and redistribution. It is worth mentioning that the concept of PG, part of the Beyond Growth agenda of which the EU was an institutional founder and on which it is still involved at the highest level, is particularly difficult to frame because of its multidimensional nature, encompassing not only economic growth but also environmental sustainability, social equity, and broader well-being considerations. GDP, on the other hand, while refinable, remains a valuable metric for providing a rough idea of the potential macroeconomic impacts of climate policies.

In 2022, the Potsdam Institute for Climate Impact Research projected global CO_2 emissions trajectories under different policy scenarios, with a corresponding forecast of temperature increases by 2100. According to the authors, current policies would lead to a 3.2°C rise, whereas a scenario implementing the Nationally Determined Contributions (NDCs) aims for a 2.6°C increase. In another research article, Brecha et al. (2022) also stated that only the most ambitious pathway, the International Energy Agency (IEA) Net-Zero Emissions by 2050 (NZE) scenario, meets the Paris Agreement's criteria to limit warming to 1.5°C.

The NZE scenario delineates a roadmap for the energy sector to eliminate CO_2 emissions by mid-century, aligning with the Paris Agreement goal to limit global warming to 1.5°C. To achieve that, emissions must drop dramatically by 2030 (nearly 40%), with renewable energy sources like solar and wind leading the change. In many regions of the world, wind and solar photovoltaics (PV) are currently the most economical sources of electricity, having experienced significant cost reductions by over 70% and 90%, respectively, in recent years (Fragkos et al. 2021; Claeys et al. 2024). According to IEA (2021), wind and solar PV will dominate global electricity generation, providing nearly 70% of the total energy by 2050. Fossil fuel demand is expected to plummet, with coal dropping by 90%, oil by 75%, and natural gas by 55%. Beyond the significant reduction in fossil fuel demand, the scenario envisions increasing clean technologies such as hydrogen and carbon capture. Additionally, it emphasizes the need for global behavioral changes and increased financial investment in the energy sector. However, uncertainties regarding technology availability and behavioral adaptation could impact the feasibility and cost of the transition.

The IEA fully updated the NZE scenario in 2023, comparing its forecasts with those of two other scenarios: one is called the Announced Pledges Scenario, which guarantees that all climate promises made by governments and businesses worldwide will be fulfilled completely and on schedule; and the other is the Stated Policies Scenario, which represents the current state of policy, based on an evaluation of the energy-related policies in effect as of the end of August 2023, sector by sector and country by country. In both cases, especially in the Stated Policies Scenario, the projected increase in global temperatures would be well over 2°C (IEA 2023).

Of course, the number of scenarios can be expanded to refine the predictions. The Network for Greening the Financial System (NGFS), a group of regulators and central banks dedicated to advancing environmental and climate-related risk management in the financial sector, developed, together with an international academic consortium, a portal to analyze seven decarbonization scenarios and their environmental and macroeconomic consequences.

In the **Net Zero 2050** scenario, ambitious global policies and rapid innovation aim to achieve net-zero CO_2 by 2050, creating high transition risks but keeping physical risks low. The **Low Demand** scenario sees behavioral changes reduce energy consumption, lowering economic pressure while also reaching net zero by 2050 with minimal carbon pricing. In the **Below 2°C** scenario, gradual policy action limits warming to below 2°C, with net-zero CO_2 reached after 2070 and low overall risks. **Delayed Transition** begins too late, leading to drastic emission reductions post-2030, resulting in high physical and transition risks. The **Nationally Determined Contributions (NDCs)** scenario fulfills pledged policies, leading to 2.6°C warming and moderate physical risks, though transition risks are low. Under **Current Policies**, no new action results in 3°C warming by 2080, causing severe and irreversible physical damage. Finally, in the **Fragmented World** scenario, uneven global efforts lead to 2.3°C warming, with fragmented technological progress and high physical risks (NGFS, 2024).

Three different IAMs produce results for the seven NGFS scenarios. One of these IAMs, developed by NGFS itself, is called REMIND-MAgPIE; in the following table, we summarize some indicative but meaningful results from this model:

Table 2: Key Transition Variables and Different Scenarios

Scenarios/key transition variables	Decarbonising electricity (electricity generation in EJ per year)	Electrifying buildings, industry and transport (energy demand in EJ per year)	Switching to carbon-neutral fuel (fuel production in EJ per year)	Storing and removing CO_2 (CO_2 removal in Mt CO_2 per year)	Improving energy efficiency across the economy (energy intensity MJ per 2010-USD)	Decarbonising agriculture, forestry and othe land use (CO_2 emissions in Mt CO_2 per year)
Net Zero 2050	Electricity from renewables increases 5-fold over the next three decades.	More than half of the energy for buildings, industry, and transport will be electric in 2050, with a similar demand in terms of EJ.	More than 40% of gaseous, liquid and solid fuels are carbon neutral in 2050.	By 2050 around 5 gT of carbon need to be removed per year to reach 1.5 °C in a cost-effective way.	Energy intensity decreases by almost 60% between 2020 and 2050.	CO_2 emissions from the AFOLU sector can reach net zero by 2035.
Low Demand	Electricity from renewables increases less than 2-fold over the next three decades.	More than half of the energy for buildings, industry, and transport will be electric in 2050, but strongly reducing the demand from 420 to 320 EJ.	Around 30% of gaseous, liquid and solid fuels are carbon neutral in 2050.	By 2050 around 5 gT of carbon need to be removed per year to reach 1.5 °C in a cost-effective way.	Energy intensity decreases by almost 65% between 2020 and 2050.	CO_2 emissions from the AFOLU sector can reach net zero by 2035.
Below 2°C	Electricity from renewables increases 4-fold over the next three decades.	Around 42% of the energy for buildings, industry, and transport will be electric in 2050.	Around 27% of gaseous, liquid and solid fuels are carbon neutral in 2050.	By 2050 around 1 gT of carbon need to be removed per year to reach 1.6 °C in a cost-effective way.	Energy intensity decreases by almost 58% between 2020 and 2050.	CO_2 emissions from the AFOLU sector can reach net zero by 2050.
Delayed Transition	Electricity from renewables increases 4-fold over the next three decades (but only after 2035).	Around 45% of the energy for buildings, industry, and transport will be electric in 2050, experiencing a considerable shock demand in the 2030s.	Around 30% of gaseous, liquid and solid fuels are carbon neutral in 2050.	By 2050 around 3 gT of carbon need to be removed per year to reach 1.6 °C in a cost-effective way.	Energy intensity decreases by almost 60% between 2020 and 2050.	CO_2 emissions from the AFOLU sector can reach net zero by 2040.
Nationally Determined Contributions	Electricity from renewables increases 3.5-fold over the next three decades.	Around 35% of the energy for buildings, industry, and transport will be electric in 2050.	Around 15% of gaseous, liquid and solid fuels are carbon neutral in 2050.	By 2050 less than 1 gT of carbon need to be removed per year to reach 2.6 °C in a cost-effective way.	Energy intensity around 50% between 2020 and 2050.	CO_2 emissions from the AFOLU sector cannot reach net zero by 2050 and will be around 2K Mt CO_2 per year.
Current Policies	Electricity from renewables increases 2-fold over the next three decades.	Around 28% of the energy for buildings, industry, and transport will be electric in 2050.	Less than 10% of gaseous, liquid and solid fuels are carbon neutral in 2050.	By 2050 there is no need of carbon removal to reach 3 °C in a cost-effective way.	Energy intensity decreases by almost 50% between 2020 and 2050.	CO_2 emissions from the AFOLU sector cannot reach net zero by 2050 and will be around 3.5K Mt CO_2 per year.
Fragmented World	Electricity from renewables increases 3.5-fold over the next three decades.	Around 35% of the energy for buildings, industry, and transport will be electric in 2050.	Around 13% of gaseous, liquid and solid fuels are carbon neutral in 2050.	By 2050 less than 0,8 gT of carbon need to be removed per year to reach 2.6 °C in a cost-effective way.	Energy intensity around 50% between 2020 and 2050.	

Source: Richters et al. (2023).

Note that the scenarios for energy transition can be from ambitious to moderate. In the scenarios for Net Zero 2050 and Low Demand, high shares of renewables, broad electrification, and huge carbon removal – on the order of 5 gigatons per year – are integral elements of the picture well before 2050. Energy efficiency may see a rise of more than 60%, while emissions from AFOLU will come to near zero. For both the Below 2°C and Delayed Transition scenarios, renewables have a fourfold increase, electrification extends to 42–45% of demand for energy, but emissions still approach near-zero. The NDCs scenario sees renewables increase by a factor of 3.5, increased electrification of around 35%, and very little carbon removal. In the Current Policies and Fragmented World scenarios, transitions are slow, the increments of renewables and carbon-neutral fuels are small, carbon removal is minimal, and AFOLU emissions stay high into 2050. The most ambitious scenario would then imply in-depth restructuring of and electrification of energy, with advanced renewable energy sources and improved energy efficiency.

At the global level, the degree of regional consequences will vary, with coal-dependent regions facing the steepest economic challenges. We can assume that decarbonization at fair terms is more challenging in regions outside of Europe, especially the coal-dependent and developing countries, including India, Indonesia, South Africa, and Brazil. These areas suffer from greater economic difficulty compared to Europe, with the same transition dilemma due to their high dependence on fossil fuels on the one hand and their insufficient financial and technological resources on the other. Decarbonization will then need to be guided by carefully designed policies along with technological innovations and financial and capacity-building support to ensure an equitable process for these specific regions. Global coordination is crucial, with richer countries providing support to the least developed ones, to avoid increasing current economic disparities (NGFS 2023).

According to these findings, following an NZE path is the preferred option to achieve decarbonization goals quickly. However, doing that can inevitably lead to changes in economic activity. **What are the potential macroeconomic consequences of implementing ambitious strategies to reach the Paris Agreement objectives?** How can we mitigate the negative supply shock for the economy caused by climate policies related to decarbonization? Are there alternative paths we could follow to limit climate and transition risks? Focusing on the energy sector, the IEA tried to provide answers in its 2021 report called "*Net Zero by 2050: A Roadmap for the Global Energy Sector.*"

Using an IAM model, the authors state that achieving net-zero emissions encompasses environmental and significant economic and social shifts. In the NZE scenario, global CO_2 emissions are projected to reach zero by 2050, necessitating considerable **investment in electricity, low-emissions fuels,**

and infrastructure, with an estimated annual need of up to USD 4 trillion by 2030 in clean energy and infrastructure to maintain momentum in energy transitions. Employment dynamics will also shift, with **potential job losses** in fossil fuel sectors being offset by **job creation in renewable sectors**. This shift will create 14 million new clean energy jobs by 2030 at the global level but will bring a loss of about 5 million jobs in the oil, gas, and coal sectors.[4] Economic disparities will occur as job gains do not match job losses in location or skill sets.[5] Looking at other macroeconomic effects, the transition should not affect global GDP by 2030 (which is expected to grow on average at 3% annually). Still, it could also lead to an 80% reduction in oil and gas revenues for producer economies and a 90% drop in tax revenues from oil and gas sales in importing countries by 2050 (IEA 2021; 2024).

In an IAM-based investigation included in the fifth section of the report "How to Achieve a Rapid, Fair, and Efficient Transformation to Net Zero Emissions," Kriegler et al. (2023) cover the challenges and strategies for achieving a just and efficient transition toward net-zero emissions, focusing on the EU.

Kriegler et al. (2023) highlight the potential reduction of Europe's reliance on fossil fuel imports; the transition to zero-carbon technologies and improved energy efficiency moves economic activities from high operating costs to more capital-intensive methods. The shift increases initial costs due to using more expensive low-carbon alternatives, potentially reducing economic output. Moreover, they explore employment impacts, predicting that 1.2 to 1.7 million new jobs will be created in sectors aligned with a low-carbon transition in the Net Zero 2050 scenario, noting that around 300,000 jobs will be lost in fossil fuel sectors. The new jobs will cover sectors such as electricity supply and clean energy manufacturing (e.g., wind turbines, EV equipment, hydrogen), the infrastructure for low-carbon technologies, building renovation, and agriculture needed to produce advanced biofuels. It is important to note that job reallocations to countries outside of the EU, as well as the associated job gains and losses beyond the energy and energy-related sectors, are not included in this analysis.

[4] See Section 4.2 below for further discussion on this aspect.

[5] To mitigate this problem, the European JTF pays particular attention to the areas where job losses are anticipated to be the largest, and to the conversion of industrial facilities with the highest GHG intensity. Eligible territories with approved territorial just transition plans at NUTS 3 level are localized all over Europe.

The report also discusses the distributional impacts of climate change mitigation measures, emphasizing that stringent policies could be regressive, affecting low-income households disproportionately. In addition, stricter climate policies in a 1.5°C scenario result in higher GDP losses (between -0.9 and -6.2% over the 2020–2050 period) with respect to the 2°C scenario, which shows no significant losses. Indeed, "*climate policies combined with redistributive policies benefit the poor and reduce inequality*" (Kriegler et al. 2023, p. 49), because reinvesting carbon tax revenues into reducing labor taxes and social contributions can mitigate these losses, reducing GDP declines by 30–70% in various models. Funds raised through a carbon tax can be allocated in several beneficial ways, including providing households with lump-sum payments, known as a "climate dividend," lowering taxes that cause economic inefficiencies, or directing monetary transfers to enhance the social security system.

There are additional indications that **a gradual GHG price increase from 2023 to 2030 and a redistribution of revenues can reduce the costs of decarbonization**, outweighed by the long-term costs of inaction (IMF 2022). The International Monetary Fund's Global Macroeconomic Model for the **Energy Transition**, a DSGE model developed to highlight the importance of credible climate and monetary policies, argues against delay due to inflation and energy security concerns. The related report discusses the macroeconomic impacts of decarbonization policies. It suggests that reducing emissions by 25% in 2030 would be more in line with the Below 2°C scenario than alternative pathways.
Specifically, the IMF proposes three policy packages to reduce emissions by 25% in 2030:

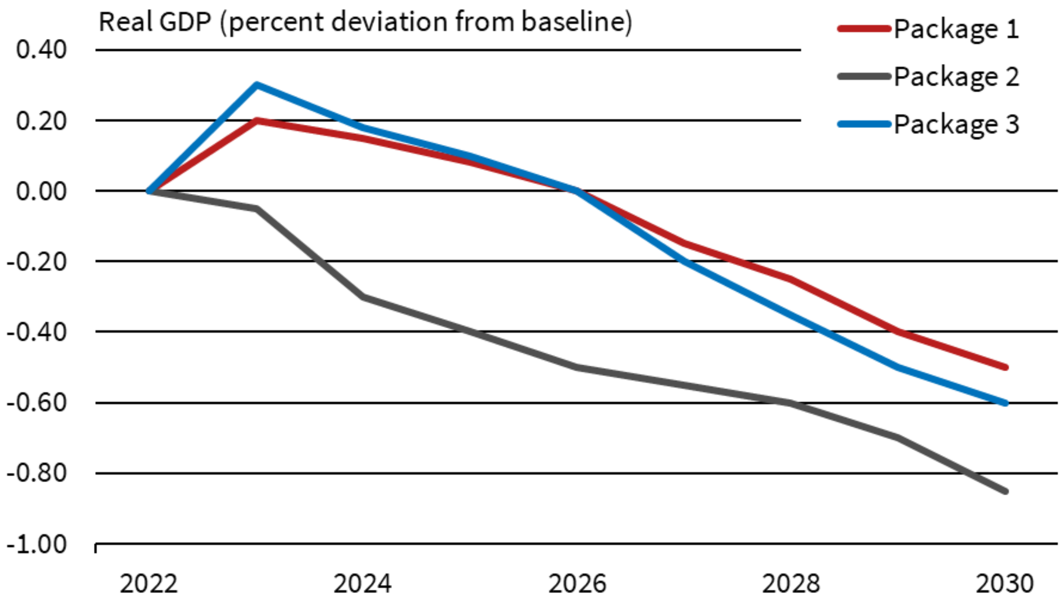
1. Gradual GHG price increase from 2023 to 2030; two-thirds of revenues used to reduce labor taxes; one-third of revenues transferred to households.
2. Gradual GHG price increase from 2023 to 2026; one-third of revenues used to reduce labor taxes; one-third of revenues transferred to households; one-third of revenues used to subsidize low-emission sectors (renewables investment, nuclear and hydropower plants, electric-vehicle purchase).
3. Gradual GHG price increase from 2023 to 2030; GHG revenues rebated at the sectoral level (electricity generation, manufacturing, services); GHG revenues from households' activities (residential energy and individual

transportation) transferred back to households; regulation of share of electric vehicles.

Considering four world regions, namely the US, the Euro Area, China, and the Rest of the World, the IMF report forecasts that the third policy package is the best to ensure a smooth transition toward low-carbon technologies; in that case, **the decarbonization policies could reduce the Euro Area GDP growth by 0.15 to 0.25 percentage points annually**, with a slight increase in inflation only up to 2028 (IMF 2022).

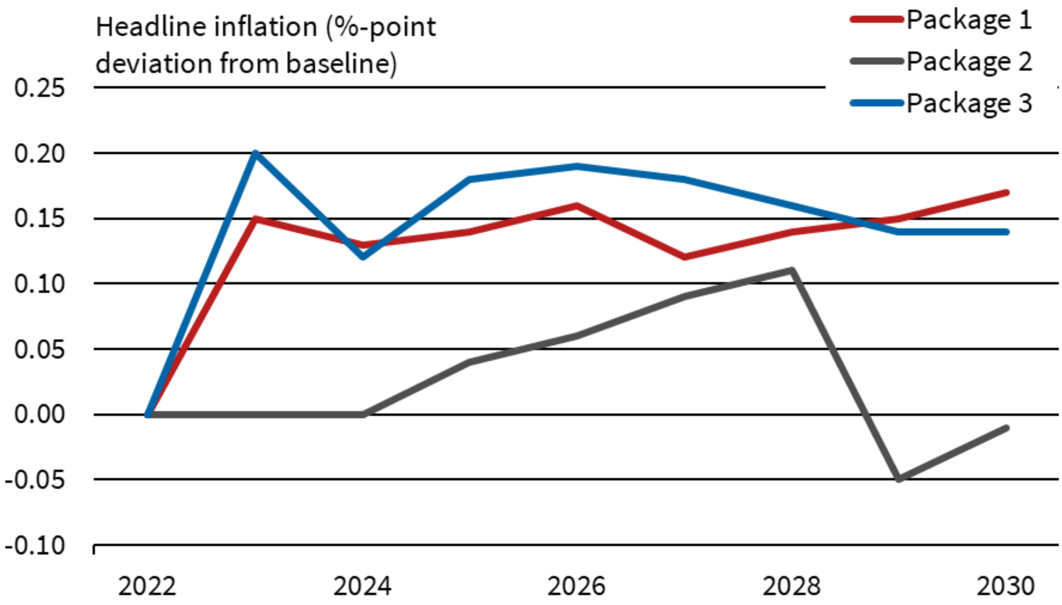
Figure 5 shows actual GDP trends and future projections for each policy package for the Euro Area, while Figure 6 indicates the inflation percentage point deviation from baseline per policy package.

Figure 5: Simulations of the Macroeconomic Impact (GDP) of Three Policy Packages in the Euro Area



Source: IMF (2022). © ifo Institute

Figure 6: Simulations of the Macroeconomic Impact (Inflation) of Three Policy Packages in the Euro Area



Source: IMF (2022). © ifo Institute

A rise in the GHG tax has been likened to an oil price shock due to its impact on energy prices (Pisani-Ferry 2021). However, despite their similarities, a GHG tax differs from an oil price shock because revenues can be reallocated within the country to partially relieve producers, consumers, or both of the burden of the new tax. Second, while the increasing GHG tax is generally gradual, oil price shocks are frequently abrupt, unanticipated, and transient.

Coenen et al. (2024) reiterate, with a DSGE model, that the way in which the carbon tax revenues are spent is critical to managing the macroeconomic impacts in Europe. For example, recycling revenues back to low-income households could prevent rising inequality. Moreover, revenue recycling may subsidize clean energy production and offset the effects on GDP. Indeed, decarbonization policies, particularly carbon taxation, have transitory inflation effects and moderate impacts on GDP. Simulations performed by the authors suggest that increasing the carbon tax to EUR 140/tCO_2 with a schedule aligned with the European Green Deal will raise inflation by between 0.2 percentage points. This inflationary pressure falls off dramatically in the end-period scenario, 2030. Over that same period, GDP is expected to fall by about 1.2%. In the simulations reported in the study, investment decreases by approximately 2.5% at its lowest point, while aggregate consumption falls by around 0.7%.

A steady carbon tax rise incentivizes energy producers to shift from “dirty” to “clean” energy. According to the authors, that further leads to a cut in carbon emissions by about 7% over the medium to long term. Nevertheless, the reduction is not deep enough to reach the more ambitious net-zero emissions goals, and **further policies are required in addition to carbon pricing.** The impact of carbon tax would be minimal without concurrent large increases in clean energy supply and efficiency improvement (Coenen et al. 2024).

In general, depending only on carbon taxation to decarbonize is economically destabilizing and politically challenging. A carbon tax of 14.2 times higher than the current carbon price is required to meet the target of the Paris Agreement at the global level, but this would lead to severe economic impacts, including unemployment peaking at 17.6% between 2024 and 2028 at the global level (instead of 4.4% as forecast in the baseline scenario where no climate policy is deployed) and company bankruptcies increasing from 7.9 to 13.4 annually (Lamperti et al. 2022). Instead, industrial regulations and green technology subsidies as part of a policy mix bring more solid outcomes. Lamperti et al. (2022) argue that a ban on new fossil fuel power plants by 2041, combined with green subsidies, would keep global warming below 1.9°C by 2100 while imposing only a modest fiscal impact. This approach also boosts employment, with the unemployment rate lower than under the baseline during peak renewable energy investments.

Focusing on the European context, Vrontisi et al. (2020) assessed the macroeconomic impacts of various EU emission pathways designed to stabilize climate change well below the 2°C target by 2050. Utilizing the PRIMES and GEM-E3 models, the research reveals that advancements in the energy sector will drive significant emission reductions by 2030. The study highlights how the adherence of other countries to stricter climate policies, in line with what the EU is doing, could significantly influence the EU’s economic outcomes, indicating **potential financial gains or losses depending on the level of international policy coordination.**[6] In a scenario that takes into account both the NDCs and the 2°C limit, lone EU action would result in a percentage change of the European GDP between -0.1% and +0.3% by 2030 and between -0.8% and +0.2% by 2050 with respect to the reference scenario (current policies). In contrast, the involvement of the rest of the world through, for example, the imposition of a

[6] See Vrontisi et al. (2020) for a detailed description of the assumptions on the climate action of other countries underlying the various scenarios.

global carbon tax, would result in a percentage change in GDP initially more penalizing (-0.1 by 2030), but then more growth-prone (+0.2%) than the alternative scenario (Vrontisi et al. 2020).

From a regional perspective, Yiakoumi et al. (2023) focused on decarbonization efforts in Eastern Mediterranean and Middle East (EMME) countries. The research explores equitable CO_2 emission allocations for 2030 among 17 countries in the EMME regions, aiming to align with the goals of the Paris Agreement. By employing 14 different effort-sharing approaches based on three principles of equity, the study identifies **feasible** (likelihood of successful transition pathways under certain conditions) and **socio-economically fair emission reduction targets**. The findings underscore the necessity for the EMME region to reduce emissions by nearly 50% from 2019 levels to maintain alignment with a 1.5°C warming scenario, highlighting that the NDCs of EMME countries are not associated with required emissions abatement targets.

In a more focused approach, Sotiriou and Zachariadis (2021) presented a multi-objective optimization framework to explore decarbonization pathways in the EU, using Cyprus as a case study. Their findings reveal that achieving a 35% reduction in emissions is feasible and economically advantageous over the current 24% target, suggesting that higher abatement levels, while costly, offer significant social benefits when external costs of emissions are considered. This suggests a socially optimal policy mix could be feasible, contingent upon **consistent public investment in infrastructure and clean technology**.

Ciccarelli and Marotta (2024) studied the short-term (ten years) impact of carbon tax and revenue recycling policies in 24 OECD countries, focusing on government, household, and corporate investments, as well as employment, industrial production, and prices. Overall, government investments rose by 1%, while household investments declined by 2% annually for 8 years. Corporate investments, initially low, recovered due to alternative technologies. Employment fell as demand shifted toward skilled workers, particularly affecting low-wage earners. Industrial production declined by 0.5% annually, driven by rising energy costs, which peaked in the fourth year. Food prices also increased.

However, countries that implemented carbon tax-and-revenue recycling saw their GHG emissions drop by about 1% each year on average while seeing business confidence rise (BCI more than 100), household investment increase by 1.5%, and employment increase by 0.2% after more temporary increases in energy prices. Countries not implementing the policy kept experiencing higher and more persistent increases in GHG emissions, negative business confidence, and job losses, particularly in emission-intensive sectors. Again, the study emphasized that carbon pricing is only one aspect of climate policy, with various policies producing different effects: for example, clean technology support acts as a supply shock.

The studies reviewed so far, even if with a different time horizon, confirm that, among the scenarios envisioned by the Network for Greening the Financial System (NGFS), Net Zero 2050 (with the 1.5°C limit) and Below 2°C are the ones that can ensure the achievement of ambitious decarbonization goals. While some are not helpful to the cause (NDCs, Current Policies, Fragmented World), the other two start from either implausible (the collapse of global energy demand in the Low Demand scenario) or strong assumptions (Delayed Transition, with climate procrastination causing future macroeconomic shocks).

The discussion should then be addressed by highlighting the main differences between the Net Zero 2050 and Below 2°C scenarios regarding environmental and socio-economic impacts.

3.3 Europe 2040 Impact Assessment Report

The macroeconomic impacts of Europe's 2040 Climate Target are analyzed in a specific section of the European Commission Impact Assessment Report. Here are the main findings of the model-based analysis called JRC-GEM-E3.

The first finding exposed by the Commission is that the EU decarbonization strategy does not strongly affect GDP growth and employment rates (European Commission 2024b). However, the EU's path to becoming a net-zero continent will determine shifts in the macroeconomic variables. To quantify these shifts, the assessment report includes a model with three different scenarios: a reference baseline (S2), a less ambitious scenario (S1), and another with the highest level of climate ambition (S3). The model also distinguishes between a global scenario, wherein the rest of the world adopts measures in line with the

Paris Agreement's 1.5°C target, and a fragmented scenario, where the rest of the world follows the NDCs.

The scenarios by 2040 generally show a more significant impact on macroeconomic variables (see Table 3 below) compared to those for 2050. In the most ambitious S3 scenario, the reduction in private consumption is more than offset by the increase in investment. S3 does not imply huge differences between the fragmented and the global alternatives, whereas for the S1 scenario, the global hypothesis results in more significant changes in the economic landscape. However, in all scenarios, the GDP is expected to return to essentially the same level by 2050. This is basically due to the underlying model assumptions of strong public investment, lower cost of renewable energies, and high profitable green technologies.

Table 3: Macroeconomic Impacts (% Change Compared to S2)

	S1 Fragmented		S1 Global		S3 Fragmented		S3 Global	
JRC-GEM-E3	2040	2050	2040	2050	2040	2050	2040	2050
GDP	0.5	0.1	0.6	0.2	-0.2	-0.1	-0.2	-0.1
Private consumption	0.7	0.1	1.8	2.1	-0.5	-0.1	-0.5	-0.1
Investment	-0.1	0.3	-0.5	-0.5	1.1	-0.1	1.1	-0.1
Exports	1.2	0.1	-0.1	-2.6	-0.8	-0.1	-0.7	0.0
Imports	0.3	0.1	1.6	1.5	0.1	-0.1	0.1	0.1
Employment	0.3	0.1	0.3	0.1	-0.1	0.0	-0.1	-0.1

Source: European Commission (2024b).

The Impact Assessment provides further information on private consumption dynamics and on the impact of short-term frictions on the economic system, highlighting the benefits that a deep decarbonization pathway could bring to companies, households, and the financial system (European Commission 2024b). However, the assessment might be affected by some critical issues.

The study does not include a full number of alternative scenarios. The Below 2°C scenario, for example, is not part of the discussion. Hänsel et al. (2020) revisited the Dynamic Integrated Climate Economy (DICE) model developed by Nordhaus in 2018 and determined that 2°C represents the economically optimal balance between future climate damages and current climate mitigation costs. On the environmental side, "*an absolute temperature limit of 2.0°C can be viewed as an upper limit beyond which the risks of grave damage to ecosystems are expected to increase rapidly*" (Stockholm Environmental Institute 1990, p. IX).

In addition, on the socio-economic side, the distributional implications of reaching net zero through a rapid transition are often neglected. Another weakness of the assessment is that the space devoted to empirical analysis of the impacts of stringent decarbonization on the financial market is not extensive. Capital markets either carry significant risks or opportunities in the current transformation, particularly relating to stranded assets – investments that will have significantly lower value in an economy with reduced dependence on fossil fuels (Saygin et al. 2019). The concept of stranded assets is concentrated mainly in carbon-intensive areas of the economy, including those like fossil fuels, power generation, and heavy industry, where regulatory change, technological innovation, and market shifts in consumer preference render certain assets unviable financially. An additional issue on which there is a research gap in modeling, in previous studies as well as in the Europe 2040 Impact Assessment, is to determine the actual contribution that carbon capture, utilization, and storage (CCUS) technologies can make to reducing transitional risks and negative macroeconomic impacts. Table 4 below summarizes the main results and assumptions emerging from the various models taken into account.

In the next section, we will discuss these findings and will try to determine the right targets and speed of decarbonization based on the existing policy tools, especially with reference to the two most relevant scenarios, namely, the 1.5°C and Below 2°C limits.

Table 4: Main Studies on Decarbonization Scenarios and Macroeconomic Implications

Author(s)/ Developer(s)	Year	Model Used	Type	Key Variables	Critical Assumptions	Macroeconomic Outcomes	Relevant Assumptions about Fast vs. Slow Decarbonization	Assumptions about Climate Policies of Rest of the World
Nieto et al.	2020	MEDEAS-World model	IAM	Energy demand, GDP, CO_2 emissions	Global economic transitions under energy constraints	Post-Growth scenario achieves 2°C target but requires radical economic shifts	Post-Growth model emphasizes radical changes for success	Assumes similar global action toward net zero
Network for Greening the Financial System	2023	Network for Greening the Financial System Scenarios	IAM	CO_2 emissions, renewable energy, temperature increases	Ambitious decarbonization strategies achieve 1.5°C	Current policies lead to 3.2°C increase; Net-zero scenarios more favorable with investments in renewable energies	Slower policies fail to meet climate goals; faster approaches needed	Scenarios assume varying levels of international coordination
International Energy Agency	2021	Net-Zero Emissions by 2050 (NZE) Scenario	IAM	Renewable energy, fossil fuel demand, CO_2 emissions	Net-zero emissions by 2050; massive investments in clean energy	Clean energy jobs increase; fossil fuel sectors decline significantly	Fast decarbonization reduces emissions by 40% by 2030	Global efforts must align with net-zero goals
Kriegler et al.	2023	NAVIGATE Project	IAM	Fossil fuel reliance, clean technology, employment, carbon tax revenues	EU transition toward low-carbon tech needs redistributive policies reinvesting carbon tax revenues in social programs	New jobs in renewable sectors, 300K jobs lost in fossil fuels; higher GDP losses in 1.5°C scenario than in the 2°C scenario	Delaying transition increases costs and risks, but acting fast is possible only with the reinvestment of carbon revenues	Assumes similar global action toward net zero
International Monetary Fund	2022	Global Macroeconomic Model	DSGE	CO_2 emissions, GDP, inflation	Rising GHG tax; policy packages to reduce emissions by 25% by 2030	Moderate impact on GDP growth; inflationary pressures initially rise	Gradual decarbonization mitigates economic shocks	US, Euro Area, China modeled for policy impacts
Coenen et al.	2024	G-Cubed Model	DSGE with some IAM and	Carbon tax revenues, GDP, inflation	Proper redistribution of revenues from carbon tax to	Carbon tax increases inflation initially but falls over	Gradual carbon tax incentivizes shift to clean energy	Relevance of global supply of fossil resources and the clearing

			CGE features		low-income households	time; GDP impact is moderate but negative growth possible		of the global market for fossil resources
Lamperti et al.	2022	DSK model	Agent-based IAM	Carbon tax, employment, energy sources	Carbon tax 14.2 times higher than current fossil fuel price needed for Paris targets	High unemployment and company bankruptcies without accompanying industrial regulations and green technology subsidies	Carbon tax alone causes economic instability and cannot guarantee a smooth transition	Analysis applied at the global level
Vrontisi et al.	2020	PRIMES and GEM-E3	CGE with some DSGE features	CO_2 emissions, GDP, EU emission pathways, transport	Global action could affect EU outcomes significantly; focus on stabilizing climate change below 2°C	Potential for both gains and losses in GDP (-0.1% to +0.3%) by 2030 based on global cooperation	Slow or fragmented efforts lead to uncertainty	Global carbon tax implementation has a positive long-term effect on EU economy
Yiakoumi et al.	2023	Linear regression methods	OLS	CO_2 emissions, equitable reduction targets	Eastern Mediterranean and Middle East countries must reduce emissions by 50% from 2019 levels to meet 1.5°C target	The emission reduction targets could lack of equity	The NDCs of EMME countries are not associated with required emissions abatement targets	No detailed assumptions
Sotiriou and Zachariadis	2021	Multi-objective optimizati on framewor k	MOOF	Emission targets, clean technology investments	Higher abatement levels are more beneficial when external costs of emissions are considered	35% reduction in emissions is feasible and economically advantageous	Faster decarbonization (35% target) offers more social and economic benefits if public investments are in place	No detailed assumptions
Ciccarelli and Marotta	2024	Economet ric model	SVAR	Carbon tax, household investments, employment, supply side	Carbon tax with revenue recycling policies lead to different impacts on investments	Household investments fell, corporate investments initially declined but recovered due to	Fast transition acts as downward supply movements; recycling revenues mitigates	Disruptive effects of transition exacerbated for low-income, high-emission countries with no history of

					and employment	alternative technologies	decarbonization impacts	environmental policy
European Commission	2024	JRC-GEM-E3	CGE with some DSGE features	GDP, employment, investments, trade, private consumption	Scenarios vary between fragmented and global; the most ambitious scenario sees significant investment shifts	GDP impact minimal by 2050; increase in private consumption in more ambitious decarbonization scenarios	Faster decarbonization yields long-term benefits; delayed transition increases costs and challenges	Fragmented or global coordination influences results; fragmented outcomes are less favorable

Source: Authors (2024).

4 Discussion

The studies analyzed in the previous section present some similarities but also many differences. They are based on different models, namely, mainly IAMs and DSGEs, as well as on heterogeneous theoretical assumptions and diverse scenarios (Nieto et al. 2020; Potsdam Institute for Climate Impact Research et al. 2021).

Some authors argue that we should pursue a fast decarbonization, whose transitional risks are mitigated by the expansion of the renewable energy market (IEA 2021) and by a targeted use of carbon market revenues (e.g., investments in social spending to reduce the distributive effects of the net-zero strategy) (Kriegler et al. 2023; Ciccarelli and Marotta 2024).

A more cautious approach is proposed by other studies, which underline that gradual decarbonization mitigates economic shocks (IMF, 2022), and a gradual carbon tax incentivizes the transition to clean energy (Coenen et al. 2024). In any case, the carbon tax alone causes economic instability and cannot guarantee a smooth transition (Lamperti et al. 2022).

Regarding the pace of the transition, it is also essential not to lose sight of the consequences that a medium-term net-zero strategy can have on the poorest or most vulnerable regions due to their dependence on fossil fuels (Yiakoumi et al. 2023). The real challenge is to balance the significant public investments that are needed to support these economies (Sotiriou and Zachariadis 2021) with the need to avoid worsening their public debt, which might generate a new debt crisis.[7]

The European Union has proposed an ambitious decarbonization plan by 2050, in line with the most stringent objectives of the Paris Agreement; the plan includes, among other things, a series of intermediate stages to be achieved by 2040. The macroeconomic impacts of this strategy are presented in the Europe 2040 Impact Assessment Report, and appear to be manageable if not, in some

[7] High public debts in the EU could limit the ability of governments to finance large-scale investments required for the transition to net-zero emissions. Additionally, debt servicing may divert funds away from social and green projects, slowing progress toward climate goals or failing in mitigating the adverse transition effects. Nonetheless, according to Han et al. (2024), there is a positive but statistically insignificant relationship between government debt and the transition to net-zero emissions. Instead, political stability is found to have a negative and statistically significant correlation with CO_2 emissions.

cases, even positive for the European economic system as a whole (European Commission 2024b). However, the assessment also presents critical issues, providing a limited number of scenarios and excluding some key elements such as stranded assets.

The review of extant studies shows the existence of trade-offs between fast and slow decarbonization. A rapid transition prevents the worst impacts of climate change, but may be economically, socially, and technologically disruptive. A more gradual transformation can allow time for more adaptation and innovation but can lock in carbon-intensive infrastructure and delay the attainment of climate goals (Kriegler et al. 2023).

We will now focus on the most critical issues and research gaps that, in our view, emerge from literature.

4.1 Impact on GDP

Despite the shift away from fossil fuels in the world economy, global GDP growth under the NZE scenario is expected to remain stable at about 3% yearly through 2030. Although the overall impact on global GDP might be moderate in the short run, sizable economic restructuring will occur in the transition. High-emissions industries, particularly in oil, gas, and coal, will decline over the coming decades and have more localized economic impacts associated with job losses. Renewable energy, on the other hand, is expected to grow and provide millions of jobs. Still, geographic and skills mismatch between job losses and gains can create adverse local economic impacts (IEA 2021). Moreover, carbon pricing is an important driver for decarbonization; ETSs can be powerful tools in this regard. Continuously growing carbon prices may turn them into a tool of economic pressure on high-emission industries, raising the production cost of companies and leading to temporary contractions in GDP within heavily affected sectors (Lamperti et al. 2022).

The less stringent Below 2°C scenario does not imply strong effects on GDP growth but leads to different environmental outcomes. It seems confirmed that a strong decarbonization, if appropriately guided with redistribution of carbon pricing revenues and investments in renewable energy, is beneficial and does not determine significant economic effects on GDP (Claeys et al. 2024). What is missing from the models, however, is the measurement of the effect of the net-zero strategy on social well-being. Indeed, **investments do compensate for consumption in terms of GDP**, but it is not evident how and if they do that in terms of welfare.

4.2 Impact on Employment

Decarbonization will imply the extensive realignment of labor markets, but this shift may not be equal geographically and may leave some skill levels mismatched between lost and gained jobs. EU climate policies have so far favored technical and professional workers over manual workers. Looking at the data, we see that increasing energy prices by 10% leads to a 17.9% growth in the employment of technicians and a 13.1% reduction in manual jobs. The stringency of environmental policy explains 17.3% of the increase of high-skilled technical workers and 14.2% of the decrease in manual worker roles (Marin and Vona 2018). That explains why **workers who may have competencies in the areas of science, technology, engineering, and mathematics (STEM) are more likely to shift into green jobs**, whereas a manual worker might find such a change much more difficult.

Another big issue is gender inequality, as 60% of women are less likely than men to get green jobs (Causa et al. 2024). These disparities really point to the need for targeted support and retraining programs so that no group gets left behind in the transition.

The Just Transition Mechanism is supposed to address these challenges by providing retraining, social protection, and economic support to help manual workers move into greener sectors from carbon-intensive sectors. The mechanism could create up to 24 million new green economy jobs by 2030, while safeguarding the livelihoods of 6 million people against long-term unemployment (ILO 2023). It puts the 1.5 million most redundancy-prone workers on long-term recovery paths and realigns labor markets with sectors that will proliferate in the coming years – for instance, renewable energy, which is expected to grow by 10–15% by 2030.

However, this must be complemented with an expanded policy set by the European Union to secure a complete and more flexible transition framework.

Investment in reskilling and upskilling programs, especially for women and low-skilled workers, is urgent to facilitate access to green jobs. Closing gender gaps and ensuring equitable access to these opportunities must be a top priority but requires time: complete retraining might take five to ten years for full-scale expansion and hence slow down the overall transition process (Causa et al. 2024). Europe needs then to accelerate funding **reskilling and upskilling initiatives**, as well as for regions heavily dependent on carbon-intensive sectors with both short-term economic support and long-term investment in green alternatives. Quicker action supported by increased cooperation among Member States will enable better coherence in the transition.

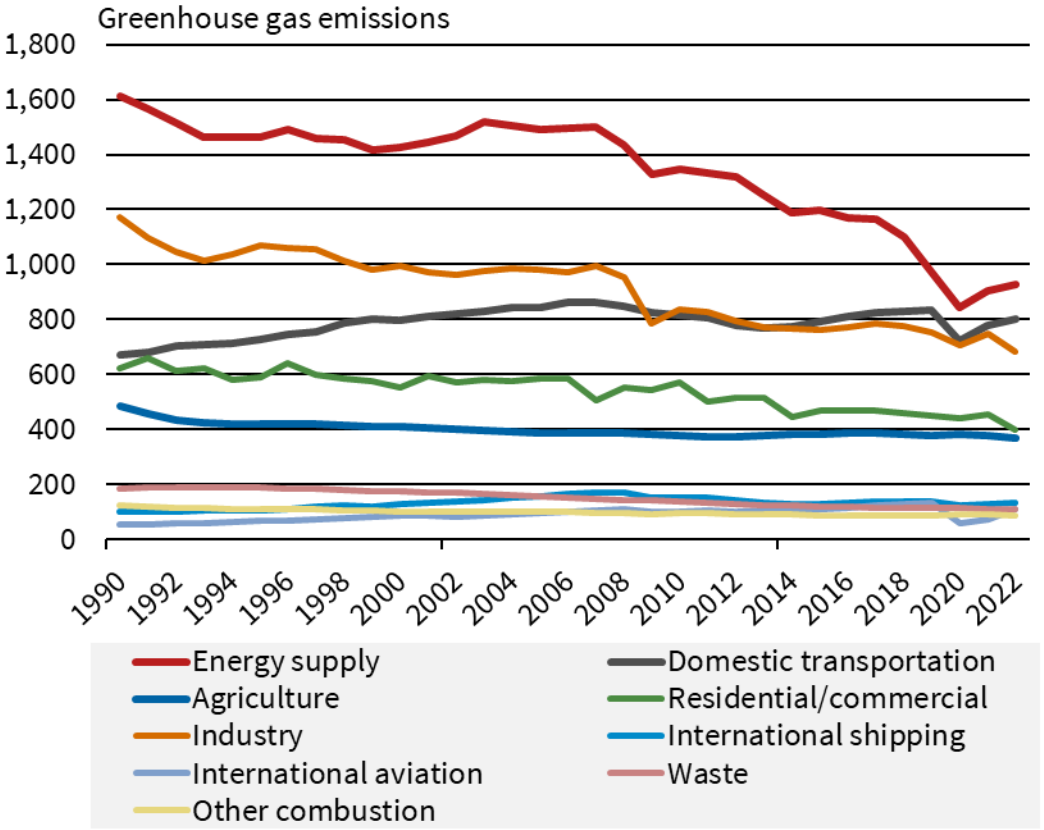
4.3 Impact on Low-Income Consumers and the Expansion of Carbon Pricing Mechanisms

The impact of decarbonization on GDP has been the object of many studies, but most of them overlook equity considerations. When equity is not factored into these analyses, the results often present a skewed picture. The distributional impacts of climate policies in regard to strategies for decarbonizing their economies constitute a growing concern by governments; to mitigate those impacts, both supporters of a more drastic approach (e.g., Kriegler et al. 2023; Ciccarelli and Marotta 2024) and those of a more gradual one (e.g., IMF 2022) agree that the main instrument is the redistribution of carbon pricing revenues. In this regard a key role can be played, at the European level, by the recycling of the revenues of both the EU ETS and the EU ETS2.

By putting a carbon price on the polluting sectors, ETSs are among the most potent measures to achieve decarbonization. According to Errendal et al. (2023), **carbon markets exert influence by increasing the costs of high-carbon goods and services**, thus discouraging their consumption; these markets encourage shifting toward low-carbon alternatives by making carbon-intensive options more expensive. Furthermore, the **revenues generated from carbon pricing are crucial for funding technological advancements** and fostering innovation in emission-reduction technologies (Errendal et al. 2023; Borghesi and Ferrari 2023).

Since its inception, the EU ETS has targeted major industrial emitters, contributing significantly to emission reductions within specific sectors like energy supply and industry (Figure 7). However, the evolving landscape of global climate needs has spotlighted the necessity for expansion and reform.

Figure 7: CO_2 Emissions by Sector in Europe (in Million Metric Tons of CO_2 Equivalent)

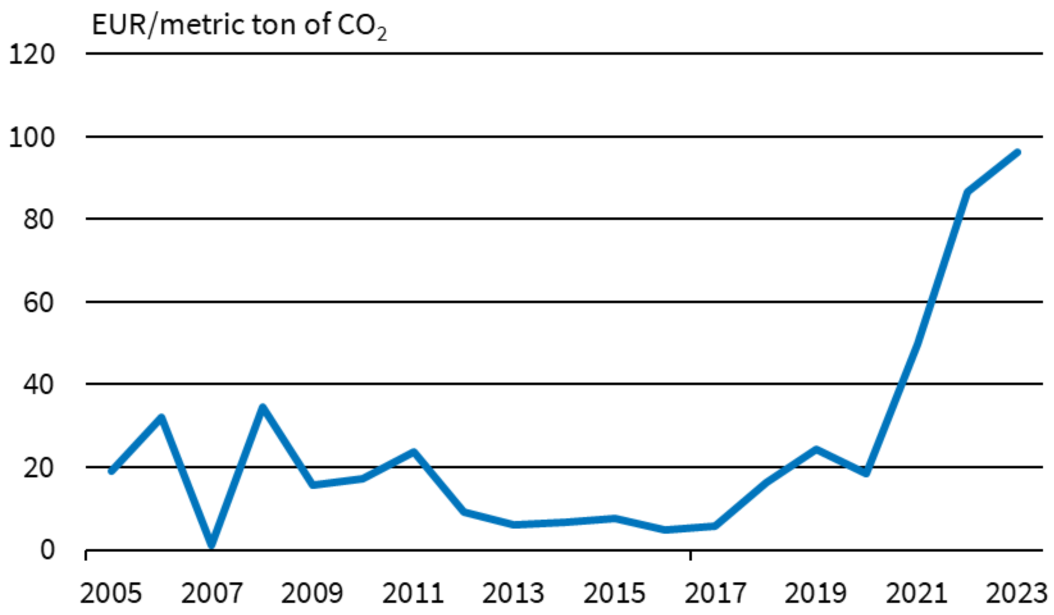


Source: European Evironment Agency (2024). © ifo Institute

The complementary market, EU ETS2, aims to encompass new sectors including emissions from buildings, transportation, and small businesses. This expansion is critical as these sectors represent a substantial portion of EU emissions, potentially leading to more comprehensive pollutant reductions and hitting consumption. Indeed, while mechanisms like the EU ETS are very critical in the reduction of GHG emissions, they may place additional burdens on households with lower incomes without proper compensation measures (Fredriksson and Zachmann 2021). Households with fewer financial resources usually allocate a higher share of their income to energy and cannot bear the upfront costs of transition to low-carbon technologies. This makes them especially vulnerable to rising energy prices (Markkanen and Anger-Kraavi 2019). Indeed, carbon markets tend to have regressive impacts, with lower-income households experiencing welfare losses of up to 15% due to higher energy costs, compared to less than 5% for higher-income groups (Vandyck et al. 2021). However, redistributing carbon revenues through lump-sum payments can reverse this trend, making the policy progressive and leading to welfare gains of up to 10% for the poorest households (Vandyck et al. 2021).

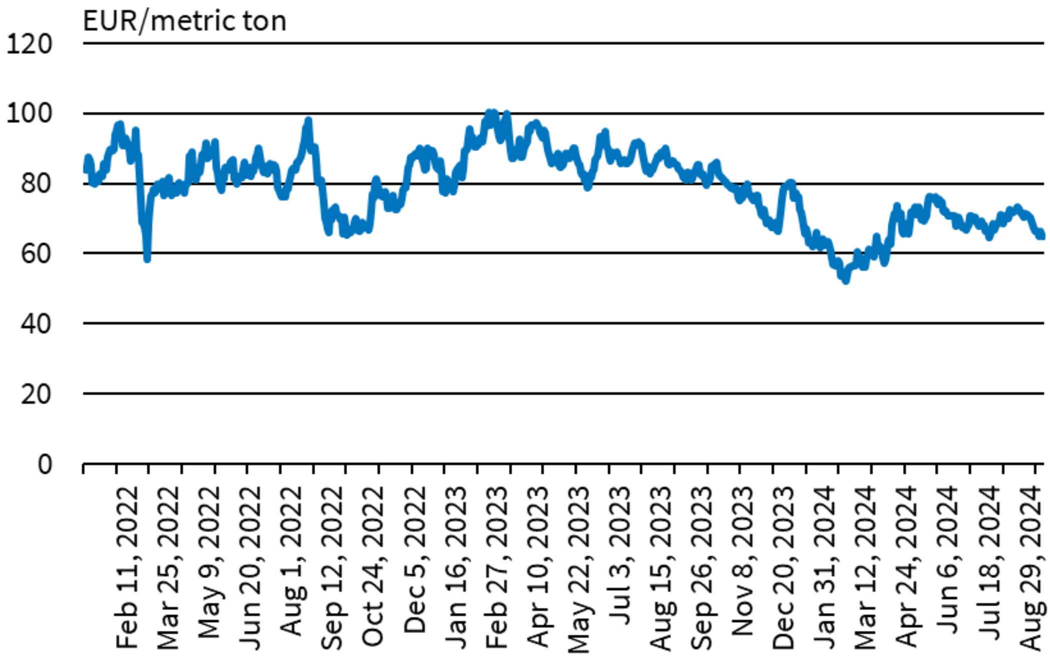
The key drivers of carbon pricing include the social cost of carbon, considering economic damage from carbon emissions; the level of ambition of climate policy targets, such as reaching net zero; and market factors like energy demand, technological development, and the availability of low-carbon options. After the solid growth experienced since 2017 following the announced implementation of the **Market Stability Reserve** (MSR; see Figure 8), the carbon price stopped growing and then began falling in autumn 2023 (Figure 9). This was because of the increase in allowance supply due to the **REPowerEU** proposal, and, paradoxically, the decrease of CO_2 emissions in Europe in 2023.

Figure 8: EU ETS Average Annual Price of Emissions Allowances in the EU



Source: ICAP (2024). © ifo Institute

Figure 9: The Price of Emissions Allowances in the EU (2022–2024)



Source: EMBER (2024). © ifo Institute

The price of ETSs follows a complex dynamic, although it is plausible to expect that it will grow significantly in the coming years (Lamperti et al. 2022). Consequently, the pressure on businesses and consumers might continue to increase, as well as the revenues of ETSs.

The funding from EU ETS and the proposed EU ETS2 could be substantial, with projected revenues between EUR 800 billion and EUR 1,500 billion by 2050 (Fuest and Pisani-Ferry 2020). These funds are envisioned to support technology and social adaptation programs through acts like the SCF. The enhancement of this plan and more apparent redistribution mechanisms are essential for maintaining public and stakeholder support. Effective redistribution strategies can alleviate potential economic burdens imposed by increased carbon costs, especially in vulnerable communities and sectors, and for SMEs that the EU ETS2 will cover.

Transparency and efficiency in these processes, with a process for **earmarking the revenues** (Borghesi and Ferrari, 2023), are fundamental to ensure that the funds both serve their intended purpose of facilitating an equitable transition to a low-carbon economy and are well communicated to a skeptical general public.

The evolution of the European carbon market through the enhancement of the EU ETS and the establishment of the EU ETS2 offers a promising pathway toward competitive decarbonization. By expanding the scope of carbon pricing, leveraging the economic benefits of carbon market revenues, and aligning international policies, Europe can effectively drive regional and global advancements in reducing carbon emissions. A further step could be the one of a Climate Club among G-7 or G-20 countries, suggested by Nordhaus (2015), which represents a strategic approach to harmonizing and coordinating climate policies. Such a club could set unified standards and guidelines for high-emitting industries, enhancing the global impact of carbon markets and balancing the macroeconomic effect of such decarbonization measures. Additionally, the proposal by Gonand et al. (2024) for a CBAM that considers average emissions across the value chain and includes export rebates for clean industries highlights a method to preserve competitiveness while promoting environmental goals.

4.4 Phasing out of Fossil Fuels and Promoting Renewable Energies

Phasing out fossil fuels and investing in renewable energy are the main assumptions of almost all decarbonization models. At COP28, the EU was a strong advocate for quickly ending the use of unabated fossil fuels globally and stressed the necessity of directing all financial activities to support the objectives of the Paris Agreement. The effort, for example, includes stopping the funding of new coal infrastructure projects in other countries and demonstrating a solid commitment to transitioning toward renewable energy sources. Despite such a position, the development in the EU is different from that of phaseouts of fossil fuels in the coming decades, and it will require revisions to achieve net-zero emissions by 2050 (European Scientific Advisory Board on Climate Change 2024).

The transition toward the 2040 climate target in Europe necessitates a rigorous re-evaluation of oil, gas, and coal production and consumption, balancing climate policies with industrial competitiveness and equity for households. **Phasing out can significantly influence the European macroeconomy by redirecting financial flows from fossil-based to renewable energy sources,**

impacting industrial operations and household energy costs. For instance, removing subsidies leads to initial increases in production costs and consumer prices, potentially disrupting the broader economic landscape, including inflation and GDP growth. **Strategically managing the phaseout could mitigate these impacts by** progressively **withdrawing from coal and gas use and reinforcing renewable energy investments** (Fries 2023). This ensures that industries have time to adapt to higher operational costs and changing energy prices. For industries reliant on fossil fuels, increased costs and reduced global competitiveness could be offset by fostering innovation and efficiency in renewable energy technologies. Indeed, we know from the literature that climate and energy policy could positively impact technological, organizational, and behavioral innovations (Borghesi et al. 2015a, b; Antonioli et al. 2016).

To address the medium-term disproportionate effect on low-income households, who spend a larger share of their income on energy, in addition to the implemented SCF and existing energy efficiency measures and directives, the EU could implement subsidies and tax credits for these families, **promoting energy efficiency upgrades that reduce overall energy consumption**. Where can we find the resources without jeopardizing the public budget, i.e., avoiding indebtedness to future generations and complying with the national constraint of a 3% primary surplus under the European Stability and Growth Pact? As mentioned above, EU ETS revenues are one possible source of subsidy financing. Other resources are expected to come from phasing out fossil fuel subsidies and leveraging public-private partnerships, as well as from CBAM-related revenues, environmental taxes, and green bond funds.[8]

Energy efficiency in buildings is a crucial aspect of the EU's strategy to reach net zero. Knobloch et al. (2019) noted that with stringent policy instruments, an almost complete decarbonization of residential heating is possible by 2050. Policies focusing on decarbonizing building heating systems by 2030 emphasize the need for advanced technologies and extensive retrofitting of existing buildings (Rüdinger et al. 2024). Regulatory measures on **energy efficiency in**

[8] Green bonds fuel investments in green technologies and spur innovation by providing funding for sustainable initiatives. They contribute to the goal of reaching net-zero emissions by directing capital toward environmentally friendly alternatives (Lee et al. 2023). The European Investment Bank (EIB) committed EUR 44.3 billion in financing in 2023 to promote environmental sustainability and climate action worldwide. This amount accounts for 60% of the Bank's total financing (EIB 2024). On December 21, 2024, the European Union Green Bonds Regulation took effect, enabling companies, regional or local authorities, and EEA supranational entities to issue "European Green Bonds" (EuGB). The hope is that this regulation will make it easier to do green investments in Europe.

new constructions and significant renovations supported by the redistribution of ETS 2 revenues can significantly contribute to such a goal.

Thus, a strategic phaseout of coal and unabated oil in the electricity sector by 2040 is critical for reducing CO_2 emissions while enhancing energy security and market stability. By 2030, Europe aims to achieve annual additions of **solar and wind capacities at scales previously unmatched**, indicating a move toward a predominantly **renewable-based energy system** (IEA 2021). To support that ambitious goal, the EU needs robust policies that incentivize renewable installations and ensure their integration into the existing grid infrastructure. Moreover, **promoting green technologies promises economic growth and job creation. It plays a critical role in achieving long-term sustainability goals**, notably in emerging sectors such as **green hydrogen production**, which is expected to rise significantly by 2050 (Bouacida 2023). In this regard, the third building block of the 2040 Europe climate target on implementing infrastructure to deliver, transport, and store hydrogen and CO_2 is critical to ensure Europe can take advantage of the opportunity.

4.5 Stranded Assets and Capital Markets

Accomplishing the goal of limiting the temperature increase to 1.5°C involves rapid carbon reductions, directly attacking the value of assets pegged to fossil fuels and other high-carbon industries. In the case of the 1.5°C limit, we know that global emissions need to fall by roughly 45% from the levels of 2010 by 2030 and reach net zero by 2050. It necessitates leaving a significant portion of fossil fuel reserves (33% of oil, 49% of gas, and 82% of coal, according to Bos and Gupta 2019) untapped to avoid exceeding these temperature limits. These dynamics create considerable financial risks for companies and investors involved in these sectors. With an actual case for the 1.5°C pathway, it is suggested that up to 40% of global coal-fired power plants be stranded by 2030 (Saygin et al. 2019).

At the global level, the transition might lead to stranded reserves worth 204 gigatons of carbon for the top 100 oil and gas companies, which is a life-size financial loss (Bos and Gupta 2019). Exposure to carbon-intensive industries further exacerbates these risks in capital markets. For example, around 40% of

European banks' loan portfolios are exposed to energy-intensive sectors, raising their vulnerability to transition risks (Chaudhary 2024). In the Below 2°C Scenario, it is estimated that USD 2.3 trillion in upstream oil and gas projects might be stranded in 2025 (Van der Ploeg and Rezai 2020).

It follows that **green finance** can play a core role in mitigating such risks. With the increasing focus on channeling capital into sustainable investment through thematic ETFs, ESG investing, green bonds, and sustainability-linked loans, significant momentum exists: the green bond market in Europe, for example, reached EUR 1.259 billion by 2021 (Council of the European Union 2023). However, Europe alone has an estimated annual financing gap of EUR 470 billion toward its climate objectives – an indication of the magnitude of the financial challenge that lies ahead (European Central Bank 2021).

Regarding the pace of the process, the Below 2°C pathway is the smoother transition; it gives fossil fuel-based industries a more extended period over which to adapt. However, the risk of stranded assets remains very high. For instance, even by 2040, as many as one-quarter of gas-fired power plants could remain stranded (Saygin et al. 2019). Even under this more relaxed scenario, around USD 1.6 trillion in oil and gas investments will be stranded between 2018 and 2025 (Van der Ploeg and Rezai 2020).

Stranded assets do not necessarily have to deal only with fossil fuels. Other sectors, such as real estate, agriculture, and transport, will be equally exposed to transition risks. For example, the automobile industry will face significant amounts of risk in transitioning from internal combustion engines to electric vehicles, with as many as EUR 600 billion in asset value reportedly being at risk by 2025 (Chaudhary, 2024). Similarly, the real estate sector is vulnerable to transition risks compelled by energy efficiency upgrades, given that 42% of Europe's total energy use comes from this sector (Chaudhary 2024). This, in turn, would imply that the capital markets should consider **disclosure of climate-related risk**, **move toward the principles of ESG**, and **shift capital into sustainable projects**.

Again, this transition requires massive effort but simultaneously opens avenues for growth in green finance and renewable sectors. As the Banking Union and Capital Markets Union of Europe develop, this will continue to be crucial in supporting green project financing and ensuring that financial institutions remain resilient through the transition (European Stability Mechanism 2024).

4.6 Supporting Competitiveness in the EU Decarbonization Path

In the models examined, the direct impact of decarbonization on industry is not quantified unless companies are included as a complementary actor in the economic system. Yet, while crucial for combating the climate crisis, the ambitious journey toward net zero in the EU presents considerable economic challenges, particularly impacting companies (IMF 2022). The contraction of GDP resulting from climate policies, predicted by short- to medium-run DSGE models, impacts companies extensively (Coenen et al. 2024). Stranded assets in the portfolio of larger companies also have an ill effect on transition risk mitigation (Bos and Gupta 2019). The transition to a low-carbon economy necessitates a shift in consumption patterns, often associated with initial high costs and disruptions in traditional industries (Fuest et al. 2024). As industries adapt to **stringent emissions regulations**, the direct costs incurred may increase consumer prices, **affecting overall economic consumption**.

To navigate these challenges, the EU needs to implement policies that minimize the costs of decarbonization and foster economic growth and efficiency (Fuest et al. 2024; Draghi 2024). These policies must encourage innovation and the efficient use of resources while making economic activities more sustainable in the long term.

Proposals like diversifying trade partners to lower the cost of energy, supporting cost-efficient energy sources (including renewables, hydrogen, bioenergy, and carbon capture, utilization, and storage [CCUS]), developing the EU clean tech industry, and implementing an industrial action plan for the automotive sector are in line with the goals above (Draghi 2024).

On our side, we think that a few actions must be prioritized. The current initiatives to help the European economy absorb the paradigm shift without shocks need more funding. The JTM, the Net Zero Industry Act, the Circular

Economy Action Plan, and the Eco-design for Sustainable Products Regulation are the relevant policies designed to address the transition toward a sustainable, low-carbon economy. The JTM alone should ensure that the shift toward a green economy is fair and inclusive, preventing regions and communities dependent on high-carbon industries from being disproportionately impacted. With a budget aimed at mobilizing EUR 150 billion, the mechanism supports the reskilling of workers, aids SMEs, and finances projects that cut emissions, thus mitigating the socio-economic risks associated with the transition. Focusing on social equity helps maintain social and political support for decarbonization efforts, which is crucial for their success. Still, the budget seems limited to reach the ambitious goal.

The Net Zero Industry Act plays a key role by focusing on scaling up Europe's industrial base in clean technologies. Aiming to produce at least 40% of Europe's clean tech needs domestically by 2030, the act reduces dependency on non-EU countries for critical renewables, batteries, and hydrogen technologies. The action may enhance the EU's competitive edge in global markets and secures its industrial base by diversifying supply chains and boosting innovation. However, this may also come with additional public debt. Moreover, **excessive bureaucracy and long timelines for accessing plan benefits** are often insurmountable obstacles for SMEs (Draghi 2024).

The Circular Economy Action Plan complements the efforts by transforming how resources are used across the economy. By promoting product longevity, repairability, and recyclability, the plan aims to reduce waste and conserves resources, which is essential for sustainable growth. Such an approach might support economic stability by reducing the input costs for industries and mitigating the volatility associated with raw material supply disruptions. However, at the moment, significant regional disparities characterize the existing recycling infrastructure. In our view, improving public waste management infrastructure is essential for reinforcing the plan, together with providing economic incentives for companies to adopt circular business models. Lastly, the Eco-design for Sustainable Products Regulation extends the eco-design approach to ensure that products sold in the EU market are more durable, repairable, and recyclable. It reduces environmental impact and drives innovation in product design and manufacturing processes, contributing to industrial competitiveness. Strengthening legislation and enforcing regulation is effective as long as gradual timelines and clear milestones are outlined.

The contribution of digital technologies to reaching the goals is not to be neglected. Thus, we support the idea of a new Industry 5.0 plan envisioning a future in which European industry drives economic and societal transitions by prioritizing digital and green initiatives. This approach complements the well-known concept of Industry 4.0 by focusing on research and innovation for a sustainable, human-centric industry, simultaneously addressing societal challenges, empowering workers, enhancing competitiveness, and supporting the environment. It aligns with EU priorities and integrates into major policy initiatives like AI regulation, the Skills Agenda and Digital Education Action plan, the industrial strategy, and the Green Deal, promoting a holistic industrial transition for societal progress. Together, **these frameworks create a starting strategy for Europe to achieve decarbonization. It is therefore desirable for the next Commission to maintain, indeed strengthen, these policy sets in order to avoid, on the one hand, neglecting decarbonization goals and, on the other hand, shifting the costs of the process onto the shoulders of the weakest agents of the production system**, such as SMEs in the most economically vulnerable Member States. The main goal of current initiatives should be to achieve decarbonization targets while also accommodating the needs of the industrial system, allowing businesses sufficient time to adapt to the ongoing revolution.

In addition to the existing plans, the expansion of the EU ETS provides a financial incentive for companies and households to reduce their emissions, while a fair redistribution of revenues could solve potential distributional concerns. Regarding this, we saw that after comparatively brief spikes in energy costs, countries that adopted carbon tax-and-revenue recycling witnessed an average 1% annual decrease in their GHG emissions, along with improvements in household investment, employment, and business confidence (Ciccarelli and Marotta 2024). So, a larger share of ETS revenues should be directed toward decarbonizing energy-intensive industries (EIIs), focusing on green hydrogen and CCUS (Draghi 2024).

4.7 Investing in Research and Development for Carbon Capture Technologies

In the context of climate policy, technological innovation refers to advancements that help industries transition to low-carbon energy solutions. However, many macroeconomic models struggle to accurately capture the influence of such innovations, particularly in integrating the economic impacts of low-carbon technologies (Mercure et al. 2019). This limitation can result in models that provide incomplete assessments of climate policies. Among the most notable innovations are carbon capture technologies (CCTs), which are central to industrial carbon management. Carbon management involves technologies that capture, transport, utilize, and store CO_2 emissions or remove CO_2 directly from the atmosphere. In Europe, these technologies are pursued along three key pathways (European Commission, 2024c):

- Carbon capture and storage (CCS): This pathway involves capturing CO_2 emissions from fossil, biogenic, or atmospheric sources and storing them in geological formations to prevent their release into the atmosphere. CCS is often seen as a promising technology for reducing CO_2 emissions, with the potential to capture large quantities of GHG and create jobs. However, it faces high initial costs, substantial energy demands, and potential environmental risks from CO_2 leakage. Continuous research and development are necessary to overcome these barriers and enhance scalability.
- Carbon capture and utilization (CCU): CO_2 is captured and reused to replace fossil-based carbon in producing synthetic fuels, chemicals, or other industrial products. CCU relies heavily on infrastructure to transport CO_2 to locations where it can be used in industrial processes or stored. This infrastructure is crucial for developing a CO_2 market in Europe, particularly for industries such as construction, synthetic fuels, and chemicals (European Commission, 2024c).
- Atmospheric CO_2 removal: This technology, also called direct air carbon capture and storage (DACCS), captures CO_2 from the atmosphere for permanent storage. While atmospheric CO_2 removal offers another technological solution, it remains controversial. Critics argue that restoring natural carbon sinks, like salt marshes and seagrass meadows along European coastlines, could achieve similar results at lower costs (Macreadie et al. 2021). Additionally, atmospheric removal is costly and

energy intensive. Some experts caution that this approach might perpetuate dependence on fossil fuels and slow the transition to renewable energy (Anderson et al. 2023).

In 2022, 44% growth in global CCUS industry capacity was observed. The capture cost varies from industry to industry and also quality/CO_2 concentration, which lies between EUR 13 and EUR 103 per metric ton (Itul et al. 2023). It is important to note that estimates for the costs of CCS technologies vary widely in the literature, reflecting differences in assumptions, technology maturity, and regional factors. Also, the data does not specifically break out DACCS (direct air carbon capture and storage).

Since 2012, the US has been the world's largest investor in private R&D on CCUS. The EU accounts for a 10% share of the global amount. In the EU's public R&D funding of 2021, Denmark was on top with a share of 39%, followed by France at 23% and Germany at 21%. In addition, the CCUS sector employs 6,400 people worldwide, of which 4,000 jobs have been claimed by the US alone. **Up to 1.4 million jobs could be developed in this sector globally by 2040.** Last but not least, CCUS captured EUR 1.5 billion in venture capital investment in 2022, up from EUR 750 million in 2021, with 38% of the total taken by the US (Itul et al. 2023).

Investment in R&D is critical for advancing CCTs. R&D fosters innovation, helping to reduce the macroeconomic impacts of decarbonization by improving the feasibility of technologies like absorption, adsorption, membrane capture, cryogenic separation, and oxy-combustion. These methods vary in their economic implications, largely due to the energy and equipment required for CO_2 separation. Tools like the Technology Development Matrix (TDM) can help guide R&D efforts by assessing the performance, cost, and commercial viability of emerging technologies (Baker et al. 2022), providing a clearer pathway for policymakers and investors.

The integration of CCUS into the EU ETS will become quite cardinal for achieving net-zero emissions by 2050 (Rickels et al. 2021). That means including mechanisms for negative emissions into the system through Carbon Removal Credits (CRCs). Future climate targets would also require revision to ETS legislation allowing CRCs in the EU, which, in turn, would support CCUS technologies.

Adding these technologies to the mix could help achieve net emissions reductions at reduced cost while continuing to meet overall caps. A regulatory authority could facilitate the use of the CRCs, which would stabilize the carbon price and make the carbon removal technologies more competitive, especially in the post-2030 phase.

4.8 Global Arena: Reinforcing International Collaboration on Climate Policies

The last point we want to raise is about the global context. International collaboration comes with significant challenges. These include differences in political priorities, economic structures, and levels of technological development, which can make it difficult to align policies and incentives. However, most of the reviewed macroeconomic models rely on open economy assumptions, which means that the models allow for the flow of goods, services, capital, and technology across borders, which is essential in a world where no country can decarbonize in isolation. Crucially, the models highlight the benefits of international cooperation, where countries collaborate by **trading carbon credits** and/or adopting harmonized regulations. Thus, these models underscore that a collective, global effort is key to a successful and equitable energy transition.

In line with this, the European effort cannot lead to major consequences if it is not shared with other countries (Vrontisi et al. 2020). To achieve decarbonization goals, joint action with the most polluting countries is necessary (Kriegler et al. 2023). The European jurisdiction has been at the forefront of climate policies for decades and has taken a leading role in the global push toward decarbonization. This is evidenced by the actions of European representatives at major environmental summits, such as the Paris COP in 2015 and all the subsequent COPs. The goal to become a carbon-neutral region by 2050 and the EU ETS are also main examples of initiatives that have been replicated by other regions of the world. In fact, some of the scenarios presented in the Europe 2040 Impact Assessment differentiate between fragmented and global efforts to decarbonization, illustrating how the macroeconomic impacts diverge under each scenario. Fragmented efforts tend to lead to higher costs and potential trade barriers, whereas global cooperation reduces inefficiencies and enhances the overall cost-effectiveness of decarbonization.

The EU's proactive approach is essential because climate change is a global, critical, and extremely thorny problem. However, the constructive attitude should not be unilateral, as policies of that nature risk being counterproductive for the macroeconomic system. For example, unilateral policies like CBAM posed great challenges for EU partners in terms of trade and compliance costs. To mitigate those adverse macroeconomic effects due to the reduction of international trade, a fertile cooperation can be achieved by identifying the most influential stakeholders, such as the United States, India, China, and the African Union.

Although complex in a setting with many actors like Europe, involving third countries in continental decarbonization is essential, especially regarding measures that directly impact these countries. It requires ensuring investment conditions in developing countries are as near as possible to those in the EU, because addressing governance and regulatory gaps in these nations is fundamental for facilitating a fair transition. The limited fiscal capacity and diverse socio-economic priorities between developed and developing nations pose challenges to creating an international level playing field, particularly in steel production more affected by CBAM. Thus, enhanced international cooperation is necessary, particularly in aligning trade regulations and subsidies to support global low-emission steel production (Bataille et al. 2023).

International cooperation in carbon markets, specifically through linking emission trading systems (ETSs), is crucial for efficiently and cost-effectively reducing global GHG emissions (Vrontisi et al. 2020). By allowing ETSs to trade allowances, the linkage aligns carbon prices across jurisdictions and targets emissions reductions where most economical. It capitalizes on economies of scale and addresses regional cost disparities. Trust, consensus on price levels, and reciprocal benefits are essential for practical cooperation and agreement implementation. Regular updates in response to economic, environmental, and technological changes ensure these systems' ongoing relevance and effectiveness. Overall, linked carbon markets enhance global capacity to meet climate goals economically, emphasizing the need for strategic alignment and robust regulatory frameworks (Borghesi and Zhu 2020; Doda et al. 2022).

Dynamic climate global governance is imperative to buffer against decarbonization efforts' potential adverse macroeconomic consequences. Adaptive policy frameworks that accommodate rapid technological innovation and shifts in economic structures can prevent economic disruptions as societies transition from fossil fuels (Hölscher and Frantzeskaki 2020). Strategic international cooperation on emergent green technologies or infrastructures is critical to fostering new industrial sectors and employment opportunities, thereby supporting economic resilience.

Furthermore, harmonizing decarbonization policies internationally prevents the risk of carbon leakage, where emissions are displaced rather than reduced globally; to successfully do that, implementing CBAM gradually, alongside targeted subsidies for renewable energy initiatives, can ensure a balance between economic growth and environmental imperatives.

With its decarbonization strategy, the EU can limit the macroeconomic effects of the transition and spur imitation effects across its partners, acting as an international benchmark for implementing effective climate measures.

5 Conclusions

To contain increasingly severe climate damage and risks, stringent policies are needed. At the same time, the ongoing transformation has macroeconomic effects that cannot be overlooked if we are to pursue an equitable ecological transition.

European institutions have embarked on a journey aimed at ensuring climate neutrality while preserving social equity by developing a complex set of deals, acts, plans, initiatives, and regulations. The European decarbonization process should continue in the future. This should be done for the remarkable environmental and social benefits it may generate, as well as for the potential imitation effect it can produce (and is partially already producing) across other jurisdictions in terms of more stringent climate policies. As economists perfectly know, there is no free lunch in the economy. This also applies to decarbonization, which can affect macroeconomic variables.

Some shocks can be expected in the coming years due to the transition to net zero, especially on the consumption and production sides (Fuest et al. 2024; Draghi 2024), though negative effects can be mitigated by corrective mechanisms (Claeys et al. 2024). For example, to mitigate employment disruptions, upskilling and reskilling programs for workers should be considered.

The impact on low-income consumers can be reduced by redirecting revenues from carbon markets. Given the growing use of the emissions trading mechanism, we advocate for a more significant redistribution of carbon market revenues toward the most vulnerable population segments, clearly showing the allocation of these funds for communication purposes (Borghesi and Ferrari 2023). This could enhance the social acceptability of climate policies.

The phasing out of subsidies to fossil fuels must be accompanied by strengthening public support for renewable energies, which have proven increasingly cost-efficient over the years. Green finance, including green bonds and ESG investing, is essential for mitigating the risk of stranded assets.
Policies such as the Just Transition Mechanism, Net Zero Industry Act, Circular Economy Action Plan, and Eco-design Regulation can also help overcome

transition risks. In addition, strengthening green initiatives and overly complex bureaucracy and extended delays in accessing the benefits of the plans is essential for achieving decarbonization goals without disproportionately impacting vulnerable sectors and SMEs.

Finally, given that global warming and its economic consequences are a transboundary issue, we advocate for prosperous international collaboration. This requires following and possibly accelerating the progress made at the last COPs, with Europe assuming leadership in managing paths and strategies toward decarbonization.

In our view, if the European Union pursues these strategies, it can manage to stay in line with its recent climate policy, reinforce the environmental results achieved so far, preserve the credibility of its climate commitments, and support its competitiveness in the future that the negative consequences of climate change will increasingly dominate.

References

Anderson, K., H.J. Buck, L. Fuhr, O. Geden, G.P. Peters and E. Tamme (2023), "Controversies of Carbon Dioxide Removal", *Nature Reviews Earth and Environment* 4(12), 808–814.

Angeli, M., C. Archer, S. Batten, A. Cesa-Bianchi, L. D'Aguanno, A. Haberis, T. Löber, S. Maxwell, R. Sajedi, M. van der Merwe, B. Wanengkirtyo and C. Young (2022), "Climate Change: Possible Macroeconomic Implications", *Bank of England Quarterly Bulletin* 62(4), 1–31.

Antonioli D., S. Borghesi and M. Mazzanti (2016), "Are Regional Systems Greening the Economy? Local Spillovers, Green Innovations and Firms' Economic Performances", *Economics of Innovation and New Technology* 25(7), 692–713.

Aubert, P. M., B. Gardin and C. Aillot (2021), "Towards a Just Transition of Food Systems. Challenges and Policy Levers for France", Institute for Sustainable Development and International Relations (IDDRI).

Baker, R., O. Alizadeh Sahraei, M. M. Dal-Cin and F. Bensebaa (2022), "A Technology Development Matrix for Carbon Capture: Technology Status and R&D Gap Assessment", *Frontiers in Energy Research* 10.

Bataille, C., N. Berghmans, A. Garg, O. Hebeda, E. La Rovère, B. McCall and M. T. Gunfaus (2023), "Innovative International Cooperation for Climate", Institute for Sustainable Development and International Relations (IDDRI).

Bellora, C. and Fontagné, L. (2023), "EU in Search of a Carbon Border Adjustment Mechanism", *Energy Economics* 123.

Bilal, A. and D. R. Känzig (2024), "The Macroeconomic Impact of Climate Change: Global vs. Local Temperature", *NBER Working Paper* 32450.

Borghesi S. and T. Zhu (2020), "Getting Married and Divorced: A Critical Review of the Literature on (De)linking Emissions Trading Schemes", *Strategic Behavior and the Environment* 8(3), 219–267.

Borghesi, S., F. Crespi, A. D'Amato, M. Mazzanti and F. Silvestri (2015a), "Carbon Abatement, Sector Heterogeneity and Policy Responses: Evidence on Induced Eco Innovations in the EU", *Environmental Science and Policy* 54, 377–388.

Borghesi S., G. Cainelli and M. Mazzanti (2015b), "Linking Emission Trading to Environmental Innovation: Evidence from the Italian Manufacturing Industry", *Research Policy* 44(3), 669–683.

Borghesi, S. and A. Ferrari (2023), "Can the EU ETS and Its Revenues Tackle the Impact of High Carbon Prices?", *EconPol Forum* 24(6), 28–31.

Bos, K. and J. Gupta (2019), "Stranded assets and stranded resources: Implications for climate change mitigation and global sustainable development", *Energy Research and Social Science,* 56.

Bouacida, I. (2023), "Developing Hydrogen for Decarbonization in Europe: How Relevant Are Contracts for Difference?", *IDDRI Policy Brief* 02/23, https://www.iddri.org/en/publications-and-events/policy-brief/developing-hydrogen-decarbonisation-europe-how-relevant-are

Brecha, R. J., G. Ganti, R. D. Lamboll, Z. Nicholls, B. Hare, J. Lewis and M. J. Gidden (2022), "Institutional Decarbonization Scenarios Evaluated Against the Paris Agreement 1.5°C Goal", *Nature Communications* 13.

Causa, O., E. Soldani, M. Nguyen and T. Tanaka (2024), "Labour Markets Transitions in the Greening Economy: Structural Drivers and the Role of Policies", *OECD Economics Department Working Papers* 1803.

Chaudhary, N. (2024), *From Stranded Assets to Assets-at-Risk. Reframing the Narrative for European Private Financial Institutions*, I4CE Institute for Climate Economics, Climate Report, https://www.i4ce.org/en/publication/stranded-assets-assets-risk-reframing-narrative-european-private-financial-institutions-climate/.

Ciccarelli, M. and F. Marotta (2024), "Demand or Supply? An Empirical Exploration of the Effects of Climate Change on the Macroeconomy", *Energy Economics* 129.

Claeys, G., M. Le Mouel, S. Tagliapietra, G. B. Wolff and G. Zachmann (2024), *The Macroeconomics of Decarbonization: Implications and Policies*, Cambridge University Press.

Coenen, G., M. Lozej and R. Priftis (2024), "Macroeconomic Effects of Carbon Transition Policies: An Assessment Based on the ECB's New Area-Wide Model with a Disaggregated Energy Sector", *European Economic Review* 167.

Council of the European Union (2023), EU Green Bonds Infographics, https://www.consilium.europa.eu/en/infographics/european-green-bonds/ (accessed August 2024).

Draghi, M. (2024), *The Future of European Competitiveness. Part A | A competitiveness strategy for Europe*, European Commission, https://commission.europa.eu/topics/eu-competitiveness/draghi-report_en.

Doda, B., S. F. Verde and S. Borghesi (2022), "ETS Alignment: A Price Collar Proposal for Carbon Market Integration. Report for the Carbon Market Policy Dialogue", Research Project Report 2022/02, Florence School of Regulation, European University Institute.

EMBER (2024), *European Electricity Prices and Costs*, https://ember-climate.org/data/data-tools/carbon-price-viewer/ (accessed in April 2024).

Energy Institute (2024), *Statistical Review of World Energy*, KPMG-Kearney-Heriot Watt University, https://www.energyinst.org/statistical-review.

Errendal, S., J. Ellis and S. Jeudy-Hugo (2023), "The Role of Carbon Pricing in Transforming Pathways to Reach Net Zero Emissions: Insights from Current Experiences and Potential Application to Food Systems, *OECD Environment Working Papers* 220.

European Central Bank (2021), "Towards a Green Capital Markets Union: Developing Sustainable, Integrated and Resilient European Capital Markets", *Macroprudential Bulletin*, https://www.ecb.europa.eu/press/financial-stability-publications/macroprudential-bulletin/focus/2021/html/ecb.mpbu_focus202110_3.en.html

European Commission (2023a), *EU ETS EU Emissions Trading System*, https://climate.ec.europa.eu/eu-action/eu-emissions-trading-system-eu-ets_en (accessed in December 2023).

European Commission (2023b), *Carbon Border Adjustment Mechanism,* https://trade.ec.europa.eu/access-to-markets/en/news/carbon-border-adjustment-mechanism-cbam (accessed in January 2024).

European Commission (2023c), *Proposal for a Regulation of the European Parliament and of the Council on Establishing a Framework of Measures for Strengthening Europe's Net-Zero Technology Products Manufacturing Ecosystem (Net Zero Industry Act),* https://eur-lex.europa.eu/legal-content/EN/TXT/HTML/?uri=CELEX:52023PC0161

European Commission (2024a), *2040 Climate Target*, https://climate.ec.europa.eu/eu-action/climate-strategies-targets/2040-climate-target_en#documents (accessed in February 2024).

European Commission (2024b), *Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions. Securing Our Future Europe's 2040 Climate Target and Path to Climate Neutrality by 2050 Building a Sustainable, Just and Prosperous Society. Part 3*, https://eur-lex.europa.eu/legal-content/EN/TXT/HTML/?uri=CELEX:52024DC0063

European Commission (2024c), *Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions: Towards an Ambitious Industrial Carbon Management for the EU*, https://eur-lex.europa.eu/legal-content/EN/TXT/HTML/?uri=CELEX:52024DC0062

European Environment Agency (2024), Greenhouse Gas Emissions by Aggregated Sector, https://www.eea.europa.eu/en/analysis/maps-and-charts/ghg-emissions-by-aggregated-sector-5 (accessed in July 2024).

European Environment Agency (2023), Total Net Greenhouse Gas Emission Trends and Projections in Europe, https://www.eea.europa.eu/en/analysis/indicators/total-greenhouse-gas-emission-trends (accessed in January 2024).

European Investment Bank (2024), *Financial Report 2023*, EIB Luxembourg.

European Scientific Advisory Board on Climate Change (2024), *Towards EU Climate Neutrality: Progress, Policy Gaps and Opportunities*, Publications Office of the European Union.

European Stability Mechanism (2024), *How Banking Union and Capital Markets Union Can Help Europe Finance the Climate Change Challenge*, ESM Blog, https://www.esm.europa.eu/blog/how-banking-union-and-capital-markets-union-can-help-europe-finance-climate-change-challenge

Fankhauser, S. M. Smith, M. Allen, K. Axelsson, T. Hale, C. Hepburn, ... and T. Wetzer (2022), "The meaning of Net Zero and How to Get it Right", *Nature Climate Change* 12(1), 15–21.

Fragkos, P., H. L. van Soest, R. Schaeffer, L. Reedman, A. C. Köberle, N. Macaluso, ... and G. Iyer (2021), "Energy System Transitions and Low-Carbon Pathways in Australia, Brazil, Canada, China, EU-28, India, Indonesia, Japan, Republic of Korea, Russia and the United States", *Energy* 216.

Fredriksson, G. and G. Zachmann (2021), "Assessing the Distributional Effects of the European Green Deal", *CESifo Forum* 22(5), 3–9.

Fries, S. (2023), "Sequencing Decarbonization Policies to Manage their Macroeconomic Impacts", *Peterson Institute for International Economics Working Paper*s 23–12.

Fuest, C. and J. Pisani-Ferry (2020), "Financing the European Union: New Context, New Responses", *Bruegel Policy Contribution* 2020/16.

Fuest, C., A. Marcu and M. Mehling (2024), "Climate Policy Priorities for the Next European Commission, *EconPol Policy Report* 48.

Giannakis, E. and G. Zittis (2021), "Assessing the Economic Structure, Climate Change and Decarbonization in Europe", *Earth Systems and Environment* 5, 621–633.

Gonand, F., P. Linares, A. Löschel, D. Newbery, K. Pittel, J. Saavedra and G. Zachmann, (2024), "Watts Next: Securing Europe's Energy and Competitiveness - Where the EU's Energy Policy Should Go Now", *EconPol Policy Report* 49.

Han, Y., M. Bao, Y. Niu and J. ur Rehman (2024), "Driving Towards Net Zero Emissions: The Role of Natural Resources, Government Debt and Political Stability", *Resources Policy* 88.

Hänsel, M. C., M. A. Drupp, D. J. A. Johansson, F. Nesje, C. Azar, M. C. Freeman, M. C., B. Groom and T. Sterner (2020), "Climate Economics Support for the UN Climate Targets", *Nature Climate Change* 10(8), 781–789.

Harris, S., J. Weinzettel, A. Bigano and A. Källmén (2020), "Low Carbon Cities in 2050? GHG Emissions of European Cities Using Production-Based and Consumption-Based Emission Accounting Methods", *Journal of Cleaner Production* 248.

International Carbon Action Partnership (ICAP) (2024), *ICAP Allowance Price Explorer*, https://icapcarbonaction.com/en/ets-prices (accessed in September 2024).

International Energy Agency (IEA) (2021), *Net Zero by 2050: A Roadmap for the Global Energy* Sector, *Special Report*, https://www.iea.org/reports/net-zero-by-2050

International Energy Agency (2024), *Global Energy and Climate Model, World Energy Outlook 2024*, https://www.iea.org/reports/global-energy-and-climate-model (accessed in March 2024).

International Energy Agency (2023), *CO_2 Emissions in 2022*, https://www.iea.org/reports/co2-emissions-in-2022

International Labour Organization (2023), Green Jobs, Green Economy, Just Transition and Related Concepts: A Review of Definitions Developed Through Intergovernmental Processes and International Organizations, https://www.ilo.org/publications/green-jobs-green-economy-just-transition-and-related-concepts-review.

International Monetary Fund (2022), "Chapter 3: Near-Term Macroeconomic Impact of Decarbonization Policies", *IMF Report*.

IPCC (2023), "Climate Change 2023: Synthesis Report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change" [Core Writing Team, H. Lee and J. Romero (eds.)].

Itul, A., A. Diaz Rincon, O. D. Eulaerts, A. Georgakaki, M. Grabowska, Z. Kapetaki, E. Ince, S. Letout, A. Kuokkanen, A. Mountraki, D. Shtjefni and M. Jaxa-Rozen, (2023), *Clean Energy Technology Observatory: Carbon Capture Utilisation and Storage in the European Union – Status Report on Technology Development, Trends, Value Chains and Markets: 2023*, Publications Office of the European Union, https://op.europa.eu/en/publication-detail/-/publication/cecd6d41-7230-11ee-9220-01aa75ed71a1/language-en

Karstensen, J., G. P. Peters and R. M. Andrew (2018), "Trends of the EU's territorial and consumption-based emissions from 1990 to 2016", *Climatic Change*, 151(2), 131–142.

Knobloch, F., H. Pollitt, U. Chewpreecha, V. Daioglou and J. F. Mercure (2019), "Simulating the Deep Decarbonization of Residential Heating for Limiting Global Warming to 1.5 °C", *Energy Efficiency* 12, 521–550.

Kriegler, E., J. Strefler, R. Gulde, et al. (2023), "How To Achieve a Rapid, Fair, and Efficient Transformation to Net Zero Emissions – Policy Findings From the NAVIGATE Project", *Potsdam Institute for Climate Impact Research*.

Lamperti, F., C. Wieners, R. Buizza, G. Dosi and A. Roventini, (2022), "Macroeconomic Policies to Stay Below 2°C with Sustainable Growth", Sant'Anna School of Advanced Studies Publication.

Lee, C-C., F. Wang and Y.-F. Chang (2023), "Towards Net-Zero Emissions: Can Green Bond Policy Promote Green Innovation and Green Space?", *Energy Economics* 121.

Lehtonen, H., E. Huan-Niemi and J. Niemi (2022), "The Transition of Agriculture to Low Carbon Pathways With Regional Distributive Impacts, *Environmental Innovation and Societal Transitions* 44, 1–13.

Macreadie, P. I., M. D. Costa, T. B. Atwood, D. A. Friess, J. J. Kelleway, H. Kennedy ... and C. M. Duarte, (2021), "Blue Carbon as a Natural Climate Solution", *Nature Reviews Earth and Environment* 2(12), 826–839.

Marin, G. and F. Vona (2018), “Climate Policies and Skill-Biased Employment Dynamics: Evidence From EU Countries”, *SciencesPo Working Paper* 23.

Markkanen, S. and A. Anger-Kraavi (2019), “Social Impacts of Climate Change Mitigation Policies and Their Implications for Inequality, *Climate Policy* 19(7), 827–844.

Mercure, J. F., F. Knobloch, H. Pollitt, L. Paroussos, S. S. Scrieciu and R. Lewney (2019), “Modelling Innovation and the Macroeconomics of Low-Carbon Transitions: Theory, Perspectives and Practical Use”, *Climate Policy* 19(8), 1019–1037.

Network of Central Banks and Supervisors for Greening the Financial System (2024), *Scenarios Portal*, https://www.ngfs.net/ngfs-scenarios-portal/explore (accessed in August 2024).

Nieto, J., Ó. Carpintero, L. J. Miguel and I. de Blas (2020), “Macroeconomic Modelling Under Energy Constraints: Global Low Carbon Transition Scenarios”, *Energy Policy* 137.

Nordhaus, W. (2015), “Climate Clubs: Overcoming Free-Riding in International Climate Policy”, *American Economic Review* 105(4), 1339–1370.

Panos, E., J. Glynn, S. Kypreos, A. Lehtilä, X. Yue, B. Ó Gallachóir ... and H. Dai (2023), “Deep Decarbonization Pathways of the Energy System in Times of Unprecedented Uncertainty in the Energy Sector”, *Energy Policy* 180.

Pianta, S., E. Brutschin, B. van Ruijven and V. Bosetti (2021), “Faster or Slower Decarbonization? Policymaker and Stakeholder Expectations on the Effect of the COVID-19 Pandemic on the Global Energy Transition”, *Energy Research and Social Science* 76.

J. Pisani-Ferry (2021), “Climate Policy Is Macroeconomic Policy, and the Implications Will Be Significant”, *Peterson Institute for International Economics*, *Policy Briefs 21-20*.

Richters, O., E. Kriegler, A. Al Khourdajie, C. Bertram, D. Bresch, A. Ciullo, E. Cornforth, R. Cui, J. Edmonds, S. Fuchs, P. Hackstock, D. Holland, I. Hurst, J. Kikstra, D. Klein, M. Kotz, C. M. Kropf, J. Lewis, I. Liadze, R. Mandaroux, M. Meinshausen, J. Min, Z. Nicholls, F. Piontek, P. Sanchez Juanino, I. Sauer, F. Sferra, M. Stevanović, B. van Ruijven, P. Weigmann, M. I. Westphal, A. Zhao and M. Zwerling (2023), “NGFS Climate Scenarios Data Set (4.2) [Data set]”.

Rickels, W., A. Proelß, O. Geden, J. Burhenne and M. Fridahl (2021), “Integrating Carbon Dioxide Removal Into European Emissions Trading”, *Frontiers in Climate* 3.

Rockström, J., O. Gaffney, J. Rogelj, M. Meinshausen, N. Nakicenovic and H. J. Schellnhuber (2017), "A Roadmap for Rapid Decarbonization" *Science* 355(6331), 1269–1271.

Rüdinger, A., A. Picart and I. Bouacida (2024), "Décarbonation Du Chauffage Dans Les Bâtiments: Enjeux Et Priorités Pour 2030", *Institute for Sustainable Development and International Relations (IDDRI), Décryptage 01/24*.

Saygin, D., J. Rigter, B. Caldecott, N. Wagner and D. Gielen (2019), "Power Sector Asset Stranding Effects of Climate Policies", *Energy Sources, Part B: Economics, Planning, and Policy* 14(4), 99–124.

Sotiriou, C. and T. Zachariadis (2021), "A Multi-Objective Optimisation Approach To Explore Decarbonization Pathways in a Dynamic Policy Context", *Journal of Cleaner Production* 319.

Tol, R. S. (2021), "The Distributional Impact of Climate Change", *Annals of the New York Academy of Sciences* 1504(1), 63–75.

UNFCCC (2023), *Nationally Determined Contributions Under the Paris Agreement. Synthesis Report by the Secretariat*, Conference of the Parties Serving As the Meeting of the Parties to the Paris Agreement (CMA), UN Climate Change Conference, United Arab Emirates Nov/Dec 2023, https://unfccc.int/documents/632334.

Vandyck, T., M. Weitzel, K. Wojtowicz, L. R. Los Santos, A. Maftei and S. Riscado (2021), "Climate Policy Design, Competitiveness and Income Distribution: A Macro-Micro Assessment for 11 EU Countries", *Energy Economics* 103.

Van der Ploeg, F. and A. Rezai (2020), "Stranded Assets in the Transition to a Carbon-Free Economy", *Annual Review of Resource Economics* 12(1), 281–298.

Van Der Wijst, K.-I., F. Bosello, S. Dasgupta, L. Drouet, J. Emmerling, A. Hof ... and D. van Vuuren (2023), "New Damage Curves and Multimodel Analysis Suggest Lower Optimal Temperature", *Nature Climate Change* 13(5), 434–441.

Vrontisi, Z., K. Fragkiadakis, M. Kannavou and P. Capros (2020), "Energy System Transition and Macroeconomic Impacts of a European Decarbonization Action Towards a Below 2 °C Climate Stabilization", *Climatic Change* 162, 1857–1875.

Waidelich, P., F. Batibeniz, J. Rising, J. S. Kikstra and S. I. Seneviratne (2024), "Climate Damage Projections Beyond Annual Temperature", *Nature Climate Change* 14, 592–599 .

World Bank (2024), CO_2 emissions (kt) - European Union | Data (worldbank.org) [accessed in April 2024].

Yiakoumi, D., C. Taliotis, T. Zachariadis and S. Griffiths (2023), "Sharing the Decarbonization Effort: Getting Eastern Mediterranean and Middle East Countries on the Road to Global Carbon Neutrality", *Climate Policy* 23*(7)*, 916–928.

List of Figures

List of Tables

Authors of this Issue

Simone Borghesi

Simone Borghesi is Director of the Florence School of Regulation – Climate at the European University Institute (EUI), President of the European Association of Environmental and Resource Economists (EAERE) and Vice Rector for International Relations at the University of Siena. He has been President of the Italian Association of Environmental and Resource Economists (2018-19) and Secretary General of the Policy Outreach Committee of EAERE (2018-23). He hold a PhD from the European University Institute.

Contact: Simone.Borghesi@eui.eu

Jacopo Cammeo

Dr. Jacopo Cammeo is a Research Associate at the Climate Area of the Florence School of Regulation, European University Institute since 2022. Previously, he was research assistant at the Department of Business and Law of the University of Siena, partner of the “OpenInnoTrain” European consortium, and post-doctoral researcher at the Department of Economics of the University of Florence. He holds a PhD in Business Administration and Management from the University of Pisa.

Contact: Jacopo.Cammeo@eui.eu