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BRINGING NATURE TO THE ECONOMIC PARADIGM: A SET OF TOOLS FOR THE ASSESSMENT AND QUANTIFICATION OF ENVIRONMENTAL EXTERNALITIES IN SPAIN, EU27 AND BEYOND

TESIS DOCTORAL

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Abbreviations

ASEAN: Association of Southeast Asian Nations
BAU : Business As Usual
CES: Constant Elasticity of Substitution function
CETA: Comprehensive Economic and Trade Agreement
CO2: Carbon Dioxide
COP: Conference of the Parties (of the UNFCCC – see below)
CPTPP: Comprehensive and Progressive Agreement for Trans-Pacific Partnership
DICE (or DICE-R): Dynamic (Regional) Integrated model of Climate and the Economy
ECD: Environmental Cobb-Douglas production function
EEA: European Environment Agency
ETS: Emission Trading Scheme of the European Union
FF: Fossil Fuels
GHG: Greenhouse Gas Emissions
GLS: Generalised Least Squares
IAM: Integrated Assessment Modelling
IEA: International Energy Agency
IPCC: Intergovernmental Panel on Climate Change
IRENA: International Renewable Energy Agency
LCOE: Lifecycle Cost of Energy
MLE: Maximum Likelihood Estimation
NAFTA: North American Free Trade Agreement
NECP: National Energy and Climate Plan
NZE: Net Zero Energy (an IEA scenario)
PRIMES: Price-Induced Market Equilibrium System
RES: Renewable Energy Sources
SFA: Stochastic Frontier Analysis
ss: steady state (as defined in economic growth theory)
TFP: Total Factor Productivity
Translog: Transcendental logarithmic production function
TSO: Transmission System Operator
UNFCCC: United Nations Framework Convention on Climate Change

Foreword

We live in unprecedented times, that become more unprecedented every day. Never before the climate change issue had been more urgent, and never before we had so many solutions in our hands. We have already reached the point where the climate conversation becomes increasingly uncomfortable: we are long past the days in which the solution to climate change consisted of adopting sustainable daily-life gestures such as recycling or changing lightbulbs. What we need now is systemic change. The trends in emissions and climate variables globally show us that we are very close to points of no return, if not already past them in some cases, and that much of the comfortable policy choices have already been exhausted.

The climate conversation is now entering a new field, one in which bold choices and ground-breaking changes will need to be made. It will no longer be about installing a solar panel in our rooftops, but about changing the entire way of producing and consuming energy. It will no longer take thinking about the future, but also reflecting on our past to repay our debts with Nature. We may also need to re-evaluate the way in which we approach the very concept of economic wealth and growth. Such is the challenge ahead of us. This thesis is a modest attempt to envisage the changes we would need to see in the future to get there, and how the policies of the future will enable collective success. A window to bring Nature to the economic paradigm.

Summary

Overcoming climate change is the largest challenge modern societies will ever have to face. The magnitude of the transformations that will need to take place has grown with every year of hesitation and insufficient action to reduce greenhouse gas (GHG) emissions and pollutants at every level of government (global, continental, national, regional or local). Now, the accelerated rise in the use of environmental resources by societal systems since the beginning of the Industrial Revolution has pushed natural ecosystems to their limits, closer than ever before to tipping points that can deal irreversible damage.

We are, to a great extent, already witnessing the effects of climate change in our daily lives. Increasingly often we watch the news of unprecedented and extreme meteorological events happening all around the world, in the form of severe draughts, floods, forest fires that indulge long-lasting damage to local communities. In the last years, such phenomena have not only become more frequent but also more geographically dispersed and affecting areas that were not as concerned before, such as Western European countries or the United States.

Of course, great progress has been made in the fight against climate change, both globally and in Europe, especially during the XXI century. On the global level, the entry into force of the Kyoto Protocol in 2005 and the landmark Paris Agreement in 2016 have marked an era of increasing importance and stringency of climate policies. In Europe, the adoption of the European Green Deal communication in 2019 and all its related legislation (i.e. the European Climate Law, Fit for 55 package and Circular Economy Action Plan), which continues to this day, has set Europe (and many countries that have followed globally) on the path towards climate neutrality by 2050. The design and implementation of these policies and agreements constitutes certainly an encouraging sign of progress in the fight against climate change. Unfortunately, such advancements have not yet been enough to contain the increase in global mean temperature caused by the accumulation of greenhouse gases in the atmosphere. Furthermore, the associated effects to climate change have been accelerating and worsening in the last years rather than decreasing.

There are, however, further solutions to this. Solutions that require one step forward in the stringency, depth and ambition of climate policies and that will largely be based on economics, understood as the science to manage scarce resources. The time and global

carbon budget (defined as the total amount of greenhouse gas emissions that can take place before triggering catastrophic climate change) we have left is becoming increasingly scarce, and therefore, economists are particularly well placed to have a say on the solutions that will have to be implemented to turn the odds of the climate emergency in our favour. In this vein, there is a fundamental concept to understand the economic dimension of climate change and climate policymaking: the notion of negative environmental externalities [1]. We can simply define those as the array of negative side-effects of economic growth in the form of greenhouse gas emissions, accumulation of air, soil and water pollutants, and generally any damage on natural ecosystems caused by human activities.

Since the beginning of the Industrial Revolution, we have witnessed unprecedented improvements in the levels of comfort and welfare in modern societies – first in Western countries, later in developing countries. However, such improvements have come at a great cost for natural ecosystems, on which we have relied on both as a source of productive inputs (such as energy and materials) and as a sink for undesirable outputs, such as greenhouse gas emissions and other pollutants. Thus, the accelerated economic growth fuelled by the discoveries of the Industrial Revolution and subsequent advancements that make our societies what they are today have been mirrored by a parallel accumulation of negative environmental externalities. This accumulation represents the debts we need to pay in the form of an increasingly costly and ambitious climate policies for mitigation and adaptation. In short words, we need to pay back our debt with Nature. This is why we need to bring Nature to the economic paradigm – to find our way back to an economic system that maximises individual and collective welfare while staying within planetary boundaries. There is, however, one piece of good news in this: environmental externalities are an economic term, and therefore we can apply economics in a useful way to tackle them.

This doctoral thesis is aimed at the general objective of widening the knowledge base on the topic of negative environmental externalities and economic growth. It does so by starting with the premise that negative environmental externalities are multifaceted and complex phenomena that interact with economic growth in different ways across sectors and geographical scopes. In order to tackle such complexity, a multi-tool approach

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[1] Bear in mind that, for conciseness, throughout the text we will refer to “negative environmental externalities” as just “externalities” in some cases, to avoid repetition and lengthy text. In every case, regardless of the term used, we refer to negative environmental externalities, which happen when economic operators do not take into consideration the environmental impacts inflicted upon society stemming from their activities (Nguyen et al. 2016)

characterised by combining different methodologies was identified as the most suitable research path. Subsequently, a choice was made to combine quantitative and qualitative methods to encompass the various ways in which negative environmental externalities and economic systems mutually impact each other. Four of these methods were selected: on the quantitative side, the econometric technique Stochastic Frontier Analysis (SFA) and Integrated Assessment Modelling (IAM) are the tools used. Both were chosen due to its specific suitability to quantify the impacts of negative environmental externalities on economic growth and on the decarbonisation of key sectors, respectively; as well as for being methodologies with room for novel research contributions in the field. On the qualitative side, policy analysis and comparative assessment were selected due to its capacity to tackle the institutional impacts of negative environmental externalities; essential to complete the picture of this doctoral thesis.

Each of these tools correspond to one chapter of this doctoral thesis, arranged from the most specific geographical scope (Spain, in Chapter 2) towards a broader one in Chapters 3 and 4 (Europe, and in particular the 27 Member States of the European Union) to arrive to the broadest geographical delimitation (i.e. the global stage) in Chapter 5. The chapters are, therefore, to be taken as a set of interconnected studies using different methodologies in diverse geographical contexts to study the same topic: the accumulation of environmental externalities as a result of economic growth and the consequences therein, both on the formulation of public climate change policies and on the design of economic modelling tools, which as shown above is the general objective of this doctoral thesis.

The first of the studies that form this doctoral thesis is presented in Chapter 2, in which a quantitative method (Integrated Assessment Modelling) is explained and applied to the most specific geographical and sectoral scope among the analyses considered: the decarbonisation of the electricity generation sector in Spain. In this case, the interaction between environmental externalities and economic growth is explicitly quantified in the modelling framework. In particular, the chapter features a newly developed Integrated Assessment Model (IAM) for the particular case of the electricity generation sector in Spain. The presented model is capable of quantifying and comparing the economic and environmental impacts of various electricity mixes, as well as of calculating the investment needs for climate mitigation different decarbonisation scenarios on a time horizon to 2050. This approach constitutes a novel application of Integrated Assessment Modelling to a reduced geographical and sectorial scope: while most IAMs are applied to many sectors at the global level at very high level of integration, the presented model only focuses on one particular sector in one country. The goal of such exercise is to produce a model relevant for the formulation of climate change policies at national level, as that is the level of public administration in which most of such policies are made and implemented, especially for the case of energy and electricity. The findings from the application of the model to the Spanish case show that scenarios that undertake deeper and earlier cuts in CO2 emissions from electricity generation would achieve better welfare results, and that further reliance on fossil fuels would imply higher costs than the investment needed for renewable energy deployment. The findings constitute an example on how the quantification of the environmental externalities associated to GHG emissions in the energy sector through IAM can constitute an insight towards the formulation of policies that address the decarbonisation of the Spanish electricity supply.

The second study is presented in Chapter 3, and as in Chapter 2 it also relies on a quantitative methodology. The geographical scope, however, increases its amplitude by considering the entire European Union with its 27 Member States (EU27), with the rationale of providing an example of quantification of environmental externalities that can be applied to the entire European economy. The sectoral scope also broadens, taking a macroeconomic approach focused on the influence of environmental externalities on economic growth. Specifically, the chapter presents a novel dynamic econometric model based on the Stochastic Frontier Analysis (SFA) methodology developed to study the intertemporal effects of the accumulation of environmental externalities on economic growth in EU27. SFA is an econometric technique used to study the long-term determinants of economic efficiency in the allocation of production factors in economic growth estimations. The advantage of SFA compared to other tools for the quantification of environmental externalities is that, when applied to production functions, allows to include exogeneous determinants of efficiency (or inefficiency) in the estimation of economic growth. Such determinants, however, are only in very rare cases in the literature applied to environmental conditions.

The contribution of the approach developed in Chapter 3 consists precisely of including environmental externalities (in particular, material extraction and CO2 emissions) in such exogeneous factors explaining inefficiency in factor allocation of economic growth.

The result is an econometric model able to estimate an environmentally-balanced Gross Domestic Product, that considers the environmental impacts of economic activities in the definition of economic wealth itself. The results of the model show that observed GDP is overestimated when the accumulation of environmental externalities is not considered. Thus, environmental impacts show significant negative effects that can eventually hamper economic growth itself. The proposed approach can be used for the definition of climate change policies in the EU27, as the environmentally-balanced GDP provides a relevant benchmark to observe the effects of such policies. The findings of the chapter also constitute an example of how the quantification of environmental externalities have not only sectoral (as seen in Chapter 2), but also macroeconomic implications vis-à-vis the way in which economic growth is modelled in production functions and macroeconomic analysis.

Chapter 4 marks the change from quantitative tools and models shown in Chapters 2 and 3 to qualitative methodologies. In this particular chapter the geographical scope used in Chapter 3 is maintained (EU27), but a radically different tool to assess environmental externalities in economic systems is considered: qualitative policy analysis. The rationale of such exercise is clear: as previously stated, the fundamental premise of this doctoral thesis is the multifaceted nature of environmental externalities, which makes the combination of different methodologies necessary to assess them. An essential component of the way in which environmental externalities interact with economic systems is the institutional dimension (i.e. the way in which rules are designed to try to integrate environmental externalities within economic systems). The European Union is at the forefront of using public policy to tackle environmental externalities, with an array of legislation and policy instruments produced to this extent. There is one among these instruments showing the clearest economic dimension, as it is aimed at the integration of environmental externalities through carbon pricing: the European Emission Trading Scheme (EU ETS), which is the focus of Chapter 4. The presented policy analysis examines the different phases that the EU ETS has gone through since its adoption in 2003, which have progressively increased the price of emission allowances in the EU aiming at a higher integration of environmental externalities, and the impacts of such changes on the most emitting sectors in Europe. The results of such review and analysis show that the upcoming revision of the EU ETS, known as Phase 4, represents an essential step in the policies needed to achieve the goal of European climate neutrality by 2050 laid down in the European Green Deal and the European Climate Law. The findings of the chapter also illustrate the fact that the institutional design on the way in which environmental externalities are integrated within economic systems can have economy-wide effects.

The last example of this doctoral thesis on the analysis of environmental externalities and economic systems is provided in Chapter 5. The study shown in this chapter retains the use of a qualitative methodology, as done in Chapter 4, but differs from all other contributions of this thesis on its geographical scope, which is the broadest of all: the global stage. To do so, it focuses on one of the sectors with the highest relevance on environmental externalities at the global level: trade. As the chapter shows, trade is chosen not only due to its direct externalities linked to GHG emissions of transport of goods, but also related to the consequences that trade agreements can have on climate change at the global level. The analysis focuses in particular on analysing and comparing the inclusion and effectiveness of clauses of environmental protection in free trade agreements, of which a diverse sample of five, covering different parts of the world, is assessed and compared. The findings show that, albeit disparities across the observed sample of free trade agreements, there is still great room for improvement in all cases to fully integrate environmental externalities in economic systems in the particular case of trade. The comparison of the agreements also reveals a fragmented approach followed by the European Union to ensure environmental protection in trade negotiations, with tensions arising between commercial and geopolitical objectives of the European agenda, such as increasing influence on strategic regions, as opposed to the environmental protection ambitions of the European Green Deal. The chapter therefore shows that the integration of environmental externalities in economic models and public policies goes beyond the domain of climate policy itself and affects other areas and objectives such as trade, constituting another example (as shown in Chapter 4) of the importance of the institutional dimension of environmental externalities.

All in all, the main findings of this thesis allow us to conclude that the integration of environmental externalities in economic systems is not only feasible, but also desirable to get a more accurate perspective to define the next generation of climate policies in Europe, Spain and beyond. Such policies will need to be able to encompass different scenarios on the evolution of the energy mix (as done in Chapter 2), as well as to factor in the intertemporal influence of cumulated environmental externalities on economic growth (Chapter 3), take into account policy interlinkages with carbon pricing policies (Chapter 4) and incorporate the global dimension of globalisation and environmental protection in trade agreements (Chapter 5). But above all, besides these analyses, the next generation of climate policies will need to be ambitious in bringing Nature to the economic paradigm and ensure a sufficient level of ambition that will help us overcome the climate emergency for the generations to come.

Chapter 1. Introduction

1.1. Presentation

Modern societies rely on an abundant array of natural resources to sustain the daily activities and industrial processes of billions of people and businesses around the globe. The use of natural commodities radically accelerated since the Industrial Revolution and the adoption of mass production systems (IPCC 2021). While such advancements have made mankind wealthier on a global scale, with access to fundamental means for transportation, education, healthcare and food systems spreading across the world and becoming increasingly accessible, they have come at a great cost for the Environment and, in turn, to economic and societal systems themselves.

Such impacts are now more evident than ever and come in different forms: environmental degradation of natural sites and local communities in areas where resources are extracted (especially in the Global South), accumulation of greenhouse gases in the atmosphere leading to global temperature increases and extreme weather events, economic and social inequalities arising from the transfer of resources from less advantageous regions to wealthier ones or worsening air quality in heavily concentrated industrial areas, to name just a few. Authoritative sources such as the Intergovernmental Panel on Climate Change (IPCC) tell us that such disruptions on economic and societal systems caused by the longstanding exploitation of natural resources have already dramatically increased in the last years and will continue to do so in the coming decades unless accelerated and decisive action to revert such trends is taken (IPCC 2022a).

The recipes to overcoming the current climate and environmental crises are already well known. We have been hearing them for decades: reduce waste and superfluous consumption habits, adopt recycling practices, increase energy efficiency in homes and offices, deploy renewable energies, protect biodiversity… while the list has gotten increasingly longer with the years, there is one particular element that has become the cornerstone element of any formulation of climate and environmental policies: we need to rapidly reduce greenhouse gas emissions, and especially carbon dioxide (CO2). More specifically, our chances to succeed in overcoming such crises lies in ensuring that by mid-century the most emitting areas worldwide have reached climate neutrality – understood as not emitting more CO2 than what is absorbed by natural ecosystems and negative emission technologies.

In this context, governments, institutions and societal actors around the world have analysed, discussed and implemented measures and policies to achieve these needed CO2 reductions. Some sectors have been identified as a priority on this endeavour, as they are the most emitting ones because they are connected to basic daily habits of everyone across the globe: they have to do with what we eat (i.e. food systems), where we go (i.e. transportation systems) and, very specially, which power sources we use (i.e. energy systems) (Ritchie, Roser and Rosado 2020; Gates 2021). To achieve such CO2 reductions in these priority sectors and in particular since the entry into force of the Kyoto Protocol in 2005, several institutions have emerged as key fora for discussion on the policies that need to be implemented. A particularly relevant one is the Conference of the Parties of the IPCC (known as COPs), which in the context of the United Nations Climate Change Convention (UNCCC) has become the main forum for climate policy negotiations at global level. Among the global milestones of such rising trend on the formulation of global climate agreements, the landmark Paris Agreement from the COP21 of 2016 stands as the most important one to date, for having established the objective of keeping the mean global temperature increase triggered by the accumulation of greenhouse gases in the atmosphere well below 2°C, and ideally less than 1.5°C by 2100 (United Nations 2015).

The Paris Agreement has entailed a fundamental change of approach in the formulation of climate policies. Such change has been twofold. First, the political impulse given by the Agreement fostered a new generation of climate policies in Europe and beyond. Shortly after the adoption of the Paris Agreement, the Von der Leyen European Commission Presidency elected in 2019 put the green transition as a fundamental priority for the European Union in the 2019-2024 legislative term and in December 2019, only a few months after taking office, the European Green Deal was already adopted as the most ambitious climate policy roadmap worldwide and with a clear objective: achieving climate neutrality in the European Union by 2050 (European Commission 2019a). Such goal has been complemented by a plethora of legislation underpinning the European Green Deal, namely the European Climate Law, Circular Economy Package and more recently the REPowerEU and Fit for 55 packages, which is aimed at transforming the European economy towards more sustainable modes of production and consumption. Such policies and legislation have been replicated beyond Europe, and in recent years most countries worldwide have incorporated climate neutrality by 2050 objectives in their laws (with the exception of China, by 2060) even if showing diverse levels of commitment (Hale at al. 2021), and countries have passed their most ambitious climate legislation. An example of this is the Inflation Reduction Act in the United States, which contains the largest ever climate investment in the US history (Bistline, Mehrotra & Wolfram 2023; The White House 2023). All in all, even if remarkable differences across countries do persist and further progress is yet to be achieved to stay on track to meet the objectives of the Paris Agreement, the XXI century has witnessed a breakthrough in the global ambition level in the design of climate policies.

Secondly, the quantitative nature of the temperature increase thresholds of "2°C, and ideally less than 1.5°C" in the Paris Agreement as well as the climate neutrality objective of the European Green Deal have opened the gates in the recent years to an increased use of quantitative tools to design the needed policies to deliver on such objectives. In this light, many international institutions, the European Commission, national governments, academia and different stakeholders have produced different pathways and scenarios to climate neutrality combining various policy changes and their impacts on key sectors.

Economic modelling has played a fundamental role in this process, as economic models have been used as relevant tools to analyse the impacts of different pathways to climate neutrality, thereby providing key information to policymakers. An example of this is the use of the PRIMES model in the Impact Assessment for the policies underpinning the European Green Deal, which has been fundamental to calibrate more specific targets delivering on the goal of climate neutrality by 2050, such as the objectives on energy efficiency, renewable energy deployment or greenhouse gas emission reductions, among others (European Commission 2021a). Similar modelling approaches have also been used at the global level, such as Integrated Assessment Models in the development of several IPCC reports which calculate the damages arising from different scenarios of potential trajectories of global greenhouse gas emissions (IPCC 2021).

However, in spite of the progress shown in the last years, economic models and projections have also been consistently showing that the current policy efforts done both at global and European level are still far from preventing the most catastrophic effects of climate change. On the global level, several IPCC reports in recent years have identified an ambition gap in the climate policies in place, which if fully implemented would cause a 2.1°C global average temperature increase, out of the limits of the Paris Agreement and assumed to cause significant disruptions and damages on natural and societal systems **(**IPCC 2022a). Such IPCC reports also made clear that to overcome the current climate emergency bold measures and ground-breaking changes will need to be implemented (IPCC 2022b). On the European level, recent analyses on the National Energy and Climate Plans (NECPs), which are the main planning tool for Member States on energy and climate policies and the most relevant instrument to track progress in the fight against climate change in the EU27 reveal that, while decarbonisation plans have substantially improved in the last decades across EU Member States, NECPs are not in line with the efforts needed under the Paris Agreement and higher ambition on establishing GHG reduction targets is still needed, especially on the targets to be met by 2030 (CAN Europe and ZERO 2020).

There is therefore an ambition gap also at European level to be filled with an upwards revision of the 2030 targets, which is being addressed with the measures planned under the Fit for 55 package and the revision of the NECPs. Such changes include stricter measures for energy efficiency, renewable energy deployment, a stricter and wider in scope EU Emission Trading Scheme towards a stronger price signal of emission allowances and higher targets for GHG reductions, among others (European Commission 2021a). The context in which this doctoral thesis is framed is, therefore, clear: the ambition of climate policies has remarkably increased in recent years but there is a need for further efforts to avoid the worst effects of climate change and to achieve climate neutrality in Europe by 2050.

1.2. Justification

In recent years, both in Europe and in the global level a significant number of climate policies have been implemented and an increasing mobilisation of all societal actors to act on climate change has emerged. Nevertheless, the efforts done until now are still far from what is needed to contain the most severe impacts of climate change (IPCC 2022a). Furthermore, we now face a turning point in climate policies. Until the present time, the solutions implemented in the fight against climate change in Europe can be considered as relatively comfortable in economic and political terms: modest increases in renewable energy deployment and energy efficiency, calls for the uptake of recycling and other circular economy practices by homes and businesses, as well as the establishment of Natura 2000 networks for biodiversity protection, among others. Such measures, while beneficial, will not entail the systemic changes needed to avoid the most severe impacts of climate change (IPCC 2022a).

What lies ahead of us will be, in contrast, a much harder road to pursue. As estimated by reports from the IPCC, the International Energy Agency (IEA) and the European Commission, there is an imperative need to scale up climate action dramatically and across all sectors during the decade up to 2030 and the years after until 2050 to achieve climate neutrality and avoid the worst effects of climate change (IEA 2021; European Commission 2021b; IPCC 2022b). This will require a fundamental change of approach to define the next generation of climate policies. Such change will need not only to increase the stringency of the current climate policies, but also to incorporate new elements. One particular element that has been often overlooked and that will need to be at the foundation of this new approach to climate policymaking is the integration of environmental externalities in economic modelling and policies.

This is, precisely, the starting point of our doctoral thesis: in order to achieve such ground-breaking change in climate policies, an economy-wide integration of environmental externalities by economic systems to make economic activities fully account for their impacts on Nature needs to be operated. However, this is not an easy task as environmental externalities are characterised by two elements: they are complex and multifaceted phenomena, and therefore its integration requires a fundamental shift in the way economic systems and institutions are conceived. In this doctoral thesis, the research started by looking at ways in which such characteristics could be encompassed in the analysis. The conclusion of such early steps of this doctoral thesis was that, in order to tackle such complex and multifaceted nature of environmental externalities, a multi-tool approach would be needed, in which different methodologies, quantitative and qualitative, would be combined to offer a joint analysis on how Nature can be brought to the economic paradigm through the integration of environmental externalities.

On the quantitative methodologies, two of them were selected: the econometric technique Stochastic Frontier Analysis (SFA) and Integrated Assessment Modelling (IAM). SFA was chosen due to its suitability to model the integration of environmental externalities at macroeconomic level, in particular through the notion of long-term determinants of inefficiency in production functions, which allows for the explicit consideration of environmental variables. For IAM the choice was made on the basis of its relevance in the IPCC reports on calculating the economic and environmental costs of different climate scenarios, and by the possibility of using IAM for sectoral analyses, in particular for the energy sector. In addition, both quantitative methodologies offer room for novel research contributions in the field, specifically via a more explicit representation of environmental externalities.

Moreover, the integration of environmental externalities in economic systems goes beyond the mere modelling of purely quantitative effects, as it also features a fundamental institutional component. In many cases, such integration takes place via regulations and policymaking, as it has been the case in the European Union and its dense array of climate change legislation, specifically since the adoption of the European Green Deal communication (European Commission 2019a). The research done in the context of this doctoral thesis needed to include this dimension, and for this reason two qualitative methodologies were selected: policy analysis and comparative assessment. Each of them was chosen due to its capacity to factor in such institutional aspects and, for the case of comparative assessment, for its suitability to perform analyses with a global geographical scope.

Such methodological choices have also conditioned the structure of this doctoral thesis, in which each chapter corresponds to a study on the integration of environmental externalities using different methodologies, applied in diverse geographical scopes (some of them applied to one single country like Spain; others to wider contexts such as Europe or the world at large). Such diversity is intentional, as we aim at capturing the complexity of the topic of the interactions between Economy and Nature in a holistic way, aiming at bridging the gaps between applied economics (and in particular the subset of applied economics largely reliant on modelling techniques), comparative economics and even legal analysis, as we firmly believe the response to the enormous challenges the current context of global climate crisis poses need breaking the silos between disciplines and relying on such a holistic approach, rather than offering solutions from isolated knowledge domains.

The findings of each chapter show that, even when using different methodologies applied to varying geographical scopes, results tend to converge towards the same concept, which titles this doctoral thesis: bringing Nature to the economic paradigm entails substantially changing the metrics, results and conventional reasoning used until now in Economics If we are to succeed and overcome the current climate challenges, the conventional economics applied until now will not work, as they will lead us to an overconsumption of natural capital to the detriment of the social and economic welfare of future generations. We need to re-consider some of the fundamental notions in Economics as a discipline and expand its scope to bring the interactions between economic and environmental systems to the core of economic analysis. Only from that basis we will be able to design and propose solutions and policies able to comprehend the complexity of the global climate crisis we are already facing today.

1.3. Research objectives

The general objective of this doctoral thesis is to contribute to the advancement of the economics of climate change by analysing the integration of environmental externalities in economics with a variety of tools used in different contexts. All of these cases try to reply to the same matter, which is also the central research question of this thesis:

How can the interactions between Economy and Nature
be integrated in economic modelling and policies?

The choice of different methodologies and geographical scopes presented throughout the different chapters in this doctoral thesis is aimed to answer the question above from a variety of viewpoints, in order to capture the complexity of such interactions and their integration in the most holistic and complete way. A broader aim of such analysis is to promote the adoption of a new economic paradigm, where the environmental consequences of economic activities are placed at the centre of societal systems. The general premise to start the research process and selection of potential studies to be undertaken has been that, given the complexity of the challenges posed by climate change, the response to the research question could not be based on one single approach or instrument, as developed in the previous Justification of this doctoral thesis. In some cases, replying to it could mean reconsidering existing policies and discuss potential changes, while in others the response could come from an innovative modelling approach.

In this vein, the general objective of this doctoral thesis has been translated into a set of specific objectives that pose different challenges stemming from the interaction between economic and environmental systems. They have been organised following an order dependent on the geographical context, from more specific areas to more generic cases and in particular from the case of Spain to the European Union and, eventually, to the global context. These specific objectives are the following:

1. The first specific objective (SO1) consists of identifying and quantifying the magnitude of environmental externalities stemming from economic activities in Spain and propose scenarios to mitigate them. Specifically, the analysis focuses on the power sector and the generation of electricity and on the economic and environmental impacts of different scenarios of electricity mix. Such impacts are calculated using the modelling technique of Integrated Assessment Modelling (IAM). The research question associated to this specific objective is *"What are the economic and environmental impacts of different electricity mixes in Spain by 2050?"*

2. The second specific objective (SO2) has the European Union as its geographical focus area and it looks at ways in which policy design and economic analysis can be improved to further integrate environmental externalities in societal choices. Two differentiated sub-objectives have been identified here. The first one (SO2.1) consists of investigating alternative formulations to the notion of economic wealth (as expressed by Gross Domestic Product) that can account for intertemporal effects of environmental externalities. The research question of this specific objective is *"What are the consequences of integrating environmental externalities in econometric estimations of Gross Domestic Product?"*. The answer to it has been pursued using an econometric modelling technique known as Stochastic Frontier Analysis (SFA). The second subobjective (SO2.2) focuses on climate policies rather than on modelling and reflects around the current role and future evolution of a fundamental policy instrument in the European Union in the path towards climate neutrality: the European Emissions Trading Scheme (EU ETS), with the research question *"What is the role of the EU ETS in the transition to climate neutrality?"*

3. The third specific objective (SO3) takes a broader angle and encompasses the integration of environmental externalities at the global scale, specifically for the case of trade policy, to try to answer to the research question *"What have been the consequences of addressing environmental externalities in regional free trade agreements around the world?*. In this case, the chosen methodology has been a comparative study that relies on economics but also goes beyond a purely economic assessment by including institutional and legal dimensions to enrich the analysis and encompass the multifaceted nature of environmental externalities.

1.4. Structure

This doctoral thesis is structured in six chapters. The first one corresponds to the introduction, which covers the starting point and main objectives of the research work, as well as the structure and justification of the doctoral thesis. As previously stated, the remaining chapters approach the topic of the integration of environmental externalities in economic systems in a variety of geographical contexts and relying on a set of different tools. In particular, Chapter 2 focuses on Spain and on the impact of environmental externalities and their mitigation on the power generation sector. Chapters 3 and 4 take a broader geographical scope (the European Union) to reflect on possible ways to integrate the intertemporal influence of environmental externalities in the notion of economic wealth and to analyse the role of the European Emissions Trading System in the transition towards European climate neutrality. Chapter 5 is focused on the global stage and on the role that trade agreements can take to prevent further exploitation of natural ecosystems. Chapter 6 gathers the final conclusions of all precedent chapters, followed by two sections containing the complete bibliography list and the merits accompanying the presented research work. The text of this doctoral thesis finishes with a reproduction of four published papers produced as a result of the research work.

The different chapters of this doctoral thesis respond progressively to the specific research objectives outlined in the previous section. Chapter 2 tackles SO1 and the research question related to it by presenting an IAM focused on the decarbonisation of the Spanish electricity generation sector, in which environmental externalities are considered explicitly in the modelling framework. Subsequently, Chapter 3 responds to SO2.1 by providing an econometric SFA model that integrates environmental externalities explicitly as a negative determinant of economic growth in a modified Cobb-Douglas production function for EU27. Thirdly, Chapter 4 fulfils SO 2.2 through a policy analysis study focused on the European Union Emission Trading Scheme and the implications of integrating environmental externalities through carbon-pricing policies. Finally, Chapter 5 corresponds to SO3 with a comparative study on the environmental protection clauses of free-trade agreements, in which the institutional component of environmental externalities is tackled.

This doctoral thesis has been elaborated in accordance with RD 99/2011 of January 28th that establishes the regulatory framework for doctoral studies in the University of Seville. It is also developed in application of the Institutional Agreement reached by the Academic Commission of the Doctoral Programme on Economic, Managerial and Social Sciences of the University of Seville of January 29th 2020, which lays down the provisions for the presentation and submission of the doctoral thesis. Based on this, a doctoral thesis with signs of quality is presented.

The two publications fulfilling the publication requirements needed in this type of doctoral thesis are "**An Integrated Assessment model for comparing electricity decarbonisation scenarios: the case for Spain**" and "**Environmental adjustment of the EU27 GDP: an econometric quantitative model**", published in Energy Policy (JCR Q1) and Environment Systems and Decisions (SJR Q1) in 2023, respectively. In both of these publications the PhD candidate Luis Antonio Galiano Bastarrica appears as main author, with the supervisors of this doctoral thesis featuring as co-authors. In addition, as a result of the research done in this doctoral thesis, two additional papers in which the PhD candidate Luis Antonio Galiano Bastarrica appears as the sole author have been published in peer-reviewed publications. These are "**El papel del Sistema Europeo de Derechos de Emisión en la transición a la neutralidad climática**", published by Institut d'Estudis Financiers in 2022 in Spanish language and "**La Protection Environnementale dans les Accords Régionaux de Libre-Échange: une étude comparée**", published in Duodecim Astra in 2021 in French language.

Chapter 2. Environmental externalities in Spain: Integrated Assessment Model for comparing electricity decarbonisation scenarios. The case of Spain

2.1. Introduction

The first of the studies on the integration of environmental externalities presented in this doctoral thesis relies on Integrated Assessment Modelling (IAM) and has the most reduced geographical and sectoral scope of all, as it focuses on the decarbonisation of the Spanish electricity generation sector. The presented model is able to quantify the environmental and economic impacts of different electricity mix scenarios in Spain by 2050. Environmental externalities are explicitly considered within the notion of damage function, which will be explained further along the chapter. In developing this model we aim at replying to the research question of specific objective SO1: *What are the economic and environmental impacts of different electricity mixes in Spain by 2050?"*.

Before explaining the main features of the model, some context on its geographical and sectoral scope is needed. As briefly presented in the Introduction, the continuous increase in global anthropogenic Greenhouse Gas (GHG) emissions since the Industrial Revolution is setting climate change closer to a tipping point, beyond which the intensity and frequency of extreme weather events and sea-level rises will remarkably increase (IPCC 2021). In Europe, such events will occur in the form of more frequent pluvial rain and floods in the North and extreme droughts and forest fires in the South and will cause disruptive economic losses if no significative policies are put in place early enough (Feyen et al. 2020; European Environment Agency 2022a). Such negative impacts on the European Union (EU) Gross Domestic Product (GDP) can reach up to 4.7% by 2050 under a high emissions scenario (van Vuuren et al. 2017; CMCC 2021; Spano et al. 2021).

For the case of Spain, losses of similar magnitude related to climate change and extreme weather events are expected, especially in the form of heatwaves, desertification, and floods in fertile land (Moreno et al. 2005; MITECO 2020a). Additionally, the recent invasion of Ukraine by Russian forces and the ongoing war have increased the need for speed and depth in transforming the European Union energy system under the REPowerEU plan. In this context, an accelerated deployment of renewable energy is not only needed for decarbonisation purposes, but also as a strategic investment to reduce Europe´s energy dependence (European Commission 2022a).

In order to tackle these prospects, climate policies have focused their efforts in the last two decades on setting mid- and long-term targets and climate-neutrality goals, with the Paris Agreement standing as one of the key milestones in setting the global objective of maintaining the projected increase of global temperature well below 2°C and ideally below 1.5°C (United Nations 2015). Today, climate change policies seem to be entering a new field and most countries worldwide have adopted decarbonisation plans to become climate neutral, in most cases by 2050 (with the exception of China, by 2060) albeit with varying levels of commitment (Hale at al. 2021). The design of cost-effective and sufficiently ambitious mitigation pathways for the most emitting sectors has therefore become crucial.

With the power generation sector being the largest contributor to GHG emissions globally, whereby it accounts for approximatively 34% of global GHG emissions (IPCC 2022b), its decarbonisation constitutes the key to the success of the climate transition in Europe and beyond, since other regions may well follow suit to what is carried out by the European Union. In Spain, electricity accounted for 15% of total CO2 emissions in 2019 (INE 2022) and it is projected to become the main energy carrier by 2040 driven by the electrification of key end users, such as transport and industry (MITECO 2020a). It is also portrayed as the sector where renewables bear maximum potential (MITECO 2020b), thereby making it the single most important sector to decarbonise in the Spanish economy.

Europe has strongly increased the ambition level towards decarbonisation with the adoption of the European Green Deal and related legislation since 2019 and aims towards climate neutrality by 2050 (European Commission 2019a). The European Climate Law made such objective binding for the EU in 2021 (European Commission 2021c). Additionally, the recently adopted “Fit for 55” package strives to deliver on an increased 2030 target of reduction of 55% GHG emissions compared to 1990 levels with a set of specific policy proposals that includes doubling the capacity of renewable energy sources (RES) within a decade from 2021 and increasing the presence of electricity as the main energy carrier before 2050 (European Commission 2021a). In Spain, parallel objectives have been laid down in Spain’s Long-Term Decarbonisation Strategy (MITECO 2020a) and the Spanish National Energy and Climate Plan (MITECO 2020b).

Additionally, the recent invasion of Ukraine by Russian forces and the ongoing war have increased the need for speed and depth in transforming the European Union energy system and has highlighted the considerable energy dependence of the continent towards non-EU energy providers. In particular, the perturbations in energy markets stemming from the conflict have resulted in an unprecedented energy crisis in Europe characterised by increasing energy prices and concerns over energy shortages to match domestic heating needs (Conti and Kneebone 2022). Some of the very short-term measures planned by several EU Member States include temporary re-starts of formerly closed coal power plants to cover gas supply shortages amounting to a 7% increase compared to 2021 levels according to the International Energy Agency prospects (IEA 2022a; Sgaravatti, Tagliapietra and Trasi 2022). The impact of such short term increased use of coal is however unlikely to have significant long term impacts on GHG emissions in the EU power sector by 2050, as the trend in coal has been matched by similar increases in wind and solar on a year to year basis (Sgaravatti, Tagliapietra and Trasi 2022).

On the other hand, the European Commission aims to address the ongoing energy crisis through the recent REPowerEU plan. Proposed in May 2022 and currently reaching the final stages of interinstitutional negotiations, the plan aims at transforming the EU energy system and ending the dependence of the EU on Russian fossil fuels by 2027 through the combination of three main pillars: enhancing energy efficiency policies to reduce energy needs, accelerate the deployment of renewable energies (i.e. to replace up to 21 billion cubic meters per year of gas by wind and solar) and diversifying gas supplies needed in the short and mid-term (Conti and Kneebone 2022; European Commission 2022a; European Council 2023a; Sgaravatti, Tagliapietra and Trasi 2022). In this context, an accelerated deployment of renewable energy is in order not only needed for decarbonisation purposes, but also as a strategic investment to reduce Europe´s energy dependence (European Commission 2022a).

Regardless of the exact trajectory that GHG emissions from the EU power sector will follow in the coming decades, the implementation of decarbonisation plans entails complex impacts, positive and negative, that need to be measured and evaluated carefully. Modelling tools such as Integrated Assessment Models (IAMs) have a crucial role to play in supplying policymakers with an informed choice of optimal pathways for the deployment of such ambitions, by providing estimations on the economic costs of changes in GHG emissions under a range of scenarios (Capellán-Pérez et al. 2014; Estrada et al. 2019).

There are several advantages that can be drawn from the use of an IAM-based approach for the particular case of modelling the impacts of decarbonising electricity supply in Spain. First, IAMs constitute a widely used modelling approach for the quantification of interlinked impacts of different paths of action on climate change policies (Pietzcker et al. 2017). Moreover, IAMs are used by authoritative sources such as the Intergovernmental Panel on Climate Change (IPCC 2021; IPCC 2022a; IPCC 2022b) in their landmark reports and constitute an active field of academic research granted with increasing relevance and recognition in the literature (Weyant 2017; van Beek et al. 2020). Thirdly, IAMs enable the integration of different disciplines (such as climate science and economics) and, even if their complexity varies greatly from one application to another, they can be calibrated more precisely than other numerical-based modelling tools that require the optimisation of complex interconnected systems such as global power system models (van Beek et al. 2020). Finally, within IAMs a calibration of the DICE-R model by Nordhaus and Sztorc (2013) was chosen as the basis to develop the presented model because of its relevance for its application to climate regional modelling (Ortiz et al. 2011) and from the fact that other types of IAMs (known as process-based) are mostly designed for global modelling and rely on assumptions that are not needed when modelling decarbonisation pathways for the case of one country (van Beek et al. 2020).

An adaptation and re-calibration of the DICE-R model seems therefore to be pertinent to the case at hand in this chapter, aimed at replying to a simple, yet challenging research question: Can IAMs be applied to the specific case of one sector in the context of one EU Member State, such as the electricity sector in Spain? And in such case, what are the adjustments needed and the insights of relevance to policymaking that can be produced with it?

The IAM presented in this chapter aims to calculate the environmental and economic costs of various scenarios of electricity decarbonisation in Spain in order to define a socially optimal renewable energy policy for electricity (Mathiesen, Lund and Karlsson 2011). It does so by adapting the DICE-R model by Nordhaus and Sztorc (2013) to the particular case of electricity generation in one single country [2]. In particular, the presented IAM uses

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[2] We discard other IAM specifications, such as MESSAGE (Huppmann et al. 2018), PAGE (Hope 2006), REMIND (Bauer et al. 2012) and FUND (Waldhoff et al. 2014), because they are mostly designed for global modelling which requires assumptions that are not needed when modelling decarbonisation pathways for electricity in one single country, as carried out herein.

as exogeneous input data the Lifecycle Costs of Energy (LCOE) for different energy sources as well as scenario projections on different energy mixes elaborated by the European Commission and the International Energy Agency (IEA) to translate such scenarios to the particular case of the electricity generation sector in Spain and thus produce endogenous projections on the economic and environmental impacts of different electricity mixes by 2050.

Several contributions of the proposed approach can be outlined: first, economic modelling of climate change has seldom been utilised for the case of Spain in the literature, with very few and specific applications such as the water-energy nexus (Khan, Linares and García-González 2016), land use change (Pulido-Velazquez et al. 2014), and the electricity market (Espinosa and Pizarro-Irizar 2018; García-Gusano and Iribarren 2018) whereby no IAMs have been employed. This study, however, is a direct application of IAMs to electricity generation. Second, national applications of IAMs remain largely unexplored and with few adjustments and calibrations, as presented in this chapter, IAMs can be adapted to produce important results for policymaking also at national level, relevant for the calibration of decarbonisation pathways. Finally, the proposed model is able to estimate economic costs and investment needed for the different scenarios: information that is needed at this stage by Spanish authorities to implement the plans outlined in the Long-Term Decarbonisation Strategy (MITECO 2020a) and the National Energy and Climate Plan (MITECO 2020b) as well as to tackle the ongoing energy crisis stemming from the invasion of Ukraine by Russian forces.

This chapter is structured as follows. Section 2.2 provides the theoretical framework for IAMs. Section 2.3 explains the characteristics and different modules of the model. The description of the data is given in Section 2.4. Section 2.5 presents and discusses the results and, finally, Section 2.6 draws the conclusions.

2.2. Integrated Assessment Models: benefits and limitations

The origin of IAMs is often traced to the Club of Rome and their “Limits to Growth” landmark publication in 1970, in which the assessment of a scenario called “World3” modelled climate change for the first time on a global scale and assessed the challenge of maintaining economic growth within a sustainable use of resources (Meadows and Randers 2013; van Beek et al. 2020).

Integrated Assessment Models model the economic impacts of climate change by linking two sets of equations: a climate module representing the dynamics of CO2 accumulation and their relative impacts on global temperature; and an economic section affected by the changes in temperature and abatement costs (Ortiz et al. 2011; Zhao et al. 2020). In IAMs, two concepts are key: the definition of damage functions and the intertemporal discount rate. Damage functions translate a change in global temperature to GDP loss by relying on a set of climate sensitivity parameters that connect the accumulation of CO2 in the atmosphere with changes in average global temperature (Bretschger and Pattakou 2019). A wide variety of approaches and functional forms have been explored in the relevant literature. Indeed, damage functions remain one of the most criticised elements of IAMs, the main criticism being that their formulation vastly affects the final estimations of the model and that approaches within the literature differ widely from each other (Diaz and Moore 2017).

The literature points out several caveats of damage functions. The use of quadratic forms fails to provide a realistic representation of climate dynamics, since tipping points of large economic losses appear too late in the temperature increase (Wouter Botzen and van den Bergh 2012; Bretschger and Pattakou 2019). Moreover, a careful assessment of impacts per sector has to be considered when estimating damage (Neumann et al. 2020), as well as adaptation policies (Estrada et al. 2019) or extreme weather events (Lempert et al. 2006; Zhang, Liu and Wang 2021). However, in spite of these critiques, and as shown in Neumann et al. (2020), even if the feedback mechanisms taking place between economies and climate are simplified, damage functions continue to be the most straightforward and widely used way to calculate environmental impacts in IAMs.

Another challenge of IAMs lies in how to implement intertemporal discounting in the model specification (Weyant 2017). In IAMs, various scenarios (often related to different mitigation pathways, plus a baseline that represents business as usual) are portrayed and placed in the decision-making process of a public agent. For the model to be useful for policymaking, a prioritisation logic between the welfare of the current generation and that of future generations needs to be implemented. This is carried out in IAMs by using an intertemporal social utility discount rate, which is used by the public agent to prioritise and compare scenarios from a social welfare standpoint (Espagne et al. 2018; Karp 2005). Given the length of the time horizons involved in these models (often until 2100), a slight change in the discount rate can yield quite different results on the final estimates, which makes IAMs highly dependent on the chosen rate (Pindyck 2013; Espagne et al. 2018).

On this topic, and as shown in Weyant (2017) and Drupp et al. (2020), there is a dispute between Stern on one hand, who considers that any positive value of the discount rate in IAMs is purely unethical since the welfare of the current generation is valued more highly than future generations (Stern 2007), and Nordhaus and Weitzman on the other hand, who propose a higher discount rate that sets climate investments in stronger competition with other investments, thereby allowing for a slower, market-driven transition (Nordhaus 2007; Weitzman 2010; Wouter Botzen and van den Bergh 2012). Nevertheless, regardless of the final value chosen by the modeller, the discount rate decisively influences the ability of the remaining carbon budget to stay below specific temperature thresholds, such as 2°C and 1.5°C (Emmerling et al. 2019) and involves debates that go beyond purely economic decisions, such as to how to evaluate the welfare of future generations when precisely it is their future that seems increasingly unclear.

2.3. The model

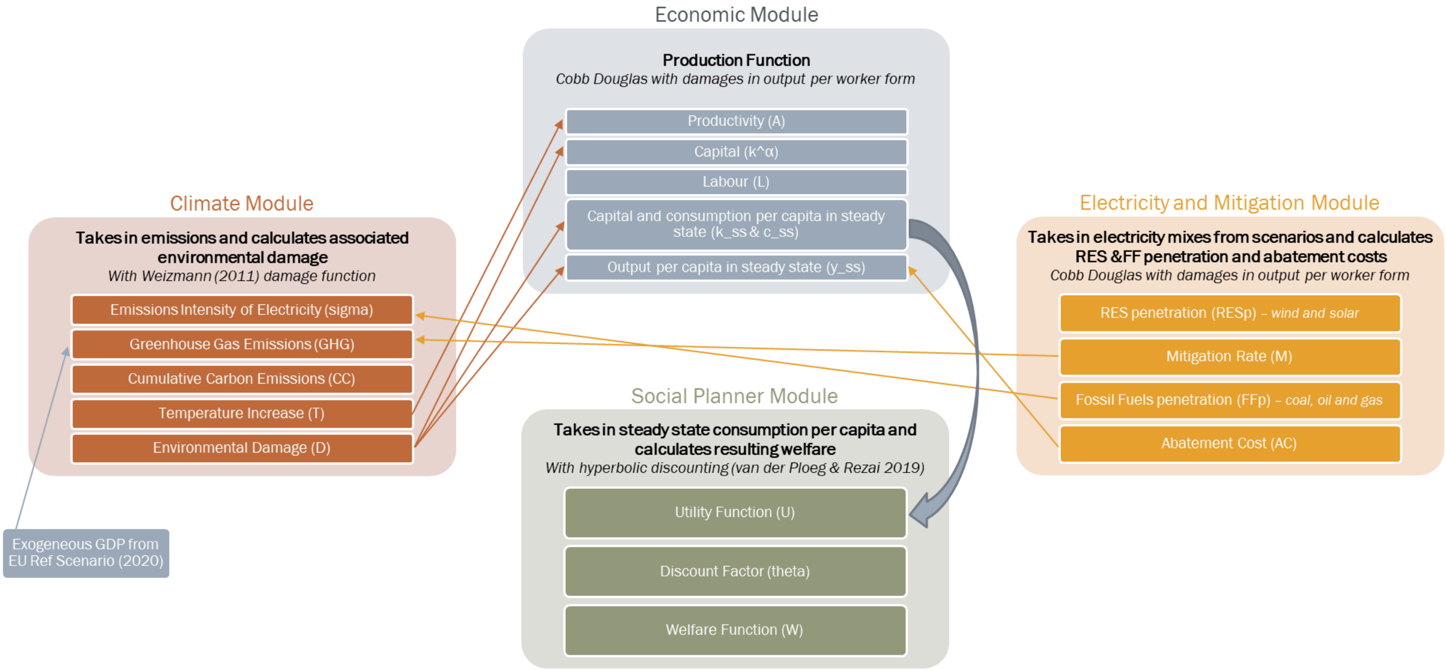
The main features of the model are presented in the following sections and in Figure 2.1 below. The model is composed of four modules: economy, climate, electricity, and social planner. The economic module includes a standard Cobb-Douglas production function in which productivity and capital accumulation are affected by climate change damage from the climate module that are estimated using the Weitzman damage function (Weitzman 2010). Economic growth follows a Ramsey-Cass-Koopmans model, in which steady-state capital and consumption per capita are calculated as key variables for long-term forecasts as in the original specification of the DICE model (Nordhaus and Yang 1996; Fankhauser and Tol 2005; Nordhaus 2007; Bauer et al. 2012; Diemer et al. 2019).

The model is completed with the electricity module, which provides the mitigation pathways of the model, which are based on exogeneous projections under different scenarios designed by the European Commission and International Energy Agency (European Commission 2011; IEA 2021). The social planner module takes in the steady-state capital and consumption per capita to calculate total welfare under the various scenarios as a key factor in the choice of one decarbonisation pathway over the other. A visual representation of the interactions between modules is provided in Figure 2.1.

Several further elements related to the functioning and scope of the presented model can be outlined before presenting its modules and functioning in detail. Firstly, while the model focuses on one particular sector in one EU Member State (i.e. the electricity generation sector in Spain), it incorporates projections from different models that include cross-effects going much beyond the electricity generation sector itself, such as changes in transport, energy efficiency policies, energy system interconnections or innovation in different low-carbon energy sources resulting from the adoption of different energy mixes. In particular, we use i.e. the European Commission energy roadmap and the Net Zero by 2050 report by the International Energy Agency for the shares of the electricity mix under different scenarios and the EU reference scenario 2020 by the European Commission for the baseline of projected electricity needs in Spain.

In addition, the changes foreseen in the electricity generation sector in Spain in the exogeneous data used in the model is in line with the Spanish National Energy and Climate Plan, which is defined in coherence with European policies in the field of energy. Thirdly, even if the presented model produces results at a relatively high level of integration (i.e. at national level), the exogeneous projections used for the baseline values of electricity uses in Spain coming from the EU Reference Scenario 2020 build on the PRIMES model, which is a bottom-up Partial Equilibrium Model that draws on microeconomic data to produce disaggregated results per sector and EU Member State. The modelling approach therefore consists of integrating the electricity generation in Spain with other policies and sectors by building on detailed bottom-up modelling results to assess the impacts of different electricity mixes by 2050 in the most accurately possible manner.

Figure 2.1 Model overview



Source: Own elaboration

2.3.1 Economic growth module

The first part of the model is its economic module, composed by a Cobb-Douglas production function with constant returns to scale. As in the original DICE model (Fankhauser and Tol 2005; Nordhaus 2007; Ortiz et al. 2011), we consider a time horizon running from 2010 to 2050. The production function is sensitive to climate change damage (Nordhaus 2007) and is expressed in terms of output per worker:

$$(1)\ y_t = D_t A_t k_t^{\alpha}$$

Where $D_t < 1$ is the value from the damage function from Weitzman (2010) at each point in time (see section 2.3); A_t is Hicks-neutral technical change or total factor productivity, and k_t^{α} is capital stock per worker. In our specification, α reflects the findings of Macías and Matilla-García (2015) and Bentolila and Saint-Paul (2003), with an income share of capital of approximately 40% for OECD countries [3].

The model follows the usual assumptions in IAMs on all variables (Ortiz et al. 2011; Weyant 2017; Espagne et al. 2018; van Beek et al. 2020): population increases at a

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[3] For the whole list of parameters, see the Annex to the chapter.

decreasing rate $g_{L,t} = g_{L,t-1}/(1+\delta_L)$, where δ_L is the population growth rate (Tsigaris and Wood 2016) that is added to the population in levels $L_t = L_{t-1} * (1+g_{L,t})$, and reflects the trends in the European Union Reference Scenario report, based on the PRIMES model (European Commission 2021d).

The dynamics of total factor productivity, A_t, are specified in a similar way to those of population, $A_t = A_{t-1} * (1+g_{A,t})$, but with one major difference: the parameter measuring the growth rate on productivity, $g_{A,t}$, is negatively affected by temperature, $g_{A,t} = \frac{g_{A,0}}{(1+\delta_A)^t} - \gamma T_t$, where δ_A is a parameter that reflects technical change and γ links temperature increases to decreases in productivity growth (Nordhaus and Sztorc 2013; Tsigaris and Wood 2016).

The calculations on the interactions between temperature and technical change are carried out on the basis of previous literature that argues for the specification of total factor productivity in IAMs in order to account for the opportunity cost regarding lost R&D that has been directed towards climate adaptation and mitigation, as well as for the negative impacts of extreme weather events (Nordhaus and Sztorc 2013; Dietz and Stern 2015; Moore and Diaz 2015; Espagne et al. 2018; Zhao et al. 2020). Under this specification, total factor productivity, A_t, decreases over time as temperature increases. The speed of the trend ultimately depends on how fast temperatures rise over the time horizon.

The economic inputs module of the model is completed with the dynamics applied to the capital stock per worker (k_t), which are in line with the Ramsey-Cass-Koopmans and Solow-Swan economic growth model and the concept of convergence to a steady state (Solow and Swan 1956; Swan 1956), as in most of IAMs (Fankhauser and Tol 2005; Hope 2006; Bauer et al. 2012; Diemer et al. 2019). By taking the approach used in DICE, in which climate impacts are channelled mostly through the production function (Nordhaus and Yang 1996; Fankhauser and Tol 2005; Nordhaus 2007), a constant savings rate (s) is used together with the pathways outlined above to calculate the steady-state capital stock per worker regarding climate damage (D_t):

$$(2)\ k_{ss,t} = \left(\frac{sA_tD_t}{\delta_k + g_{L,t}}\right)^{\frac{1}{1-\alpha}}$$

Where capital stock per worker is also affected by temperature. In this case, the link with increasing temperatures is formed via a more accelerated depreciation of assets due to extreme weather events (Stern 2013; Pietzcker et al. 2017). This link is carried out in the model via the specification of the capital depreciation parameter, $\delta_K = \delta_0 * \delta_1 T_t$, whereby δ_0 is the initial capital depreciation rate and δ_1 is a parameter that measures the change of depreciation from the temperature increase, T_t (Stern 2013). With the steady-state capital stock per worker in place, the steady-state income and consumption per worker can be obtained in Equations (3) and (4) respectively:

(3) $y_{ss,t} = D_t A_t k_{ss,t}^{\alpha}$

(4) $c_{ss,t} = (1 - s) y_{ss,t}$

The steady-state consumption per worker is a particularly relevant variable in the model, since it is the variable employed to compute the discounted utility to assess the social pertinence of each scenario.

2.3.2 Climate module

A The second part of the model is the climate module, in which the environmental impacts of the various electricity decarbonisation scenarios are calculated based on the DICE and DICE-R models (Nordhaus 2007; Nordhaus and Sztorc 2013) [4]. The intensity of electricity (σ_t) of the greenhouse gas emissions provides the starting point. Since only one sector is addressed (i.e., electricity generation), σ_t is directly linked to the percentage of penetration of fossil fuels in the electricity mix (FFp_t) in the EU27 at each point in time:

(5) $\sigma_t = FFp_t$

There are obvious advantages to specifying the intensity of electricity emissions in such a straightforward way instead of using an exogenous source. On the one hand, the model gains significant coherence, since emission intensity becomes directly linked to the policy choice on the presentation of renewables in the electricity mix. On the other hand, in this way the intensity of electricity emissions mirrors the results of the different scenarios

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[4] It is assumed that, since Spanish GHG emissions only account for a fraction of total GHG emissions, the endogenous levels of GHG emissions and mitigation pathways under scenarios at each point in time are calculated for the 27 Members of the European Union (EU27). The economic impacts of each scenario (i.e., climate losses) are then estimated at national level for the case of Spain.

evaluated with IAM, thereby making the overall tool more relevant for the policy decision-making.

The level of Greenhouse Gas Emissions is calculated as in the DICE-R model. An exogeneous level of projected GDP for the EU27 to 2050 ($\bar{Y}_t$) from the EU Reference Scenario report based on the PRIMES model (European Commission 2021d) is employed:

(6) $GHG_t = (1 - M_t)\sigma_t \bar{Y}_t$

Where σ_t is the intensity of electricity emissions (Equation (5)) and M_t is the cumulated abatement. It is easy to determine that the mitigation measures planned towards the decarbonisation of electricity supply (i.e., by increasing the penetration of renewables in the electricity mix) exert a direct effect on reducing the amount of GHG emissions in the model. As in most IAMs, our focus is on cumulative carbon emissions (CC_t) as the main pollutant in the model to which changes in temperature are attributed (Nordhaus 2007; Nordhaus and Sztorc 2013), leaving aside other GHG emissions that are less relevant in the case of electricity generation (INE 2022). The cumulative carbon emissions are calculated as follows:

(7) $CC_t = CC_{t-1} + \left(\frac{GHG_t}{CtoCO2_{cr}}\right)$

Where the level of carbon emissions grows cumulatively on a rate equal to the sum of the cumulated carbon emissions of the previous period (CC_{t-1}) and the carbon emissions taking place within the same period, which need to be calculated by dividing the GHG emissions from Equation (6) over the chemistry ratio of CO_2 to carbon ($CtoCO2_{cr}$) to focus only on carbon as the key pollutant. In order to treat carbon emissions as a global pollutant, the same initial value is taken for carbon emissions as in the DICE-R 2013 calibration: 530 billion tons already emitted globally (Nordhaus and Sztorc 2013).

The climate module of the model is completed with the equations on temperature change and the damage function (Nordhaus 2007; Weitzman 2010; Nordhaus and Sztorc 2013):

(8) $T_t = CC_t * CCR$

(9) $D_t = 1 \Big/ \left[1 + \left(\frac{T_t}{\theta_1}\right)^{\theta_2} + \left(\frac{T_t}{\theta_3}\right)^{\theta_4}\right]$

Where Equation (8) models the increase in projected temperature as a direct consequence of cumulative carbon emissions (Equation (7)), with the carbon-climate change response parameter (CCR) [5] as the parameter linking the temperature with the emissions (Matthews, Solomon and Pierrehumbert 2012).

Equation (9) contains the climate change damage function proposed by Weitzman (2010). It includes four damage parameters, θ_1 to θ_4, which are calibrated using an expert panel to the values $\theta_1 = 20.46$, $\theta_2 = 2$, $\theta_3 = 6081$, and $\theta_4 = 6754$. As shown in Weitzman (2010) and Wouter Botzen and van den Bergh (2012), these calibrations yield a tipping point in economic growth at 6°C beyond which disruptive climate events are triggered. Additionally, the application of this damage function results in climate policy that is significantly more stringent than that employed when applying the standard damage function used by Nordhaus (2007) in DICE, which tends to show only marginally small impacts on economic growth even when temperatures reach unconceivable thresholds beyond 8°C of increase (Wouter Botzen and van den Bergh 2012; Bretschger and Pattakou 2019). Besides, Bretschger and Pattakou (2019) and Zhao et al. (2020) propose alternative specifications to the damage function, such as polynomial functions of up to quadratic form, which yield climate policy that is even more stringent for small increases of temperature. Although these new approaches appear promising and deserve attention, they have yet to be widely accepted as standard within the IAM literature.

We have opted for a climate change damage function exclusively dependent on temperature since temperature-denominated damage functions continue to be the most widely used in the IAM literature, largely because the increase in temperature remains the variable that attracts the most attention in climate science and international climate agreements, such as the Paris Agreement (Wouter Botzen and van den Bergh 2012; Moore and Diaz 2015; Neuman et al. 2020; IPCC 2021). Although there are other approaches in the IAM literature to damage functions, such as those that are sensitive to extreme climate events (Zhang, Liu and Wang 2021), sectoral climate impacts (Zhao et al. 2020), and abrupt

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[5] The CCR parameter yields an estimated linear relationship between cumulated CO_2 in the atmosphere and projected temperature increase, calibrated by Matthews, Solomon and Pierrehumbert (2012) of 1.8 Celsius degrees increase in mean temperature for every 1000 Gigatons of cumulative CO_2 emissions released into the atmosphere. Such an estimation brings simplicity to the calculations in the model and is in line with recent proposals on the estimation of damage in climate change damage functions in IAMs (Bretschger & Pattakou 2019).

climate change (Lempert et al. 2006), no consensus has yet been agreed in the literature as to how to include these effects in a standard way (Espagne et al. 2018).

2.3.3 Electricity and mitigation module

The third part of the model is its electricity and mitigation module, in which the impacts of different exogenous scenarios on the future evolution of the electricity mix for Spain are tested. Under each scenario, which will be described in Section 2.4, the model calculates the resulting proportions of renewables (including solar and wind) and fossil fuels (including coal, oil, and natural gas) in the electricity mix. The negative environmental impact from a higher presence of fossil fuels is captured by a higher intensity of electricity emissions, σ_t , which in turn results in higher cumulated emissions and climate damage. Conversely, a greater penetration of renewables in the electricity mix results in a higher cumulated abatement, which reduces cumulated emissions but entails abatement costs stemming from the deployment of the capacities required.

Such costs are calculated using the levelised cost of electricity (LCOE) of wind and solar generation, as calculated in the Fraunhofer study on LCOEs for renewable energies (Ueckerdt et al. 2013; Fraunhofer 2021). The model focuses only on wind and solar technologies because all other renewables (i.e., hydropower, geothermal, tidal) are forecasted to play a minor important role in the energy transition in Spain in all scenarios consulted (European Commission 2011; European Commission 2021d; IEA 2021; MITECO 2020a).

Consequently, the cumulated abatement, M_t, under each scenario is calculated directly from the penetration in the electricity mix of wind [6] and solar power, $RESp_t$, which is taken as an exogeneous value under each scenario:

(10) $M_t = RESp_t$

(11) $RESp_t = (SolESQ_t + WinESQ_t)/TotalESQ_t$

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[6] For the case of wind power, both offshore and onshore generation are considered by the IEA when calculating LCOEs. Since the model only accounts for wind in general, we have applied an arithmetic mean between the two LCOEs (for offshore and onshore wind) to obtain the LCOE used by the model.

Where $SolESQ_t$ and $WinESQ_t$ are the exogeneous values under each scenario for electricity generation in Gigawatt-hours (Gwh) for solar and wind power in Spain, respectively, and $TotalESQ_t$ refers to the total exogeneous electricity generation in Spain, which is taken from the EU Reference scenario 2020 from the PRIMES model (European Commission 2021d) in all scenarios of the model to ensure consistency of the calculations. The penetration of fossil fuels into the electricity mix is calculated in a similar way and as can be seen from Equation (5), it is taken as the endogenous value for the intensity of electricity emissions, which is in turn the main driver of cumulated emissions (and, therefore, of climate damage) in the model:

$$(12)\ FFp_t = (CoalESQ_t + OilESQ_t + GasESQ_t)/TotalESQ_t$$

Where $CoalESQ_t$, $OilESQ_t$, and $GasESQ_t$ refer to the exogeneous value under each scenario for electricity generation in Gigawatt-hours (Gwh) for coal, oil, and natural gas under each scenario for Spain.

As in all IAMs, the model needs to be completed by an abatement cost function that calculates the consequences of reducing emissions on the steady-state income per capita. To this end, the convex abatement cost function from the DICE-R model of Nordhaus and Sztorc (2013) has been employed in which the total abatement costs, AC_t, are a function of cumulated abatement, M_t, specified as follows:

$$(13)\ AC_t = \omega_t M_t^{\theta_{AC}}$$

Where the cumulated abatement is weighted by an exponent, θ_{AC}, calibrated as 2.8 in the DICE-R model; and an abatement cost parameter, ω_t, declines at a rate equal to the change in the productivity rate in each period, $g_{A,t}$. This yields an abatement cost, AC_t, which shows very marginal values in the early decades of the period (mainly 2010 to 2020) and then gradually increases with the penetration of renewables in the electricity mix over the period. Abatement costs complete the model by entering the calculation of the steady-state output per capita given in Equation (3):

$$(14)\ y_{ss,t} = (1 - AC_t) D_t A_t k_{ss,t}^{\alpha}$$

In this way, the trajectory of the level of output per capita is endogenously determined by two fundamental costs: the climate damage and the cumulated abatement, in which reducing units of the former implies an increase in the latter. The model is employed to compare how this relationship holds when variable compositions of the electricity mix are modelled for Spain over the period 2010 to 2050. Such changes are evaluated using Equation (4) (consumption per capita in steady state) for the calculations on utility and welfare, which we detail in the following section.

2.3.4 Social planner module: A note on discounting and utility calculations

An additional module representing the decision-making process of a public policy body is included in the model to compare results of the various scenarios. This module includes the utility calculations processed in most IAMs, which involve analysing the welfare of the current versus the future generation (Pindyck 2013). The level of welfare is affected by the total abatement costs and the cumulated climate change damage at each point in time, which directly influence the level of consumption per capita, as shown in Equation (15): this is calculated as the discounted sum of the utility of steady-state consumption per capita over the entire time horizon, which in our case runs from 2010 to 2050:

(15) $W = \sum_{2010}^{2050} \theta_t L_t U(c)_t$

Where θ_t is the discount factor, which enables the inclusion of the intergenerational dilemma, calculated under the following form:

(16) $\theta_t = \frac{1}{1+\rho(year-2010)}$

The discount factor displayed in equation (16) corresponds to hyperbolic discounting. As revealed in the Introduction, there is extensive debate in the literature on IAM regarding the way in which future welfare needs to be discounted when analysing climate scenarios. Hyperbolic discounting tends to place more policy effort in terms of the reduction in emissions reduction on closer generations than on more distant ones, which results in climate policy of a more stringent nature [7]. We deem this to constitute a realistic assumption for our model, in which the time horizon is comparatively shorter than in the usual IAMs [8] and is in line with the most stringent climate policy imposed in the European

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[7] See Karp (2005) and van der Ploeg & Rezai (2019) for more details on the application of hyperbolic discounting on climate change economics, and Laibson (1997) and Andersen et al. (2008) for general knowledge on hyperbolic discounting.

[8] Time horizons in IAMs tend to run until at least the year 2100. In our case, we opt for a shorter period because the objective is to analyse the economic consequences of different scenarios towards climate neutrality for the case of Spain, which, as across the entire European Union, is set to happen by 2050.

Union, through which a large part of the decarbonisation effort is going to be made over the next two decades (European Commission 2021b).

Another key element frequently under discussion in IAMs is that of the calibration of the rate of pure time preference, ρ. In climate modelling, the value of this parameter determines the importance given to losses in future levels of consumption. Under such high values of ρ, the bulk of the emission reductions are placed on future generations, with the overall transition to climate neutrality taking place at a slower pace and with greater temperature increases (Wouter Botzen and van den Bergh 2012; Emmerling et al. 2019). The Stern-Nordhaus controversy is particularly relevant in this matter: while in the DICE model by Nordhaus, ρ is set at a higher value to match interest rates, linking the pace of decarbonisation to market trends (Nordhaus 2007; Espagne et al. 2018), in Hope's PAGE model, ρ is calibrated on ethical grounds, linked to the probability of disastrous events under higher temperatures (Stern 2007; Stern 2013; van der Ploeg and Rezai 2019).

An application of the Stern approach seems more up to date given the current context of repeated warnings of the consequences of increased temperatures and the extreme weather events that have already been set in motion globally (IPCC 2021). Such choice is also in line with the most recent IAM literature, which seems to be shifting towards an institutionally centred role of IAMs that aim to avoid previous underestimations of the potential impacts of accelerated climate change (Espagne et al. 2018; Estrada et al. 2019; van Beek et al. 2020; Zhang, Liu and Wang 2020). The approach taken in PAGE (Hope 2006), with a rate of pure time preference equal to 0.015, is, therefore, the approach taken in our model.

The final element of the social planner module is the functional form of the utility function. As shown in Equation (16), welfare is calculated in IAMs as the sum of discounted utility, but the latter needs to be specified under a function. This topic is also the focus of significant debate in IAMs, as the choice of the rate in marginal utility for each level of per capita consumption (η) can greatly affect the sensitivity to income inequality. This form is normally stated as follows (Norstad 1999):

$$(17)\ U(c)_t = \begin{cases} \frac{c^{1-\eta}}{1-\eta}\ if\ \eta \neq 1 \\ \ln(c)\ if\ \eta = 1 \end{cases}$$

In this matter, we also follow the approach taken in the PAGE model by Hope (2006), in which an iso-elastic utility function is used. This corresponds to the $\eta = 1$ case, which enables the impacts of the different scenarios on per capita consumption to be aggregated in a more straightforward way (i.e., aggregating them in the welfare function, as in Equation (16), with no further adjustments). As a downside, this makes the model insensitive to distributional concerns and equity, although in our case the main focus of the model is to provide a common tool to compare aggregated costs of different electricity decarbonisation scenarios, while leaving out of the analysis the way in which those costs are distributed.

2.4. Data and scenario description

The model described in Section 2.3 has been applied to quantify the environmental and economic impacts of a variety of scenarios. The composition of the electricity mix therein is taken as an exogeneous input to the model, upon which such impacts are calculated.

A summary of the assessed scenarios is provided in Table 2.1. Four electricity sources have been considered, as these are projected to increase or decrease the most in the decades up to 2050 in Europe (European Commission 2011; IEA 2021) and in Spain (MITECO 2020b): solar photovoltaic (Solar PV) energy, wind energy (including offshore and onshore), nuclear fission, and fossil fuels. The latter is a joint category in which all fossil-fuel power plants are considered, including conventional power plants using solids (i.e., coal) and oil as well as those using gas turbines [9].

In total, five scenarios have been considered. Four of these form part of the Impact Assessment of the European Commission's energy roadmap to 2050 (European Commission 2011). Table 2.1 outlines the average shares on electricity generation and costs per source in each of the scenarios from 2010 to 2050. Fossil fuels and nuclear fission are more present in the BAU scenario than in any other, as the scenario only gathers the

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[9] Other electricity sources, such as hydropower, geothermal and tidal power, have not been considered because they are not projected to change as much in the next decades either for Spain or Europe. The bulk of the electricity decarbonisation efforts in Spain and Europe will be carried out by wide-scale deployment of renewables (mainly solar and wind) and the phase out of fossil fuels (including coal, oil, and gas) (European Commission 2011; IEA 2021; MITECO 2020b).

measures in place by EU Member States in the Energy 2020 strategy (European Commission 2011; European Commission 2021d). The IEA NZE scenario outlines the changes needed to attain zero use of fossil fuels for power generation by 2050, but it does so by relying on nuclear power. The opposite case takes place for the Low Nuclear scenario. The High RES scenario gathers the largest average share of renewable energy.

Another fundamental component of the data and scenario description of the proposed model is the information related to costs of the different energy technologies involved, which need to be adapted to the particular case (i.e. Spain). Two fundamental characteristics of the Spanish electricity system have been identified: its relative isolation in terms of energy interconnections with the rest of Europe and a particular need for additional investments in terms of energy storage to integrate large shares of variable renewable energies (i.e. wind and solar) (Red Eléctrica de España 2019a). These two characteristics act as framework conditions in which the model operates, and therefore needed to be clearly identified in the literature.

To this end, a literature review for the figures for the Levelised Cost of Electricity (LCOEs) [10] of the four electricity sources in the proposed model has been conducted. Its sources, which were selected due to their relevance and pertinence to the presented model, include two landmark reports from authoritative sources in the energy sector at global level (i.e. IRENA and IEA) and two empirical literature surveys done by Fraunhofer and Lazard (Fraunhofer 2021; IEA 2021; Lazard 2021; IRENA 2022). The results, which can be consulted in Table 2.3 of the Annex and that have been used for the sensitivity analysis on LCOEs presented in the Results section, point in all cases to remarkably lower LCOEs for renewable energies (solar and wind) than for fossil fuels and nuclear energy. Several factors can explain this. First, higher LCOEs for fossil fuels and nuclear energy can be due to the very nature of the assets used in power generation in these cases, which entail higher capital costs. Secondly and in particular for the case of fossil fuels, another set of explaining factors are of regulatory nature and largely include the assumed increasing price of coal over the period and the influence of GHG emissions pricing mechanisms such as the EU Emission Trading Scheme (IEA 2021).

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[10] LCOE is equal to the Net present value of an electricity installation over its lifetime and is expressed in US dollars per megawatt hour. This allows for proper cost comparisons across different energy sources. We take values from Table B.1 of the IEA Net Zero Report, EU series (IEA 2021).

Besides, the issue of intermittency in electricity generation of renewables such as solar and wind is well known and recognised, and so it is the need to accompany their deployment with grid-scale energy storage (European Court of Auditors 2019; Andrey et al. 2020; IEA 2021; Fraunhofer 2021; IRENA 2022). Such importance was already made clear by the European Commission in its 2018 Communication “A Clean Planet for All” which states that deployment of energy storage would need to increase by six times to accommodate large shares of variable renewable energies such as wind and solar (European Commission 2018) and investments at the global level seem to be moving in that direction, as identified by the IEA (IEA 2022b). In such context, a key objective of the literature review was to identify a set of LCOEs from a single data source that would not only be representative of the different costs of the energy technologies in the model and their evolution over time but would also integrate the issue of energy storage deployment for the case of renewable energies.

Incorporating cost information on energy storage in the model was not a straightforward task, as the LCOEs for utility-scale energy storage vary greatly across geographical locations in Europe and beyond due to the influence of complex and interconnected factors such as the material composition of the batteries, the exact location of utility-scale storage plants or other elements such as solar irradiation patterns, grid losses and even regulatory obstacles in permitting (Chun Sing and Mcculloch 2016; Ziegler et al. 2019; Andrey et al. 2020; Fraunhofer 2021).

Among the sources consulted in the LCOE literature review, the study done by Fraunhofer on the Levelized Cost of Electricity Renewable Energy Technologies (Fraunhofer 2021) seems to be the most pertinent, as it is the only source that includes sufficient and explicit data (i.e. able to be incorporated in the model) on energy storage for renewables. Several options are provided in the report (i.e. small, large and utility scale storage, of which we take the latter) with detailed explanations on the assumptions used. In addition, the Fraunhofer study considers the closest geographical scope to the case of the proposed model, as it focuses on one single European country (i.e. Germany) as compared to the other sources, which calculate LCOEs at global level (IEA 2021; Fraunhofer 2021; Lazard 2021; IRENA 2022). Finally, the most fundamental advantage of Fraunhofer (2021) compared to the rest of LCOE sources is the fact that it is the only study in the sample providing clear projections until 2040 with specific data on LCOEs for batteries, which makes it suitable to be integrated in the proposed model. A slight shortcoming, however, is that the Fraunhofer report does not include figures on LCOEs for nuclear energy in its scope. As a solution to this, the data for nuclear was obtained from IEA (2021), which provides detailed information on the assumptions and trends incorporated in the final LCOEs for nuclear.

An additional fundamental factor to consider when integrating costs in the model is the issue of energy networks and interconnections. A highly-interconnected electricity system is necessary for the integration of higher shares of renewable energies in the electricity mix and the decarbonisation of energy supply as a whole, as it allows for dispatching clean energy to meet peak demand at a reduced cost for the electricity system (Crozier and Baker 2022; Yang 2022). Together with enhanced energy storage (as pointed out in the paragraph above), energy interconnections can bring the needed additional flexibility that the integration of renewables as the main electricity source will require to meet the goals of the Paris Agreement and the objective of climate neutrality by 2050 of the European Green Deal (European Commission 2019a; Mehigan, Gallachóir and Deane 2022). This is why the European Commission has set a target for interconnection of at least 15% of domestic electricity production able to be transported to neighbouring countries by 2030 among EU Member States (European Commission 2017a).

The current geopolitical landscape has also influenced the prospects for energy interconnections in Europe. After the invasion of Ukraine by Russian forces and the resulting energy crisis, the recent REPowerEU package has stressed the importance of speeding up the process of interconnection of national energy systems of EU Member States, in order to increase the EU's energy system resilience and flexibility to shocks such as the accelerated phase-out of Russian fossil fuels, as well as the integration of variable renewable energies as main generation technologies in the longer term (European Commission 2022a).

The Spanish case, however, presents certain specificities when it comes to interconnections, which need to be incorporated in the proposed model as framework conditions. The electricity system in Spain is connected to France, Andorra, Portugal and Morocco, and its interconnection ratio to the EU electricity system only amounts to a maximum of 3.5 GW – only 3% of installed capacity and much below the 15% EU target for interconnection for 2030 (Red Eléctrica de España 2019a; IEA 2022c). Such lack of interconnections has given rise to the term “electricity island” to describe the Spanish electricity system. Furthermore, forecasts on expected cross-border electricity capacities for 2025, 2030 and 2040 elaborated by ENTSO-E (the association for cooperation of European Transmission System Operators), point out that the situation will not change significantly in the coming decades and that Spain will continue to be significantly isolated from the rest of Europe in the future (ENTSO-E 2023). The recent suspension of the long-negotiated submarine electrical connection project with France through the Gulf of Biscay after an over 80% increase of the total expected cost of the project seems to confirm such forecasts (Monforte 2023).

The isolated condition of the Spanish electricity system has been examined as well in the academic literature: Auguadra, Ribó-Pérez and Gómez-Navarro (2023) find out that the small capacity in international interconnections of Spain makes energy storage play a more important role in energy decarbonisation than previously thought; Abadie and Chamorro (2021) elaborate on the economics of an additional France-Spain interconnectors and the impacts it would have on the market outlook for energy technologies in Spain; while Göransson et al. (2014) analysed that the congestion existing between isolated systems such as the Spanish one to the rest of Europe gave raise to congestion problems in the network, thereby negatively impacting the overall energy costs in the system.

It is therefore safe to establish for the purposes of the model that, due to its isolation, the changes in the Spanish electricity system in the coming decades towards energy decarbonisation will not be influenced in a great extent by fluctuations in the energy mix of neighbouring countries (France, Portugal, Andorra, Morocco) but rather by the changes taking place within the Spanish system itself. In particular, the isolated nature of the Spanish electricity system makes additional energy storage and electricity interconnections two fundamental pillars to ensure the necessary flexibility to accommodate an increasingly larger share of renewables in the electricity mix (Red Eléctrica de España 2019b; Auguadra, Ribó-Pérez and Gómez-Navarro 2023).

The elements outlined above needed to be integrated as framework conditions specific to the Spanish electricity system for the characterisation of the different scenarios. This has been incorporated in the proposed model through a second cost component complementary to LCOEs only for the case of wind and solar, expressing the need for additional electricity interconnections to accommodate renewables and ensure system flexibility. This cost component for interconnections has been calculated from the 2021-2026 Electrical Networks Development Plan of the Spanish TSO (Red Eléctrica de España 2019b). All information on the input data on electricity mix per scenario and costs per source (including energy storage and interconnections for renewables) is provided in Table 2.1 below.

Table 2.1 Average electricity mix per scenario and costs per source

Scenarios /Variables	**BAU**	**IEA NZE**	**High RES**	**Low Nuclear**	**Energy Efficiency**	**LCOEs per source, US $/MWh, average**	**Additional costs per MWh for additional electricity interconnections for renewables, US $/MWh**
Electricity mix (shares per source, %, average 2010 - 2050)							
Solar PV (incl. utility scale storage)	8,5%	19,2%	14%	11,4%	11%	79.6	2.86
Wind (incl. offshore and onshore)	24%	22%	31,3%	29,1%	28,3%	84.9	2.86
Nuclear	10.5%	9.2%	8%	7%	9.3%	128.3	N/A
Fossil fuels (incl. solids, oil, and gas fired)	40.6%	26.3%	30.65%	36%	34.1%	147.8	N/A
Data source	European Commission (2011), Current Policy Initiatives scenario	IEA (2021), Net Zero by 2050 report, Table A.3, total generation	European Commission (2011), High RES scenario	European Commission (2011), Low Nuclear scenario	European Commission (2011), Energy Efficiency scenario	Fraunhofer (2021) study on Levelized Cost of Electricity Renewable Energy Technologies for wind, solar and fossil fuels; IEA (2021) for nuclear	Red Eléctrica de España (2019b), 2021-2026 Electrical Networks Development Plan

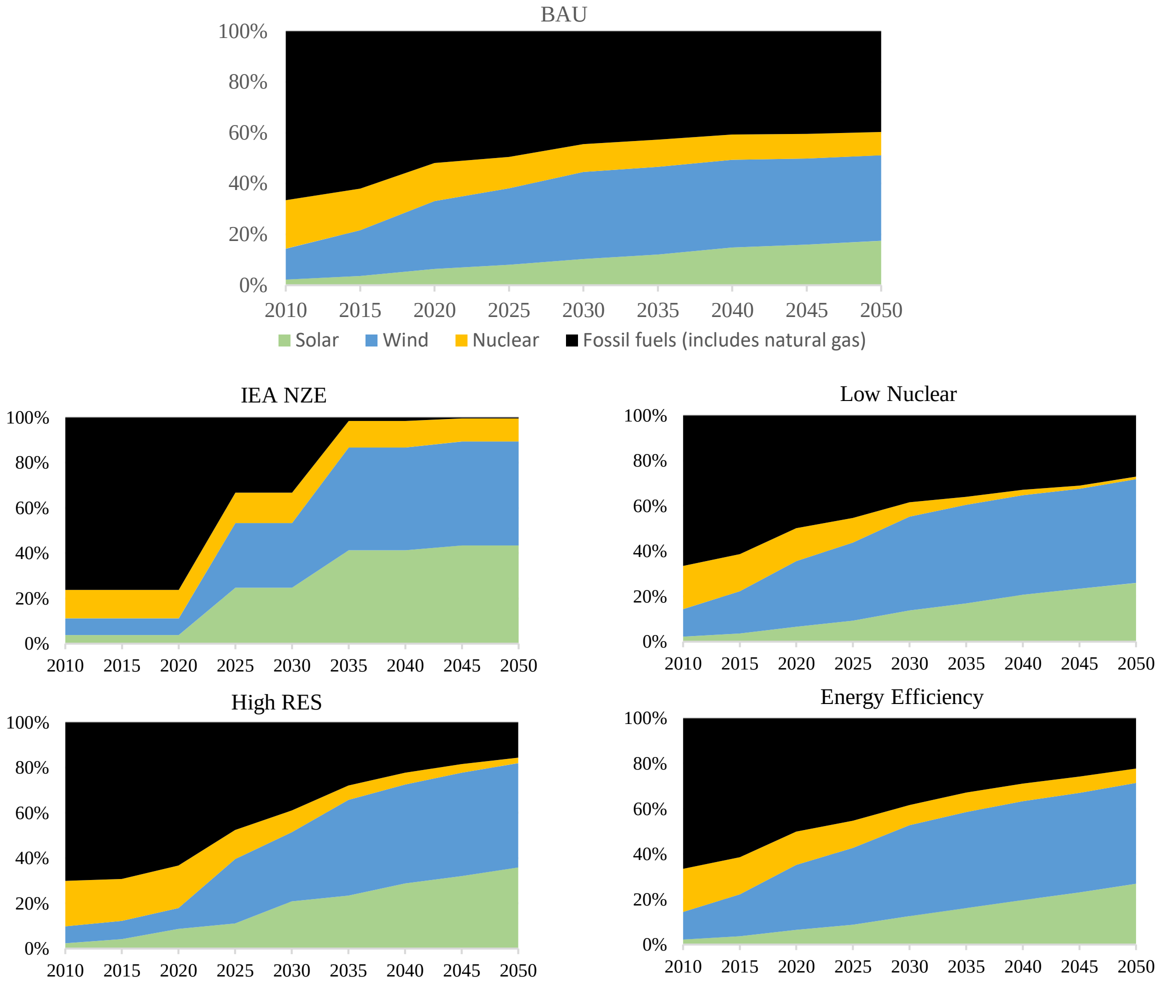
Notes: BAU: Business as Usual scenario; IEA NZE: International Energy Agency's Net-Zero Emissions by 2050 scenario; RES: Renewable Energy Sources; LCOEs: Levelised Cost of Electricity, which are taken from the projections until 2040 given by the Fraunhofer (2021) study – for more information see Table 2.3 in the Annex. The Fraunhofer study does not include nuclear in the analysis, which is why we rely on the figures given in IEA (2021) as LCOEs for nuclear in Europe. Finally, the values for the additional interconnections for renewables are calculated from the projections in Red Eléctrica de España (2019b), taking as a starting point the additional investment needs foreseen in the report for the deployment of 89 GW of wind and solar renewables (1872 M€) for a period of six years (2021-2026).

Figure 2.2 provides an overview of the dynamics in the various scenarios. While in all of these scenarios the presence of renewables (wind and solar) increases over the time horizon, the magnitude of the effect varies greatly. Under the BAU scenario, fossil fuels decrease their share in the electricity mix by only 20%, and still constitute 40% thereof by 2050. The picture is opposite in IEA NZE where, even if this is a scenario of global context instead of European, the biggest increase in both wind and solar power from among the scenarios assessed brings an electricity mix mostly based on renewables, with nuclear remaining relatively stable over the period and fossil fuels brought to net zero.

The High RES scenario also portrays a large reduction on fossil fuels, which remain at 11% in the mix by 2050, while also achieving a significant reduction in nuclear dependence via an accelerated deployment of renewables, especially regarding wind energy. In the Low Nuclear scenario, bringing nuclear energy to a minimum within the mix comes at the cost of a lower deployment of renewable energy and further reliance on fossil fuels.

The Energy Efficiency scenario achieves slightly higher reductions in the presence of fossil fuels than does the Low Nuclear option, which presents a moderate deployment of renewable energy. The Energy Efficiency scenario, however, has a differential point to all other scenarios thanks to its introduction of highly stringent commitments on energy savings, which leads to a decrease of 41% in final the energy demand by 2050 (European Commission 2011), which, as will be presented in the Results section, entails lower investment costs for the implementation of the scenario in the Spanish case.

Figure 2.2 Electricity mix under different scenarios



Source: Own elaboration based on the sources outlined in Table 2.1 (European Commission 2011; Red Eléctrica de España 2019b; IEA 2021; Fraunhofer 2021)

The shares in the electricity mix in each period under the different scenarios are expressed for the European Union in the case of the scenarios taken from the Impact Assessment of the European Commission (European Commission 2011) (i.e., BAU, Low Nuclear, High RES, and Energy Efficiency scenarios) and for the world in the case of IEA NZE (IEA 2021). The results for the Spanish electricity generation sector used in the model are calculated as follows:

$$(18)\ Q_{ES,\varphi_i,t} = share(\%)_{scenario,\varphi_i,t} * Q_{ES-REF,total,t}$$

Where $Q_{ES,\varphi_i,t}$ refers to the total amount of electricity generated in Spain (in gigawatt hours, Gwh) from a given technology φ_i (where φ represents all four available technologies in the model: $i = solar, wind, nuclear, fossil\ fuels$) at each point in time. $share(\%)_{scenario,\varphi_i,t}$ are the shares taken from each of the scenarios (BAU, IEA NZE, Low Nuclear, High RES, and Energy Efficiency, as presented above). $Q_{ES-REF,total,t}$ refers to the gross electricity generation in Spain (also in Gwh) and is taken from the EU Reference Scenario from the PRIMES model (European Commission 2021d).

The result of applying Equation (18) is the electricity mix in Spain under each of the scenarios at each point in time (2010 to 2050), which is used as an exogeneous input to the model calculations. Additionally, the LCOEs from Table 2.1 have been employed to calculate the required investment for the implementation of renewable energies in each period under the different scenarios ($IRES_{ES,t}$) by multiplying the forecast electricity necessary from solar and wind by their respective LCOEs. An exchange rate of US \$ to € from 2019 has been utilised to translate the LCOEs to € ($ER_{\$/€}$) (IEA 2021). This is summarised in the following expression:

$$(19)\ IRES_{ES,t} = \left[\left(LCOE_{solar,t} * Q_{ES,solar,t}\right) + \left(LCOE_{solar,t} * Q_{ES,solar,t}\right)\right] * ER_{\$/€}$$

A final indicator provided in Section 2.5 is that of the climate output gap (COG_t), which gives a measure of the foregone potential output given by environmental damage under each scenario. This indicator is an important output of IAMs, since it can allow for comparisons between the cost of the temperature increase to the mitigation costs under different scenarios (Weyant 2017). In the proposed model, this is calculated as a simple benchmark between the modelled output per capita in steady state (as calculated in Equation (14) and multiplied by population, L_t) and the theoretical level of steady-state output per capita that would have been achieved in the absence of temperature change ($\widehat{y_{ss,t}}$), which is calculated using the same logic as in Equation (14) but removing the temperature from the specification of the total factor productivity and output itself. Therefore, the climate output gap is calculated as follows:

$$(20)\ COG_t = \left(y_{ss,t} - \widehat{y_{ss,t}}\right) * L_t$$

The results of the model are presented in the following section.

2.5. Results

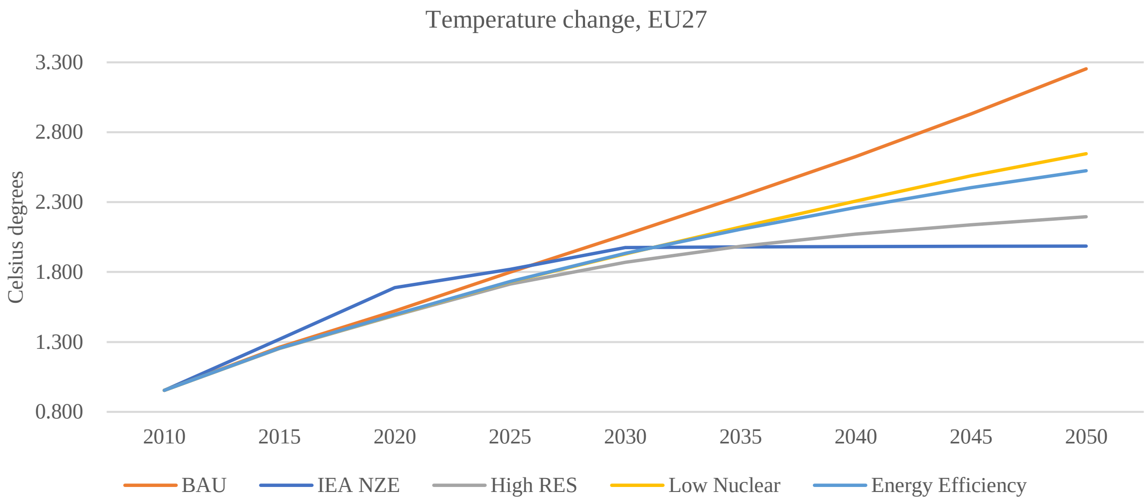
The model presented in the previous section has been applied to the electricity generation sector in Spain. The outcome is a forecast of the estimated economic and environmental impacts of introducing the electricity decarbonisation pathways foreseen in the BAU, IEA NZE, High RES, Low Nuclear, and Energy Efficiency scenarios, which are outlined in this section.

Figure 2.3 projects the changes in temperature over the time horizon under the different scenarios, calculated for EU27. The BAU scenario points to a remarkably higher temperature increase, of over 3°C by 2050, which is explained by the large reliance on fossil fuels (never below 30% of the total electricity supply) that persists even at the end of the period and is in line with equivalent BAU scenarios shown in the IPCC AR6 report, which show similar temperature increases (IPCC 2021). The policies considered in the BAU scenario are able to deliver only a moderate reduction of approximately 20% by 2030 (compared to 2010) of the share of fossil fuels: insufficient to maintain temperatures within safe levels by 2050. The result shows that additional policy efforts are needed to those summarised as current policy initiatives in the European Commission roadmap towards energy 2050 (European Commission 2011).

Low Nuclear and Energy Efficiency scenarios show similar results in terms of temperature increase, by remaining above 2.3°C by 2050. This shows that intermediate approaches, such as those pursued in scenarios where no steep decrease in the share of fossil fuels in electricity generation is introduced, also fall short in preventing temperature from increasing dramatically. Only the IEA NZE scenario manages to contain the temperature change, even though it does so by stabilising the temperature at 1.8°C by 2050 and slightly lagging behind all the other scenarios at the beginning of the period. All of this shows that the effects of CO2 emissions on temperature are persistent, and that containing temperature increase requires steep reductions in the share of fossil fuels in electricity generation.

Nevertheless, caution needs to be exercised when reading these results. The proposed model focuses on the changes arising from one sector (electricity generation) by applying ceteris paribus reasoning, while if change were introduced in other sectors, such as transport, industry, and land use, the figures for temperature increase would certainly become worse. The fact that the temperature increases from BAU are remarkably higher than those of other scenarios (i.e., High RES, IEA NZE) indicates that electricity generation is a particularly influential sector on the overall trend of emissions and climate change. Additionally, the fact that none of the scenarios manage to maintain temperatures within the Paris Agreement ranges (well below 2°C, and ideally less than 1.5°C) indicates that a joint effort with measures placed in other sectors is needed. Electricity is, in short, a key sector in which deeper cuts of CO2 emissions need to be achieved, but it is certainly not the only one in which such changes need to take place.

Figure 2.3 Temperature change under various scenarios, EU27

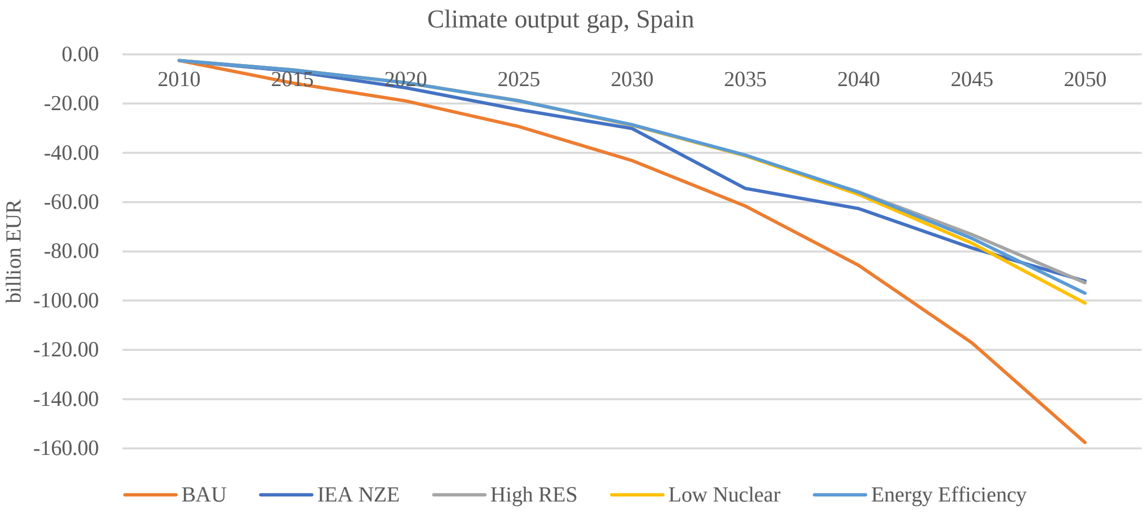


Source: Own elaboration based on modelling results

One key feature of IAMs is their potential to translate changes in temperature into forecast economic impacts. The damage function chosen in our model (Weitzman 2010) is sufficiently sensitive to estimate such impacts in scenarios of moderate temperature increase, such as those presented in our results. Figure 2.4 provides a representation of the economic impacts of each of the scenarios and reveals that the gap between the potential steady-state output (i.e., where influence of temperature is not considered) and the actual output grows much higher when fossil fuels have a greater share in the electricity mix. The maximum losses take place in the BAU scenario, with a climate output gap equal to 105 billion euros by 2050.

All other scenarios achieve significantly lower losses, of close to but still less than 70 billion euros by 2050. This shows that even in the scenarios where more climate ambition is brought forward in the form of the deployment of renewables, there is a deadweight loss that is potentially unavoidable in the long term. This finding can also be linked to the need for a fair transition, in which unavoidable costs should not be imposed on the most vulnerable sectors or income groups to prevent the climate crisis from generating further income inequalities.

Figure 2.4 Climate change losses under different scenarios



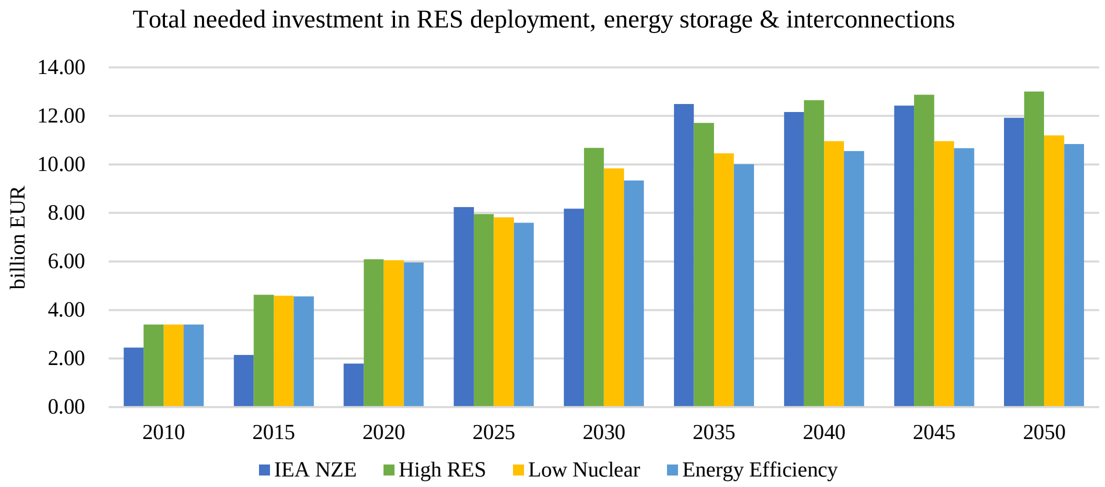
Source: Own elaboration based on modelling results

Mitigation strategies differ across scenarios. Our proposed model also calculates the investment needed in the deployment of renewable energy (which in our case is limited to solar and wind) for the implementation of these scenarios for the case of Spain in real life, using LCOEs using LCOEs from Fraunhofer (2021) as in Equation (20) and including the complementary investments in energy storage and energy interconnections needed to integrate increasing levels of renewables in the electricity mix, as discussed in the data and scenario description. As shown in Figure 2.5, the investment needed in solar and wind electricity generation including storage and interconnections grows by more than three times over the period across scenarios, from around 3 billion euros in 2010 to over 10 billion by 2050. However, such investment needs are still lower than the climate losses that the Spanish economy would incur if no measures were put in place (i.e., 160 billion euros by 2050, as shown in Figure 2.4).

The investment figures vary to some degree between scenarios, with High RES and IEA NZE tending to be those that need the highest levels of investment in renewables: 13 and 11.9 billion euros by 2050, respectively. The enhanced energy efficiency policies in the

Energy Efficiency scenario lead to a remarkable 20% decrease in the total investment needed: down to 10.8 billion euros, although with values very close to the Low Nuclear scenario. The reduction of final energy demand does therefore play a significant role in reducing the total costs of the transition in the Spanish electricity system.

Figure 2.5 Investment required in solar and wind energy deployment, energy storage and interconnections

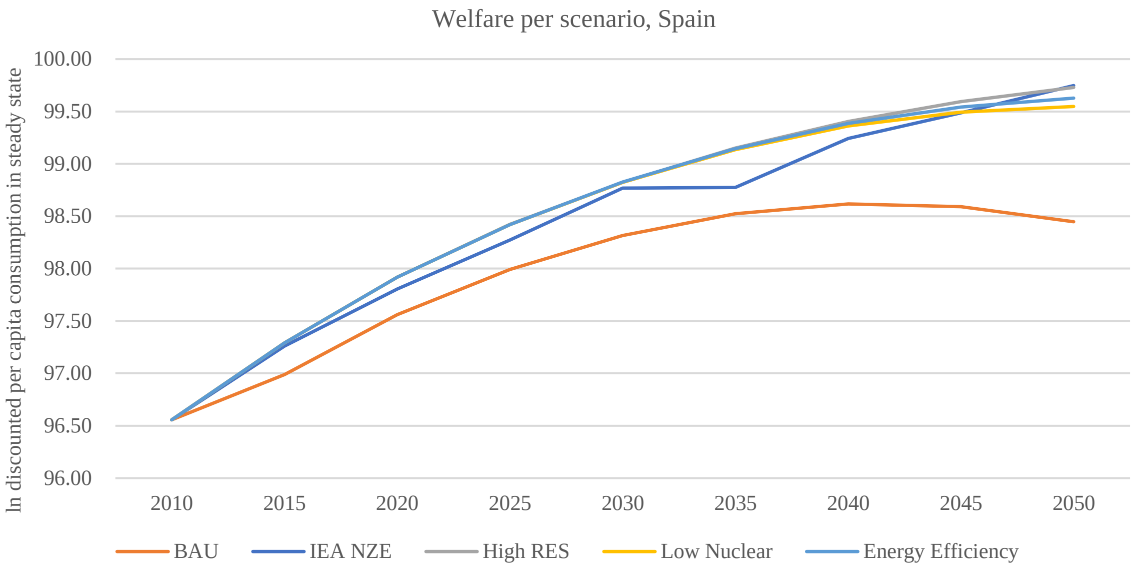


Source: Own elaboration based on modelling results

Having presented the results of the different scenarios, the social planner module described by Equations (16) and (17) is subsequently applied to compute the different welfare levels per scenario and therefore define the most preferable scenario. Figure 2.6 shows the results of the calculated discounted utility in each scenario over the period. The results reveal a clear outcome: the levels of welfare under the BAU scenario are systematically lower than all other scenarios over the entire time horizon, and they even enter a decreasing trend as from 2040. The persistence of fossil fuels in the electricity mix (and their associated damage in the form of temperature increase, harming total factor productivity and the steady-state levels of per capita income and consumption) seems to outweigh the abatement costs of all the decarbonisation scenarios. This is a key finding of the proposed model, as it shows that any policy option is preferable to maintaining the current state of play of the BAU scenario in terms of social welfare.

Conversely, the levels of welfare achieved in each of the policy scenarios are very similar over the period. When the levels of discounted utility are aggregated for the entire period to estimate total welfare (as in Equation (16)), the BAU scenario still gets the lowest value (equal to 881,6), while all decarbonisation scenarios (IEA NZE, High RES, Low Nuclear, and Energy Efficiency) obtain very similar results, with values around 886 of total welfare. High RES shows the highest level of total welfare (886.9) and seems to be the scenario that should be implemented by policymakers when economic and environmental concerns are assessed with our proposed model.

Figure 2.6 Welfare per scenario



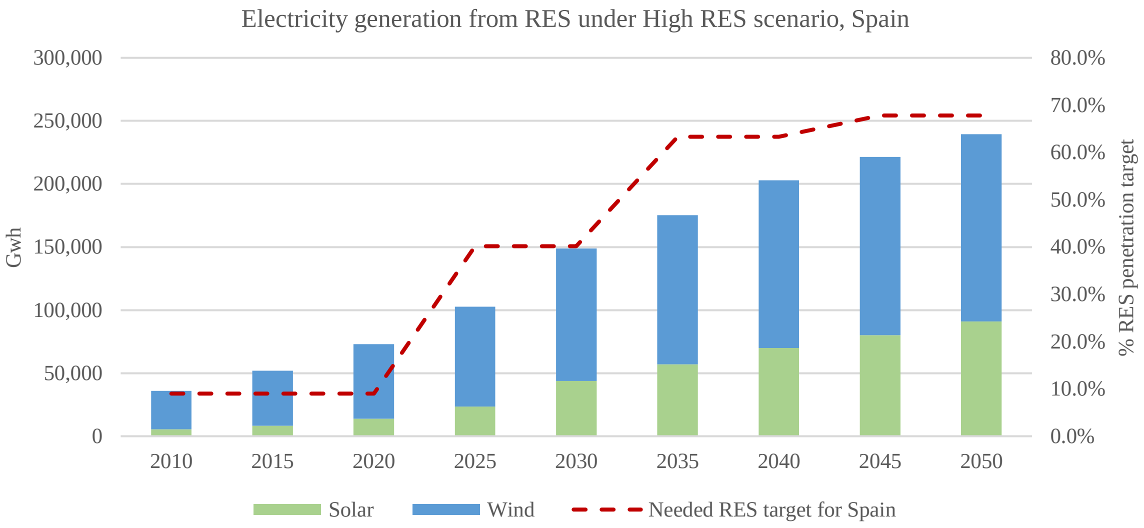
Source: Own elaboration based on modelling results

As a final assessment in the results of the model, a closer examination of the main metrics of the chosen scenario, High RES, is provided in Figures 2.7 and 2.8. Figure 2.7 shows the composition and generation of the renewable electricity supply over the time horizon in the High RES scenario. Wind (including both onshore and offshore) is the dominate renewable energy at all times, although solar generation increases at a faster pace. By 2050, roughly one third of renewable electricity is supplied by solar power plants while the remaining two thirds come from wind energy.

One major policy recommendation to be extracted from the model is that policymakers should ensure that the changes in electricity supply follow the same trajectory as that outlined in the High RES scenario. One possible way to do this is to follow the logic of European legislation, in which targets are frequently employed to guide policies and markets to a socially desirable outcome. For instance, the EU Renewable Energy Directive, currently under revision, intends to introduce an increased target of 40% of renewable energy at EU level by 2030 (European Commission 2022b). According to the findings of the proposed model, electricity in Spain should follow a similar pathway: as can be observed in Figure 2.7, a minimum of 40% of electricity in Spain should originate from renewable sources.

Spanish policymakers should, in addition to this, introduce specific targets, that is, 63% of renewable electricity by 2035 and 68% by 2050, in order to ensure that a minimum of 175 Gwh of electricity from renewable sources is installed by 2035 and 239 Gwh by 2050. As shown in Figure 2.5, achieving this in Spain would entail a total investment of 13 billion euros: this is but a small fraction of the total amount of investment in renewables for the entire energy sector foreseen in the Spanish National Energy and Climate Plan, that is, 91.76 billion euros (MITECO 2020b).

Figure 2.7 Electricity generation from RES under the High RES scenario and target

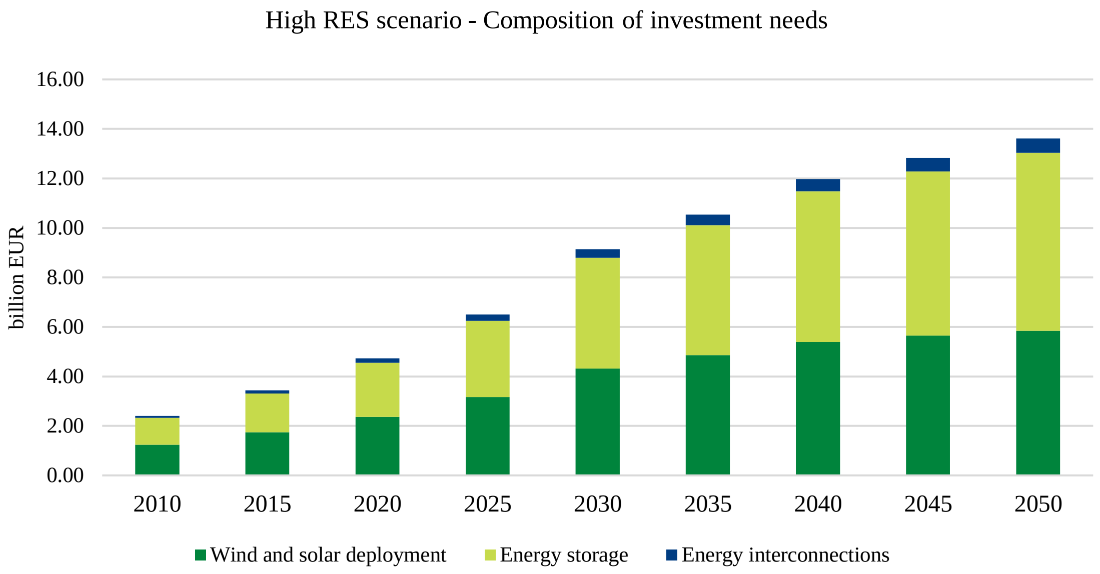


Source: Own elaboration based on modelling results

The description of results achieved in High RES can be supplemented by analysing the composition of the needed investments to deploy the scenario in the Spanish electricity system. This is shown in Figure 2.8. As explained in Section 2.4, the use of LCOEs from Fraunhofer (2021), which foresee the deployment of energy storage to integrate solar energy at utility scale; together with the estimations from Red Eléctrica de España (2019b) on the additional interconnections for renewables allows us to decompose the subtotals of the needed investment in three categories: the deployment of wind and solar itself, energy storage and interconnections.

The three categories described provide an estimation on the needed investments to implement the High RES scenario while accounting for the reality of the Spanish electricity system on the ground. As can be seen from Figure 2.8, for the implementation of the scenario it is equally important to secure sufficient investments in wind and solar deployment as for energy storage. This is coherent with the findings of Abadie and Chamorro (2021), which, as mentioned in the data and scenario description, stress the specific importance of energy storage in Spain given the isolation of the Spanish electricity system. Finally, the needed investments in energy interconnections for the integration of renewables, even if sizeable (i.e. 570 million euros by 2050) represent a minor fraction of the total investment over the time horizon.

Figure 2.8. Composition of investment needs of High RES scenario



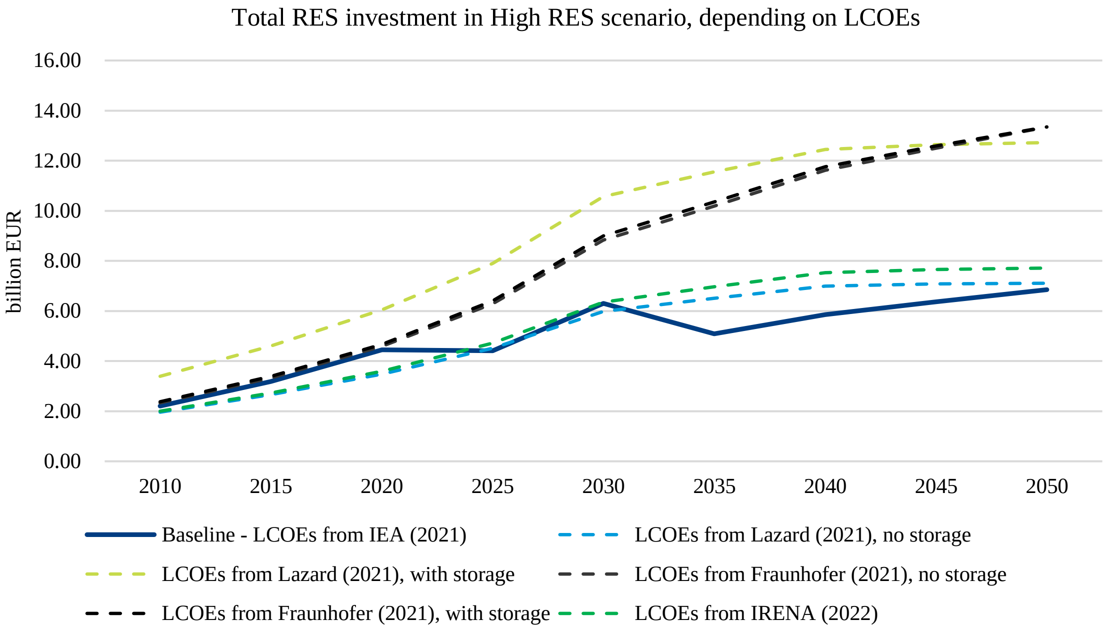
Source: Own elaboration based on modelling results and figures from energy interconnections from Red Eléctrica de España (2019b)

Lastly, and on the basis of the literature review presented in Section 2.4, a sensitivity analysis on the underlying LCOEs for the investment needed under the High RES scenario has been performed. The results are shown in Figure 2.9 below. As it can be observed, the required total investment for the deployment of renewables varies substantially depending on whether the LCOEs used in the model include or not energy storage, increasing remarkably when the latter is considered.

However, and as explained in the LCOEs literature review in Section 2.4 and its results in the Annex, an important caveat needs to be considered when relying on LCOEs for utility-scale storage solutions for renewables in the analysis of IAM results. The values of these indicators vary greatly across literature, as the total cost depends on very different elements and assumptions such as the location of the renewable energy plants, the materials used in the batteries or other factors such as solar irradiation and energy grid losses (Chun Sing and Mcculloch 2016; Ziegler et al. 2019; Fraunhofer 2021; Lazard 2021).

In any case, in spite of these difficulties, when considering energy storage in the results from the High RES scenario of the presented model, the findings still point out at the fact that regardless of the potential LCOE options to be chosen for the modelling available across literature, even in the most expensive case (i.e. up to 13.35 billion euros if the LCOEs from Fraunhofer (2021) with storage are used) deploying renewable energies to decarbonise electricity supply in Spain is always a more cost-effective option than continuing with the emissions associated with electricity generation and its associated losses in the BAU scenario (i.e., 160 billion euros by 2050, as shown in Figure 2.4).

Figure 2.9. LCOE sensitivity analysis results



Source: Own elaboration based on LCOEs from IEA (2021), Fraunhofer (2021), Lazard (2021) and IRENA (2022).

2.6. Conclusions and policy implications

In this Chapter, an Integrated Assessment Model has been presented for the assessment of the economic and environmental impacts of various decarbonisation pathways for electricity generation in Spain from 2010 to 2050. The model has been developed using the DICE-R model by Nordhaus and Sztorc (2013) as a starting point, whereby the most up-to-date and relevant literature on damage functions and social welfare discounting is incorporated, together with the most adequate most widely used data sources on electricity shares and costs (European Commission 2011; Red Eléctrica de España 2019b; IEA 2021; European Commission 2021d; Fraunhofer 2021; IEA 2021). In addition, the specific situation of the Spanish electricity system (i.e. its isolation to the rest of the EU in terms of interconnections) as well as the needs for additional energy storage to accommodate intermittent renewable energies such as wind and solar have been integrated as framework conditions to the model.

The outcome of the research work is a model capable of comparing the potential consequences of introducing different levels of ambition in the decarbonisation of electricity, which constitutes a key pillar of climate change policies. This provides a highly relevant tool for policymaking, since it enables Spanish authorities to compare various policy options, anticipate their effects on social welfare, and foresee the investment needs for the deployment of renewables (wind and solar), energy storage and additional energy interconnections over a long time horizon. The presented model thereby replies to the research question linked to the specific objective SO1 of this doctoral thesis, which is "*What are the economic and environmental impacts of different electricity mixes in Spain by 2050?*".

To reply to the research question above, five scenarios from exogeneous sources such as the European Commission and the IEA have been territorialised to the particular case of the electricity sector in Spain. The model computes the economic and environmental impacts of each scenario, allowing for comparisons between them and facilitating decision-making processes by public agents. The results show a strong preference for scenarios in which deep cuts in CO2 emissions from electricity generation are achieved. Conversely, the negative effects on social welfare from climate damage caused by the persistence of fossil fuels in the electricity mix are worthy of note: the BAU scenario, used as a baseline for the assessment, shows significantly lower social welfare values and cumulated losses in all periods of the time horizon. Such losses, estimated to be worth 160 billion euros by 2050 in the BAU scenario, are much higher than the mitigation costs of the most ambitious scenario (High RES), equal to 13 billion euros. The message is therefore clear: a polluting electricity mix has already become a much more expensive option in the long term than a renewable electricity mix.

Several extensions of the presented model can be conceived, which provide room for further research. In addition to adding other possible scenarios or disaggregating the assessment to make the model granular enough to incorporate key drivers of electricity demand (i.e., buildings, industry, transport), one possible improvement could be made by introducing geographical data to enable the model to display optimal locations for the deployment of the scenarios, not only in terms of economic costs, but also environmental impacts on biodiversity, protected ecosystems and landscape.

2.7. Annex to the chapter – Model technical specification and parameters

Table 2.2 below summarises all parameters used in the model, including their values, short description and source in the Integrated Assessment Modelling literature:

Table 2.2 Modelling parameters, by source

General parameters				
Description	**Symbol**	**Value**	**Unit**	**Source and notes**
Initial population growth rate	g_L(0)	0,02300	2.3% annual increase	EU Reference Scenario 2020 (European Commission 2021d)
Parameter affecting population growth	delta_L	0,052	parameter	Nordhaus and Sztorc (2013)
Spain population in 2010	L(0)	46,487	million people	INE (2022). Spanish National Statistics Institute
Initial TFP	A_0	3,80	parameter	Nordhaus and Sztorc (2013)
Initial TFP growth rate	g_A0	0,079	parameter	Nordhaus and Sztorc (2013)
Change in productivity growth rate	delta_A	0,006	parameter	Nordhaus and Sztorc (2013)
Parameter affecting productivity growth due to change in temperature	gamma	0,001	parameter	Nordhaus and Sztorc (2013)
Spain GDP in 2010	Y(0)	1078989	M€15	EU Reference Scenario 2020 (European Commission 2021d)
Initial cumulated CO2 emissions	CC(0)	530	billion tons CO2 already emitted globally	Nordhaus and Sztorc (2013)
Carbon to CO2 conversion rate (44/12)	CtoCO2_cr	3,667	parameter	Chemistry
Carbon-Climate Response parameter	CCR	0,0018	parameter showing temperature increase per cumulative 000 Gt of CO2eq emitted in the atmosphere	Mathews et al. (2012). Parameter showing a close to linear relationship at a 95% confidence for the model array studied in the chapter
Weitzman damage function parameter 1	D_1	20,46	parameter	Weitzman (2010)
Weitzman damage function parameter 2	D_2	2	parameter	Weitzman (2010)
Weitzman damage function parameter 3	D_3	6081	parameter	Weitzman (2010)

General parameters				
Weitzman damage function parameter 4	D_4	6754	parameter	Weitzman (2010)
Savings rate	s	0,12	rate	Eurostat (2023). Average household saving rate from 2010 to 2020
Initial capital depreciation rate	delta_0	0,1	parameter	Nordhaus and Sztorc (2013)
Change in depreciation rate due to temperature	delta_1	0,001	parameter	Stern (2013)
Cobb-Douglas: exponent capital	alfa	0,4	parameter	Taken from literature review on the empirical range of this parameter among others done in Macias and Matilla-Garcia (2015) where based on results from Bentolila and Saint-Paul (2003) they estimate an alpha of around 40% for OECD countries
Rate of pure time preference (for utility discounting)	rho	0,015	parameter	Various sources, mainly aligned with Stern review as welfare of future generations is highly valued and climate policy is more stringent
Rate of change in marginal utility for each level of per capita consumption - for utility function	eta	1	Parameter - change in marginal utility for each level of per capita consumption	Necessary level of “eta” to have an iso-elastic utility function (Norstad (1999), in which allocation results in the scenario are not sensible to the distribution of wealth. “eta”. In our IAM we follow the example of the PAGE2002 model and take the case of eta = 1, as this allows the aggregation of the impacts in per capita consumption into the welfare function (Hope 2006)
Exchange rate from US $ to €	N/A	0.9421	exchange rate USD vs EUR	European Central Bank (2023), from 04/03/2023.
Exchange rate from € to US $	N/A	1.0615	exchange rate EUR vs USD	European Central Bank (2023), from 04/03/2023.
Additional costs per MWh for additional electricity interconnections for renewables	N/A	2.55	US $ per MWh	Red Eléctrica de España (2019b). Calculated taking as a starting point the additional investment needs foreseen in the report for the deployment of 89 GW of wind and solar (1872 M€) for a period of six years (2021-2026).
Mitigation parameters *(Used in scenarios other than BAU)*				
Description	**symbol**	**value**	**unit**	**source and notes**
Initial abatement cost parameter	omega_0	0,06	parameter	Nordhaus (2007)
Exponent abatement cost function	theta_AC	2,8	parameter	Nordhaus and Sztorc (2013)

Table 2.3 below summarises the results of the Lifecyle Costs of Energy (LCOEs) literature review referred to in Section 2.4, including the different values of the LCOEs per each technology and their source. The table also includes short explanations on the assumptions that needed to be done to allow for comparisons of the LCOEs across the different sources, as in some cases (such as solar energy) there were different sub-technologies that needed to be grouped to provide single representative value.

Table 2.3. Literature review on LCOEs

LCOEs literature review results				
	IRENA (2022)	**Fraunhofer (2021)**	**Lazard (2021)**	**IEA (2021)**
Solar PV, no storage (US $/MWh, average)	46.31	46.65	34.00	37.00
Solar PV with storage (US $/MWh, average)	*N/A (not provided)*	77.75	70.50	*N/A (not provided as single data point)*
Wind (incl. offshore and onshore), no storage (US $/MWh, average)	52.09	82.93	53.00	47.00
Wind (incl. offshore and onshore) **with storage** (US $/MWh, average)	*N/A (not provided)*	*N/A (not provided as single data point)*	89.50	*N/A (not provided as single data point)*
Nuclear (US $/MWh, average)	*N/A (not in scope of the study)*	*N/A (not in scope of the study)*	167.50	128.30
Fossil fuels (incl. solids, oil, and gas fired) (US $/MWh, average)	*N/A (not in scope of the study)*	144.38	113.83	162.50
Energy storage LCOE (US $/MWh, average)	*N/A (provided only for residential batteries)*	*N/A (not provided as single data point)*	36.50	*N/A (not provided as single data point)*
% of LCOE decrease per year (used in LCOEs sensitivity analysis in case of no projection by 2050)	*5.7% for wind and 8% for solar per year for the period 2010-2021*	*Projections by 2040 for the particular case of Germany are already provided in the report: changing the units of the report to US $/MWh the results for 2040 are 44.5 for Solar PV, 46.65 for Solar PV with storage and 67.1 for wind (average including onshore and offshore)*	*6% for wind and 7.5% for solar per year for the period 2009-2021*	*Projections by 2050 are already provided in the report and are included in all scenarios in the model*

Does the report incorporate LCOE projections that evolve over time at least until 2050?	*No*	*No*	*No*	*Yes*
Does the report include figures to the particular case of Europe?	*Yes*	*No*	*No*	*Yes*
Notes on assumptions in each source	Data with no particular geographical scope. Data in energy storage is provided in Box 3.2 (page 94) of the report but for the particular case of behind-the-meter residential lithium-ion batteries in Europe, contrary to utility scale as the other reports which therefore cannot be compared with other figures.	Data for the particular case of Germany. As for all other cases, we take values for utility-scale PV. In this report, data on the LCOEs is provided only for the case of Solar PV utility scale and not as an independent data point. The values for the different LCOEs are taken as an estimation from the values in Figure 5 of the report (page 17). Nuclear is not part of the scope of the report.	Data with no particular geographical scope. For Solar PV, two types are provided: Crystalline Utility Scale and Thin Film Utility Scale - we take the average of the two. For wind, a higher LCOE is given for the particular case of offshore, which is included in the calculation of the average LCOE. For nuclear and fossil fuels, the LCOEs corresponding to fully depreciated assets is not considered. For gas, the case of using green or blue hydrogen reported by Lazard is not considered.	Data taken for the particular case of Europe. Table A3 includes data on battery storage at global level but only for the particular case of transport (EVs). In addition, in Figure 4.18 of IEA electricity system flexibility is considered as well – a large part of the flexibility is provided by a considerable deployment of batteries and demand response systems, but LCOEs on such storage is not provided.

The full code and parameters of the presented model has been made available in Excel format for full disclosure and further use by interested researchers in the following link of the files repository system of the University of Seville:

https://idus.us.es/handle/11441/145566.

Chapter 3. Environmental externalities in Europe (I). Environmental adjustment of the EU27 GDP: An econometric quantitative model

3.1. Introduction

This chapter makes use of another quantitative methodology for integrating environmental externalities in economic systems, in this case an econometric technique called Stochastic Frontier Analysis (SFA). However, it differs from Chapter 2 in its geographical and sectoral scope, considering all EU Member States (EU27) and taking a macroeconomic perspective. In Europe, climate policies are shifting from defining targets and roadmaps for climate neutrality (European Commission 2019a) to specific policies to reduce greenhouse gas (GHG) emissions (i.e., the “Fit for 55” package in the European Union) (European Commission 2021a). Such movements give rise to new and fundamental questions that can only be tackled at macroeconomic level: Will climate policies reduce the dependency of economic growth on natural commodities? Will we be able to maintain the current levels of welfare and living conditions in a decarbonised world? Such questions, even if uncomfortable, need to be addressed when designing credible climate policies.

This chapter aims to quantify these dynamics by including proxy variables for the use of environmental resources (in particular, CO2 emissions and material extraction) in a production function and by studying their dynamic relationship with the evolution of the EU27 GDP for the period from 2000 to 2018. This will be carried out via the concept of efficiency in production functions, and by analysing whether the accumulation of environmental externalities over time exerts an effect on productivity in economic growth, with the aim of addressing a fundamental research question, in relation to specific objective SO2.1 of this research: *What are the consequences of integrating environmental externalities in econometric estimations of Gross Domestic Product?”.*

Economic growth is often measured by the evolution of Gross Domestic Product (GDP) over time. As shown in Stratford (2020), the production of goods and services that amount to the total GDP in each period is largely reliant on the interplay of economic systems with their surrounding natural environment and on the use of natural capital or environmental goods. The evolution of GDP over time has frequently been explained by economists via the concept of the production function. Under this approach, the allocation of different proportions of production factors and their associated productivities constitutes the main drivers of change in GDP, with the Cobb-Douglas production function as the cornerstone model (Cobb and Douglas 1928).

Additionally, the very concept of production functions relies on the premise that the right combination of production inputs produces outputs that are to be considered "desirable", such as economic growth and increased wealth in the form of goods and services, whereas the correlative accumulation of bad outputs (i.e., in the form of increasing environmental damage due to the excessive use of natural goods as input for production processes) tends to be ignored.

Similarly, the Economy-Environment interplay has been largely overlooked in the analysis of economic growth (Mäler 2001; Moretti, Vanschoenwinkel and Van Passel 2021), despite the evidence that CO2 increases global temperature and causes major environmental changes (Nordhaus 1991) and the persistent effects of previously emitted CO2 and its associated environmental disruptions (IPCC 2018). These dynamics, in which economic growth is linked to an extensive use of natural resources, have been amplified by an ever-increasing availability of financial streams (Hagens 2020) that often fail to include the real environmental cost as a shadow price of financial decisions (Bulckaen and Stampini 2009). This has resulted in a parallel accumulation of costs in the form of negative environmental externalities that need to be mitigated by the current and future generations, who will bear most of the cost of climate change (Stern 2007; Tsigaris and Wood 2016).

The interactions between economic growth and material extraction have been explored from a variety of perspectives in the recent literature, including the concepts of eco-efficiency (Zabalza Bribián, Valero Capilla and Aranda Usón 2011; Yu, Zhang and Miao 2018), exergy (Dai, Chen and Sciubba 2014; Carmona et al. 2021), net primary productivity (Du et al. 2021), and in applications of Hotelling's model in the circular economy (Hoogmartens, Eyckmans and Van Passel 2018). All these approaches rely on one principle: economic growth has persistently been driven by an increasing and unsustainable pressure on natural material resources that needs to be considered in modelling applications.

Conversely, the integration of these dynamics on production functions remains a largely unexplored line of research. Their inclusion is fundamental since, if environmental costs are not considered in a production function, modelling optimisations applied when designing public policy can lead to misleading outcomes in which an excessive use of environmental goods shows no repercussions on the projected economic growth. As pointed out by Moretti, Vanschoenwinkel and Van Passel (2021), accounting for these dynamics of environmental externalities is key to designing policy responses more accurately and it has been the focus of recent economic literature for a variety of sectors under different modelling approaches (Mangmeechai 2014; Kiet et al. 2020; Lv et al. 2020; Wang et al. 2020).

This chapter assesses the integration of the Economy-Environment interplay in production functions. As a premise for the analysis, the following question is posed as a starting point: Does the unconstrained use of environmental goods over time eventually become a negative determinant of economic growth? The answer, as explained below, requires taking an intermediate stance between macroeconomic and microeconomic levels. In this regard, we consider that Stochastic Frontier Analysis (SFA) provides the most appropriate modelling framework for a variety of reasons. First, SFA enables a deeper understanding of the influence of the accumulation of environmental externalities on economic growth (Wang et al. 2020). Second, SFA takes an intermediate approach between a macroeconomic estimation of production functions and a microeconomic estimation in which the abatement decisions of individual agents can be factored in (Greene 1982). This approach aims to fill the gap existing between different modelling techniques, by using a similar rationale to that of Rogna (2020). Finally, by including explicit proxy variables representing environmental externalities in the parameters of the SFA model, a clearer representation is attained of the way in which the economy interacts with the environment, thereby allowing the quantification of the consequences of ignoring these interactions in the estimation of GDP.

The literature on SFA models is vast and has greatly evolved since the seminal papers by Aigner, Lovell and Schmidt (1977) and Meeusen and Van den Broeck (1977) to include a broad range of sectors and applications (Fernandez and Koop 2005). The added value of SFA lies in its ability to explain heterogeneity in observed values via the concept of distance to an unobserved frontier. When applied to production functions, SFA enables not only assessing the complexity of technical inefficiency for a given set of inputs (Mastromarco 2008), but also including exogenous variables as determinants of efficiency. The latter, however, has rarely been linked to environmental conditions (Wang et al. 2020) and provides opportunities for further research. Additionally, SFA approaches have hitherto been focused on particular sectors with almost no attempts to estimate technical inefficiency in production functions in a macroeconomic context (de la Fuente-Mella et al. 2020).

Three contributions of this study can be outlined. First, we propose an alternative specification of GDP that considers the intertemporal influence of negative environmental externalities. Second, this alternative specification is quantified through an SFA estimation of a production function that explicitly considers the macroeconomic impacts of environmental externalities. Finally, our results are applied to the model by Havik et al. (2014), which is a modelling tool for policy design developed for the European Commission. In particular, on the latter, we propose a modification of the Total Factor Productivity (TFP) specification to render the model sensitive to the accumulation of environmental externalities.

The chapter is structured as follows. In Section 3.2, the relevant SFA literature and theoretical specification of the model are discussed. The proposed model and EU27 macroeconomic data are described in Section 3.3. Section 3.4 presents the results obtained for an array of SFA econometric estimations, while Section 3.5 covers the implications of the results for EU environmental policy and includes the proposal for a modification on the TFP specification of the model by Havik et al. (2014). Section 3.6 concludes.

3.2. Literature review

Empirical explanations of long-term determinants of economic growth using production functions can be traced back to the model by Harrod (1939), where long-term economic growth is explained through a dynamic set of factors that result in an oscillating steady-state equilibrium. The neoclassical growth model of Solow and Swan (Solow and Swan 1956) contested this result, arguing that it was built on the notion that production factors intervened in production functions in fixed proportions. This approach claimed that it was the variant combination of capital, labour, technical progress, and especially capital accumulation propelled by technological advancements that drove the economy towards a stable equilibrium. These models became the dominant line of reasoning in the explanation of long-term economic growth in the economic literature until the end of the 20th century, and still exert decisive influence (Boianovsky and Hoover 2009). Environmental externalities, however, were not included in the analysis of growth.

In the 1990s, a new approach emerged with the models of Lucas (1988) and Romer (1990). This new paradigm paved the way to the estimation of production functions that included elements beyond just the usual production factors. Negative environmental externalities, understood as undesirable outputs of production processes that ultimately affect the path of economic growth in the long run, constituted one of these possible new elements.

A first contemporary approach to the estimation of production functions reflecting externalities is well presented by Burnside et al. (2006), where external effects are captured through the returns of scale of the production function with no explicit representation of undesirable outputs. The influence of external effects over production is considered only implicitly, and the key parameter to estimate is the change in the returns of scale of the production function given a change in the external effects (Basu and Fernald 1995).

Conversely, there are contributions in which undesirable outputs are explicitly considered from which three subgroups can be identified, including a first family of “top-down” analyses, where the dynamics of externalities in production are analysed from a general perspective, by considering the economy as a whole and by estimating an environmental production function. A second subgroup of approaches can be referred to as “bottom-up” since they take the perspective of a rational economic agent and its incentives to reduce pollution. Finally, there is stochastic frontier analysis (SFA), which we identify as a middle option between the two aforementioned subgroups.

Within the “top-down” category, we include the approaches given by translog (transcendental logarithmic) and CES (constant elasticity of substitution) production functions. On the one hand, translog functions have been used extensively in the economic literature since they enable variability in the returns of scale of the production function (Boisvert 1982; Heathfield and Wibe 1987; Raihana 2012) and allow for a feasible estimation of environmental production functions (Zhou, Zhou and Fan 2014; Cisco and Gatto 2021). On the other hand, CES functions arise as a Cobb-Douglas extension that permit an elasticity of substitution between inputs other than unity (Heathfield and Wibe 1987), albeit for only a reduced number of production inputs (Henningsen and Henningsen 2011). These approaches enjoy the advantage of taking a broad perspective and aiming to estimate the production function for the entire economy of a country or sector(s); they are criticised, however, on the grounds of failing to take the perspective of the economic agent into consideration (Färe, Grosskopf and Pasurka 2007).

The “bottom-up” approaches estimate environmental externalities through their shadow prices. These are defined as the opportunity cost of desirable output to be surrendered by a rational agent in order to comply with environmental regulations and to reduce units of the associated undesirable output of the production process (Färe et al. 1993; Zhou, Zhou and Fan 2014). In other words, valuable production efforts are reallocated to mitigation, thereby causing an opportunity cost. Proponents of this approach argue that the perspective of the rational agent needs to be the viewpoint for the calculation of mitigation pathways, since, in the end, emission reduction efforts are largely carried out by private agents (Zhou, Zhou and Fan 2014). However, climate change remains a public policy issue, especially in Europe, where a public authority (i.e., EU institutions) calibrates targets and adopts regulations, while considering the economy as a whole and/or entire sectors.

In short, “bottom-up” approaches appear to be rather limited in their scope and fail to conceive climate change as a policy-driven issue (which is particularly the case in the EU), whereas the “top-down” approaches do not take the perspective of the representative agent into consideration. To overcome these drawbacks, in our understanding, an intermediate stance between these approaches needs to be taken, and this is where SFA can come into play. Therefore, SFA is employed in our estimations to include proxy variables representing environmental externalities (i.e. CO2 emissions and material extraction) in addition to the usual production factors, together with two sets of control variables. This could be considered a “top-down” approach that takes a general perspective of economic growth and the economy as a whole.

However, the use of stochastic frontier analysis as an estimation technique enables the ineffective behaviour of individual observations to be reflected within the sample (Mastromarco 2008), as well as external effects outside the sphere of control of the producer (Daraio and Simar 2005). Additionally, since SFA analyses how such behaviour influences efficiency, it therefore provides the appropriate modelling framework for the estimation of an environmental production function and for the proposal of a modification of TFP in the model by Havik et al. (2014), as presented later.

Stochastic frontier analysis was first proposed by Aigner, Lovell and Schmidt (1977) and Meeusen and Van de Broeck (1977). By introducing a composite error term that included individual technical efficiency, the authors estimated a frontier production function that explained the variance across individuals. The main benefit of this formulation is that it allows the maximum achievable output to be estimated given a set of inputs, thereby providing a more precise definition of the production function and the determinants of growth (Mastromarco 2008; Rao et al. 2019). The economic rationale of such an approach, as shown by Aigner, Lovell and Schmidt (1977), relies on considering elements which the individual economic agent can directly manage (such as production factors) together with elements that remain outside the agent's direct sphere of control.

The economic literature has used efficiency analysis via SFA to study a broad range of policy-oriented fields (Lovell 1995; Fernandez and Koop 2005); this includes efficiency analysis that considers environmental conditions. Most examples of the latter are related to the quantification of environmental externalities on agricultural productivity (Reinhard et al., 1999), analysing the effects of the management of natural resources in development programmes (Bravo-Ureta, Greene and Solís 2012) or quantifying the influence of externalities on crop yields (Kiet et al. 2020; Wang et al. 2020).

However, studies based on SFA methodologies have so far tended to ignore the accumulation of environmental externalities over time and take only sectoral perspectives. In our case, an SFA-based model is proposed. The model explicitly includes proxy variables that represent environmental externalities (in particular, CO2 emissions and material extraction) to estimate a production function that accounts for intertemporal environmental effects while taking a macroeconomic approach. The contribution of the model consists of explicitly including the effects of environmental externalities in an econometric estimation to quantify their influence on economic growth, and of applying said model to the EU for comparison with observed data. To the best of our knowledge, no study of this kind can be found in the literature.

3.3. Methods, data and estimation

In this section, our model is presented and estimated for the EU27 data, which will enable implications for environmental policies to be extracted. In recent years, the European

Commission has stepped up its policy efforts towards the goal of climate neutrality by 2050, as laid out in the European Green Deal (European Commission 2019a) with policy initiatives such as the revised Circular Economy Action Plan (European Commission 2020a), the 2030 Climate Target Plan (European Commission 2020b), and the recent "Fit for 55" package (European Commission 2021a).

In this context, quantification of environmental externalities and their effect on economic growth constitutes a highly relevant task in the design of credible climate policy, hence the application of our proposed model to the EU.

3.3.1 Model description

The original SFA model by Aigner, Lovell and Schmidt (1977) can be expressed as follows:

$$(21)\ y_{it} = f\ (x_{it}, \beta) + u_i + v_i$$

Where "y_{it}" is the production level in each period (t) for a set of individual observations (i), which in our case are the 27 Member States of the European Union. "$f[x_{it}(t), \beta]$" is the estimated frontier production function, "x_{it}" a vector of production inputs (in our case capital and labour), and "β" a vector of technology parameters. The model takes a composite error measure where "u_i" is a measure of technical inefficiency. "v_i" is a random error term. In the original model, time played no role in the determination of inefficiency (Aigner, Lovell and Schmidt 1977). This approach has been expanded to accommodate dynamic effects on all variables of the model, as carried out by Greene (2005) [11]:

$$(22)\ y_{it} = f\ (x_{it}, \beta_{it}) + u_{it} + v_{it}$$

Where the variables are the same as in Equation (21) but are allowed to change both across time and individuals in the sample. Following Kiet et al. (2020) and Wang et al. (2020), determinants of inefficiency linked to environmental externalities can be introduced

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[11] We omit the firm-specific term of the Greene (2005) model, since the country-specific characteristics of the different Member States are captured by the control variables presented in section 3.3.

as additional variables within the inefficiency term, u_{it}. Hence, the following specification of the term is proposed:

$$(23)\ u_{it} = \sum_{j=0}^{n} \gamma_j\, mat_{it-j} + \sum_{k=0}^{m} \delta_k co2_{it-k} + \varepsilon_{it}$$

The specification of the inefficiency term (u_{it}) presented in Equation (23) incorporates an intertemporal influence of environmental externalities quantified by lags up to a generic “n” and “m” order for material extraction and CO2 emissions, respectively. Such intertemporal relation tries to capture the persistent effects of environmental externalities on economic growth, which have been explored in the relevant literature, whereby for instance past levels of emissions reduce the remaining carbon budget and therefore imply negative economic effects (Capellán-Pérez et al. 2014: Friedlingstein et al. 2014). The choice of using lags in Equation (23) is an attempt to model such effects in a SFA modelling context. ε_{it} is a random, white noise error term.

In most of the applied SFA modelling literature, the parameters of interest to be estimated are those contained in the technology vector β in Equation (22), since they represent the marginal contribution of each production input (Rao et al. 2019). However, in our case, the relevant parameters are those of the variables representing environmental externalities (γ_j and δ_k) since they represent the quantified effect of CO2 emissions and material extraction on GDP. With the econometric estimation of the model, we intend to test whether a representative lag specification of both variables in the sample range for EU27 exists, which serves as our initial modelling hypothesis.

The model presented in previous equations needs an explicit functional form to be estimated. There are sufficient examples in the literature that point out the utility of using a simple Cobb-Douglas production function for this purpose (Havik et al. 2014). Our function appears as follows:

$$(24)\ Y_{it} = A_i * K_{it}^{\beta_1} * L_{it}^{\beta_2} * \Phi_{it}$$

Where Φ_{it} is the intertemporal externality term in Equation (23) in its exponential form, that is:

$$(25)\qquad \Phi_{it} = \prod_{j=0}^{n} MAT_{it-j}^{\gamma_j} * \prod_{k=0}^{m} CO2_{it-k}^{\delta_k}$$

The parameters (to be estimated by SFA) are those in Equations (23) and (24). The constant A_i refers to neutral technological change. Equation (22) can be fitted in Equation (24) by taking logarithms, which will also facilitate the comparison with other modelling approaches and the interpretation of the results in terms of elasticities. The final model to be estimated is therefore the following:

$$(26)\ y_{it} = a_i + \beta_1 k_{it} + \beta_2 l_{it} + \sum_{j=0}^{n} \gamma_j\, mat_{it-j} + \sum_{k=0}^{m} \delta_k co2_{it-k} + v_{it}$$

3.3.2 Sample and measures

The proposed model in Equation (26) will be applied to a selection of key variables observed in the 27 Member States of the European Union during the latest longest available period in Eurostat: 2000 to 2018. Gross Domestic Product (Y) will be the explained variable of the model and, together with Gross Fixed Capital Formation (K), it is expressed in real terms to prevent price-related distortions. To this end, the Eurostat deflator with base 2015 for every year and Member State has been used (Eurostat 2021). As a proxy for labour (L), people aged between 15 and 64 from the Eurostat Labour Force Survey (Eurostat 2020a) have been considered.

The proxy variable for materials (Mat), Direct Material Inputs, is calculated by Eurostat as the sum of all materials extracted in Europe (known as domestic extraction) and materials imported from non-EU countries for all branches of activity (Eurostat 2020b). This yields a measure of the total extraction generated by economic activity, either inside the economy or in foreign markets, thereby accounting for the total input of materials outsourced from the environment. As for emissions (CO2), we limit ourselves to the case of carbon dioxide, since it provides better data availability and is the most commonly present particle in air pollution in developed countries (Stern 2017). Table 3.1 shows the main variables and descriptive statistics.

Table 3.1 Descriptive statistics for key variables

Variable name	Unit	Code	Observed values	Mean	Standard Deviation	Min. value	Max. value
Gross Domestic Product	Millions of euros	Y	513	369274.57	610653.32	3032.24	3504696.19
Gross Fixed Capital Formation	Millions of euros	K	513	80104.77	127913.13	721.04	753744.44
Labour	Thousands of people	L	510	6696.91	8923.85	143.00	40636.00
Direct Material Inputs	Thousands of tonnes	Mat	513	320305.42	381375.69	3450.17	1754895.74
Carbon Dioxide Emissions	Thousands of TOEs	CO2	513	115256.46	175909.89	-3887.52	891957.83

Note: Individuals in the sample are the Member States of the European Union (without counting Malta, which is omitted after having been identified as an outlier in the sample) with data from 2000 to 2018 inclusive.

Source: All data comes from the Eurostat Database (Eurostat 2021).

3.3.3 Sample adjustments

Several adjustments to the dataset of the key variables shown in Table 3.1 were implemented prior to the econometric estimations. First, the outlier detection routine by Dehon, Gassner and Verardi (2009) was applied, which led to the exclusion of Malta from the analysis. Second, cluster-robust standard errors were employed, which have also been implemented by clustering Member States in order to factor in heterogeneity between the different countries. Logs of all variables were also taken, not only to account for the functional form described in Equation (24), but also to render homogeneous units of measurement of the variables reported in Table 3.1.

Emissions and resource utilisation tend to show strong correlation with GDP, which can lead to the omitted variable bias and misleading results if a sufficient set of control variables is not included in the econometric estimation. To avoid this, two sets of control variables have been introduced as reported in Table 3.2. On the one hand, time dummy variables for the years 2008, 2009, and 2010, reflect the effects of the crisis that were still structurally negative during those years (Altdorfer 2017). On the other hand, structural dummy variables further account for the heterogeneous income distribution across Member States of the European Union (Fredriksen 2012).

Additionally, in Table 3.2, EU27 has been divided into three groups in terms of income (“high income”, “middle income”, and “low income”) by ranking them according to per capita GDP in Purchase Power Parity from 2018, the latest year for available data

(Eurostat 2020c) [12]. The data has then been sorted into a stacked time series in terms of Member State and imported into STATA for dynamic panel data SFA analysis using the “sfpanel” STATA code package developed by Belotti et al. (2013).

Thus, the model to be estimated is specified as follows:

$$(27)\ y_{it} = a_i + \beta_1 k_{it} + \beta_2 l_{it} + \textstyle\sum_{j=0}^{n} \gamma_j\, mat_{it-j} + \sum_{k=0}^{m} \delta_k co2_{it-k} + d2008 + d2009 + d2010 + middle + low + v_{it}$$

Although several econometric techniques are available for the estimation of Equation (27), the Maximum Likelihood Estimation method (MLE) remains as the reference method used across a wide range of applications within the relevant SFA literature (Mastromarco 2008). For our data, MLE seems to be more appropriate than other available alternatives such as Data Envelopment Analysis (as carried out in Sueyoshi, Yuan and Goto 2017 and Yu, Zhang and Miao 2018) and the Generalised Method of Moments (as in Acheampong 2018) for several reasons. On the one hand, our sample is large (27 individuals observed over 19 years covering 5 variables). For large samples, the parametric assumptions underlying the MLE method are more suitable to the observed data, and its results remain largely robust compared to other estimation techniques, such as the Generalised Method of Moments (Behr and Tente 2008).

On the other hand, MLE is related to the incidental parameter problem (Lancaster 2000), under which the number of parameters to be estimated increases with the number of observations (Emvalomatis, Stefanou and Oude Lansink 2011). This problem, however, arises when the number of individuals observed in the sample is large and the time horizon is relatively short (Belotti et al. 2013). Our panel is sufficiently balanced between individuals and time since 27 individuals are observed over 19 periods.

Regarding the modelling of the lags in the variables representing environmental externalities (material extraction and CO2 emissions), an initial estimation of lags up to an order of t-10 has been tested. Given the length the time horizon (t = 18), beginning the time series analysis by t-10 is considered a sufficient starting point. Several rounds of econometric estimations using different SFA approaches were done, arriving to a

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[12] This has resulted in the following categories: A first group of “high-income” Member States includes AT, BE, DE, DK, FI, IE, LU, NL, and SE. This category constitutes the reference group and is therefore not included in the econometric estimations. A second category, classified as “middle-income” countries, includes CZ, CY, ES, FR, IT, LT, SI, and SK. The remaining countries, BG, EE, EL, HR, LV, HU, PO, PT, and RO, are listed under “low-income”.

parsimonious model where a maximum number of lagged variables were significant. The results are presented in the next section.

3.4. Results

The results of econometric modelling using SFA are shown in Table 3.2 across a broad range of SFA estimations and as a GLS-based benchmark, as shown in Greene (2005). The reason for the application across this range of estimations is to ensure that the results obtained from the econometric analysis involve a truly empirical relationship between the variables, specifically regarding the dynamics of the environmental externality variables on GDP in the production function. As explained in Section 3.3, Table 3.2 shows the distribution of lags in material extraction and CO2 emissions that obtains a parsimonious model in most estimations.

The reasoning underlying the selection of these particular estimation methods can be summarised as follows. All models presented in Table 3.2 are panel data models and use maximum likelihood for the estimation of the coefficients. Other approaches, such as those presented in Schmidt and Sickles (1984), Cornwell, Schmidt and Sickles (1990), and Lee and Schmidt (1993), have been omitted from the analysis since they use other estimation techniques to render the results more comparable. Most of the models presented in Table 3.2 are based on fixed-effect panel-data estimation techniques since the observed sample of countries remains the same over time. However, random-effect approaches, such as those presented in Battese and Coelli (1995) and in Greene (2005) are also included to render the SFA modelling sample more representative.

It is particularly relevant to estimate the model by Greene (2005), given its potential to consider unobserved heterogeneity when estimating inefficiency (Kumbhakar, Horncastle and Wang 2015), although the large number of parameters to be estimated makes the incidental parameter problem an issue for the inference of the results (Belotti et al. 2013). The result of the Greene (2005) specification is therefore to be interpreted cautiously. The fixed-effect models by Kumbhakar (1990) and Battese and Coelli (1992) estimate SFA production frontiers with a lower number of individuals in the sample, but a time horizon similar to our case. However, these approaches estimate a common intercept for all individuals in the sample, thereby leading to problems of misspecification (Belotti et al. 2013). Conversely, in Pitt and Lee (1981) and Battese and Coelli (1988), larger panels of individuals are analysed but over shorter times (only three periods), and inefficiency is assumed to be time-invariant.

A second classification across the different SFA estimations can also be made in terms of the way in which time is dealt with in each model, between time-varying (where inefficiency is expected to be largely explained by time rather by the differences between individuals in the sample) and time-invariant, with the opposite assumption. In our case, the observed data regarding the number of individuals (N = 26) is more prolific than in the number of time periods (t = 19), but this difference is only slight, hence the presentation of both time-invariant and time-varying approaches appears to be appropriate.

Table 3.2 Estimation results

	Time-Varying Parametric model (Kumbhakar 1990)	Time-Varying Decay model (Battese and Coelli 1992)	Inefficiency Effects model (Battese and Coelli 1995)	Time-Invariant model with half- normal distribution (Pitt and Lee 1981)	Time-Invariant model with truncated-normal distribution (Battese and Coelli 1988)	True Random Effects model with half-normal distribution (Greene 2005)	Generalised Least Squares
Model type	FE; TV; HN	FE: TV; TN	RE; TV; TN	FE; TI; HN	FE; TI; TN	RE; PI; HN	RE; N/A; N/A
Key variables							
ln K_t	0.857 *** (0.053)	0.997 *** (0.043)	1.006 *** (0.046)	0.969 *** (0.075)	0.969 *** (0.077)	0.906 *** (0.079)	0.942 *** (0.079)
ln L_t	0.284 ** (0.093)	0.257 ** (0.096)	0.245 * (0.099)	0.298 * (0.161)	0.297 * (0.165)	0.364 ** (0.129)	0.328 * (0.172)
ln Mat_t	-0.589 *** (0.111)	-0.907 *** (0.173)	-0.894 *** (0.208)	-0.858 *** (0.138)	-0.858 *** (0.137)	-0.515 ** (0.183)	-0.829 *** (0.136)
ln Mat_{t-1}	0.359 ** (0.116)	0.585 ** (0.176)	0.579 ** (0.201)	0.499 ** (0.171)	0.499 ** (0.171)	0.182 (0.142)	0.494 *** (0.176)
ln $CO2_{t-2}$	-0.040 (0.026)	-0.129 * (0.060)	-0.123 * (0.071)	-0.131 * (0.063)	-0.131 * (0.063)	-0.044 (0.064)	-0.141 * (0.071)
ln $CO2_{t-3}$	0.096 * (0.055)	0.166 * (0.075)	0.161 * (0.084)	0.176 * (0.068)	0.176 ** (0.067)	0.034 (0.058)	0.156 * (0.064)
Control variables							
d2008	0.003 (0.027)	-0.176 *** (0.031)	-0.182 *** (0.029)	-0.167 *** (0.038)	-0.167 *** (0.038)	-0.133 *** (0.028)	-0.161 *** (0.038)
d2009	0.042 (0.035)	-0.152 *** (0.042)	-0.158 *** (0.034)	-0.140 *** (0.037)	-0.140 *** (0.037)	-0.116 *** (0.031)	-0.135 *** (0.037)
d2010	0.060 * (0.033)	0.008 (0.029)	0.004 (0.024)	0.007 (0.025)	0.007 (0.025)	-0.024 (0.032)	0.011 (0.024)
middle	-0.129 * (0.061)	-0.138 * (0.066)	-0.131 * (0.071)	-0.149 (0.092)	-0.167 (0.095)	-0.158 * (0.095)	-0.187 * (0.098)
low	-0.158 * (0.094)	-0.125 * (0.070)	-0.107 (0.072)	-0.063 (0.076)	-0.140 (0.092)	-0.086 (0.103)	-0.209 * (0.091)
cons	3.043 ***	3.022 ***	3.071 ***	3.507 ***	3.506 ***	3.927 ***	3.468 ***

	Time-Varying Parametric model (Kumbhakar 1990)	Time-Varying Decay model (Battese and Coelli 1992)	Inefficiency Effects model (Battese and Coelli 1995)	Time-Invariant model with half- normal distribution (Pitt and Lee 1981)	Time-Invariant model with truncated-normal distribution (Battese and Coelli 1988)	True Random Effects model with half-normal distribution (Greene 2005)	Generalised Least Squares
	(0.484)	(0.570)	(0.582)	(0.931)	(0.945)	(0.596)	(0.967)
Parameters							
σ_u	0.305 *** (0.037)	-	0.687 (0.543)	0.194 *** (0.045)	0.194 *** (0.048)	0.265 *** (0.040)	0.126
σ_v	0.133 *** (0.019)	0.036 (0.008)	0.173 ** (0.053)	0.158 *** (0.181)	0.158 *** (0.005)	0.024 (0.034)	N/A - Non-SFA model
Log-likelihood	211.848	99.462	99.737	146.681	146.681	173.632	N/A - Non-ML estimation

Notes : FE: Fixed Effects; RE: Random Effects; TV: Time-Varying SFA model; TI: Time-Invariant SFA model; PI: Persistent Inefficiency model; HN: half normal distribution for the inefficiency term; TN: truncated normal; σ_u: standard deviation of measured inefficiency; σ_v: standard deviation of error term. ***, **, * denote that the coefficients are significant at 1%, 5%, and 10% levels, respectively. The z–statistics are given in parentheses.

Source: Own elaboration based on modelling results, which rely on the models by Pitt and Lee (1981), Battese and Coeli (1988) Kumbhakar (1990), Battese and Coelli (1992), Battese and Coeli (1995) and Greene (2005).

The results from Table 3.2 suggest a negative correlation of CO2 emissions and material extraction with GDP. When each of the environmental externality variables approaches t = 0, their contribution to the overall efficiency changes from a positive to a negative sign. The negative effect of the externality over the overall production efficiency in the frontier is more pronounced in the case of materials than in CO2 emissions. Importantly, these results hold coherently across all SFA estimations presented in the table with significant results, including the GLS benchmark. The sum of the technology coefficients of the standard production inputs (capital and labour) is roughly equal to 1 across all estimations, which supports the general assumption of constant returns to scale of the production function and greatly simplifies the estimation and interpretation of the results (Havik et al. 2014).

Our results are partially in line with those found by Capello (1998) and Wang et al. (2020), insofar as these authors argue the presence of environmental externalities as a significantly negative factor of change in economic growth that should be modelled in the framework in production functions. Furthermore, our results seem to indicate the existence of a tipping point beyond which environmental externalities generate an intertemporal shadow price on economic growth. Beyond a certain threshold in the past use of environmental commodities, the associated environmental externalities begin to exert negative consequences on economic growth. This can be explained by the current climate policy context: the longer climate action is delayed, the more costly and stringent mitigation and adaptation policies need to become (IPCC 2018).

Importantly, the obtained results also reflect the notion of intergenerational equity: the negative effects of externalities associated to past levels of economic growth (expressed by the coefficients of the model) persist until the present, thereby imposing external costs on the current generation. Policymakers therefore face the trade-off between either surrendering present welfare in order to guarantee the wellbeing of future generations by establishing a strict climate policy or leaving most of the effort to future generations (mostly on climate adaptation) by adopting a more relaxed approach on mitigation at present (Stern 2007). The implications of these dynamics have been assessed by the United Nations as one of the main factors to be considered in cost-benefit analyses of climate policy (United Nations 2013; Skillington 2019).

The notion of intergenerational equity is related to the scarcity of environmental commodities, which also explains the modelling results of Table 3.2. The successive extraction of materials from the environment and/or the emission of CO2 over time reduce the availability of their associated environmental goods (Common 1996), that is, remaining materials and air quality, respectively. Economic growth relies on the use of these environmental commodities, but when they become increasingly scarce, a negative influence on economic growth can be observed, hence the values obtained in the coefficients of the model. This assumption uses a similar reasoning to that of the Environmental Kuznets curve (Dinda 2004; Marsiglio, Ansuategi and Gallastegui 2016; Stern 2017) but applied to environmental externalities: when undesirable outputs are accumulated up to a tipping point, they start affecting economic growth negatively (Selden and Song 1994; Dinda 2004; Yu, Zhang and Miao 2018).

Following Moretti, Vanschoenwinkel and Van Passel et al. (2021), we identify the use of natural resources for the production of economic goods as the determinant of environmental externalities. Under this approach, for the case of material extraction, the increasing need for the production of additional goods stemming from economic growth translates into an ever-increasing scarcity of the materials required, which in turn increases their price and eventually harms economic growth itself. For emissions, the feedback loops are more complicated since they entail the reduction of air quality and associated damage linked to the accumulation of CO2 emissions. From an economic perspective, and analogously to the case of materials, the increasing need for additional production translates into higher emissions, thereby resulting in increasing environmental damage, thereby also harming economic growth.

The model confirms the initial modelling hypothesis and provides further insights on the interaction between economic growth and environmental commodities that are coherent with the economic reality. Values closer to the present ($t = 0$) can be expected to affect economic growth more negatively (hence the marginally higher values of the obtained coefficients closer to $t = 0$), as they have accumulated for a longer period than the same variables observed at a previous moment in time. The effect, however, differs between externalities. While materials become scarce at the very same moment of extraction ($t = 0$), CO2 emissions take longer periods of time to accumulate in the atmosphere and then influence economic growth (Tsigaris and Wood 2016).

All estimations show similar coefficients, both of the technology and the externality parameters, with the exception of the model by Kumbhakar (1990), which shows a downward bias. Except for the case of Greene (2005), all variables show appropriate levels of individual significance. One possible explanation for the differences in the results from the Kumbhakar (1990) model involves its underlying assumptions, which make it fit for any variation (of any sign) on the efficiency in the frontier, whereas in our model this effect is largely of negative sign. Another comparison can be drawn in the results if we distinguish between the random and fixed-effect approaches. Overall, in our case, a fixed-effect modelling approach seems justified from a theoretical standpoint, since the same set of individuals (EU Member States) are observed over the time horizon.

Finally, it can also be noted that time-invariant models show a marginally better fit in terms of log-likelihood than do time-varying models. This is, to a certain extent, coherent with the economic reality. Given the still large and structural differences in income across EU27, better results are achieved by models that estimate inefficiency by granting special importance to these differences that persist over time (Fredriksen 2012). The best results combining significance, log-likelihood, and appropriateness to the data observed are those coming from fixed-effect, time-invariant models such as those proposed by Pitt and Lee (1981) and Battese and Coelli (1988), which yield almost identical results. However, the Pitt and Lee (1981) model in the original paper by the authors is applied to a dataset that is much more similar to our case. The latter, therefore, yields the most relevant result and is hence the one selected for Section 3.5 below, in which the modelling results are discussed.

3.5. Implications of the model on EU climate policymaking

3.5.1 Proposal for a modification of GDP estimation in Havik et al. (2014) model

For the reasons laid out in the section above, we have chosen the Pitt and Lee (1981) estimation results to trace the economic policy implications of our findings. To this end, we apply these results to the production function methodology used by the European Commission for the calculation of potential growth rates and output gaps, as developed by Havik et al. (2014). The production function in this model also features capital and labour, as does ours, although no attention is paid to environmental dynamics and externalities. In this respect, the dynamics captured by Equation (26), under the Pitt and Lee (1981) estimation shown in Table 3.2, can be used to render the production function of the Havik et al. model sensitive to such interactions. Since an SFA estimation has been utilised that allows us to reason in efficiency terms, the TFP specification of the model is the appropriate place to include our proposed modification (Kiet et al. 2020; Wang et al. 2020).

The production function in Havik et al. (2014) is a Cobb-Douglas production function with capital and labour adjusted for capacity utilisation and efficiency:

$$(28)\ Y = L^{\alpha}K^{1-\alpha}TFP$$

Where total factor productivity (TFP) is defined as:

$$(29)\ TFP = (E_L^{\alpha}E_K^{1-\alpha})(U_L^{\alpha}U_K^{1-\alpha})$$

The first term of TFP accounts for the adjustment on the overall level of efficiency. E_L and E_K account for efficiency of labour and capital respectively, adjusted by a technology parameter (α). The second term captures excess capacity (represented as U_L and U_K, utility coefficients of labour and capital respectively, also adjusted by α) (Havik et al. 2014). Kiet et al. (2020) and Wang et al. (2020) show that environmental externalities can be introduced as additional variables within the inefficiency term in SFA models. The following modification to the specification of TFP can therefore be proposed on the basis of our results:

(30) $TFP = (E_L^{\alpha} E_K^{1-\alpha} + ENV_{MAT,\ CO2})(U_L^{\alpha} U_K^{1-\alpha})$

With $ENV_{MAT,CO2}$ as an estimated function that accounts for the cumulative effect of environmental externalities, which, in our case, are dependent on material extraction and CO2 emissions. By considering Equation (25) and following the Pitt and Lee (1981) estimation reported in Table 3.2, we can propose the following formulation for the ENV function:

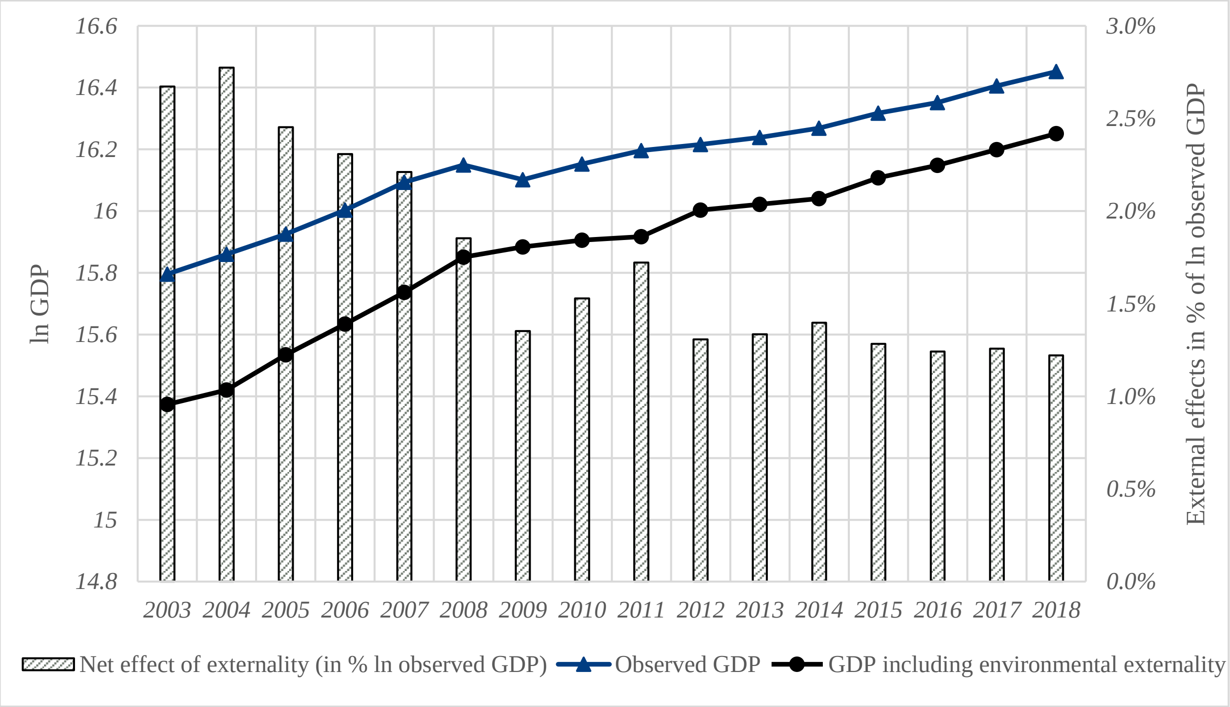
(31) $ENV_{MAT,\ CO2} = -0.858 * ln\, mat_{i,t} + 0.499 * ln\, mat_{i,t-1} - 0.131 * ln\, co2_{i,t-2} + \ 0.176 * ln\, co2$

With the specification as shown in Equations (30) and (31), the estimation of overall efficiency in the production function includes the influence of negative environmental externalities. The result is a production function that captures the presence of environmental dynamics and that can be used as a basis for the calculation of an environmentally balanced GDP series that considers the interactions between economic growth, material extraction, and CO2 emissions in EU27. We call this an environmentally balanced estimation of GDP.

3.5.2 Comparison of an environmentally-balanced GDP series with observed GDP

We can compare the environmentally balanced estimation of GDP elicited in the previous section with observed GDP to show the consequences of applying the proposed modification in TFP to the model by Havik et al. (2014). Figure 3.1 shows the differences between observed GDP and the resulting calculation of GDP using the ENV function in Equation (31) and the results from the Pitt and Lee (1981) estimation from Table 3.2. Since the results include lags of up to t-3 in the specification of the externality, results for only the period 2003 to 2018 are reported. The data includes all the EU27 countries except Malta, which, as explained in previous sections, was identified as an outlier and therefore removed from the sample. Since the model has been calculated in logarithmic terms, the results are presented likewise.

Figure 3.1 Observed and estimated GDP with environmental externality



Source: Own elaboration based on modelling results

Figure 3.1 reveals a negative effect of the accumulation of the environmental externality in all periods. The growth of observed GDP is systematically overestimated when environmental externalities are not taken into consideration. The persistence of undesirable outputs, generated by economic growth in the form of accumulation of CO2 in the atmosphere and by increased pressure on natural resources caused by material extraction, show a negative influence on GDP. As stated in Section 3.4, this can also be explained in policy terms: the longer society waits to adopt stringent climate policies that can have a tangible effect on CO2 reduction [13], the higher the costs that arise in terms of the needed climate mitigation and adaptation (IPCC 2018).

The net effect of the environmental externality (calculated as the difference between observed GDP and calculated GDP with environmental externality) is presented in bars in the graph as an additional indicator and shows that the gap between observed GDP and GDP with environmental effects has reduced over time (from 2.8% of observed GDP in 2004 to

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[13] We are aware that climate mitigation extends beyond CO2 and that an array of Greenhouse Gases and local pollutants must be brought into the picture for it to be complete. Our model focuses on CO2 only because this is the main indicator targeted in the referred EU climate policies and constitutes the main driver of climate change.

1.2% in 2018). This change could be attributed to the introduction of mores stringent climate policies that has taken place within the European Union in recent years. The gap between the two GDP values represents the opportunity cost in terms of growth in the presence of externalities and can be used as a relevant indicator for policymaking in EU27 to measure the impacts of reducing environmental externalities over time. In the absence of environmental externalities as a by-product of economic growth, the gap between the two variables should equal zero; this should constitute the long-term quantitative objective of EU climate policy.

The results presented in Figure 3.1 are also relevant from an economic theory standpoint. The model proposed in this chapter is an endogenous growth model that builds on the ideas already presented in the endogenous growth models of Romer (1990) and Lucas (1988). In our model, the environmental externalities resulting from the GDP increase over time which ends up compromising growth itself. Not only does economic growth generate wealth, but it also incurs environmental costs that eventually reduce future levels of wealth. To this end, we aim to present a simple representation of the quantitative consequences of the intergenerational equity dilemma for the EU27 case.

3.6. Chapter conclusions

In this chapter, the quantification of environmental externalities using econometric efficiency analysis has been explored to propose a definition of an environmentally balanced production function for the EU27. We have analysed the determinants of economic growth while explicitly considering its associated negative environmental externalities, focusing on CO2 emissions and material extraction. The proposed model relies on the theoretical framework of endogenous growth models and uses SFA for the quantification of the external effects.

After controlling for Member State heterogeneity and for the break in the series caused by the years of the economic crisis (2008 to 2010), we estimated the coefficients of an environmentally balanced estimation of GDP growth. Our modelling approach obtains representative results across a broad range of SFA estimations. Moreover, the model proposed presents implications for economic theory and policymaking, since it provides an analytical representation of endogenous economic growth negatively influenced by the accumulation of environmental externalities and an analytical pathway to keep economic growth within environmental boundaries.

The econometric estimation of the model quantifies the influence of CO2 emissions and material extraction (representing environmental externalities) on economic growth. Both variables show positive signs in past levels and negative signs when approaching $t = 0$ on all SFA estimations. This confirms other findings in the literature, under which environmental externalities become a negative determinant of efficiency in the production function when they accumulate over time (Selden and Song 1994; Yu, Zhang and Miao 2018). The findings also indicate that such a negative influence only takes place after a certain tipping point, beyond which the use of environmental commodities compromises economic growth itself.

The model has been applied in order to propose a modification in the Cobb-Douglas production function modelling tool of the European Commission presented in Havik et al. (2014), in the form of the inclusion of the influence of environmental externalities in the definition of efficiency in total factor productivity. The use of efficiency analysis (SFA) in the econometric estimation provides grounds for the proposal of such a change. The results achieved provide a benchmarking metric between environmentally balanced GDP and observed GDP for both the quantification and a more accurate representation of the impacts of environmental dynamics on economic growth, which can be employed on the evaluation and design of climate change policies in the EU.

With our contribution, we have intended to reply to the research question related to specific objective SO2.1: *What are the consequences of integrating environmental externalities in econometric estimations of Gross Domestic Product?*, since the proposed model provides insights on the quantitative relationship between GDP growth and the accumulation of environmental externalities. Climate policies, which aim at precisely reducing such accumulation of side costs of economic growth, are portrayed in the proposed modelling approach as a way to ensure continuous economic growth kept within environmental boundaries, as shown in Figure 3.1 in the GDP series including the environmental externality. Prosperity is possible without compromising the welfare of future generations.

The approach used presents some limitations, especially because environmental externalities go beyond material extraction and CO2 emissions. On the one hand, economic activities generate pollutants that are not included in our model. On the other hand, there are environmental damages, such as biodiversity loss, that are not captured by the coefficients shown in Table 3.2. The model and this research are rather aimed at bringing the issue of dynamic environmental externalities to the attention of economic growth modelling.

The model can also be expanded in several ways. Further research is needed as regards the dynamics of the relationship between economic growth and the accumulation of environmental externalities. The use of datasets with a longer time horizon together with an increase in the granularity of the data to observe these interactions on a sectoral level could also yield significant results.

Broadening the scope of the environmental externality considered in the model by including local air pollutants and other greenhouse gases such as methane, sulphur dioxide, and nitrogen oxides may also provide meaningful insights into this topic, as may the inclusion of other impacts such as the loss of biodiversity and water use.

Chapter 4. Environmental externalities in Europe (II). The EU Emission Trading Scheme and its future on the transition to European climate neutrality

4.1. Introduction

The European Emissions Trading System (EU ETS) is a fundamental instrument among climate change policies in the EU. Conceived as a carbon-pricing mechanism, the EU ETS is based on the allocation and trade of emission allowances among the most emitting industries in the EU. These industries need to acquire a sufficient number of these permits to cover their emissions. In this way, a price to the environmental externalities produced by such players is revealed, driving (at least in theory) mitigation incentives towards the most cost-effective solutions and sectors. The EU ETS is therefore a significant example of how economic systems can integrate environmental externalities by relying on climate policy instruments, in this case a pricing mechanism. In this Chapter we will apply policy analysis techniques to assess the EU ETS in detail, its contribution to climate neutrality as a vehicle for the integration of environmental externalities in the EU and its role within climate policy to achieve GHG reductions in complex sectors. In doing so, we will aim at replying to the following research question, in relation to specific objective SO2.2 of the research: *"What is the role of the EU ETS in the transition to climate neutrality?"*.

The EU ETS has certainly achieved significant emission reductions in key sectors of the European economy such as electricity generation or the production of essential materials such as cement or steel, among others. These reductions amounted in 2022 to more than 750 million tonnes of GHG emissions since the adoption of the EU ETS in 2003 (European Commission 2022c; European Environment Agency 2022b) – a rate of annual emission reduction equivalent to the annual volume of GHG emissions from countries such as Denmark or Bulgaria (European Environment Agency 2022b). This has given the EU ETS significant credit among climate policy instruments in the EU as a mechanism able to operate GHG emission reductions in hard to abate, energy intensive sectors. This has been particularly the case for the production of cement and steel.

In the current context, where the climate emergency is coping with inflationary tensions resulting from the ongoing energy crisis stemming from the Russian invasion of Ukraine, the EU ETS has increased its importance in the EU as a key element in achieving the 2050 climate neutrality commitments in the EU set out in the Green Deal and the European Climate Law (European Commission 2019a; European Commission 2021c; Zaklan, Wachsmuth and Duscha 2021). However, the future of the EU ETS must strike a balance between increased climate ambition and its influence on the final prices of fundamental commodities such as electricity and essential materials such as steel, aluminium or cement (Oharenko 2021a; Pietzquer, Osorio and Rodrigues 2021).

This Chapter presents the main elements characterising the functioning of the EU ETS as a carbon pricing instruments and the way in which the integration of environmental externalities is embedded in its design. It will also discuss the strengths of the EU ETS as a climate policy instrument and the main points of discussion surrounding its influence on the price of fundamental commodities; an issue of vital importance in the current context of inflationary crisis. More specifically, Section 4.2 includes a brief reference to the regulatory context underlying the EU ETS and the successive revisions that have been made to it. Section 4.3 details the functioning of the EU ETS as a mechanism able to influence incentives towards the decarbonisation of polluting industries and its contribution to the transition to climate neutrality. Section 4.4 explains the key issues for the future of the EU ETS. Section 4.5 provides the conclusions.

4.2. The EU ETS regulatory context

The EU ETS was first constituted in the 2003 EU ETS Directive following the adoption of the Kyoto Protocol in 1997, which included among its provisions the setting of binding emission reduction targets for industrialised economies (European Commission 2022c). The Kyoto Protocol confronted the EU with the need to design and agree on a new instrument to achieve its commitments (Sato et al. 2022). In its original formulation, the EU ETS followed the success of a similar scheme, conceived specifically for reducing sulphur dioxide emissions launched in the 1990s in the USA (Aldy and Stavins 2011; Sato et al. 2022).

The EU ETS was designed from the outset as a cap-and-trade system. In this type of emission reduction instruments, a limit or "cap" is set on the total volume of GHG emissions that certain sectors and economic activities can generate per year. The economic sectors included in the EU ETS are set in Annex I of Directive 2003/87/EC and mainly include energy-intensive industries such as steel or cement production and electricity generation (in particular combustion installations exceeding 20 MW of thermal input), as well as glass, paper pulp, and ceramic manufacturing (European Commission 2023a). In addition, Annex II of the same Directive defines the GHG covered by EU ETS, which is not only limited to Carbon Dioxide (CO2) but includes other gases with high global warming potential such as Methane (CH4) or Nitrous Oxide (NO2).

Individual emission permits (called “allowances”) are issued, so that each economic operator within the scope of the EU ETS must acquire sufficient permits to cover its total volume of GHG emissions (European Commission 2022c). In the event of a surplus of allowances over emissions, these can be traded on the emission allowance market. As a result, a time-varying price of GHG emissions is revealed, which in principle can spur incentives of emitting industries towards the adoption of decarbonisation practice, whose cost can (at least partially) be recuperated from the income of selling the emission allowances that are no longer needed after decarbonisation. The result of this is that, if implemented correctly, carbon pricing systems like the EU ETS can tackle GHG emission reductions where they cost the least, as decarbonisation incentives of industrial players will be guided, through carbon pricing, towards the most cost-effective activities and sectors (Oharenko 2021a; European Commission 2022c; Pellerin-Carlin et al. 2022). This cost-effectiveness element has made cap-and-trade systems like the EU ETS often preferred and considered more beneficial than other options such as command-and-control systems, where emission reductions are imposed mandatorily by a public agent, with economic operators bearing no margin of manoeuvre on which sectors and activities to tackle the needed GHG reductions.

Another fundamental element of cap-and-trade systems like the EU ETS, which defines a large part of their performance to deliver GHG reductions is auctioning. Auctions are the main method for allocating allowances to EU industries within the scope of the EU ETS, in which such operators need to place bids to acquire the amount of allowances they need to cover their GHG emissions (European Commission 2022c). Through these auctions and exchange of permits, a financial incentive is created for sectors within the EU ETS, allowing to achieve a GHG emission reduction price at minimum economic cost which favours investments in emission-reducing technologies (Aldi and Stavins 2012; Capros et al. 2019; Oharenko 2021a; Khan and Johansson 2022). In addition, auctioning of permits generates substantial economic revenues for the public sector (in this case, the EU), which exceeded 57 billion euros in total between 2012 and the first half of 2020 (European Commission 2022c). These revenues are mostly redirected to the EU ETS sectors most negatively affected by the system in the form of free allowances [14] to prevent their relocation to third countries, while the rest is dedicated to financing energy infrastructure modernisation projects (through the so-called Modernisation Fund) or to finding innovations that advance in decarbonising the energy system and European industry (through the Innovation Fund) (Pellerin-Carlin et al. 2022; Sandbag 2022).

The EU ETS has undergone several reforms (called "Phases") since its adoption in 2003, with the aim of increasing the pace of GHG emission reductions and achieving the climate policy objectives set out in European legislation. In this sense, the successive Phases have acted on two elements of the EU ETS: On the one hand, the total number of ETS allowances available on the market ("cap") has been reduced annually in order to increase their scarcity (and thus, their price) and thus direct financial incentives towards further GHG emission reductions. Additionally, the number of sectors of application within the EU ETS has also increased progressively (Oharenko 2021a; European Commission 2022c):

Figure 4.1 Phases of the EU ETS

Source: Own elaboration based on European Commission (2022c)

As can be seen in Figure 4.1, the current phase of the EU ETS is Phase 4. This Phase is characterised by a higher ambition in terms of GHG emission reductions and number of sectors covered by the EU ETS, in the context of the adoption of the "Fit for 55" legislative package in July 2021, which includes measures necessary to achieve a 55% emission reduction by 2030 compared to 1990 for the EU as a whole as an overall target (European Commission 2021a; European Parliament 2022; European Council 2023b).

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[14] As we will see later in the Chapter, these free allowances are one of the main sources of criticism of the EU ETS from different actors. It is considered that these free allowances overcompensate certain industries and reduce the effectiveness of the EU ETS as a deterrent mechanism from emitting GHG. The successive reforms done to the EU ETS have tried to tackle this issue by reducing the amount of those free allocations.

In particular, Phase 4 of the EU ETS includes among others, reductions in the EU ETS of 62% by 2030 compared to 2005 levels [15], the inclusion of new sectors such as aviation, maritime transport and fuels for road transport and use in buildings, as well as the acceleration of the pace of annual reduction of the allowance cap from the previous 2.2% annual rate of reduction to 4.3% until 2027 and 4.4% as of 2028 (Efthymiou and Papatheodorou 2019; Christodoulou et al. 2021; Dominioni 2022, European Commission 2022d; European Council 2023c). Measures for Phase 4 also include the possibility of making greater use of ETS resources to address the energy crises, the gradual elimination of free allowances in certain sectors in parallel to the introduction of the Carbon Border Adjustment Mechanism (which we will cover later on this Chapter) and, most importantly, the possibility of using up to 65 billion euros to mitigate the potential adverse social effects of the EU ETS on fuels for road transport and buildings (European Commission 2021b; European Commission 2022d; European Parliament 2022; Sandbag 2022; European Council 2023c).

Phase 4 of the EU ETS is the most recent example of integration of environmental externalities featured in this doctoral thesis. In particular, after lengthy and complex negotiations, the amendment to the EU ETS Directive introducing the measures for Phase 4 were published in the EU Official Journal on 16 May 2023 and entered into force on 5 June 2023 (European Parliament 2022; Bureau Veritas 2023; European Council 2023b). Therefore, the exact impact of these measures is still uncertain, but their consequences can be clearly anticipated. These will be a price increase in EU ETS allowances to strengthen the direction of incentives towards further decarbonisation as well as the potential risk of including sectors that are much closer to citizens (aviation and fuels for road transport and buildings), in which final users could bear the higher costs stemming from a more stringent EU ETS (Oharenko 2021a; Sato et al. 2022). The integration of environmental externalities in such sectors through carbon pricing policies is proving to be more challenging than in the rest of EU ETS sectors, given that if Phase 4 is not correctly implemented, the burden of a higher price of emission allowances in the EU ETS might be passed on by industries towards final consumers.

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[15] This entails an increase of 19 percentage points from the previous GHG emission reduction target of Phase 3 in the EU ETS (European Council 2023c).

4.3. The EU ETS in the EU's green transition

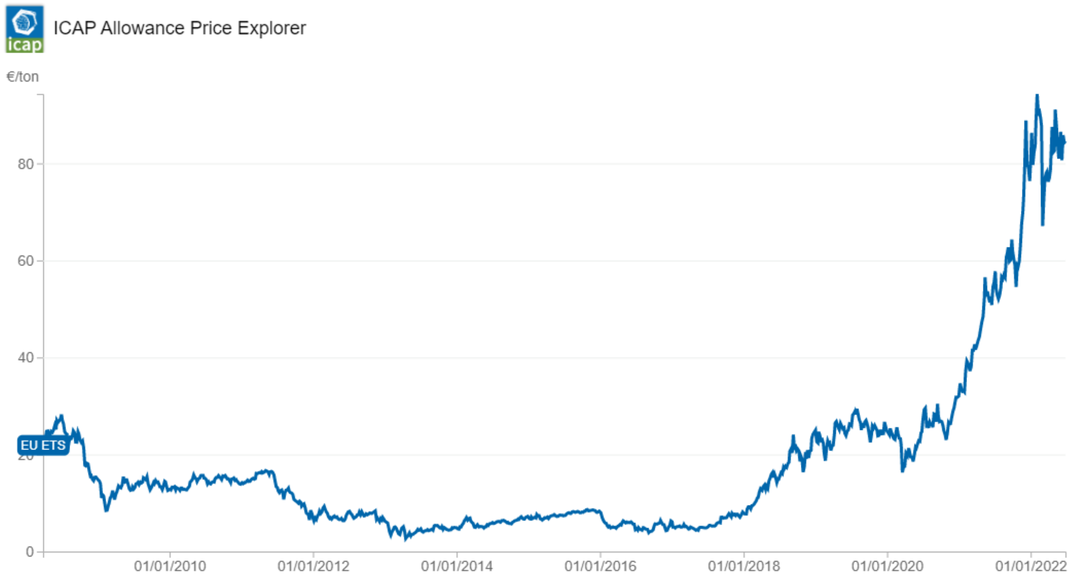
As previously explained in this Chapter, the EU ETS is a key instrument in EU climate policy, essential for achieving GHG emission reductions in key sectors at a reduced cost compared to other methods (Aldi and Stavins 2012; Khan and Johansson 2022), thereby contributing decisively to meeting the EU's 2050 climate neutrality targets set in the European Green Deal and the European Climate Law (European Commission 2019a; European Commission 2021c). In total, EU ETS installations reduced their GHG emissions by 35% between 2005 and 2019 (European Commission 2022d). Overall, since 2005, the EU ETS has managed to reduce GHG emissions from power generation plants and energy-intensive industries by 42.8% since 2005, equivalent to 750 million tonnes of GHG emissions (European Commission 2022d).

As explained in the previous Section, the EU ETS has achieved these GHG emission reductions through a pricing mechanism based on financial incentives generated through the auctioning and exchange of emission allowances, in a system known as "cap-and-trade". Such systems differ from other instruments such as environmental taxes or command-and-control systems, where reductions are set directly through fiscal policy or direct regulation through emission standards (Aldi and Stavins 2012; European Commission 2022c). The limitations of such approaches, widely studied in the academic literature, are summarised by their lower effectiveness in acting on the incentives of the most polluting sectors, while cap-and-trade systems are characterised precisely by their ability to act on these incentives and achieve significant GHG emission reductions in sectors where it costs less (Zaklan, Wachsmuth and Duscha 2021; Khan and Johansson 2022; Sato et al. 2022).

The condition for a cap-and-trade system such as the EU ETS to be effective in delivering significant GHG reductions is that the price of emission allowances is sufficiently high; so that acquiring them represents a significant cost for emitting sectors (Dominioni 2022). The higher the price of allowances, the greater the ability of the system to generate incentives for each economic operator in the EU ETS to adopt technologies to reduce (or eliminate) GHG emissions and thus not undergo the cost of acquiring the necessary allowances.

Therefore, the price of emission allowances ultimately determines the deterrent power of the cap-and-trade systems. And that has precisely been the main challenge of the EU ETS since its adoption. As can be seen in Figure 4.2, the successive phases of the EU ETS have seen an increasing the price of allowances, but during the first twenty years of its existence, their price has not exceeded 30 euros per tonne of emissions and in many cases has remained below 10 euros (ICAP 2022), raising doubts about the sufficient deterrence of the EU ETS and its ability to capture the real costs of environmental externalities associated to polluting activities. It has not been until the end of 2020 and in particular since the publication of the "Fit for 55" package that the price of allowances has increased substantially, placing it over 80 euros per tonne of emissions in 2022 (Sato et al. 2022). As we will see in the next Section, the consequences of stricter and broader in sectorial scope carbon pricing in the context of the recently adopted Phase 4 of the EU ETS are at the centre of the debate on the future of the EU ETS as a climate policy instrument in the EU.

Figure 4.2 Evolution of EU ETS allowance prices



Source: ICAP (2022)

4.4. The future of the EU ETS

The reform of the EU ETS in Phase 4 is a good example of how complex the design of policy instruments able to integrate environmental externalities through pricing mechanism can become. The rejection of the legal text in the plenary session of the European Parliament in June 2022 made the negotiations on Phase 4 particularly lengthy and complex, which only arrived at a final agreement and publication in the EU Official Journal on 16 May 2023, with entry into force on 5 June 2023 (European Parliament 2022; Taylor 2022; Bureau Veritas 2023; European Council 2023b). The conflicting positions among political groups in the European Parliament can be explained by the very nature of the EU ETS: as a GHG emissions pricing instrument, there is concern about the influence that a stricter EU ETS could have on a potential increase of fundamental goods such as energy [16] or critical raw materials such as cement or steel (Gerlagh, Heijmans and Rosendahl 2022). The current energy crisis and inflationary pressures triggered by the Russia-Ukraine conflict has heightened these concerns (Taylor 2022).

The link between the reform of the EU ETS and the current context of the energy crisis is particularly relevant. As we saw earlier, greater climate ambition entails raising the price of GHG emissions permits, in order exert a greater pressure on the incentives for decarbonisation in the most polluting sectors. However, stricter carbon pricing can have two possible effects: on the one hand, tighter rules on carbon pricing can indeed trigger higher incentives towards more ambitious decarbonisation plans in polluting industries; on the other, the higher price of emission allowances associated with a more stringent EU ETS faces the risk of a pass-on to final consumers, in which the higher cost driven by the allowances are simply transmitted to the prices of fundamental goods such as energy, cement or steel, essential for the competitiveness of the EU economy (Cornago 2022). This is an example of how the integration of environmental externalities requires a systemic approach, in which all possible consequences of such integration are assessed before making policy choices.

In order to prevent such pass-on to final consumers in the case of energy distribution prices (which would aggravate the current energy crisis), a proposal that received particular attention during the debate of Phase 4 of the EU ETS was to use the practice known as "frontloading", which simply consists of bringing forward the auctioning calendar of emission allowances to increase the economic returns for the EU from the auctions (Quemin 2022; Simon 2022). These additional revenues would be used to finance the EU action plan against the energy crisis, known as "REPowerEU", which includes measures to remedy the current energy costs (European Commission 2022a). The success of “frontloading”,

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[16] Electricity generation reliant on fossil fuels is one of the sectors included in Annex I of Directive 2003/87/EC which regulates the sectors in the scope of the European Union Emission Trading Scheme, hence the concerns of the influence of the EU ETS on the energy crisis.

however, depends ultimately on whether the surplus produced by the more frequent emission allowances auctions can be of enough quantity to mitigate the potential impacts on final energy prices – a question that raised significant concerns during the negotiations.

Another major concern for the future of the EU ETS is its potential influence on the competitiveness of European industries, and in particular on the consequences that stricter carbon pricing may have on investment decisions of private undertakings (Ismer, Neuhoff and Pirlot 2020). A particularly important phenomenon in this regard is known as carbon leakage, which consists of the relocation of European GHG-emitting companies to third countries with less stringent environmental regulations. Carbon leakage will be tackled in Phase 4 of the EU ETS with the introduction of the obligation for products imported into the EU from sectors within the scope of the EU ETS to purchase sufficient permits to cover the GHG emissions generated in their production, even if the production took place outside the borders of the EU (European Commission 2021e; European Commission 2021f). Such mechanism, known as Carbon Border Adjustment Mechanism (CBAM), was one of the most debated elements in the negotiations of Phase 4 of the EU ETS, also because the CBAM would substitute the system of compensation to undertakings most affected by carbon pricing through free emission allowances, thereby increasing the stringency of carbon pricing in the EU (Sandbag 2022; Sato et al. 2022).

An additional obstacle in the design and negotiation of the CBAM was to ensure that it would be aligned with the multilateral trade rules of the World Trade Organisation (WTO), so as to not be perceived as a barrier of tariff to trade with third countries outside the EU. The European Parliament took a significant role in this by making sure the CBAM would be aligned with WTO rules (European Parliament 2021a), in an example of how the integration of environmental externalities often goes beyond the sectors to which it is initially conceived (energy-intensive and hard to abate sectors for the case of CBAM) and affects related domains such as trade. In any case, despite the lengthy negotiations, the CBAM was published in the EU Official Journal at the same time than the rest of proposals under Phase 4 of the EU ETS: on 16 May 2023, with entry into force on 5 June 2023 (Bureau Veritas 2023; European Council 2023b). The CBAM will be effectively applied from 1 October 2023 with a transitional phase towards full reporting obligations by 31 January 2024 and, importantly, with a larger scope than the EU ETS, covering cement, iron, steel, aluminium, fertilisers, electricity and hydrogen (European Commission 2023b).

The third of the main concerns in the future of the EU ETS is its potential influence on the European Union's global competitiveness by positioning itself as the economy with the strictest carbon pricing system in the global economy (Ismer, Neuhoff and Pirlot 2020). However, systems similar to the EU ETS have been implemented in economies of similar importance, such as China and the USA (Kapnick 2021; World Bank 2022), reducing such potential risks of regulatory divergence between the European Union and the rest of the world. In addition, the previously mentioned CBAM also aims to address the risk of regulatory divergence between the EU and the rest of the world, placing all products arriving at the European borders on a level playing field taking into account their emissions at origin.

Finally, the future of the EU ETS will also depend on its role at the global level. The EU ETS is the world's largest and most established GHG emissions pricing instrument. The agreements adopted at the recent COP26 in Glasgow included a key milestone: laying the ground for the implementation of the controversial Article 6 of the Paris Agreement for the creation of a global GHG emissions market (United Nations 2021). At the same time, systems similar to the EU ETS have been implemented [17] in economies of the greatest global importance (Kapnick 2021; World Bank 2022). In the future, the implementation of COP agreements, if successful, will involve linking the EU ETS with these other similar systems. Europe, however, stands as the benchmark for carbon pricing policies in the global level and in this light the way in which rules will be defined in the EU ETS will exert a key influence on the final design and ambition level of other carbon pricing mechanisms globally.

4.5. Chapter conclusions

This Chapter has analysed the key role of the EU ETS as a GHG emissions pricing mechanism and climate policy instrument, including a detailed explanation on the functioning of the EU ETS, the mechanisms explaining the evolving prices of emission allowances and the potential drawbacks of an excessively low value for them, thereby replying to the research question of this Chapter, *"What is the role of the EU ETS in the transition to climate neutrality?"*. The changes to be implemented under Phase 4 of the EU

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[17] There are currently 68 carbon pricing systems worldwide, with countries such as China, Indonesia, Chile, Uruguay, Canada or South Africa with mechanisms of this kind in place (World Bank 2022).

ETS have been described in detail as they constitute a decisive milestone towards achieving the EU's 2050 climate neutrality commitments in the European Green Deal and the European Climate Law (European Commission 2019a; European Commission 2021c). The EU ETS also represents a fundamental example of a climate policy instrument aimed at integrating environmental externalities to influence incentives of polluting industries.

The implementation of Phase 4 of the EU ETS, which entered into force on 5 June 2023 after lengthy negotiations within the EU institutions, has been and will be a challenging and complex process. It is necessary to find a balance between a stricter GHG emissions permit pricing mechanism that generates sufficient financial incentives to decarbonise polluting sectors whilst ensuring that the prices of essential goods such as energy or the global competitiveness of the European economy remain under control. Phase 4 of the EU ETS shows that when policy instruments try to integrate the entire scope of environmental externalities of certain sectors (in this case hard to abate, energy-intensive industries) in the economic paradigm, a holistic approach taking into account all effects of such integration needs to be adopted. The measures foreseen under Phase 4 to mitigate the potential social adverse effects that increased carbon pricing of fundamental goods might have, in particular the 65 billion euros available to address the impacts of the inclusion of buildings and road transport in the EU ETS, seem to be a step in the good direction (European Council 2023b). Time will tell whether with this reform the EU ETS will finally become a sufficiently deterrent mechanism for hard to abate sectors, driving the EU closer to the goal of climate neutrality by 2050.

Chapter 5. Environmental externalities in the global stage. Environmental protection in Free Trade Agreements: A comparative study

5.1. Introduction

In this chapter, we tackle the integration of environmental externalities in economic systems with the broadest possible angle – the global stage, with the aim of replying to the research question associated to research objective SO3: *"What have been the consequences of addressing environmental externalities in regional free trade agreements around the world?*. Regarding the sectoral scope of this chapter, there are few examples in which we can observe attempts of economic systems to accommodate the effects and costs of environmental externalities. While the obvious choice might seem the multilateral negotiations done in the context of the United Nations Framework Convention on Climate Change (UNFCCC) and its Conference of the Parties (COP), to which we owe the adoption of the Paris Agreement, an even more relevant choice, yet often overlooked, is the negotiation of free trade agreements. The relevance of such choice relies on the fact that trade negotiations possess the unique nature of combining purely economic national incentives with other geopolitical and strategic aims of the negotiating countries. In recent years, one of those other aims has been precisely the integration of environmental externalities. Trade is, therefore, the chosen sectoral scope of the study presented in this Chapter.

Firstly, a word of context on trade negotiations at the global level should be provided. The proliferation of regional free trade agreements (FTAs) since the end of the 20th century has become a major factor in the integration of environmental externalities in trade agreements at the global level. The stagnation of the multilateral approach to global trade negotiations led by the World Trade Organisation (WTO) since the Doha negotiating rounds has led to the development of a regionalist approach, pushed by the main global economic powers (Crawford and Fiorentino 2005). Such trade regionalism, characterised by bilateral and selective negotiation of free trade agreements, has resulted in a normative mosaic of different regional trade agreements protecting different, and often diverging, national strategic interests (Deblock 2006).

Economic regionalism in trade negotiations is often seen as a risk to the coherence of international economic relations, and even to free trade itself. Indeed, the economic literature has defined the relationship between economic regionalism in regional FTAs and the multilateralism proposed by the WTO as two opposed approaches to global commercial relations, marked by a complex coexistence (Deblock 2006). In regional FTAs, the validity of the most-favoured-nation clause is called into question by the establishment of more privileged conditions between groups of countries compared to the rest of the world, posing a risk of discrimination against non-signatory countries (Crawford and Fiorentino 2005). However, the importance of regional FTAs is also seen as an opportunity for multilateralism, as it gives negotiating countries the chance to reach deeper compromises (for instance, on the integration of environmental externalities) that would not be feasible in the context of the WTO and, importantly, go beyond the strictly commercial agenda (OECD 2007).

Such conception of regional FTAs as agreements able to go beyond purely commercial interests, and therefore, able to integrate environmental externalities in their formulation, is based on two main ideas. First, some authors within the literature see regionalism as an accelerator of multilateralism, provided that adherence to regional FTAs is open to non-signatory countries without discrimination (Menon 2005). Second, the proliferation of regional FTAs and their increasing importance in global trade relations has brought about a change of approach in negotiations: there has been a shift from a multilateral approach focused almost exclusively on the reduction of trade barriers (tariff and non-tariff), where progress has become rather modest in recent years (Colyer 2012) to a more fragmented approach in which countries can move beyond the debate on trade liberalisation and negotiate on related issues, including the protection of environmental resources and the adoption of standards to fight climate change (OECD 2007).

This ambivalent relationship between regionalism and multilateralism has not gone unnoticed by the WTO, which, since 2002, has set up a specific working group called the “Negotiating Group on Rules”, which attempts to assert the primacy of multilateral agreements over regional FTAs. Conversely, the European Commission in its recent Communication “Trade Policy Review — An open, sustainable and assertive trade policy”, called for the need for a thorough reform of the WTO, “including through open multilateral agreements”, in a clear sign that the role of multilateralism in global trade negotiations needs to be profoundly revised (European Commission 2021g).

In addition, regardless of its multilateral or regional form, globalisation and free trade have also been strongly criticised in recent years. Critics point out the fact that the benefits of these agreements are sometimes not fairly distributed between higher and lower income countries. Under such conception, FTAs would function as a mechanism transferring rents from lower income countries with reduced labour and capital costs to developed countries (Shah 2006). The literature remains divided on this matter. Some economists argue that data available is not sufficiently clear to conclude that trade liberalisation has a negative effect on all lower income countries and in all FTAs in a consistent way (Aisbett 2007). Other economists, such as Nobel Prize Joseph Stiglitz, criticise FTAs as amplifying mechanisms for increasing income inequalities between workers and investors, both in rich and poor countries (Stiglitz 2017).

In this context of questioning the benefits of trade liberalisation and, above all, multilateralism, the EU has made a profound change in its trade agenda with the adoption of the European Green Deal (European Commission 2019a). Chapter 3 of the Green Deal Communication, titled “The EU as a global actor” focuses on the external dimension of European climate policy. In this chapter, trade policy is mentioned as a key element in supporting the euro green agenda; bilateral free trade agreements are conceived as an opportunity to forge climate policy outside Europe, and therefore as a vehicle for the integration of environmental externalities. In 2019, these clauses in the European Green Deal Communication established a new mandate for European trade policy, in which EU trade negotiations could have become a new EU executive instrument to promote the climate transition at global level (Bjerkem 2019; European Commission 2019a). However, on the other hand, the European trade agenda has often shown other motivations, linked to geopolitical gains in some regions without necessarily having the environment as a priority (Céu 2021).

The EU is in the process of developing a number of initiatives to implement this mandate for an external division of the Green Deal in the field of trade policy. There are many examples: The Carbon Border Adjustment Mechanism (CBAM), the inclusion of sustainable development chapters (SDRs) in FTAs negotiated by the EU and the inclusion of sustainability criteria in the EU trade strategy. The CBAM is a particularly relevant example om how environmental externalities have been integrated in the design and implementation of an economic policy such as trade, which has already been covered in Chapter 4 of this doctoral thesis. As a reminder, the CBAM aims to establish a carbon pricing mechanism for goods imported by the EU with the aim of addressing the incentives of economic actors for less carbon-intensive products and to avoid the relocation of more polluting industries, in what is known as carbon leakage (European Commission 2021f; European Commission 2023b). However, these EU initiatives have been strongly criticised by key trading partners such as the USA, who see them as a unilateral measure against the spirit of free trade, which should only be used as a last resort (Oharenko 2021b). Conversely, the European Parliament expressed its views on the CBAM in a specific report, stating that a WTO-compliant CBAM could be possible as long as carbon tariffs are neither arbitrary nor discriminatory (European Parliament 2021a). This is yet another example on how the integration of environmental externalities can have fundamental consequences at the global level; in this case in trade relations between two economic powers like the EU and the USA.

As regards the adoption of SRD chapters in FTAs, the European Commission gave new impetus to this with a 2017 non-paper entitled “Trade and Sustainable Development (TSD) chapters in EU Free Trade Agreements (FTAs)” (European Commission 2017b). The report calls for greater use of sustainable development clauses in free trade agreements, in particular through the creation of bilateral committees with European members and members of signatory countries, known as TSD committees. The problem of this initiative, as pointed out by the European Economic and Social Committee in its opinion on the subject, has been its lack of coercive force and sanctions in the event of failure to comply with the TSD chapters (European Economic and Social Committee 2017).

The recent Commission Communication “Trade Policy Review — An open, sustainable and assertive trade policy” is a clear summary of the priorities of European trade policy. Sustainable development and the green agenda are mentioned as one of the three main objectives of the strategy, which gives a clear sense of importance to it (European Commission 2021g). In addition, initiatives that could be considered unilateral (such as CBAM) are listed as “autonomous” initiatives in which the EU aims to strike a balance between WTO compliance and its objective of achieving its policy agenda, with sustainable supply chains standing as a key objective (European Commission 2021g). The European example shows the complexity of striking a balance between an influential trade agenda and a strong ecological ambition in which environmental externalities are integrated in economic decisions. Nevertheless, the number of free trade agreements containing environmental protection provisions has increased significantly since 2000, even with varying degrees of stringency and ambition (Colyer 2012).

We may ask ourselves about the reasons for the heterogeneity in the results of these attempts at integrating environmental externalities in the text of regional FTAs in which the EU takes part. Such heterogeneity can be explained by a set of factors, which we will use in this chapter to screen a sample of regional FTAs and analyse the way in which environmental externalities have been integrated. The degree of economic development of the countries involved is the first of these factors of divergence, particularly where there are significant differences between those negotiating the agreement (Nemati, Hu and Reed 2019). Secondly, the underlying motives that invite states to negotiate can also play a role in the outcome of the agreement. These motivations may include, for example, obtaining more resources to achieve their sustainable development goals, sharing some costs to increase efficiency in the production of goods, or improving environmental cooperation, among others (OECD 2007). Finally, the severity and binding force of the clauses included in the agreements and systems of governance and conflict resolution also play a significant role (Colyer 2012).

In this Chapter we use five criteria (countries involved, motivation, implementation, types of provisions and governance) to examine and compare five very divergent examples of regional FTAs [18]: the North American Free Trade Agreement (NAFTA), the Comprehensive Economic and Trade Agreement between Canada and the European Union (CETA), the Comprehensive and Progressive Trans-Pacific Partnership Agreement (CTPP), the Association of Southeast Asian Nations (ASEAN) and ultimately the trade agreement between the EU and MERCOSUR. The goal of such analysis will be to reply to the following research question, in relation to specific objective SO3 of this research: "*What have been the consequences of addressing environmental externalities in regional free trade agreements around the world?*". After analysing the aforementioned four criteria for each of the regional FTAs in the sample, the empirical reasons for the similarities and divergences between the, will be presented, as an attempt to explain the observed heterogeneity in the integration of environmental externalities in trade agreements.

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[18] We will justify this sample in the next section of the Chapter.

The first section of this Chapter explains in detail the five criteria that will be used in the regional FTAs sample. The following sections cover each of the analysed agreements: ASEAN (Section 5.3), NAFTA (Section 5.4), CPTPP (Section 5.5), CETA (Section 5.6) and the EU-MERCOSUR Agreement (Section 5.7). Section 5.8 concludes and addresses a series of factors that explain the differences between the agreements.

The choice of the proposed sample of agreements deserves an explanation before presenting the findings. The main decision factor for selecting the regional FTAs in the sample was to cover a wide and heterogeneous variety of cases: agreements between developing countries (ASEAN), developed (NAFTA, CETA) and with and without the participation of the EU (CETA and EU-MERCOSUR for the former; CPTPP for the latter). In each of them, the integration of environmental externalities has been addressed from a different standpoint, either as part of a wider integration process (ASEAN) or as a delicate point in the ratification process of the Agreement (EU-MERCOSUR), among others. We will see how, in each case, the four criteria used to analyse the sample played a decisive role in the final outcome. The environment is a difficult asset to protect, and its protection sometimes conflicts with other objectives of trade agreements. This article attempts to show such complexity and the different ways of dealing with it in a variety of cases.

5.2 Environment as a subject of negotiation in FTAs

The inclusion of environmental protection clauses in the regional FTAs is a rather recent phenomenon which has, however, been considered to be controversial by economic literature, as it departs from an interrogation on the *status quo* of trade negotiations: To what extent can we ensure that free trade is positive for the environment? Such question whose answer is anything but obvious, plays an essential role in the negotiating dynamics of the agreements and in particular in the final results of the integration of environmental externalities. The results of recent studies found in the economic literature are divided as regards a univocal impact of regional FTAs on natural ecosystems and environmental protection (Nemati, Hu and Reed 2019). However, since 1995 there has been a broader consensus on the ways in which regional FTAs, if not properly designed and implemented, can negatively impact natural ecosystems. There are three key effects in this respect that act in different directions and result in the observed complexity on the relationship between regional FTAs and environmental impacts the scale, composition and technical effects.

(Grossman and Krueger 1991; Nemati, Hu and Reed 2019). Such effects are explained as follows:

- *Scale effect.* The liberalisation of trade flows leads to an increase in economic activity between the States which are signatories to the Free Trade Treaties (TLC), and consequently carbon dioxide (CO2) emissions associated with the production processes will also increase.
- *Composition effect.* Where competition from the signatory countries of a regional FTA is based on a difference in environmental regulation, trade liberalisation may lead to risks to some extent, as each country will tend to specialise in areas where regulation is less stringent. For example, if two States (say A and B) have very different regulations in two sectors (agriculture and manufacturing), A with stricter legislation on agricultural production and B on manufacturing, once the regional FTA between A and B enters into force A's agricultural undertakings may be encouraged to relocate production to B where the legislative framework is more favourable. The same trend will occur with manufacturing companies in country B. The integration achieved after the signature of the regional FTA can facilitate such movements, known as carbon leakage.
- *Technical effect.* There may be technological transfers between signatories of a regional FTA, especially if the agreement includes countries with different levels of development. Less developed states can reduce CO2 intensity (understood as Units of CO2 emissions per unit of GDP) by adopting more advanced technologies that were not available before trade relations were liberalised.

As it can be noticed, while the scale and composition effect generate adverse environmental impacts, the technical effect acts in the opposite direction. These three effects are common to all negotiations of environmental protection provisions in regional FTAs, but their final impact depends on a set of criteria that we will reduce to five in this study. We will explain each of them below and then use them to examine the proposed FTAs sample. Others could have been used to make a more comprehensive analysis, but we decided to limit the number of criteria to the most important ones to facilitate comparisons:

- *Countries involved*. Nemati, Hu and Reed detect significant differences in the environmental impact of regional FTAs depending on the level of development of the countries involved (Nemati, Hu and Reed 2019). When regional FTAs are concluded between developed and developing countries, agreements tend to show negative environmental results, whereas in the case of agreements between developing countries the effect is not. One of the reasons for this is the composition effect of regional FTAs just mentioned: the reduction of trade barriers results in the relocation of more polluting industries, which aim to use more lax regulations to increase their emissions (Grossman and Krueger 1991).

- *Motivations*. States may agree on the adoption of environmental protection clauses in regional FTAs for various reasons (OECD 2007): contribute to sustainable development, avoid regulatory asymmetries or improve political cooperation. However, the provisions may also face reluctance among countries during negotiations (OECD 2007): the coherence with the multilateral trade agreements already in place, the fear of creating new barriers to trade due to environmental provisions, or simply the absence of a clear and ambitious political compromise in favour of them, are obstacles to their inclusion in regional FTAs and therefore hamper the integration of environmental externalities.

- *Implementation.* We can differentiate between two stages in the implementation of the environmental provisions in regional FTAs: the inclusion of environmental compromises in the text of the agreements and the application of these provisions. As regards the first point protection clauses may be present in an FTA in a variety of ways (Colyer 2012): as a section in the main agreement, as a secondary and separate agreement or in the form of general provisions in the preamble. The way in which compromises are placed in the text confuses their ultimate effectiveness (OECD 2007). In addition, the final implementation of the measures may be conditioned by the instruments provided for in the FTAs and its applicability. In the analysis of each agreement in the sample and for practical reasons, we will examine the implementation together with the types of provisions.

- *Types of provisions.* The environmental aspects can be reflected in regional FTAs in much diverging ways. To simplify the comparative analysis, we will adopt OECD terminology to classify provisions into four types (OECD 2007): narrow (where the environment is treated as a secondary issue to tariff reduction), general (clauses are designated to address the environmental problems that liberalisation may entail), components of a broader integration strategy (environmental standards are understood to be an area that needs to be harmonised to integrate the economies that are part of the agreement) and cooperation (environment is seen as a separate area from trade where ad hoc mechanisms to coordinate efforts between countries need to be established).
- *Governance systems and conflict resolution.* Lastly, consideration must also be given to the institutional mechanisms created to ensure an effective governance and the implementation of environmental provisions in regional FTAs.

5.3 ASEAN: environmental protection as a vehicle for economic integration

ASEAN is the least recent agreement of the sample proposed in this test, signed in Bangkok in 1967. However, it was only in the 1990s that its members began to follow a substantial liberalisation of their trade (Menon 2005). This effort led to the creation of AFTA, the ASEAN Free Trade Area, between 2003 and 2004 (ASEAN 2021a). In our case, we will refer to the ASEAN Comprehensive Agreement and not just AFTA, as it is a regional FTA that brings together the nations of Southeast Asia around cooperation mechanisms that went further than strictly economics and aimed at a relative integration of environmental externalities. As a matter of fact, ASEAN is considered as the most prosperous example of economic association between developing countries (ASEAN 2021b).

Countries involved. ASEAN includes Malaysia, Indonesia, Brunei, Vietnam, Cambodia, Laos, Myanmar, Singapore, Thailand and the Philippines. We could argue that in the long term this agreement will contribute to the overall reduction of CO2 emissions as there are no strong asymmetries between the signatory countries, and therefore no incentives for the reallocation of polluting industries (i.e. composition effect) (Nemati, Hu and Reed

2019). However, in the short term, regional FTAs between developing economies such as the ones of ASEAN can create incentives to adopt lower environmental standards to accelerate economic growth in spite of the parallel accumulation of environmental externalities. Such phenomenon is aggravated by the absence of less polluting alternative technologies in these countries (Yao et al. 2019). Nevertheless, in the case of ASEAN, the implementation of the agreement was guided by outstanding commitments between Member States on institutionalisation and compliance with environmental standards. The main subjects for such commitments are coastal preservation, sustainable urban development and stricter regulations on chemical substances, among others (ASEAN 2021b).

Underlying motivations. Contrary to the examples of NAFTA, CPTPP and CETA that will be presented further on this Chapter, the underlying motivations for ASEAN countries go beyond purely economic incentives and trade liberalisation. In a region characterised by an extreme diversity of political systems and religions, the priority of signatory countries was not only linked to the removal of trade barriers. On the contrary, the purpose of the agreement was, first, to establish a sustainable framework for cooperation to ensure the stability of the region and, second, to speak with a united voice in the global scene, in a historical context (i.e. from 1960 to 1970) of strong competition between the capitalist bloc and the USSR (Mahbubani and Severino 2014). In this sense, ASEAN has been used not only as a free trade agreement, but also as a vehicle for integration and cooperation between signatory states. Such broader angle of the agreement allowed for the partial integration of environmental externalities, in the form of the aforementioned environmental commitments.

Types of provisions. ASEAN is an example of environmental protection included in a broader integration effort. In this approach, the environment is not seen as a matter related (and secondary) to trade, but as an area with its own identity in an economic integration process. More specifically, environmental provisions are included in the ASEAN under the authority of the ASEAN Socio-Cultural Community, a body that designates and implements coordinated environmental and social justice strategies (ASEAN 2016a). A relevant example of such governance is the Strategic Plan on the Environment 2016-2025 (ASPEN), which serves to steer specific actions within a series of strategic priorities identified by ASPEN (ASEAN 2016b). The plan includes key areas such as climate change or the conservation of maritime resources (USAID 2021).

Governance. ASEAN environmental rules are applied in practice with a variety of working groups that monitor and coordinate the implementation of ASPEN by Member States in the key areas identified in the Plan (ASEAN 2017). Annual reports are published to monitor progress towards the policy objectives and actions outlined in the ASPEN (ASEAN 2017). All ASEAN parties are signatories to the Paris Agreement, and these progress reports include the correlation of ASEAN initiatives with the UN Agenda (ASEAN 2017). Other agreements have even been concluded through environmental cooperation, such as the setting of energy intensity reduction targets between the signatories (ASEAN 2020).

ASEAN is therefore an example of progressive environmental protection in regional FTAs. In 1967, the signatory countries did not consider environmental protection a priority. However, after prolonged approximation, they decided to go beyond the purely commercial framework and to commit themselves also to environmental protection, thereby integrating environmental externalities in their economic reasoning and decisions. Even if it is difficult to assess whether these commitments will be sufficient for signatory countries to comply with the Paris Agreement, the result of integrating such externalities is a much deeper, comprehensive integration process that has benefitted signatories.

5.4 NAFTA: Environmental protection clauses as an integral part of trade negotiations

Signed in 1992 between Canada, Mexico and the United States and effective two years later, NAFTA was the first regional FTA to contain environmental provisions in its original text (NAFTA 2021). In contrast to ASEAN, the environmental protection clauses and integration of environmental externalities were endorsed already at the time of the negotiations. NAFTA is also a key example of the relationship between environment and trade, as these provisions are not included as an exception, but as an integral part of the text of the agreement (OECD 2007). On 1st July 2020, NAFTA was replaced by the US-Mexico-Canada Agreement (USMCA). USMCA is considered a renegotiation of NAFTA initiated by the Trump administration to further protect US industries by reinforcing their intellectual property rights and avoiding social dumping to Mexico, among others (Chatzky, McBride and Sergie 2020).

As regards environmental protection, USMCA includes a specific chapter on the environment (Chapter 24) which includes for the first time an explicit list of environmental agreements signed by its members (Vaughan 2018). In addition, specific commitments on improving air pollution and reducing marine pollution have also been introduced (Malkawi and Kazmi 2020). The latter was the result of a negotiation process in which Canada pushed to include stricter environmental standards on the text of the agreement (Simeu 2020).

In this case, the integration of environmental externalities was the result of unilateral pressure of one of the signatories, as opposed to the ASEAN, where it was the result of collective action and agreement among members. In spite of this, USMCA is expected to deliver more ambitious environmental protection than NAFTA, even if the text of the Agreement still does not refer to the Paris Agreement and the acquis of the United Nations Convention on Climate Change (Vaughan 2018). Although USMCA is the most recent agreement, in this section we will focus on NAFTA, as the explanatory factors observed are very similar and the latter is the agreement that determined the level of environmental protection between the three signatories.

Countries involved. NAFTA is a trade agreement establishing a free trade area between Canada, the United States and Mexico. It is a comprehensive agreement, trying to address all the issues arising from free trade, including environmental protection. What is relevant for the comparative analysis of this agreement is the fact that NAFTA includes two advanced economies (the United States and Canada) and one developing country (Mexico). That is why, at the time of the negotiations, there were concerns about the environmental effects of removing trade barriers in Mexico vis-à-vis the United States and the Canada. Indeed, the relocation of polluting industries to a country with already high levels of CO2 emissions such as Mexico was a real risk at the time of the negotiations. This is a clear example of the composition effect previously explained (Grossman and Krueger 1991).

Underlying motivations. In the case of NAFTA and as opposed to other cases in the assessed sample, the motivations of the signatories were remarkably different since the beginning of the negotiations (Delaneau and du Luart 1996): the USA aimed at consolidating the Canadian and Mexican markets by reducing trade barriers; adopting a more regionalist than multilateral strategy to achieve this. Canada needed to reduce its export dependency from the USA market and get access to Mexico. The latter, with a smaller economic weight, had a persistent need to attract direct foreign investment to boost job creation and consolidate the national productive system. The integration of environmental externalities only emerged in the negotiations at a later stage following pressure from environmental interest groups (Grossman and Krueger 1991). Conversely, at the time of the USMCA negotiation, the Environment emerged from the outset as a major factor for negotiations from the Canadian side.

Types of provisions. Although the protection of environmental standards was not the priority objective of NAFTA signatory states, the compromises reached were remarkable. NAFTA contains legally binding environmental provisions and a specific additional cooperation package on the matter (OECD 2007). It is a general agreement within the meaning of the OECD definition (OECD 2007), because the provisions address specific environmental problems which that can be aggravated by the liberalisation of trade between the signatory States (i.e. through the scale effect previously explained).

Governance. The Supplementary Agreement provided in Articles 8 to 19 foresees the creation of a Tripartite Task Force known as “Commission for Environmental Cooperation” to implement the provisions of the NAFTA Environmental Agreement, as well as to serve as a forum for discussion between the three governments and to resolve any divergences that may result from it (CEC 2021), is a significant example of institutionalisation of environmental protection. In this case we see that in some agreements the integration of environmental externalities can imply institutional changes among signatories.

In short, NAFTA is a frontrunner agreement on the institutionalisation of environmental protection. This is a remarkable example of governance and enforcement of environmental provisions in the FTAs. The agreement also shows the importance of popular pressure in trade negotiations: lobbying from environmental groups was fundamental to increase the credibility of the environmental commitments of the agreement.

5.5 CPTPP: An encouraging approach

CPTPP is one of the most recent and ambitious regional FTAs. Signed on 8 March 2018 in Santiago de Chile, its primary aim is to consolidate trade and reduce trade barriers between more than ten countries on both sides of the Pacific. Members of the CPTPP include Australia, Brunei, Canada, Chile, Japan, Malaysia, Mexico, New Zealand, Peru, Singapore and Vietnam.

The CPTPP also has significant geopolitical implications that go beyond trade itself, as it is seen as the successor of the Trans-Pacific Partnership (TPP) fostered by the Obama administration to counterbalance the increasing power of China in the Pacific region (Stephens and Kucharski 2022). Since its creation in 2018, discussions around the inclusion of three additional signatories to the agreement have been undergoing: China, Taiwan and the United Kingdom. Concerning the latter, on 31 March 2023 the UK government announced a substantial conclusion of the negotiations, which had started two years earlier. The UK might therefore soon become a new member of the CPTPP (Kane 2023). The cases of China and Taiwan, however, present broader and more complex geopolitical consequences: while some CPTPP members, such as Japan, see the potential accession of Taiwan as an opportunity to promote the rules-based order of WTO as opposed to China, while others see in the latter an opportunity to get access to a vast market. In any case, such implications go beyond the scope of the inclusion of environmental externalities in the economic paradigm and therefore will not be discussed in this doctoral thesis.

Countries involved. Similarly, to NAFTA, CPTPP involves both developed countries (Australia, Canada, Singapore, etc.) and developing states (Brunei, Vietnam, Peru and others). However, in the CPTPP, the economic and social disparities between the countries involved in the negotiations are more pronounced. Moreover, during this process and after the 2016 presidential elections, the United States decided to withdraw from the agreement (initially called TPP, which included almost 40 % of the world economy) due to the risk of US jobs being relocated to member countries with lower wages (Sekine 2018; SCMP 2019).

Underlying motivations. The objective of the CPTPP is to establish almost total reductions in customs duties between signatories, but also to provide for specific measures for small and medium-sized enterprises and related matters such as environmental protection (Rana and Ji 2019). Besides, there were deeper and wider political motivations behind this agreement, the most significant one of them being the attempts by the United States (at the time of the Obama administration) to establish a compensatory power in the Pacific region to cope with the growth of the Chinese economy (SCMP 2019). Such wider scope of the underlying motivations of signatories makes the CPTPP closer to ASEAN in our sample.

Types of provisions. The withdrawal of the United States from the original TPP was, paradoxically, a chance for the signatory states as it levelled the playing field for participation and decision-making. The agreement was considered innovative in a significant number of areas, including environmental protection (Rana and Ji 2019). As far as the latter is concerned, the CPTPP includes a chapter on environmental protection, making this agreement a general regional FTA in the sense of the OECD definition (OECD 2007). The signatories pursued a twofold objective in the CPTPP environmental provisions: on the one hand, creating a set of binding environmental protection measures for the parties, that would fully integrate environmental externalities. On the other, avoiding that environmental protection would be reduced to a collateral factor to be treated in a secondary place within the negotiations (NZMFA 2021a; NZMFA 2021b). The latter objective is of major importance as it places the environment on an equal footing with the other CPTPP priorities.

Governance. The CPTPP is also innovative through the institutional means provided in the agreement. There are specific dispute resolution provisions and cooperation mechanisms between signatories, as well as references to international protection agreements. The most innovative provision is the possibility of using voluntary and flexible mechanisms to increase environmental protection among signatories by going beyond the agreed text in the CPTPP, provided that such enhanced protection does not create any rigidity to trade between signatory states.

In summary, the CPTPP is a unique example in the proposed sample. The withdrawal of the USA from the agreement marked a profound change in the dynamics of the negotiations. The agreement moved from a purely commercial project to a wider range of integration, in which the environment is located on an equal footing with trade. It is therefore a fundamental example of integration of environmental externalities in trade policy.

5.6 CETA: the European reference

CETA (the trade agreement between Canada and the European Union) was a controversial regional FTA from the start of the negotiations, precisely because of the concerns on its potentially negative environmental effects as well as the inclusion of arbitration as a dispute resolution system (European Public Service Union 2017). On this point, the Court of Justice of the EU has ruled on the integration of arbitration into the European legal system (FoodWatch 2021). Although the Court of Justice found the arbitration provisions of the agreement to be compatible with the EU Treaties, a legal review had to be carried out to ensure that these provisions did not infringe the *acquis Communautaire* (European Commission 2019b). Such concerns from different actors on the application of the agreement have led to a partial ratification of its text, with only 17 EU Member States having ratified it [19] while 10 missing on December 2022 (Rooke 2022).

Countries involved and underlying motivations. CETA reduces trade barriers between two of the world's most developed economies. Despite the varying results of empirical studies (Nemati, Hu and Reed 2019), a reasonable expectation to draw from the commercial integration of two highly developed and competitive economies would have been a reduction of future GHG emissions by increasing the efficiency of both economies towards less polluting solutions (the so-called technical effect) (Yao et al. 2019). However, the agreement found resistance in public opinion and the popular response through demonstrations was heard across the EU (European Public Service Union 2017). Therefore, questions arise on the content of CETA and why its provisions mobilised citizens against its ratification.

Types of provisions and governance. There are two major concerns about CETA's environmental provisions: First, there is a lack of a real compromise on environmental protection, as Chapter 22 of the Agreement does not contain legally binding commitments going beyond the Paris Agreement, in particular on climate change (Angot et al. 2017; European Commission 2021h). On the other hand, the ICS (Investment Court System) provided for in the agreement as an arbitrage instance is considered as a risk of intrusion of private interests of polluting industries into EU environmental regulations. Finally, the absence in the agreement of a ban on subsidies for polluting industries is also a cause for concern. CETA is, therefore, an example of unsuccessful and insufficient attempts of integration of environmental externalities in trade policy. When such attempts are exposed to public opinion, they can generate enough resistance from public opinion to jeopardise the ratification of the agreement – A circumstance that CETA shares with other regional FTA

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[19] The EU Member States that on December 2022 had ratified the CETA agreement are Austria, Croatia, Czechia, Denmark, Estonia, Finland, Germany, Latvia, Lithuania, Luxembourg, Malta, the Netherlands, Portugal, Romania, Slovakia, Spain, and Sweden (Rooke 2022).

in our sample: the EU-MERCOSUR agreement. This gives a measure on the importance of environmental considerations in trade agreements in which the EU takes part.

It would appear that a more demanding benchmark is used to examine CETA's provisions than those of the other agreements in the sample. However, the EU is a key player in environmental policy, characterised by ambitious measures against climate change (among others). Therefore, the standard of requirement must be as high when comparing the environmental provisions of the agreements between the EU and the rest of the world.

In conclusion, CETA remains a controversial example of a trade agreement with regards to environmental protection. The trade integration of two developed countries seems more complex than in the case of less developed countries (see the example of the CPTPP). EU environmental rules, especially after the adoption of the European Green Deal, put pressure on the European trade agenda to be consistent with the European agenda for the green transition. The arbitration system provided for in the text of the Agreement, common in Anglo-Saxon courts, is seen as a risk of relaxation of measures on the European side.

5.7 EU-MERCOSUR: the global dimension of basic environmental-protection

The comparative analysis of this Chapter concludes with a reference to the most recent debate on environmental protection in regional FTAs in the EU: the still ongoing debate taking place within the European institutions on the ratification and implementation of the regional FTA between the EU and MERCOSUR. This agreement is one of the most impactful of European trade policy. However, it took about 20 years to be negotiated. As in CETA, its clauses met with the dissatisfaction of European public opinion precisely because of the public perception of an insufficient integration of environmental externalities, resulting in a lack of ambition in the environmental commitments in the agreement. In the case of EU-MERCOSUR, such environmental concerns related to the risks of deforestation of the Amazon forest that a liberalisation of trade without sufficient environmental protection clauses could cause, particularly under the Bolsonaro administration (Marques da Silva 2023).

After lengthy negotiations, an agreement of principles to ensure ratification of the agreement was reached in June 2019 (European Parliament 2021b), with no further progress on the ratification of the agreement (European Parliament 2021c). After the 2019 agreement, European representatives were divided on a trade deal which was seen as a success of business goals for some and as an incompatibility with the external dimension of the European Green Deal for others (European Parliament 2021b). This latter line of thinking sees the EU as the reference in terms of sustainable economic growth in the world and questions whether the EU-MERCOSUR agreement is compatible with this idea (European Commission 2020c; European Commission 2020d). A relevant attempt to disentangle the matter took place at an informal ministerial meeting in Berlin in 2020 between the representatives of the two parties (European Commission 2020d). The result of the discussion was an informal compromise agreeing to apply the Agreement within the environmental limits set by the Paris Agreement. However, only three months later (March 2021), the Austrian Parliament decided to oppose the ratification of the agreement due to doubts as to its compatibility with the European Green Deal (Euractiv 2021). This is an example of tensions between the EU's trade and green agendas and on how, just like in CETA, an insufficient integration of environmental externalities can even compromise the success of a regional FTA. In any case, the arrival of the Lula administration on 1 January 2023 seems to have sparked new hopes for a ratification of the agreement still in 2023, as the position of Brazil towards the protection of the Amazon forest could have significantly changes compared to the previous administration (Marques da Silva 2023).

States involved and underlying motivations. MERCOSUR is South America's most important trading bloc. The economic weight of its four founding members (Argentina, Brazil, Paraguay and Uruguay) and the two states that have accessed it (Venezuela and Bolivia) make it the fifth largest economy in the world (Mercosur 2021). Trade gains for MERCOSUR states are significant, as the EU is one of the key regions for the trade flows of its members (Mendez-Parra et al. 2020). The motivation for MERCOSUR countries to negotiate such an agreement with the EU is rather based on economic grounds. On the European side, there would also be economic implications such as the protection of protected designations of origin or the opening up of public markets to European companies. However, in the case of the EU, the agreement is also seen as an opportunity to go beyond purely commercial relations and strengthen the EU's geopolitical presence in the US-American region (Gracia 2021), an aspect highlighted by the Portuguese Presidency of the Council of the EU (Céu 2021) and fundamental to the Swedish and Spanish Presidencies taking place in 2023, in particular to counterbalance the increasing Chinese influence in the region (Marques da Silva 2023).

Types of provisions and governance. The environmental clauses of the EU-MERCOSUR agreement are grouped in a specific chapter related to sustainable development. These provisions have been included in the principle that trade development cannot prevent the application of the commitments of the Paris Agreement. The parties also negotiated the inclusion of a special dispute resolution procedure as an enforcement mechanism (European Commission 2020c). This pattern has been strongly criticised for its lack of coercive force, as it does not provide any instruments applicable in the event of a dispute between the parties (Colli 2019).

The environmental challenge of the EU-MERCOSUR agreement is mainly linked to the differences and asymmetries between the production structures of the two parties. While the EU exports to MERCOSUR mainly highly manufactured products (medicines, aircraft, automotive components), MERCOSUR has specialised its exports in agri-food products such as soya or beef (Ghiotto and Echaide 2019). It is precisely the expansion of these products that arises most environmental concerns. Soya and beef are linked to high consumption of natural resources and increased deforestation (CAN Europe 2020): part of the forest fires in the Amazon were caused by human activity aimed at releasing land for the production of these products (Colli 2019).

During the negotiations, a Sustainability Impact Assessment was conducted by the London School of Economics to determine the environmental impact of the agreement. Using macroeconomic modelling techniques, the report concluded that the agreement would only have a negligible impact on CO2 emissions (Mendez-Parra et al. 2020). However, the economic models used to predict the environmental effects of the expansion of these products has been undermined by recent studies that claim an underestimation of its impact on the Amazon forest (Ghiotto and Echaide 2019).

As we have shown above, the EU-MERCOSUR agreement is a key example of environmental protection clauses in trade agreements. The explanation is clear: it can be the first major trade agreement that will not be ratified by the EU due to its environmental impacts. In addition, the EU faces a dilemma in the ratification of this agreement: if it continues to promote the agreement as it stands, its credibility as a change actor in climate diplomacy will be called into question. There will also be a high risk of contradicting the Green Deal's external action message. On the other hand, if the agreement is ultimately not ratified by the Member States, the EU risks losing its strength as a geopolitical player.

5.8 Chapter conclusions

The comparative study of the environmental protection clauses of NAFTA, CPTPP, ASEAN, CETA and EU-MERCOSUR reveals significant differences in the four proposed variables: States involved, motivations, types of provisions and governance. It was highlighted that the differences in the objectives of the agreements and the dynamics of the negotiations, as well as the degree up to which environmental externalities had been sufficiently integrated in trade policy decisions had a significant influence on the final outcome of the agreements. The heterogeneity of FTAs in environmental protection also depends on geopolitical factors: the individual positions of each state and their pre-willingness to cooperate, as well as the very history between parties, may condition the negotiations. In this sense, ASEAN illustrates environmental protection as a vehicle for integration between States that have long been part of the same agreement. We also found that the environmental aspect and a successful integration of environmental externalities become more important when agreements include developed countries with strict environmental regulations (especially the EU).

Significant differences in the timing of the agreements also emerged as a factor of divergence across FTAs. On the one hand, ASEAN addressed the environmental issue at a later stage of integration. This is rather logical: these negotiations took place in the 1960s, when there was no such significant pressure in the public debate on the environmental issue. Otherwise, in all the other agreements we examined, environmental protection was addressed from the outset of the negotiations, even with a significant divergence in each example. In the most recent cases, such as the EU-MERCOSUR agreement, the protection of the environment has become so important that it risks derailing the ratification of the regional FTA. It can be deducted that the integration of environmental externalities can no longer be ignored as a decisive factor to be assessed and implemented in the process of drafting and negotiating trade agreements. These findings provide the answers needed to the research question associated to research objective SO3: *"What have been the consequences of addressing environmental externalities in regional free trade agreements around the world?*.

Environmental protection, in conclusion, found its place in the FTAs of the proposed sample in significantly different ways, with varying degrees of success. Unfortunately, trade negotiations still seem far from recognising the key role of environmental protection in the FTAs. Climate change and the potentially negative impacts linked to the commercial liberalisation of certain products are not yet at the centre of the debate. As shown in the ratification of the EU-MERCOSUR agreement, the EU is facing a fundamental dilemma when negotiating strategic regional FTAs, which sometimes seem to contradict its climate policy agenda in the context of the European Green Deal.

A delicate equilibrium must be found by the European authorities in order to ensure coherence between different and potentially contradictory political agendas (trade and climate). The trade agenda must be effectively integrated into the European climate ambition. European public authorities must ensure that the level of ambition of environmental regulations within the EU is also respected in EU trade actions around the world. It is essential for the credibility of the European project that the EU continues to be the global reference for climate ambition, even if this leads to more complex relations. The response to this is a complete and credible integration of environmental externalities across all EU policies, in particular for trade in the global stage.

Chapter 6. Doctoral thesis conclusions

6.1. General conclusions

The current climate policies and societal mobilisation on climate topics will not bring sufficient decarbonisation efforts to avoid the most adverse effects of climate change. Such measures need a qualitative turning point; a change of approach towards the next generation of climate policies that will get economic systems on the right pathway towards full sustainability. The integration of environmental externalities is precisely the lacking element in the formulation of climate change policies and in the design and use of economic modelling tools, much needed to implement the necessary structural and systemic changes to avoid the most adverse effects of climate change in Europe and beyond. Furthermore, the integration of environmental externalities in economic modelling and climate policies represents an opportunity to change the current economic paradigm and put the environmental impacts of human activities at the centre of economic decision-making, in order to ensure that consumption and production patterns take place within planetary boundaries. The main conclusions of this doctoral thesis are summarised in the coming paragraphs, sorted by order of appearance along the text.

Chapter 2 presents the characteristics, functioning and results of an Integrated Assessment Model developed taking the DICE-R model by Nordhaus and Sztorc (2013) as a starting point and capable of quantifying and comparing the economic and environmental costs of adopting different electricity mixes in Spain by 2050. The model constitutes a novel application of Integrated Assessment Modelling to a reduced sectoral and geographical scope, as compared to the often global assessments of these models and opens a new field for research in IAMs (Galiano Bastarrica et al. 2023a). Additionally, the developed model incorporates the needed energy system integration changes needed to accommodate increasing shares of electricity generated by variable renewable energy sources (wind and solar) by introducing an explicit representation of the energy storage and interconnection needs, thereby tackling the entire scope of costs for renewable electricity deployment (Galiano Bastarrica et al. 2023a).

Furthermore, the insights produced by the model are of relevance to the implementation of the REPowerEU plan and constitute an applied example of a policy scenario towards achieving the European Green Deal climate neutrality objective (European

Commission 2019a; European Commission 2021b; European Commission 2022a). Finally, the developed model also quantifies significantly higher climate damage figures than the DICE-R model developed by Nordhaus and Sztorc (2013), showing remarkable levels of climate losses in scenarios with relatively modest temperature increases (i.e. between 1.8°C and 3.3°C) (Galiano Bastarrica 2023a). This is due to its reliance on a stricter representation of the impact that temperature has on economic systems done through the climate damage function from Weitzman (2010) combined with the hyperbolic discounting of utility as shown in Karp (2005) and van der Ploeg and Rezai (2019). The intentions behind this are twofold: on one side, they constitute an effort to bring the model as close as possible to the EU climate policy framework, which has the highest standards of environmental protection; secondly, it is an attempt to fully integrate environmental externalities stemming from economic growth in IAMs, which is the core focus of this doctoral thesis.

The findings provided by the model developed in Chapter 2 fulfil research objective SO1 and the research question *"What are the economic and environmental impacts of different electricity mixes in Spain by 2050?"* in three ways (Galiano Bastarrica et al. 2023a): First, by showing that maximum welfare is achieved in those scenarios where environmental externalities of electricity generation are integrated the most, i.e. in those electricity mixes that allow for the fastest and greatest penetration of renewable energies (wind and solar). Second, by illustrating that the economic losses caused by the accumulation of environmental externalities in the "Business as Usual" scenario (i.e. GHG emissions in the case of electricity generation) far outweigh the investment costs for the implementation of decarbonisation scenarios with high presence of renewable energies in the electricity mix. Sensitivity analyses with different projected costs of electricity sources (using Levelised Costs of Electricity (LCOEs) as measure) were conducted to ensure that the result on higher costs of the accumulation of environmental externalities compared to the renewable energies deployment cost would hold for different LCOEs, which was found to be the case. Lastly, the total investment costs of the preferred scenario of the model, "High RES", show that achieving a decarbonised electricity system in Spain by 2050 would cost 13 billion euros; a figure significantly below the 91 billion euros foreseen in the Spanish NECP (MITECO 2020b; Galiano Bastarrica et al. 2023a).

Chapter 3 tackles the issue of integrating environmental externalities in the notion of economic wealth, as measured by Gross Domestic Product. It does so by relying on the findings of an econometric model that applies, for the first time, the Stochastic Frontier Analysis methodology to a Ramsey-Cass-Koopmans endogenous growth model (Nordhaus and Yang 1996; Fankhauser and Tol 2005; Nordhaus 2007; Bauer et al. 2012; Diemer et al. 2019; Galiano Bastarrica 2023b). Such methodology enables to factor in inefficiency elements that are often not considered in the definition of production functions, thereby offering a suitable instrument to integrate environmental externalities in economic growth modelling. The developed model does precisely that by including an intertemporal specification of environmental externalities, which take the form of lagged values of material extraction and carbon dioxide emissions resulting from economic activities (Galiano Bastarrica 2023b). This was done by taking the modelling SFA framework done by Belotti et al. (2013), which could be easily applied in STATA, and adapting it to the different SFA estimations available in the economic literature, in particular those by Pitt and Lee (1981), Battese and Coelli (1988), Kumbhakar (1990), Battese and Coelli 1992, Battese and Coelli (1995 and Greene (2005). The rationale of such modelling exercise was to develop a model able to produce an estimation of the shadow prices of economic growth in terms of accumulation of environmental externalities in the EU27 (Bulckaen and Stampini 2009; Zhao et al. 2014), with the objective of developing a metric that could be used for EU policy-making (Galiano Bastarrica et al. 2023b).

The results produced by the model in Chapter 3 fulfil the research objective SO 2.1 and answer the research question *"What are the consequences of integrating environmental externalities in econometric estimations of Gross Domestic Product?"*. Such results, which were significant across all SFA estimations included in the study, allowed for the estimation of the coefficients of an environmentally-balanced GDP specification. Such specification, which factors in the intertemporal influence of cumulated environmental externalities, has subsequently been applied to propose a modification to the Cobb-Douglas production function of an economic growth modelling tool used by the European Commission (Havik et al. 2014). The results of this application are a benchmarking metric (calculated as the difference between environmentally-balanced and observed GDP), which provides a more accurate representation of the impacts of environmental dynamics on economic growth, which can be employed on the evaluation and design of climate change policies in the European Union.

Chapter 4 also has Europe (and the 27 Member States of the European Union in particular) as its geographical scope. This study, however, differs to all others as it relies on a different methodology other than economic modelling: policy analysis. This Chapter analyses the functioning of the European Union's Emission Trading Scheme (EU ETS) as a mechanism for the integration of environmental externalities through carbon pricing (Galiano Bastarrica 2022). In particular, it analyses the issue of the excessive abundance of emission allowances in the first three phases of the EU ETS, which has led to an excessively low price per allowance and a lack of deterrence of the overall mechanism.

Chapter 4 also shows that the EU ETS is, however, called to play a bigger role in the transition to climate neutrality in the coming three decades as its Phase 4 is aimed at making the EU ETS a more effective policy instrument that can further integrate environmental externalities. The main changes under such Phase are increasing the annual rate of removal of ETS allowances from the market, introducing new sectors under the EU ETS such as aviation and fuels for road transport and buildings and increasing the GHG reduction target by 2030 up to 62% compared to 2005 levels (European Commission 2022d; European Council 2023c). In addition, the Chapter also shows that the integration of environmental externalities through carbon pricing entails a particularly complex policy design, which in the case of Phase 4 of the EU ETS has entailed going beyond the initial scope of the instrument and adopting in parallel the Carbon Border Adjustment Mechanism to tackle the global dimension of carbon pricing in line with WTO rules (European Parliament 2021a; European Commission 2023b; European Council 2023b).

The policy analysis undertaken in Chapter 4 fulfils research objective SO 2.2 and answer the research question *"What is the role of the EU ETS in the transition to climate neutrality?"* by providing insights on the economic consequences of the upcoming review of the EU ETS. The findings of the policy analysis show that the role of the EU ETS in the transition to climate neutrality will be to act as a more stringent and broader in scope carbon-pricing mechanism which can exert a more prominent influence on financial incentives of economic operators towards decarbonisation and get closer to a full integration of the environmental externalities stemming from their activities (Galiano Bastarrica 2021). As shown in the Chapter, the impacts of such further integration of environmental externalities are a matter for careful study and calibration, as increased carbon pricing can entail significant risks of passing on the final cost of fundamental goods such as energy to consumers (Cornago 2022; Sandbag 2022; Sato et al. 2022).

Finally, Chapter 5 focuses on the integration of environmental externalities in free trade agreements. This Chapter has the broadest geographical scope (i.e. the global level) of all studies presented in this doctoral thesis. Its methodology also differs from all others as it relies on comparative analysis; a distinct methodology to economic modelling and policy analysis. A selected sample of free trade agreements covering all parts of the world is examined, in order to understand to which degree the integration of environmental externalities has been observed in global trade policies, in particular by comparing environmental protection clauses in their texts. Other elements of each agreement were added to the analysis to enrich its conclusions and better understand the observed divergences in the sample. Such additional factors included the degree of economic development and possible asymmetries of the countries involved, their motivations to negotiate free trade agreements, the nature of the agreed provisions and the governance mechanisms established to ensure adherence to such environmental protection clauses (Galiano Bastarrica 2021).

The findings of the comparative analysis done in Chapter 5 show that all these factors play a decisive influence in the degree of protection granted to environmental resources in the final text of the agreements, and that two other factors also seem to have fundamental influence: The first one is the timing in the negotiations, as the final degree of protection increases when environment is considered a fundamental topic since the beginning of the negotiations. The second one concerns the increasing political pressure in Europe towards further environmental protection, which decisively altered the course of the ratification process of the EU-MERCOSUR agreement (European Parliament 2021b; Galiano Bastarrica 2021; Marques da Silva 2023). Overall, the comparative analysis performed in Chapter 5 fulfils research objective SO3 and the research question "*What have been the consequences of addressing environmental externalities in regional free trade agreements around the world?*", as the Chapter explains the dynamics and tension between trade liberalisation and environmental protection, showing the additional complexity of translating the problem of the integration of environmental externalities in economic systems and climate policies to the global level.

In conclusion, the findings of each individual chapter of this doctoral thesis contribute to answering the main research question *"How can the interactions between Economy and Nature be integrated in economic modelling and policies?"* from three different angles: economic modelling (both through newly-developed applications of Integrated Assessment Modelling and Stochastic Frontier Analysis as done in Chapters 2 and 3), policy analysis (Chapter 4) and comparative analysis (Chapter 5). The different results achieved by applying these methodologies to the same research problem show the complexity of the integration of environmental externalities in economic systems and climate policies. A comparison between all Chapters indicates that narrowing the geographical and sectoral scope when operating such integration, as done in Chapter 2 with just one country and one sector helps or in Chapter 3 with a specific modelling framework in the case of economic growth can improve the usability, granularity and policy relevance of the results, which can be applied in real life in a more straightforward way than in other cases.

More general applications of the integration of environmental externalities as done in all other chapters are however equally relevant: redefining the notion of wealth and economic progress towards one compatible with planetary boundaries (as done in Chapter 3), reflecting about the role of more stringent carbon pricing instruments in climate policy (Chapter 4) and taking such reflections to the global stage and analyse the lessons learnt in the inclusion of environmental protection clauses in free trade agreements (Chapter 5). The four studies included in this doctoral thesis provide a combined framework to tackle the integration of environmental externalities in the economic paradigm. They show that in order to define the climate change policies of tomorrow, a holistic approach, able to incorporate all dimensions of such integration (i.e. in the understanding of economic growth, in decarbonisation modelling, in policy analysis and in trade agreements at the global level, as shown in the different Chapters) is needed. Only if such policies integrate fully environmental externalities and are designed with sufficient ambition, they will be able to overcome the worst effects of climate change in Europe and beyond. Economics, in any case, will play a fundamental role in such task.

6.2. Future lines of research

The conclusions exposed in the previous section bring a clear message: the integration of environmental externalities in economic systems and climate policies can provide tangible benefits in implementing the needed structural changes to avoid the most severe impacts of climate change. Such change of paradigm entails reconsidering the way in which modelling tools frame environmental dynamics and their interactions with economic growth, as well as the way in which climate policies themselves are designed: which sectors do they impact on, which negotiation process is observed to arrive to agreed provisions or the specific instruments used to meet their goals (i.e. carbon pricing instruments or others). These considerations, developed in detail in this doctoral thesis, can provide fertile land for new research activities in the field of climate change economics.

In particular, some suggestions for further research within climate change economics on the integration of environmental externalities in economic systems and climate policies would be the following:

1. Integration of environmental externalities in spatial planning of renewable energy plants, in particular biodiversity preservation and landscape conservation.
2. Further developing regionalised Integrated Assessment Models and explore applications on more than one sector (i.e. electricity generation and transport) or by considering a further sample of energy sources than the ones used in Chapter 2.
3. Develop regionalised Integrated Assessment Models that incorporate geographically-specific climate risks in the definition of climate damage functions. If, for instance, the area for which the IAM is designed is particularly vulnerable to droughts, the climate damage functions used could be sensible to such particularity. This would make the predictions of the model more accurate to the reality of the territory.
4. Further explore applications of the environmentally-balanced GDP series presented in Chapter 3 and the review of the notion of economic progress. Geographical analyses for Europe could be done, observing how the

benchmark with observed GDP has evolved over time for different Member States of the European Union.

5. Development and application of a regionalised Integrated Assessment Model to understand the impacts of different configurations of the EU Emission Trading Scheme by 2050 in Europe or in a particular Member State.
6. Broaden the scope of the integration of environmental externalities to also include social externalities such as income inequalities. Such an approach would have significant value in the definition of economic models on trade policy observing the principle of due diligence.

Developing applied studies in the proposed lines above would further contribute to further bringing Nature to the economic paradigm – an endeavour in which all of us must succeed to grant the future generations similar levels of welfare to the ones we have experienced. Climate change policies and economics are, at the end of the day, a matter of intergenerational justice.

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Merits supporting the doctoral thesis

This section outlines the merits supporting this doctoral thesis, including the published papers associated to it and the complementary research activities completed throughout the PhD programme at the University of Seville until present time.

As a result of the research work undertaken in this doctoral thesis, focused on the integration of negative environmental externalities in economic systems, four papers have been published in peer-reviewed publications and journals in three different languages (English, French and Spanish). Such linguistic diversity in the publications presented in this doctoral thesis is presented as an additional strength of the research work. Two of these papers have been published in high-ranking peer-reviewed academic journals with the PhD candidate Luis Antonio Galiano Bastarrica appearing as main author, which are the following: (in both cases using the open access publishing option):

- ❖ *Energy Policy* (ISSN 0301-4215) is an international peer-reviewed journal published by ScienceDirect focused on addressing the policy implications of energy supply and use from their economic, social, planning and environmental aspects. The journal publishes a broad spectrum of academic papers that explicitly address policy issues involving energy supply or use. It is indexed, among others, in Web of Sciences and belongs to the *Journal Citation Reports (JCR)* catalogue with a SJR of 2.29 in 2022 overall increasing in the last five years and an Impact Score of 7.37. It has two publishing categories: “Energy (miscellaneous)” and “Management, Monitoring, Policy and Law”, ranking in the first quartile (Q1) in both of them. The journal allows and supports open access publications; an option that was taken for the publication of the paper “**An Integrated Assessment model for comparing electricity decarbonisation scenarios: the case for Spain**”.
- ❖ *Environment Systems and Decisions* (formerly The Environmentalist, ISSN 2194-5411) is an international peer-reviewed journal published by Springer and focused on the interrelations between economic, environmental, social and technological systems. The journal publishes technical articles, editorials and review articles with the aim of advancing theory, methodology and

applications to better understand such interconnections from an interdisciplinary perspective. It is indexed, among others, in the *SCOPUS* catalogue with a SJR of 0.82 in 2022 overall increasing in the last five years and an Impact Score of 3.96 in 2021. It only has one publishing category, "Environmental Science (miscellaneous)", in which it ranks in the first quartile (Q1). The journal allows and supports open access publications; an option that was taken for the publication of the paper "**Environmental adjustment of the EU27 GDP: an econometric quantitative model**".

Additionally, also as a result of the research work underpinning this doctoral thesis, the PhD candidate Luis Antonio Galiano Bastarrica has published two papers in which he appears as the only author, published in the following peer-reviewed publications:

- The *Institut d'Estudis Financiers* (IEF) is a private foundation set up by the main financial institutions in Spain and supported by the Catalan Government with the objective of disseminating knowledge to financial actors. It publishes technical articles and academic papers on a variety of economic topics of relevance to financial actors in English, Spanish and Catalan. The publication of the paper "**El papel del Sistema Europeo de Derechos de Emisión en la transición a la neutralidad climática**" took place as a request from the IEF itself, that reached out to Luis Antonio Galiano Bastarrica through the European University Institute of Florence (Italy). The proposal consisted of producing a research piece on the economic relevance and functioning of the European Emissions Trading Scheme as well as its role on the path to European climate neutrality. The publication was done in Spanish language.

- *Duodecim Astra* is an international peer-reviewed, interdisciplinary student-run journal of European studies based at the College of Europe in Bruges (Belgium). It is a novel journal, established in 2020, and therefore not yet indexed in journal catalogues. The publication of the paper "**La Protection Environnementale dans les Accords Régionaux de Libre-Échange: une étude comparée**" took place in the first-ever issue of the journal, focused on the Future of Europe. The publication was done in French language.

The list below summarises the main research activities complementary to the development and writing of the published papers. These activities have been carried out during the development of the PhD thesis to strengthen the research work and are presented as merits supporting it.

The list is the following (activities are presented in chronological order, from more to less recent):

- Enrolment and participation in the course “Python for Beginners - Learn Programming from scratch” organised by Udemy. The course, held in online format, included detailed lessons to get acquainted with the programming language Python and supporting software (Pycharm). The goal in pursuing this course was to obtain new skills to be used in the PhD thesis modelling activities or in future research work, in particular for more detailed modelling techniques on the decarbonisation of the energy system and other sectors. The course was followed during March 2023, with the date of completion on March 26th, 2023. The total length of the online course was 2.5 hours. Additional time was needed to process the knowledge and learn to use the associated software.

- Enrolment and participation in the course “Mastering Energy and Power System Optimization in GAMS” organised by Udemy. The course, held in online format, included detailed and applied lessons to get acquainted with the programming language GAMS and supporting software (GAMS IDE, GAMS Studio) and apply this to the design and application of economic modelling of decarbonisation of energy systems. The goal in pursuing this course was to obtain new skills to be used in the PhD thesis modelling activities or in future research work, in particular for more detailed modelling techniques on the decarbonisation of the energy system. The course was followed during March and April 2023, with the date of completion on April 15th, 2023. The total length of the online course was 5.5 hours. Additional time was needed to process the knowledge and learn to use the associated software.

- Participation and presentation in “Back to University” initiative as expert on EU climate change policies, organised by the European Documentation Centre in the University of Seville on March 23rd, 2023.

- Participation and presentation as expert on Climate Change Economics in the "Young Europeans Volunteering for Europe" event with 38 youth ambassadors coming from 7 European countries, organised by the Centre for European Volunteering in Brussels on March 19th, 2023.

- Presentation of the communication "*Integrated Assessment tool for the decarbonisation of energy supply: an application to the Spanish electricity market*" in the 6th International Conference on Management, Economics and Finance (ICMEF), held from March 10th to March 12th in Prague, Czech Republic.

- Presentation of the communication "*Modelo de Análisis Integrado para comparación de escenarios de descarbonización del Sistema eléctrico español*" in XXXV ASEPELT International Congress, held from June 29th to July 2nd 2022 in Madrid, Spain.

- Presentation of the communication "*An Integrated Assessment Model for Comparing Electricity Decarbonisation Scenarios: The case for Spain*" in VI Workshop FCEYE, held from June 23rd to June 24th 2022 in Seville, Spain.

- Presentation of final results of the underlying model and manuscript of the paper "*An Integrated Assessment model for comparing electricity decarbonisation scenarios: the case for Spain*" in a research seminar organised by Research Group in Applied Economics of the Economics Faculty of the University of Seville, held on March 11th 2022 in Seville, Spain.

- Presentation of preliminary results of the model underpinning the paper "*An Integrated Assessment model for comparing electricity decarbonisation scenarios: the case for Spain*" in a research seminar organised by Research Group in Applied Economics of the Economics Faculty of the University of Seville, held on December 15th 2022 in Seville, Spain.

- Presentation of the communication "*Re-Defining Sustainable Growth Pathways in the European Union: A Stochastic Frontier Analysis Estimation*" in IV AJICEDE Congress, held from December 16th to December 17th 2021 in Madrid, Spain.

- Participation in the European Night of Researchers 2021 with a video recorded in the studios of the University of Seville with other members of the Research Group in

Applied Economics. My intervention used insights from the paper "*Environmental adjustment of the EU27 GDP: An econometric quantitative model*" to raise awareness of the importance of adopting circular economy practices in daily life. The activity took place from June to July in 2021.

- Participation in the first edition of the contest "Tu Tesis en un Hilo", organised by CRUE, in which candidates needed to summarise the content of their PhD thesis in a sequence of tweets published in the social media platform Twitter. I participated with a Twitter thread explaining the content of my research in environmental externalities and climate change. The activity took place in April 2021.

- Presentation of the communication "*Re-Thinking Gross Domestic Product: A Quantification of Environmental Externalities Using Stochastic Frontier Analysis*" in V Workshop FCEYE, held from June 22nd to June 23rd 2021 in Seville, Spain.

- Presentation of the communication "*Re-Thinking GDP: A Quantification of Environmental Externalities Using Stochastic Frontier Analysis*" in the XXIII Applied Economics Meeting, a research congress held from June 3rd to June 4th 2021 in fully online format.

- Enrolment and participation in the course "Introduction to R programming" organised by the Centre for Andalusian Studies of the Andalusian Government. The course, held in online format, included detailed lessons to get acquainted with the programming language R and it included the realisation of a written assignment to obtain a certificate. The goal in pursuing this course was to obtain new skills to be used in the PhD thesis modelling activities or in future research work. The activity took place from April 14th to April 28th 2021.

Published papers

In the following pages the original text and publication layout of the published papers is presented, from more to less recent. These papers are the following:

1. "**An Integrated Assessment model for comparing electricity decarbonisation scenarios: the case for Spain**", published in 2023 in *Energy Policy* (Galiano Bastarrica et al. 2023a)

2. "**Environmental adjustment of the EU27 GDP: an econometric quantitative model**", published in 2023 in *Environment Systems and Decisions* (Galiano Bastarrica et al. 2023b)

3. "**El papel del Sistema Europeo de Derechos de Emisión en la transición a la neutralidad climática**", published in 2022 in *Institut d'Estudis Financiers* (Galiano Bastarrica 2022)

4. "**La Protection Environnementale dans les Accords Régionaux de Libre-Échange: une étude comparée**", published in 2021 in *Duodecim Astra*. (Galiano Bastarrica 2021)

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An Integrated Assessment Model for comparing electricity decarbonisation scenarios: The case for Spain

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A B S T R A C T

The decarbonisation of electricity supply poses a major milestone in the mitigation of climate change. Integrated Assessment Models (IAMs) provide a relevant instrument for the quantification and comparison of the economic and environmental impacts of various electricity decarbonisation scenarios, despite having rarely been applied to a national context. In this paper, an IAM able to calculate such impacts on the electricity sector in Spain is presented. Developed using the latest IAM modelling literature, the proposed model is able to estimate changes in temperature, climate-induced economic losses, and investment needs for climate mitigation corresponding to a range of electricity decarbonisation scenarios on a time horizon to 2050. The findings show that scenarios that undertake deeper and earlier cuts in CO_2 emissions from electricity generation would achieve better welfare results, and that further reliance on fossil fuels would imply higher costs than the investment needed for renewable energy deployment in Spain. The findings constitute an insight towards the formulation of policies that address the decarbonisation of the Spanish electricity supply.

1. Introduction

The continuous increase in global anthropogenic Greenhouse Gas (GHG) emissions since the Industrial Revolution is setting climate change closer to a tipping point, beyond which the intensity and frequency of extreme weather events and sea-level rises will remarkably increase (IPCC, 2021). In Europe, such events will occur in the form of more frequent pluvial rain and floods in the North and extreme droughts and forest fires in the South and will cause disruptive economic losses if no significative policies are put in place sufficiently promptly (EEA, 2022; Feyen et al., 2020). Such negative impacts on the European Union (EU) Gross Domestic Product (GDP) can reach up to 4.7% by 2050 under a high emissions scenario (Galiano Bastarrica et al., 2023; Spano et al., 2021; van Vuuren et al., 2017). For the case of Spain, losses of similar magnitude related to climate change and extreme weather events are expected, especially in the form of heatwaves, desertification, and floods in fertile land (MITECO, 2020a; Moreno et al., 2005).

In order to tackle these prospects, climate policies have focused their efforts in the last two decades on setting mid- and long-term targets and climate-neutrality goals, with the Paris Agreement standing as one of the key milestones in setting the global objective of maintaining the projected increase of global temperature well below 2 °C and ideally below 1.5 °C (United Nations, 2015). Today, climate change policies seem to be entering a new field and most countries worldwide have adopted decarbonisation plans to become climate neutral, in most cases by 2050 (with the exception of China, by 2060) albeit with varying levels of commitment (Hale et al., 2021). The design of cost-effective and sufficiently ambitious mitigation pathways for the most emitting sectors has therefore become crucial.

With the power generation sector being the largest contributor to GHG emissions globally, whereby it accounts for approximatively 34% of global GHG emissions (IPCC, 2022), its decarbonisation constitutes the key to the success of the climate transition in Europe and beyond, since other regions may well follow suit to what is carried out by the European Union. In Spain, electricity accounted for 15% of total CO_2 emissions in 2019 (INE, 2022) and it is projected to become the main energy carrier by 2040 driven by the electrification of key end users, such as transport and industry (MITECO, 2020a). It is also portrayed as the sector where renewables bear maximum potential (MITECO, 2020b), thereby making it the single most important sector to

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decarbonise in the Spanish economy.

Europe has strongly increased the ambition level towards decarbonisation with the adoption of the European Green Deal and related legislation since 2019, and aims towards climate neutrality by 2050 (European Commission, 2019). The European Climate Law made such objective binding for the EU in 2021 (European Commission, 2021a). Additionally, the recently adopted "Fit for 55" package strives to deliver on an increased 2030 target of reduction of 55% GHG emissions compared to 1990 levels with a set of specific policy proposals that includes doubling the capacity of renewable energy sources (RES) within a decade from 2021 and increasing the presence of electricity as the main energy carrier before 2050 (European Commission, 2021b). In Spain, parallel objectives have been laid down in Spain's Long-Term Decarbonisation Strategy (MITECO, 2020a) and the Spanish National Energy and Climate Plan (MITECO, 2020b).

Additionally, the recent invasion of Ukraine by Russian forces and the ongoing war have increased the need for speed and depth in transforming the European Union energy system and has highlighted the considerable energy dependence of the continent towards non-EU energy providers. In particular, the perturbations in energy markets stemming from the conflict have resulted in an unprecedented energy crisis in Europe characterised by increasing energy prices and concerns over energy shortages to match domestic heating needs (Conti and Kneebone, 2022). Some of the very short-term measures planned by several EU Member States [1] include temporary re-starts of formerly closed coal power plants to cover gas supply shortages amounting to a 7% increase compared to 2021 levels according to the International Energy Agency prospects (IEA, 2022a, Sgaravatti et al., 2022). The impact of such short term increased use of coal is however unlikely to have significant long term impacts on GHG emissions in the EU power sector by 2050, as the trend in coal has been matched by similar increases in wind and solar on a year to year basis (Sgaravatti et al., 2022).

On the other hand, the European Commission aims to address the ongoing energy crisis through the recent REPowerEU plan. Proposed in May 2022 and currently reaching the final stages of interinstitutional negotiations, the plan aims at transforming the EU energy system and ending the dependence of the EU on Russian fossil fuels by 2027 through the combination of three main pillars: enhancing energy efficiency policies to reduce energy needs, accelerate the deployment of renewable energies (i.e. to replace up to 21 billion cubic meters per year of gas by wind and solar) and diversifying gas supplies needed in the short and mid-term (European Council, 2023; European Commission, 2022a; Conti and Kneebone, 2022; Sgaravatti et al., 2022). In this context, an accelerated deployment of renewable energy is in order not only needed for decarbonisation purposes, but also as a strategic investment to reduce Europe's energy dependence (European Commission, 2022a).

Regardless of the exact trajectory that GHG emissions from the EU power sector will follow in the coming decades, the implementation of decarbonisation plans entails complex impacts, positive and negative, that need to be measured and evaluated carefully. Modelling tools such as Integrated Assessment Models (IAMs) have a crucial role to play in supplying policymakers with an informed choice of optimal pathways for the deployment of such ambitions, by providing estimations on the economic costs of changes in GHG emissions under a range of scenarios (Capellán-Pérez et al., 2014; Estrada et al., 2019).

There are several advantages that can be drawn from the use of an IAM-based approach for the particular case of modelling the impacts of decarbonising electricity supply in Spain. First, IAMs constitute a widely used modelling approach for the quantification of interlinked impacts of different paths of action on climate change policies (Pietzcker et al., 2017). Moreover, IAMs are used by authoritative sources such as the Intergovernmental Panel on Climate Change (IPCC, 2022; IPCC, 2021) in their landmark reports and constitute an active field of academic research granted with increasing relevance and recognition in the literature (Weyant, 2017; van Beek et al., 2020). Thirdly, IAMs enable the integration of different disciplines (such as climate science and economics) and, even if their complexity varies greatly from one application to another, they can be calibrated more precisely than other numerical-based modelling tools that require the optimisation of complex interconnected systems such as global power system models (van Beek et al., 2020). Finally, within IAMs a calibration of the DICE-R model by Nordhaus and Sztorc (2013) was chosen as the basis to develop the presented model because of its relevance for its application to climate regional modelling (Ortiz et al., 2011) and from the fact that other types of IAMs (known as process-based) are mostly designed for global modelling and rely on assumptions that are not needed when modelling decarbonisation pathways for the case of one country (van Beek et al., 2020).

An adaptation and re-calibration of the DICE-R model seems therefore to be pertinent to the case at hand in this paper, aimed at replying to a simple, yet challenging research question: Can IAMs be applied to the specific case of one sector in the context of one EU Member State, such as the electricity sector in Spain? And in such case, what are the adjustments needed and the insights of relevance to policymaking that can be produced with it?

The IAM presented in this paper aims to calculate the environmental and economic costs of various scenarios of electricity decarbonisation in Spain in order to define a socially optimal renewable energy policy for electricity (Mathiesen et al., 2011). It does so by adapting the DICE-R model by Nordhaus and Sztorc (2013) to the particular case of electricity generation in one single country. In particular, the presented IAM uses as exogeneous input data the Lifecycle Costs of Energy (LCOE) for different energy sources as well as scenario projections on different energy mixes elaborated by the European Commission and the International Energy Agency to translate such scenarios to the particular case of the electricity generation sector in Spain and thus produce endogenous projections on the economic and environmental impacts of different electricity mixes by 2050.

Several contributions of the proposed approach can be outlined: first, economic modelling of climate change has seldom been utilised for the case of Spain in the literature, with very few and specific applications such as the water-energy nexus (Khan et al., 2016), land use change (Pulido-Velazquez et al., 2014), and the electricity market (Espinosa and Pizarro-Irizar, 2018; García-Gusano and Iribarren, 2018) whereby no IAMs have been employed. This paper, however, is a direct application of IAMs to electricity generation. Second, national applications of IAMs remain largely unexplored and with few adjustments and calibrations, as presented in this paper, IAMs can be adapted to produce important results for policymaking also at national level, relevant for the calibration of decarbonisation pathways. Finally, the proposed model is able to estimate economic costs and investment needed for the different scenarios: information that is needed at this stage by Spanish authorities to implement the plans outlined in the Long-Term Decarbonisation Strategy (MITECO, 2020a) and the National Energy and Climate Plan (MITECO, 2020b) as well as to tackle the ongoing energy crisis stemming from the invasion of Ukraine by Russian forces. The paper is structured as follows. Section 2 provides the theoretical framework for IAMs. Section 3 explains the characteristics and different modules of the model. The description of the data is given in Section 4. Section 5 presents and discusses the results and, finally, Section 6 draws the conclusions.

2. Integrated Assessment Models: benefits and limitations

The origin of IAMs is often traced to the Club of Rome and their "Limits to Growth" landmark publication in 1970, in which the assessment of a scenario called "World3" modelled climate change for the first

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[1] Austria, Denmark, France, Germany, Greece, Hungary, Italy, the Netherlands and Romania have planned measures in this direction (Sgaravatti et al., 2022).

time on a global scale and assessed the challenge of maintaining economic growth within a sustainable use of resources (Meadows and Randers, 2013; van Beek et al., 2020).

Integrated Assessment Models model the economic impacts of climate change by linking two sets of equations: a climate module representing the dynamics of CO_2 accumulation and their relative impacts on global temperature; and an economic section affected by the changes in temperature and abatement costs (Ortiz et al., 2011; Zhao et al., 2020). In IAMs, two concepts are key: the definition of damage functions and the intertemporal discount rate. Damage functions translate a change in global temperature to GDP loss by relying on a set of climate sensitivity parameters that connect the accumulation of CO_2 in the atmosphere with changes in average global temperature (Bretschger and Pattakou, 2019). A wide variety of approaches and functional forms have been explored in the relevant literature. Indeed, damage functions remain one of the most criticised elements of IAMs, the main criticism being that their formulation vastly affects the final estimations of the model and that approaches within the literature differ widely from each other (Diaz and Moore, 2017). The literature points out several caveats of damage functions. The use of quadratic forms fails to provide a realistic representation of climate dynamics, since tipping points of large economic losses appear too late in the temperature increase (Wouter Botzen & van den Bergh, 2012; Bretschger and Pattakou, 2019). Moreover, a careful assessment of impacts per sector has to be considered when estimating damage (Neumann et al., 2020), as well as adaptation policies (Estrada et al., 2019) or extreme weather events (Lempert et al., 2006; Zhang et al., 2021). However, in spite of these critiques, and as shown in Neumann et al. (2020), even if the feedback mechanisms taking place between economies and climate are simplified, damage functions continue to be the most straightforward and widely used way to calculate environmental impacts in IAMs.

Another challenge of IAMs lies in how to implement intertemporal discounting in the model specification (Weyant, 2017). In IAMs, various scenarios (often related to different mitigation pathways, plus a baseline that represents business as usual) are portrayed and placed in the decision-making process of a public agent. For the model to be useful for policymaking, a prioritisation logic between the welfare of the current generation and that of future generations needs to be implemented. This is carried out in IAMs by using an intertemporal social utility discount rate, which is used by the public agent to prioritise and compare scenarios from a social welfare standpoint (Espagne et al., 2018; Karp, 2005). Given the length of the time horizons involved in these models (often until 2100), a slight change in the discount rate can yield quite different results on the final estimates, which makes IAMs highly dependent on the chosen rate (Pindyck, 2013; Espagne et al., 2018). On this topic, and as shown in Weyant (2017) and Drupp et al. (2020), there is a dispute between Stern on one hand, who considers that any positive value of the discount rate in IAMs is purely unethical since the welfare of the current generation is valued more highly than future generations (Stern, 2007), and Nordhaus and Weitzman on the other hand, who propose a higher discount rate that sets climate investments in stronger competition with other investments, thereby allowing for a slower, market-driven transition (Nordhaus, 2007; Wouter Botzen & van den Bergh, 2012). Nevertheless, regardless of the final value chosen by the modeller, the discount rate decisively influences the ability of the remaining carbon budget to stay below specific temperature thresholds, such as 2 °C and 1.5 °C (Emmerling et al., 2019) and involves debates that go beyond purely economic decisions, such as to how to evaluate the welfare of future generations when precisely it is their future that seems increasingly unclear.

3. The model

The main features of the model are presented in the following subsections and in Graph 1 below. The model is composed of four modules: economy, climate, electricity, and social planner. The economic module includes a standard Cobb-Douglas production function in which productivity and capital accumulation are affected by climate change damage from the climate module that are estimated using the Weitzman damage function (Weitzman, 2010). Economic growth follows a Ramsey-Cass-Koopmans model, in which steady-state capital and consumption per capita are calculated as key variables for long-term forecasts as in the original specification of the DICE model (Nordhaus and Yang, 1996; Fankhauser and Tol, 2005; Nordhaus, 2007; Bauer et al., 2012; Diemer et al., 2019). The electricity module provides the mitigation pathways of the model, which are based on exogeneous projections under different scenarios designed by the European Commission and International Energy Agency (European Commission, 2011; IEA, 2021). The social planner module takes in the steady-state capital and consumption per capita to calculate total welfare under the various scenarios as a key factor in the choice of one decarbonisation pathway over the other. A visual representation of the interactions between modules is provided in Graph 1.

Several further elements related to the functioning and scope of the presented model can be outlined before presenting its modules and functioning in detail. Firstly, while the model focuses on one particular sector in one EU Member State (i.e. the electricity generation sector in Spain), it incorporates projections from different models that include cross-effects going much beyond the electricity generation sector itself, such as changes in transport, energy efficiency policies, energy system interconnections or innovation in different low-carbon energy sources resulting from the adoption of different energy mixes .[2] In addition, the changes foreseen in the electricity generation sector in Spain in the exogeneous data used in the model is in line with the Spanish National Energy and Climate Plan, which is defined in coherence with European policies in the field of energy. Thirdly, even if the presented model produces results at a relatively high level of integration (i.e. at national level), the exogeneous projections used for the baseline values of electricity uses in Spain coming from the EU Reference Scenario 2020 build on the PRIMES model, which is a bottom-up Partial Equilibrium Model that draws on microeconomic data to produce disaggregated results per sector and EU Member State. The modelling approach therefore consists of integrating the electricity generation in Spain with other policies and sectors by building on detailed bottom-up modelling results to assess the impacts of different electricity mixes by 2050 in the most accurately possible manner.

3.1. Economic module

The first part of the model is its economic module, composed by a Cobb-Douglas production function with constant returns to scale. As in the original DICE model (Fankhauser and Tol, 2005; Nordhaus, 2007; Ortiz et al., 2011), we consider a time horizon running from 2010 to 2050. The production function is sensitive to climate change damage (Nordhaus, 2007) and is expressed in terms of output per worker:

$$y_t = D_t A_t k_t^{\alpha} \tag{1}$$

where $D_t < 1$ is the value from the damage function from Weitzman (2010) at each point in time (see subsection 3.2); A_t is Hicks-neutral technical change or total factor productivity, and k_t^{α} is capital stock per worker. In our specification, α reflects the findings of Macías and Matilla-García (2015) and Bentolila and Saint-Paul (2003), with an income share of capital of approximately 40% for OECD countries .[3]

The model follows the usual assumptions in IAMs on all variables

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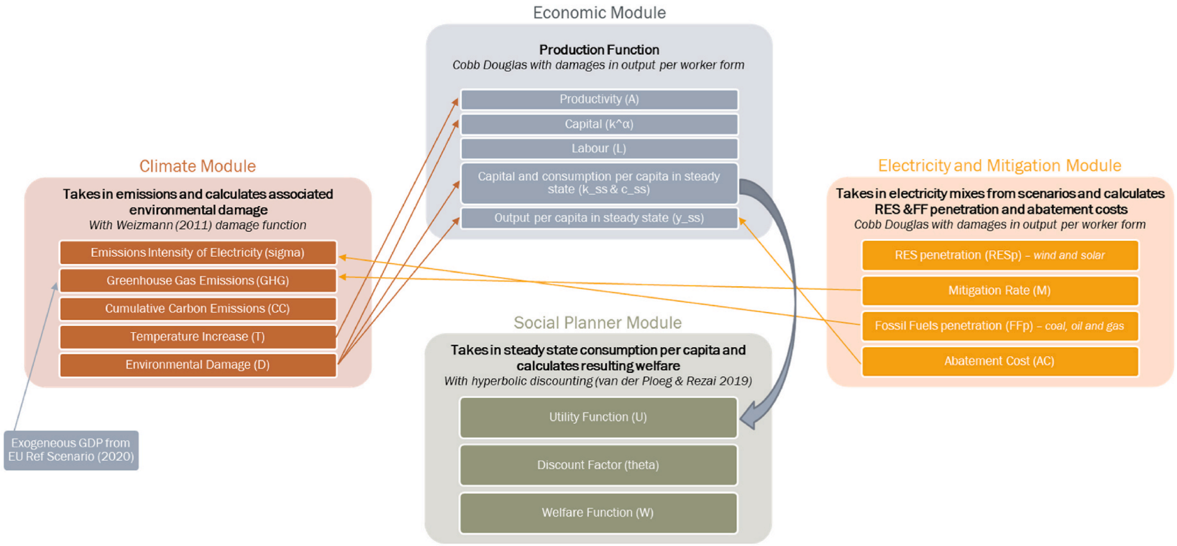
[2] In particular, we use i.e. the European Commission energy roadmap and the Net Zero by 2050 report by the International Energy Agency for the shares of the electricity mix under different scenarios and the EU reference scenario 2020 by the European Commission for the baseline of projected electricity needs in Spain.

[3] For the whole list of parameters, see the Appendix.



Graph 1. Model overview.

(Ortiz et al., 2011; Weyant, 2017; Espagne et al., 2018; van Beek et al., 2020): population increases at a decreasing rate $g_{L,t} = g_{L,t-1}/\ (1 + \delta_L)$, where δ_L is the population growth rate (Tsigaris and Wood, 2016) that is added to the population in levels $L_t = L_{t-1} * (1 + g_{L,t})$, and reflects the trends in the European Union Reference Scenario report (European Commission, 2021c).

The dynamics of total factor productivity, A_t, are specified in a similar way to those of population, $A_t = A_{t-1} * (1 + g_{A,t})$, but with one major difference: the parameter measuring the growth rate on productivity, $g_{A,t}$, is negatively affected by temperature, $g_{A,t} = \frac{g_{A,0}}{(1+\delta_A)^t} - \gamma T_t$, where δ_A is a parameter that reflects technical change and γ links temperature increases to decreases in productivity growth (Nordhaus and Sztorc, 2013; Tsigaris and Wood, 2016). This is carried out on the basis of previous literature that argues for the specification of total factor productivity in IAMs in order to account for the opportunity cost regarding lost R&D that has been directed towards climate adaptation and mitigation, as well as for the negative impacts of extreme weather events (Nordhaus and Sztorc, 2013; Dietz and Stern, 2015; Diaz and Moore, 2017; Espagne et al., 2018; Zhao et al., 2020). Under this specification, total factor productivity, A_t, decreases over time as temperature increases. The speed of the trend ultimately depends on how fast temperatures rise over the time horizon.

The economic inputs module of the model is completed with the dynamics applied to the capital stock per worker (k_t), which are in line with the Ramsey-Cass-Koopmans and Solow-Swan economic growth model and the concept of convergence to a steady state (Solow and Swan, 1956), as in most of IAMs (Fankhauser and Tol, 2005; Hope, 2006; Bauer et al., 2012; Diemer et al., 2019). By taking the approach used in DICE, in which climate impacts are channelled mostly through the production function (Nordhaus, 2007; Fankhauser and Tol, 2005), a constant savings rate (s) is used together with the pathways outlined above to calculate the steady-state capital stock per worker regarding climate damage (D_t):

$$k_{ss,t} = \left(\frac{sA_tD_t}{\delta_k + g_{L,t}}\right)^{\frac{1}{1-\alpha}} \tag{2}$$

where capital stock per worker is also affected by temperature. In this case, the link with increasing temperatures is formed via a more accelerated depreciation of assets due to extreme weather events (Stern, 2013; Pietzcker et al., 2017). This link is carried out in the model via the specification of the capital depreciation parameter, $\delta_K = \delta_0 * \delta_1 T_t$, whereby δ_0 is the initial capital depreciation rate and δ_1 is a parameter that measures the change of depreciation from the temperature increase, T_t (Stern, 2013). With the steady-state capital stock per worker in place, the steady-state income and consumption per worker can be obtained in expressions (3) and (4) respectively:

$$y_{ss,t} = D_tA_tk_{ss,t}^{\alpha} \tag{3}$$

$$c_{ss,t} = (1 - s)y_{ss,t} \tag{4}$$

The steady-state consumption per worker is a particularly relevant variable in the model, since it is the variable employed to compute the discounted utility to assess the social pertinence of each scenario.

3.2. *Climate module*

The second part of the model is the climate module, in which the environmental impacts of the various electricity decarbonisation scenarios are calculated based on the DICE and DICE-R models (Nordhaus 2008; Nordhaus and Sztorc, 2013).[4] The intensity of electricity (σ_t) of the greenhouse gas emissions provides the starting point. Since only one sector is addressed (i.e., electricity generation), σ_t is directly linked to the percentage of penetration of fossil fuels in the electricity mix (FFp_t) in the EU27 at each point in time:

$$\sigma_t = FFp_t \tag{5}$$

There are obvious advantages to specifying the intensity of electricity emissions in such a straightforward way instead of using an exogenous source. On the one hand, the model gains significant coherence, since emission intensity becomes directly linked to the policy choice on the presentation of renewables in the electricity mix. On the other hand, in this way the intensity of electricity emissions mirrors the results of the different scenarios evaluated with IAM, thereby making the overall tool more relevant for the policy decision-making.

The level of Greenhouse Gas Emissions is calculated as in the DICE-R model. An exogeneous level of projected GDP for the EU27 to 2050 ($\overline{Y}_t$) from the EU Reference Scenario report (European Commission, 2021c)

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[4] It is assumed that, since Spanish GHG emissions only account for a fraction of total GHG emissions, the endogenous levels of GHG emissions and mitigation pathways under scenarios at each point in time are calculated for the 27 Members of the European Union (EU27). The economic impacts of each scenario (i.e., climate losses) are then estimated at national level for the case of Spain.

is employed:

$$GHG_t = (1 - M_t)\sigma_t \overline{Y}_t \tag{6}$$

where σ_t is the intensity of electricity emissions (Equation (5)) and M_t is the cumulated abatement (see Subsection 3.3). It is easy to determine that the mitigation measures planned towards the decarbonisation of electricity supply (i.e., by increasing the penetration of renewables in the electricity mix) exert a direct effect on reducing the amount of GHG emissions in the model.

As in most IAMs, our focus is on cumulative carbon emissions (CC_t) as the main pollutant in the model to which changes in temperature are attributed (Nordhaus, 2007; Nordhaus and Sztorc, 2013), leaving aside other GHG emissions that are less relevant in the case of electricity generation (INE, 2022). The cumulative carbon emissions are calculated as follows:

$$CC_t = CC_{t-1} + \left(\frac{GHG_t}{CtoCO2_{cr}}\right) \tag{7}$$

where the level of carbon emissions grows cumulatively on a rate equal to the sum of the cumulated carbon emissions of the previous period (CC_{t-1}) and the carbon emissions taking place within the same period, which need to be calculated by dividing the GHG emissions from Equation (6) over the chemistry ratio of CO_2 to carbon ($CtoCO2_{cr}$) to focus only on carbon as the key pollutant. In order to treat carbon emissions as a global pollutant, the same initial value is taken for carbon emissions as in the DICE-R 2013 calibration: 530 billion tons already emitted globally (Nordhaus and Sztorc, 2013).

The climate module of the model is completed with the equations on temperature change and the damage function (Nordhaus, 2007; Weitzman, 2010; Nordhaus and Sztorc, 2013):

$$T_t = CC_t * CCR \tag{8}$$

$$D_t = 1 \Big/ \left[1 + \left(\frac{T_t}{\theta_1}\right)^{\theta_2} + \left(\frac{T_t}{\theta_3}\right)^{\theta_4}\right] \tag{9}$$

where Equation (8) models the increase in projected temperature as a direct consequence of cumulative carbon emissions (Equation (7)), with the carbon-climate change response parameter (CCR)[5] as the parameter linking the temperature with the emissions (Matthews et al., 2012).

Equation (9) contains the climate change damage function proposed by Weitzman (2010). It includes four damage parameters, θ_1 to θ_4, which are calibrated using an expert panel to the values $\theta_1 = 20.46$, $\theta_2 = 2$, $\theta_3 = 6081$, and $\theta_4 = 6754$. As shown in Weitzman (2010) and Wouter Botzen & van den Bergh (2012), these calibrations yield a tipping point in economic growth at 6 °C beyond which disruptive climate events are triggered. Additionally, the application of this damage function results in climate policy that is significantly more stringent than that employed when applying the standard damage function used by Nordhaus (2008) in DICE, which tends to show only marginally small impacts on economic growth even when temperatures reach unconceivable thresholds beyond 8 °C of increase (Wouter Botzen & van den Bergh, 2012; Bretschger and Pattakou, 2019). Bretschger and Pattakou (2019) and Zhao et al. (2020) propose alternative specifications to the damage function, such as polynomial functions of up to quadratic form, which yield climate policy that is even more stringent for small increases of temperature. Although these new approaches appear promising and deserve attention, they have yet to be widely accepted as standard within the IAM literature.

We have opted for a climate change damage function exclusively dependent on temperature since temperature-denominated damage functions continue to be the most widely used in the IAM literature, largely because the increase in temperature remains the variable that attracts the most attention in climate science and international climate agreements, such as the Paris Agreement (Wouter Botzen & van den Bergh, 2012; Diaz and Moore, 2017; J.E. Neuman et al. 2020; IPCC, 2021). Although there are other approaches in the IAM literature to damage functions, such as those that are sensitive to extreme climate events (Zhang et al., 2021), sectoral climate impacts (Zhao et al., 2020), and abrupt climate change (Lempert et al., 2006), no consensus has yet been agreed in the literature as to how to include these effects in a standard way (Espagne et al., 2018).

3.3. Electricity and mitigation module

The third part of the model is its electricity and mitigation module, in which the impacts of different exogenous scenarios on the future evolution of the electricity mix for Spain are tested. Under each scenario, which will be described in Section 4, the model calculates the resulting proportions of renewables (including solar and wind) and fossil fuels (including coal, oil, and natural gas) in the electricity mix. The negative environmental impact from a higher presence of fossil fuels is captured by a higher intensity of electricity emissions, σ_t , which in turn results in higher cumulated emissions and climate damage. Conversely, a greater penetration of renewables in the electricity mix results in a higher cumulated abatement, which reduces cumulated emissions but entails abatement costs stemming from the deployment of the capacities required. These costs are calculated using the levelised cost of electricity (LCOE) of wind and solar generation, as calculated by the Fraunhofer study on LCOEs for renewable energies (Ueckerdt et al., 2013; Fraunhofer, 2021). The model focuses only on wind and solar technologies because all other renewables (i.e., hydropower, geothermal, tidal) are forecast to play a minor important role in the energy transition in Spain in all scenarios consulted (European Commission, 2011; European Commission et al., 2020; IEA, 2021; MITECO, 2020a).

Consequently, the cumulated abatement, M_t, under each scenario is calculated directly from the penetration in the electricity mix of wind [6] and solar power, $RESp_t$, which is taken as an exogeneous value under each scenario:

$$M_t = RESp_t \tag{10}$$

$$RESp_t = (SolESQ_t + WinESQ_t) \,/\, TotalESQ_t \tag{11}$$

where $SolESQ_t$ and $WinESQ_t$ are the exogeneous values under each scenario for electricity generation in Gigawatt-hours (Gwh) for solar and wind power in Spain, respectively, and $TotalESQ_t$ refers to the total exogeneous electricity generation in Spain, which is taken from the EU Reference scenario 2020 (European Commission, 2021c) in all scenarios of the model to ensure consistency of the calculations. The penetration of fossil fuels into the electricity mix is calculated in a similar way, and, as can be seen from Equation (5), it is taken as the endogenous value for the intensity of electricity emissions, which is in turn the main driver of cumulated emissions (and, therefore, of climate damage) in the model:

$$FFp_t = (CoalESQ_t + OilESQ_t + GasESQ_t) \,/\, TotalESQ_t \tag{12}$$

where $CoalESQ_t$, $OilESQ_t$, and $GasESQ_t$ refer to the exogeneous value

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[5] The CCR parameter yields an estimated linear relationship between cumulated CO_2 in the atmosphere and projected temperature increase, calibrated by Matthews et al. (2012) of 1.8 Celsius degrees increase in mean temperature for every 1000 Gigatons of cumulative CO_2 emissions released into the atmosphere. Such an estimation brings simplicity to the calculations in the model and is in line with recent proposals on the estimation of damage in climate change damage functions in IAMs (Bretschger and Pattakou, 2019).

[6] For the case of wind power, both offshore and onshore generation are considered by the IEA when calculating LCOEs. Since the model only accounts for wind in general, we have applied an arithmetic mean between the two LCOEs (for offshore and onshore wind) to obtain the LCOE used by the model.

under each scenario for electricity generation in Gigawatt-hours (Gwh) for coal, oil, and natural gas under each scenario for Spain.

As in all IAMs, the model needs to be completed by an abatement cost function that calculates the consequences of reducing emissions on the steady-state income per capita. To this end, the convex abatement cost function from the DICE-R 2013 model of Nordhaus and Sztorc (2013) has been employed in which the total abatement costs, AC_t, are a function of cumulated abatement, M_t, specified as follows:

$$AC_t = \omega_t M_t^{\theta_{AC}} \tag{13}$$

where: the cumulated abatement is weighted by an exponent, θ_{AC}, calibrated as 2.8 in the DICE-R 2013 model; and an abatement cost parameter, ω_t, declines at a rate equal to the change in the productivity rate in each period, $g_{A,t}$. This yields an abatement cost, AC_t, which shows very marginal values in the early decades of the period (mainly 2010 to 2020) and then gradually increases with the penetration of renewables in the electricity mix over the period. Abatement costs complete the model by entering the calculation of the steady-state output per capita given in Equation (3):

$$y_{ss,t} = (1 - AC_t) D_t A_t k^{\alpha}_{ss,t} \tag{14}$$

In this way, the trajectory of the level of output per capita is endogenously determined by two fundamental costs: the climate damage and the cumulated abatement, in which reducing units of the former implies an increase in the latter. The model is employed to compare how this relationship holds when variable compositions of the electricity mix are modelled for Spain over the period 2010 to 2050. Such changes are evaluated using Equation (4) (consumption per capita in steady state) for the calculations on utility and welfare, which we detail in the following subsection.

3.4. Social planner module: A note on discounting and utility calculations

An additional module representing the decision-making process of a public policy body is included in the model to compare results of the various scenarios. This module includes the utility calculations processed in most IAMs, which involve analysing the welfare of the current versus the future generation (Pindyck, 2013). The level of welfare is affected by the total abatement costs and the cumulated climate change damage at each point in time, which directly influence the level of consumption per capita, as shown in Equation (15): this is calculated as the discounted sum of the utility of steady-state consumption per capita over the entire time horizon, which in our case runs from 2010 to 2050:

$$W = \sum_{2010}^{2050} \theta_t L_t U(c)_t \tag{15}$$

where θ_t is the discount factor, which enables the inclusion of the intergenerational dilemma, calculated under the following form:

$$\theta_t = \frac{1}{1 + \rho(year - 2010)} \tag{16}$$

The discount factor displayed in equation (16) corresponds to hyperbolic discounting. As revealed in the Introduction, there is extensive debate in the literature on IAM regarding the way in which future welfare needs to be discounted when analysing climate scenarios. Hyperbolic discounting tends to place more policy effort in terms of the reduction in emissions reduction on closer generations than on more distant ones, which results in climate policy of a more stringent nature.[7] We deem this to constitute a realistic assumption for our model, in which the time horizon is comparatively shorter than in the usual IAMs[8] and is in line with the most stringent climate policy imposed in the European Union, through which a large part of the decarbonisation effort is going to be made over the next two decades (European Commission, 2021b).

Another key element frequently under discussion in IAMs is that of the calibration of the rate of pure time preference, ρ. In climate modelling, the value of this parameter determines the importance given to losses in future levels of consumption. Under such high values of ρ, the bulk of the emission reductions are placed on future generations, with the overall transition to climate neutrality taking place at a slower pace and with greater temperature increases (Wouter Botzen & van den Bergh, 2012; Emmerling et al., 2019). The Stern-Nordhaus controversy is particularly relevant in this matter: while in the DICE model by Nordhaus, ρ is set at a higher value to match interest rates, linking the pace of decarbonisation to market trends (Nordhaus, 2007; Espagne et al., 2018), in Hope's PAGE model, ρ is calibrated on ethical grounds, linked to the probability of disastrous events under higher temperatures (Stern, 2007, 2013; van der Ploeg and Rezai, 2019). An application of the Stern approach seems more up-to-date given the current context of repeated warnings of the consequences of increased temperatures and the extreme weather events that have already been set in motion globally (IPCC, 2021). Such choice is also in line with the most recent IAM literature, which seems to be shifting towards an institutionally-centred role of IAMs that aim to avoid previous underestimations of the potential impacts of accelerated climate change (Espagne et al., 2018; Estrada et al., 2019; Van Beek et al., 2020; Zhang et al., 2021). The approach taken in PAGE (Hope, 2006), with a rate of pure time preference equal to 0.015, is, therefore, the approach taken in our model.

The final element of the social planner module is the functional form of the utility function. As shown in Equation (16), welfare is calculated in IAMs as the sum of discounted utility, but the latter needs to be specified under a function. This topic is also the focus of significant debate in IAMs, as the choice of the rate in marginal utility for each level of per capita consumption (η) can greatly affect the sensitivity to income inequality. This form is normally stated as follows (Norstad, 1999):

$$U(c)_t = \begin{cases} \dfrac{c^{1-\eta}}{1-\eta} \; if\ \eta \neq 1 \\ \ln(c) if\ \eta = 1 \end{cases} \tag{17}$$

In this matter, we also follow the approach taken in the PAGE model by Hope (2006), in which an iso-elastic utility function is used. This corresponds to the $\eta = 1$ case, which enables the impacts of the different scenarios on per capita consumption to be aggregated in a more straightforward way (i.e., aggregating them in the welfare function, as in Equation (16), with no further adjustments). As a downside, this makes the model insensitive to distributional concerns and equity, although in our case the main focus of the model is to provide a common tool to compare aggregated costs of different electricity decarbonisation scenarios, while leaving out of the analysis the way in which those costs are distributed.

4. Data and scenario description

The model described in Section 3 has been applied to quantify the environmental and economic impacts of a variety of scenarios. The composition of the electricity mix therein is taken as an exogeneous input to the model, upon which such impacts are calculated.

A summary of the assessed scenarios is provided in Table 1. Four electricity sources have been considered, as these are projected to

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[7] See Karp (2005) and van der Ploeg and Rezai (2019) for more details on the application of hyperbolic discounting on climate change economics, and Laibson (1997) and Andersen et al. (2005) for general knowledge on hyperbolic discounting.

[8] Time horizons in IAMs tend to run until at least the year 2100. In our case, we opt for a shorter period because the objective is to analyse the economic consequences of different scenarios towards climate neutrality for the case of Spain, which, as across the entire European Union, is set to happen by 2050.

Table 1
Average electricity mix per scenario and costs per source.

Scenarios /Variables	BAU	IEA NZE	High RES	Low Nuclear	Energy Efficiency	LCOEs per source, US $/MWh, average	Additional costs per MWh for additional electricity interconnections for renewables, US $/MWh
Electricity mix (shares per source, %, average 2010–2050)							
Solar PV (incl. utility scale storage)	8.5%	19.2%	14%	11.4%	11%	79.6	2.86
Wind (incl. offshore and onshore)	24%	22%	31.3%	29.1%	28.3%	84.9	2.86
Nuclear	10.5%	9.2%	8%	7%	9.3%	128.3	N/A
Fossil fuels (incl. solids, oil, and gas fired)	40.6%	26.3%	30.65%	36%	34.1%	147.8	N/A
Data source	European Commission (2011), Current Policy Initiatives scenario	IEA (2021), Net Zero by 2050 report, Table A.3, total generation	European Commission (2011), High RES scenario	European Commission (2011), Low Nuclear scenario	European Commission (2011), Energy Efficiency scenario	Fraunhofer (2021) study on Levelized Cost of Electricity Renewable Energy Technologies for wind, solar and fossil fuels; IEA (2021) for nuclear	Red Eléctrica de España (2019b), 2021–2026 Electrical Networks Development Plan

Notes: BAU: Business as Usual scenario; IEA NZE: International Energy Agency's Net-Zero Emissions by 2050 scenario; RES: Renewable Energy Sources; LCOEs: Levelised Cost of Electricity, which are taken from the projections until 2040 given by the Fraunhofer (2021) study – for more information see Table 3 in the Appendix. The Fraunhofer study does not include nuclear in the analysis, which is why we rely on the figures given in IEA (2021) as LCOEs for nuclear in Europe. Finally, the values for the additional interconnections for renewables are calculated from the projections in Red Eléctrica de España (2019b), taking as a starting point the additional investment needs foreseen in the report for the deployment of 89 GW of wind and solar renewables (1872 M€) for a period of six years (2021–2026).

increase or decrease the most in the decades up to 2050 in Europe (European Commission, 2011; IEA, 2021) and in Spain (MITECO, 2020b): solar photovoltaic (Solar PV) energy, wind energy (including offshore and onshore), nuclear fission, and fossil fuels. The latter is a joint category in which all fossil-fuel power plants are considered, including conventional power plants using solids (i.e., coal) and oil as well as those using gas turbines.[9]

In total, five scenarios have been considered. Four of these form part of the Impact Assessment of the European Commission's energy roadmap to 2050 (European Commission, 2011). Table 1 outlines the average shares on electricity generation and costs per source in each of the scenarios from 2010 to 2050. Fossil fuels and nuclear fission are more present in the BAU scenario than in any other, as the scenario only gathers the measures in place by EU Member States in the Energy 2020 strategy (European Commission, 2011, 2021b). The IEA NZE scenario outlines the changes needed to attain zero use of fossil fuels for power generation by 2050, but it does so by relying on nuclear power. The opposite case takes place for the Low Nuclear scenario. The High RES scenario gathers the largest average share of renewable energy.

Another fundamental component of the data and scenario description of the proposed model is the information related to costs of the different energy technologies involved, which need to be adapted to the particular case (i.e. Spain). Two fundamental characteristics of the Spanish electricity system have been identified: its relative isolation in terms of energy interconnections with the rest of Europe and a particular need for additional investments in terms of energy storage to integrate large shares of variable renewable energies (i.e. wind and solar) (Red Eléctrica de España, 2019a). These two characteristics act as framework conditions in which the model operates, and therefore needed to be clearly identified in the literature. To this end, a literature review for the Levelised Cost of Electricity (LCOEs) [10] of the four electricity sources of the proposed model has been conducted. Its sources, which were selected due to their relevance and pertinence to the presented model, include two landmark reports from authoritative sources in the energy sector at global level (i.e. IRENA and IEA) and two empirical literature surveys done by Fraunhofer and Lazard (Fraunhofer, 2021; IEA, 2021; Lazard, 2021; IRENA, 2022). The results, which can be consulted in Table 3 of the Appendix and that have been used for the sensitivity analysis on LCOEs presented in the Results section, point in all cases to remarkably lower LCOEs for renewable energies (solar and wind) than for fossil fuels and nuclear energy. Several factors can explain this. First, higher LCOEs for fossil fuels and nuclear energy can be due to the very nature of the assets used in power generation in these cases, which entail higher capital costs. Secondly and in particular for the case of fossil fuels, another set of explaining factors are of regulatory nature and largely include the assumed increasing price of coal and the influence of GHG emissions pricing mechanisms such as the EU Emission Trading Scheme (IEA, 2021).

Besides, the issue of intermittency in electricity generation of renewables such as solar and wind is well known and recognised, and so it is the need to accompany their deployment with grid-scale energy storage (European Court of Auditors, 2019; European Commission et al., 2020; Fraunhofer, 2021; IEA, 2021; IRENA, 2022). Such importance was already recognised by the European Commission in its 2018 Communication "A Clean Planet for All" which states that deployment of energy storage would need to increase by six times to accommodate large shares of variable renewable energies such as wind and solar (European Commission, 2018) and investments at the global level seem to be

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[9] Other electricity sources, such as hydropower, geothermal and tidal power, have not been considered because they are not projected to change as much in the next decades either for Spain or Europe. The bulk of the electricity decarbonisation efforts in Spain and Europe will be carried out by wide-scale deployment of renewables (mainly solar and wind) and the phase out of fossil fuels (including coal, oil, and gas) (European Commission, 2011; IEA, 2021; MITECO, 2020b).

[10] LCOE is equal to the Net present value of an electricity installation over its lifetime and is expressed in US dollars per megawatt hour. This allows for proper cost comparisons across different energy sources. We take values from Table B1 of the IEA Net Zero Report, EU series (IEA, 2021).

moving in that direction, as identified by the IEA (IEA, 2022b). In such context, a key objective of the literature review was to identify a set of LCOEs that would not only be representative of the different costs of the energy technologies in the model, but also would integrate the issue of energy storage deployment for the case of renewable energies. Incorporating cost information on energy storage in the model was not straightforward, as the LCOEs for utility-scale energy storage vary greatly across geographical locations in Europe and beyond due to the influence of complex and interconnected factors, such as the material composition of the batteries, the exact location of utility-scale storage plants or other elements such as solar irradiation patterns, grid losses and even regulatory obstacles in permitting (Chun Sing and Mcculloch, 2016; Ziegler et al., 2019; European Commission et al., 2020; Fraunhofer, 2021).

Among the sources consulted in the LCOE literature review, the study done by Fraunhofer on the Levelized Cost of Electricity Renewable Energy Technologies (Fraunhofer, 2021) seems to be the most pertinent, as it is the only source that includes sufficient and explicit data (i.e. able to be incorporated in the model) on energy storage for renewables. Several options are provided in the report (i.e. small, large and utility scale storage, of which we take the latter) with detailed explanations on the assumptions used. In addition, the Fraunhofer study considers the closest geographical scope to the case of the proposed model, as it focuses on one single European country (i.e. Germany) as compared to the other sources, which calculate LCOEs at global level (IEA, 2021; Fraunhofer, 2021; Lazard, 2021; IRENA, 2022). Finally, the most fundamental advantage of Fraunhofer (2021) compared to the rest of LCOE sources is the fact that it is the only study in the sample providing clear projections until 2040 with specific data on LCOEs for batteries, which makes it suitable to be integrated in the proposed model. A slight shortcoming, however, is that the Fraunhofer report does not include figures on LCOEs for nuclear energy in its scope. As a solution to this, the data for nuclear was obtained from IEA (2021), which provides detailed information on the assumptions and trends incorporated in the final LCOEs for nuclear.

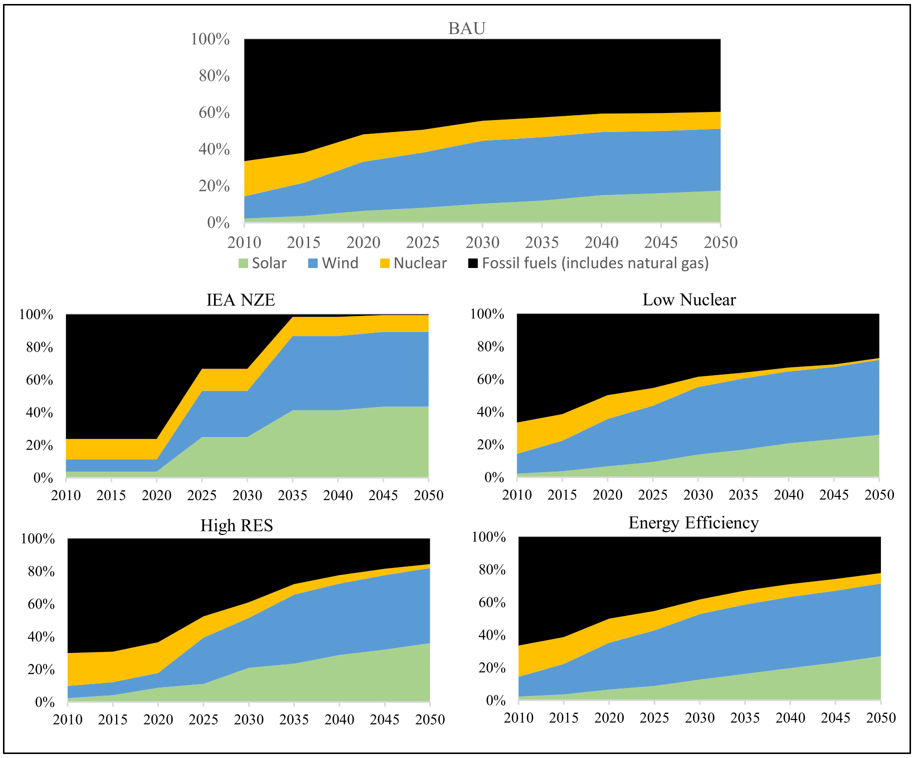
An additional fundamental factor to consider when integrating costs in the model is the issue of energy networks and interconnections. A highly-interconnected electricity system is necessary for the integration of higher shares of renewable energies in the electricity mix and the decarbonisation of energy supply as a whole, as it allows for dispatching clean energy to meet peak demand at a reduced cost for the electricity system (Crozier and Baker, 2022; Yang, 2022). Together with enhanced energy storage (as pointed out in the paragraph above), energy interconnections can bring the needed additional flexibility that the integration of renewables as the main electricity source will require to meet the goals of the Paris Agreement and the objective of climate neutrality by 2050 of the European Green Deal (European Commission, 2019; Mehigan et al., 2022). This is why the European Commission has set a target for interconnection of at least 15% of domestic electricity production able to be transported to neighbouring countries by 2030 among EU Member States (European Commission, 2017). After the invasion of Ukraine by Russian forces and the resulting energy crisis, the recent REPowerEU package has stressed the importance of speeding up the process of interconnection of national energy systems of EU Member States, in order to increase the EU's energy system resilience and flexibility to shocks such as the accelerated phase-out of Russian fossil fuels, as well as the integration of variable renewable energies as main generation technologies in the longer term (European Commission, 2022a).

The Spanish case, however, presents certain specificities when it comes to interconnections, which need to be incorporated in the proposed model as framework conditions. The electricity system in Spain is connected to France, Andorra, Portugal and Morocco, and its interconnection ratio to the EU electricity system only amounts to a maximum of 3.5 GW – only 3% of installed capacity and much below the 15% EU target for interconnection for 2030 (Red Eléctrica de España, 2019a; IEA, 2022c). Such lack of interconnections has given rise to the term "electricity island" to describe the Spanish electricity system. Furthermore, forecasts on expected cross-border electricity capacities for 2025, 2030 and 2040 elaborated by ENTSO-E (the association for cooperation of European Transmission System Operators), point out that the situation will not change significantly in the coming decades and that Spain will continue to be significantly isolated from the rest of Europe in the future (ENTSO-E, 2023). The recent suspension of the long-negotiated submarine electrical connection project with France through the Gulf of Biscay after an over 80% increase of the total expected cost of the project seems to confirm such forecasts (Monforte, 2023).

The isolated condition of the Spanish electricity system has been examined as well in the academic literature: Auguadra et al. (2023) find out that the small capacity in international interconnections of Spain makes energy storage play a more important role in energy decarbonisation than previously thought; Abadie and Chamorro (2021) elaborate on the economics of an additional France-Spain interconnectors and the impacts it would have on the market outlook for energy technologies in Spain; while Göransson et al. (2014) analysed that the congestion existing between isolated systems such as the Spanish one to the rest of Europe gave raise to congestion problems in the network, thereby negatively impacting the overall energy costs in the system.

It is therefore safe to establish for the purposes of the model that, due to its isolation, the changes in the Spanish electricity system in the coming decades towards energy decarbonisation will not be influenced in a great extent by fluctuations in the energy mix of neighbouring countries (France, Portugal, Andorra, Morocco) but rather by the changes taking place within the Spanish system itself. In particular, the isolated nature of the Spanish electricity system makes additional energy storage and electricity interconnections two fundamental pillars to ensure the necessary flexibility to accommodate an increasingly larger share of renewables in the electricity mix (Red Eléctrica de España, 2019b; Auguadra et al., 2023). As stated above, these elements needed to be integrated as framework conditions specific to the Spanish electricity system for the characterisation of the different scenarios. This has been incorporated in the proposed model through a second cost component complementary to LCOEs only for the case of wind and solar, expressing the need for additional electricity interconnections to accommodate renewables and ensure system flexibility. This cost component for interconnections has been calculated from the 2021–2026 Electrical Networks Development Plan of the Spanish TSO (Red Eléctrica de España, 2019b). All information on the input data on electricity mix per scenario and costs per source (including energy storage and interconnections for renewables) is provided in Table 1 below.

Graph 2 provides an overview of the dynamics in the various scenarios. While in all of these scenarios the presence of renewables (wind and solar) increases over the time horizon, the magnitude of the effect varies greatly. Under the BAU scenario, fossil fuels decrease their share in the electricity mix by only 20%, and still constitute 40% thereof by 2050. The picture is opposite in IEA NZE where, even if this is a scenario of global context instead of European, the biggest increase in both wind and solar power from among the scenarios assessed brings an electricity mix mostly based on renewables, with nuclear remaining relatively stable over the period and fossil fuels brought to net zero. The High RES scenario also portrays a large reduction on fossil fuels, which remain at 11% in the mix by 2050, while also achieving a significant reduction in nuclear dependence via an accelerated deployment of renewables, especially regarding wind energy. In the Low Nuclear scenario, bringing nuclear energy to a minimum within the mix comes at the cost of a lower deployment of renewable energy and further reliance on fossil fuels. The Energy Efficiency scenario achieves slightly higher reductions in the presence of fossil fuels than does the Low Nuclear option, which presents a moderate deployment of renewable energy. The Energy Efficiency scenario, however, has a differential point to all other scenarios thanks to its introduction of highly stringent commitments on energy savings, which leads to a decrease of 41% in final the energy demand by 2050



Graph 2. Electricity mix under different scenarios.

(European Commission, 2011), which, as will be presented in the Results section, entails lower investment costs for the implementation of the scenario in the Spanish case.

The shares in the electricity mix in each period under the different scenarios are expressed for the European Union in the case of the scenarios taken from the Impact Assessment of the European Commission (European Commission, 2011) (i.e., BAU, Low Nuclear, High RES, and Energy Efficiency scenarios) and for the world in the case of IEA NZE (IEA, 2021). The results for the Spanish electricity generation sector used in the model are calculated as follows:

$$Q_{ES,\varphi_i,t} = share(\%)_{scenario,\varphi_i,t} * Q_{ES-REF,total,t} \qquad (19)$$

where $Q_{ES,\varphi_i,t}$ refers to the total amount of electricity generated in Spain (in gigawatt hours, Gwh) from a given technology φ_i (where φ represents all four available technologies in the model: $i = solar, wind, nuclear, fossil\ fuels$) at each point in time. $share(\%)_{scenario,\varphi_i,t}$ are the shares taken from each of the scenarios (BAU, IEA NZE, Low Nuclear, High RES, and Energy Efficiency, as presented above). $Q_{ES-REF,total,t}$ refers to the gross electricity generation in Spain (also in Gwh) and is taken from the EU Reference Scenario 2020 (European Commission, 2021c). The result of applying Equation (19) is the electricity mix in Spain under each of the scenarios at each point in time (2010–2050), which is used as an exogeneous input to the model calculations. Additionally, the LCOEs from Table 1 have been employed to calculate the required investment for the implementation of renewable energies in each period under the different scenarios ($IRES_{ES,t}$) by multiplying the forecast electricity necessary from solar and wind by their respective LCOEs. An exchange rate of US \$ to € has been utilised to translate the LCOEs to € ($ER_{\$/€}$) (IEA, 2021; European Central Bank, 2023). This is summarised in the following expression:d

$$IRES_{ES,t} = \left[\left(LCOE_{solar,t} * Q_{ES,solar,t}\right) + \left(LCOE_{wind,t} * Q_{ES,wind,t}\right)\right] * ER_{\$/€} \qquad (20)$$

A final indicator provided in Section 5 is that of the climate output gap (COG_t), which gives a measure of the foregone potential output given by environmental damage under each scenario. This indicator is an important output of IAMs, since it can allow for comparisons between the cost of the temperature increase to the mitigation costs under different scenarios (Weyant, 2017). In the proposed model, this is calculated as a simple benchmark between the modelled output per capita in steady state (as calculated in Equation (14) and multiplied by population, L_t) and the theoretical level of steady-state output per capita that would have been achieved in the absence of temperature change ($\widehat{y_{ss,t}}$), which is calculated using the same logic as in Equation (14) but removing the temperature from the specification of the total factor productivity and output itself. Therefore, the climate output gap is calculated as follows:

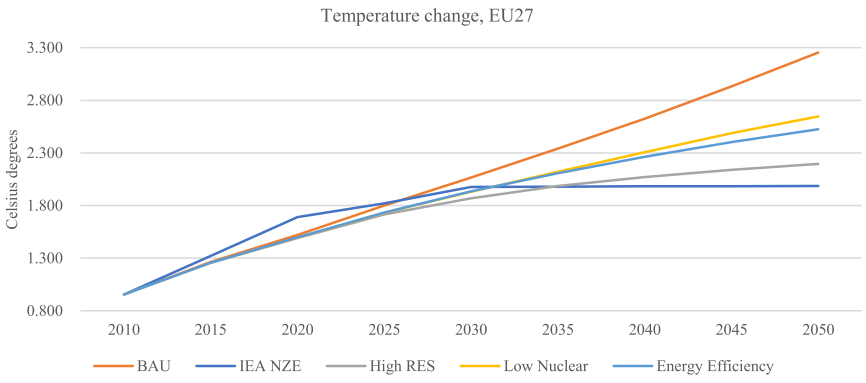
$$COG_t = \left(y_{ss,t} - \widehat{y_{ss,t}}\right) * L_t \qquad (21)$$

The results of the model are presented in the following section.

5. Results

The model presented in the previous section has been applied to the electricity generation sector in Spain. The outcome is a forecast of the estimated economic and environmental impacts of introducing the electricity decarbonisation pathways foreseen in the BAU, IEA NZE, High RES, Low Nuclear, and Energy Efficiency scenarios, which are outlined in this section.

Graph 3 projects the changes in temperature over the time horizon under the different scenarios, calculated for EU27. The BAU scenario points to a remarkably higher temperature increase, of over 3 °C by 2050, which is explained by the large reliance on fossil fuels (never below 30% of the total electricity supply) that persists even at the end of the period and is in line with equivalent BAU scenarios shown in the IPCC AR6 report, which show similar temperature increases (IPCC, 2021). The policies considered in the BAU scenario are able to deliver only a moderate reduction of approximately 20% by 2030 (compared to 2010) of the share of fossil fuels: insufficient to maintain temperatures within safe levels by 2050. The result shows that additional policy efforts are needed to those summarised as current policy initiatives in the



Graph 3. Temperature change under various scenarios, EU27.

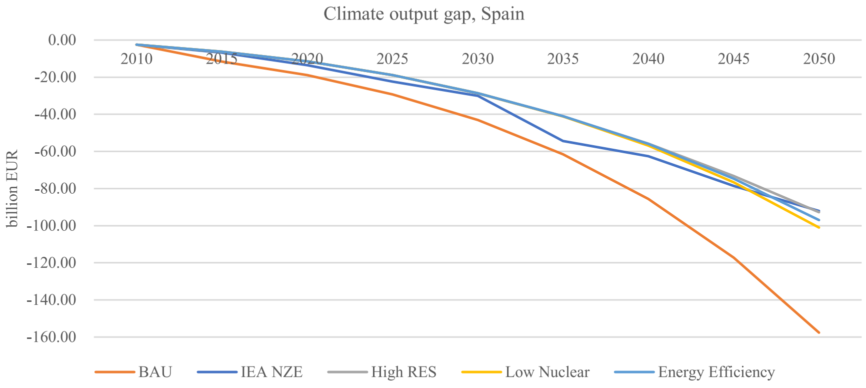
European Commission roadmap towards energy 2050 (European Commission, 2011).

Low Nuclear and Energy Efficiency scenarios show similar results in terms of temperature increase, by remaining above 2.3 °C by 2050. This shows that intermediate approaches, such as those pursued in scenarios where no steep decrease in the share of fossil fuels in electricity generation is introduced, also fall short in preventing temperature from increasing dramatically. Only the IEA NZE scenario manages to contain the temperature change, even though it does so by stabilising the temperature at 1.8 °C by 2050 and slightly lagging behind all the other scenarios at the beginning of the period. All of this shows that the effects of CO_2 emissions on temperature are persistent, and that containing temperature increase requires steep reductions in the share of fossil fuels in electricity generation.

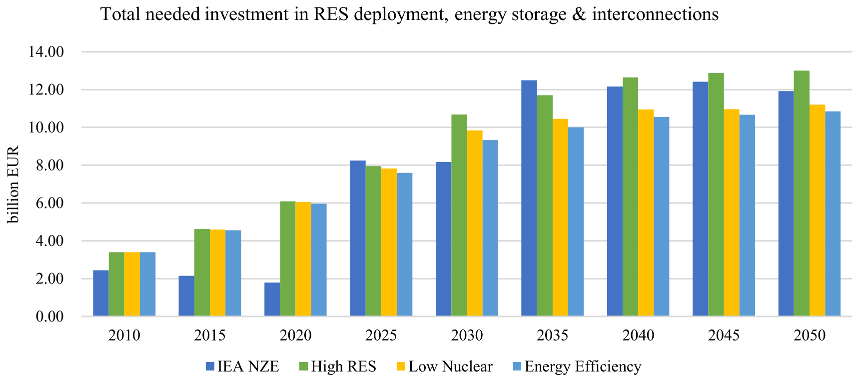
Nevertheless, caution needs to be exercised when reading these results. The proposed model focuses on the changes arising from one sector (electricity generation) by applying *ceteris paribus* reasoning, while if change were introduced in other sectors, such as transport, industry, and land use, the figures for temperature increase would certainly become worse. The fact that the temperature increases from BAU are remarkably higher than those of other scenarios (i.e., High RES, IEA NZE) indicates that electricity generation is a particularly influential sector on the overall trend of emissions and climate change. Additionally, the fact that none of the scenarios manage to maintain temperatures within the Paris Agreement ranges (well below 2 °C, and ideally less than 1.5 °C) indicates that a joint effort with measures placed in other sectors is needed. Electricity is, in short, a key sector in which deeper cuts of CO_2 emissions need to be achieved, but it is certainly not the only one in which such changes need to take place.

One key feature of IAMs is their potential to translate changes in temperature into forecast economic impacts. The damage function chosen in our model (Weitzman, 2010) is sufficiently sensitive to estimate such impacts in scenarios of moderate temperature increase, such as those presented in our results. Graph 4 provides a representation of the economic impacts of each of the scenarios and reveals that the gap between the potential steady-state output (i.e., where influence of temperature is not considered) and the actual output grows much higher when fossil fuels have a greater share in the electricity mix. The maximum losses take place in the BAU scenario, with a climate output gap equal to 105 billion euros by 2050. All other scenarios achieve significantly lower losses, of close to but still less than 70 billion euros by 2050. This shows that even in the scenarios where more climate ambition is brought forward in the form of the deployment of renewables, there is a deadweight loss that is potentially unavoidable in the long term. This finding can also be linked to the need for a fair transition, in which unavoidable costs should not be imposed on the most vulnerable sectors or income groups to prevent the climate crisis from generating further income inequalities.

Mitigation strategies differ across scenarios. Our proposed model also calculates the investment needed in the deployment of renewable energy (which in our case is limited to solar and wind) for the implementation of these scenarios for the case of Spain in real life, using LCOEs from Fraunhofer (2021) as in Equation (20) and including the complementary investments in energy storage and energy interconnections needed to integrate increasing levels of renewables in the electricity mix, as discussed in Section 4. As shown in Graph 5, the investment needed in solar and wind electricity generation including storage and interconnections grows by more than three times over the period across scenarios, from around 3 billion euros in 2010 to over 10 billion by 2050. However, such investment needs are still lower than the climate losses that the Spanish economy would incur if no measures were put in place (i.e., 160 billion euros by 2050, as shown in Graph 4).



Graph 4. Climate change losses under different scenarios.



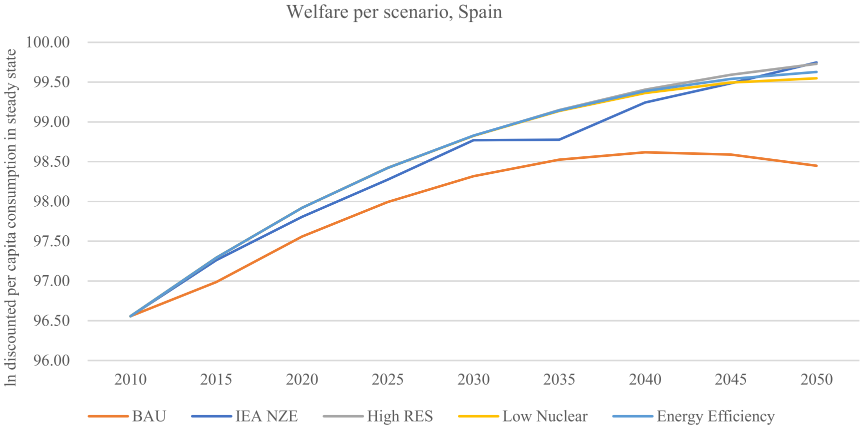
Graph 5. Investment required in solar and wind energy deployment, energy storage & interconnections.

The investment figures vary to some degree between scenarios, with High RES and IEA NZE tending to be those presenting the highest levels of investment in renewables: 13 and 11.9 billion euros by 2050, respectively. The enhanced energy efficiency policies in the Energy Efficiency scenario lead to a remarkable 20% decrease in the total investment needed: down to 10.8 billion euros, although with values very close to the Low Nuclear scenario. The reduction of final energy demand does therefore play a significant role in reducing the total costs of the transition in the Spanish electricity system.

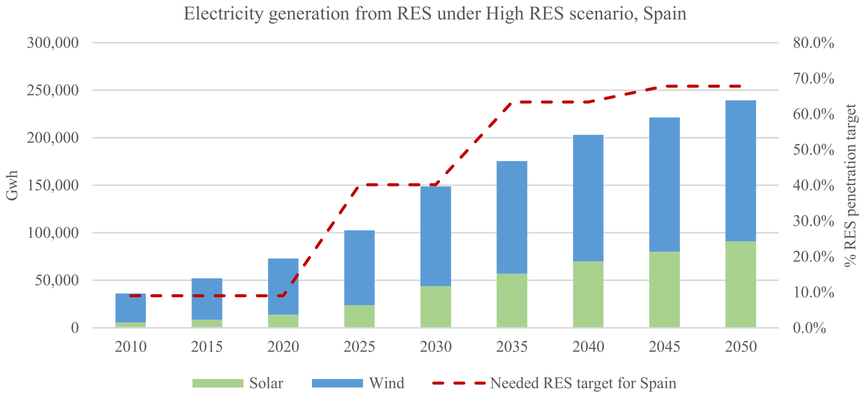
Having presented the results of the different scenarios, the social planner module described by Equations (16) to (18) is subsequently applied to compute the different welfare levels per scenario and therefore define the most preferable scenario. Graph 6 shows the results of the calculated discounted utility in each scenario over the period. The results reveal a clear outcome: the levels of welfare under the BAU scenario are systematically lower than all other scenarios over the entire time horizon, and they even enter a decreasing trend as from 2040. The persistence of fossil fuels in the electricity mix (and their associated damage in the form of temperature increase, harming total factor productivity and the steady-state levels of per capita income and consumption) seems to outweigh the abatement costs of all the decarbonisation scenarios. This is a key finding of the proposed model, as it shows that any policy option is preferable to maintaining the current state of play of the BAU scenario in terms of social welfare.

Conversely, the levels of welfare achieved in each of the policy scenarios are very similar over the period. When the levels of discounted utility are aggregated for the entire period to estimate total welfare (as in Equation (16)), the BAU scenario still gets the lowest value (equal to 881,6), while all decarbonisation scenarios (IEA NZE, High RES, Low Nuclear, and Energy Efficiency) obtain very similar results, with values around 886 of total welfare. High RES shows the highest level of total welfare (886.9) and seems to be the scenario that should be implemented by policymakers when economic and environmental concerns are assessed with our proposed model.

As a final assessment in the results of the model, a closer examination of the main metrics of the chosen scenario, High RES, is provided in Graphs 7 and 8. Graph 7 shows the composition and generation of the renewable electricity supply over the time horizon in the High RES scenario. Wind (including both onshore and offshore) is the dominate renewable energy at all times, although solar generation increases at a faster pace. By 2050, roughly one third of renewable electricity is supplied by solar power plants while the remaining two thirds come from wind energy. One major policy recommendation to be extracted from the model is that policymakers should ensure that the changes in electricity supply follow the same trajectory as that outlined in the High RES scenario. One possible way to do this is to follow the logic of European legislation, in which targets are frequently employed to guide policies and markets to a socially desirable outcome. For instance, the EU Renewable Energy Directive, currently under revision, intends to introduce an increased target of 40% of renewable energy at EU level by 2030 (European Commission, 2022b). According to the findings of the proposed model, electricity in Spain should follow a similar pathway: as can be observed in Graph 7, a minimum of 40% of electricity in Spain should originate from renewable sources. Spanish policymakers should, in addition to this, introduce specific targets, that is, 63% of renewable electricity by 2035 and 68% by 2050, in order to ensure that a minimum



Graph 6. Welfare per scenario.

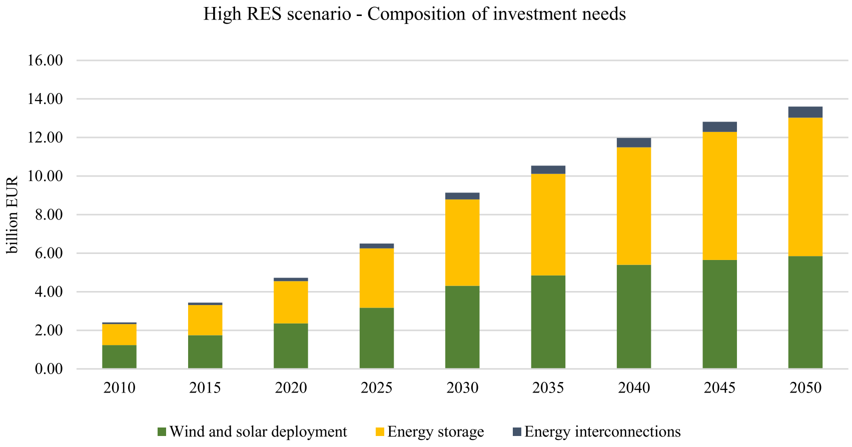


Graph 7. Electricity generation from RES under the High RES scenario and target required.

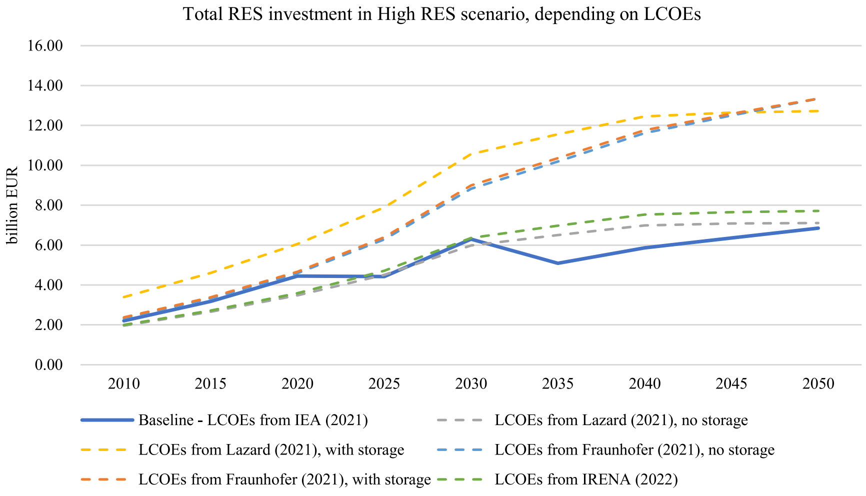
of 175 Gwh of electricity from renewable sources is installed by 2035 and 239 Gwh by 2050. As shown in Graph 5, achieving this in Spain would entail a total investment of 13 billion euros: this is but a small fraction of the total amount of investment in renewables for the entire energy sector foreseen in the Spanish National Energy and Climate Plan, that is, 91.76 billion euros (MITECO, 2020b).

The description of results achieved in High RES can be supplemented by analysing the composition of the needed investments to deploy the scenario in the Spanish electricity system. This is shown in Graph 8. As explained in Section 4, the use of LCOEs from Fraunhofer (2021), which foresee the deployment of energy storage to integrate solar energy at utility scale; together with the estimations from Red Eléctrica de España (2019b) on the additional interconnections for renewables allows us to decompose the subtotals of the needed investment in three categories: the deployment of wind and solar itself, energy storage and interconnections. Such three categories combine provide an estimation on the needed investments to implement the High RES scenario while accounting for the reality of the Spanish electricity system on the ground. As can be seen from Graph 8, for the implementation of the scenario it is equally important to secure sufficient investments in wind and solar deployment as for energy storage. This is coherent with the findings of Abadie and Chamorro (2021), which, as mentioned in Section 4, stress the specific importance of energy storage in Spain given the isolation of the Spanish electricity system. Finally, the needed investments in energy interconnections for the integration of renewables, even if sizeable (i.e. 570 million euros by 2050) represent a minor fraction of the total investment over the time horizon.

Lastly, and on the basis of the literature review presented in Section 4, a sensitivity analysis on the underlying LCOEs for the investment needed under the High RES scenario has been performed. The results are shown in Graph 9 below. As it can be observed, the required total investment for the deployment of renewables varies substantially depending on whether the LCOEs used in the model include or not energy storage, increasing remarkably when the latter is considered. However, and as explained in the LCOEs literature review in Section 4 and its results in the Appendix, an important caveat needs to be considered when relying on LCOEs for utility-scale storage solutions for renewables in the analysis of IAM results. The values of these indicators vary greatly across literature, as the total cost depends on different elements and assumptions such as the location of the renewable energy plants, the materials used in the batteries or other factors i.e. solar irradiation and energy grid losses (Chun Sing and Mcculloch, 2016; Ziegler et al., 2019; Fraunhofer, 2021; Lazard, 2021). In any case, in spite of these difficulties, when considering energy storage in the results from the High RES scenario of the presented model, the findings still point out at the fact that regardless of the potential LCOE options to be chosen for the modelling available across literature, deploying renewable energies to decarbonise electricity supply in Spain is always a more cost-effective option than continuing with the emissions associated with electricity generation and its associated losses in the BAU scenario (i.e., 160 billion euros by 2050, as shown in Graph 4).



Graph 8. Composition of investment needs of High RES scenario.



Graph 9. LCOE sensitivity analysis results.

6. Conclusion and policy implications

In this paper, an Integrated Assessment Model has been presented for the assessment of the economic and environmental impacts of various decarbonisation pathways for electricity generation in Spain from 2010 to 2050. The model has been developed using the DICE-R 2013 model by Nordhaus and Sztorc (2013) as a starting point, whereby the most up-to-date and relevant literature on damage functions and social welfare discounting is incorporated, together with the most adequate and widely used data sources on electricity shares and costs (European Commission, 2011; Red Eléctrica de España, 2019b; European Commission, 2021c; Fraunhofer, 2021; IEA, 2021). In addition, the specific situation of the Spanish electricity system (i.e. its isolation to the rest of the EU in terms of interconnections) as well as the needs for additional energy storage to accommodate intermittent renewable energies such as wind and solar have been integrated as framework conditions to the model.

The outcome is a model capable of comparing the potential consequences of introducing different levels of ambition in the decarbonisation of electricity, which constitutes a key pillar of climate change policies. This provides a highly relevant tool for policymaking, since it enables Spanish authorities to compare various policy options, anticipate their effects on social welfare, and foresee the investment needs for the deployment of renewables (wind and solar), energy storage and additional energy interconnections over a long time horizon.

A total of five scenarios have been compared with the proposed model. The results show a strong preference for scenarios in which deep cuts in CO_2 emissions from electricity generation are achieved. Conversely, the negative effects on social welfare from climate damage caused by the persistence of fossil fuels in the electricity mix are worthy of note: the BAU scenario, used as a baseline for the assessment, shows significantly lower social welfare values and cumulated losses in all periods of the time horizon. Such losses, estimated to be worth 160 billion euros by 2050 in the BAU scenario, are much higher than the mitigation costs of the most ambitious scenario (High RES), equal to 13 billion euros. The message is therefore clear: a polluting electricity mix has already become a much more expensive option in the long term than a renewable electricity mix.

Several extensions of this model can be applied, which provide room for further research. In addition to adding other possible scenarios or disaggregating the assessment to make the model granular to key electricity demand sectors (i.e., buildings, industry, transport), one possible improvement could be made upon introducing geographical data to enable the model to display optimal locations for the deployment of the scenarios, not only in terms of economic costs, but also environmental impacts on biodiversity, protected ecosystems, and landscape.

CRediT authorship contribution statement

Luis Antonio Galiano Bastarrica: Conceptualization, Formal analysis, Investigation, Writing – original draft, Writing – review & editing. **Eva M. Buitrago Esquinas:** Data curation, Supervision, Funding acquisition, Writing – review & editing. **María Ángeles Caraballo Pou:** Methodology, Validation, Resources, Writing – review & editing. **Rocío Yñiguez Ovando:** Project administration, Validation, Funding acquisition, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

We have attached the data and model file as additional material in the revised submission. We are willing to share this data and file in open access if the paper is published.

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Appendix

Table 2 below summarises the parameters used in the model including their value and source.

Table 2
Modelling parameters, by source

General parameters

Description	Symbol	Value	Unit	Source & notes
Initial population growth rate	g_L(0)	0,02300	2.3% annual increase	EU Reference Scenario 2020 (European Commission, 2021c)
Parameter affecting population growth	delta_L	0,052	parameter	Nordhaus and Sztorc (2013)
Spain population in 2010	L(0)	46,487	million people	INE (2022). Spanish National Statistics Institute
Initial TFP	A_0	3,80	parameter	Nordhaus and Sztorc (2013)
Initial TFP growth rate	g_A0	0,079	parameter	Nordhaus and Sztorc (2013)
Change in productivity growth rate	delta_A	0,006	parameter	Nordhaus and Sztorc (2013)
Parameter affecting productivity growth due to change in temperature	gamma	0,001	parameter	Nordhaus and Sztorc (2013)
Spain GDP in 2010	Y(0)	1078989	M€15	EU Reference Scenario 2020 (European Commission, 2021c)
Initial cumulated CO2 emissions	CC(0)	530	billion tons CO2 already emitted globally	Nordhaus and Sztorc (2013)
Carbon to CO2 conversion rate (44/12)	CtoCO2_cr	3667	parameter	Chemistry
Carbon-Climate Response parameter	CCR	0,0018	parameter showing temperature increase per cumulative 000 Gt of CO2eq emitted in the atmosphere	Matthews et al. (2012). Parameter showing a close to linear relationship at a 95% confidence for the model array studied in the paper
Weitzman damage function parameter 1	D_1	20,46	parameter	Weitzman (2010)
Weitzman damage function parameter 2	D_2	2	parameter	Weitzman (2010)
Weitzman damage function parameter 3	D_3	6081	parameter	Weitzman (2010)
Weitzman damage function parameter 4	D_4	6754	parameter	Weitzman (2010)
Savings rate	s	0,12	rate	Eurostat (2023). Average household saving rate from 2010 to 2020
Initial capital depreciation rate	delta_0	0,1	parameter	Nordhaus and Sztorc (2013)
Change in depreciation rate due to temperature	delta_1	0,001	parameter	Stern (2013)
Cobb-Douglas: exponent capital	alfa	0,4	parameter	Taken from literature review on the empirical range of this parameter among others done in Macías and Matilla-García (2015) where based on results from Bentolila and Saint-Paul (2003) they estimate an alpha of around 40% for OECD countries
Rate of pure time preference (for utility discounting)	rho	0,015	parameter	Various sources, mainly aligned with Stern review as welfare of future generations is highly valued and climate policy is more stringent
Rate of change in marginal utility for each level of per capita consumption - for utility function	eta	1	Parameter - change in marginal utility for each level of per capita consumption	Necessary level of “eta” to have an iso-elastic utility function (Norstad (1999), in which allocation results in the scenario are not sensible to the distribution of wealth. “eta”. In our IAM we follow the example of the PAGE2002 model and take the case of eta = 1, as this allows the aggregation of the impacts in per capita consumption into the welfare function (Hope, 2006)
Exchange rate from US $ to €	N/A	0.9421	exchange rate USD vs EUR	European Central Bank (2023), from 04/03/2023.
Exchange rate from € to US $	N/A	1.0615	exchange rate EUR vs USD	European Central Bank (2023), from 04/03/2023.
Additional costs per MWh for additional electricity interconnections for renewables	N/A	2.55	US $ per MWh	Red Eléctrica de España (2019b). Calculated taking as a starting point the additional investment needs foreseen in the report for the deployment of 89 GW of wind and solar (1872 M€) for a period of six years (2021–2026).
Mitigation parameters *(Used in scenarios other than BAU)*				
Description	**symbol**	**value**	**unit**	**source & notes**
Initial abatement cost parameter	omega_0	0,06	parameter	Nordhaus (2007)
Exponent abatement cost function	theta_AC	2,8	parameter	Nordhaus and Sztorc (2013)

Table 3 below summarises the results of the LCOE literature review referred to in Section 4.

Table 3
Literature review on LCOEs

LCOEs literature review results

	IRENA (2022)	Fraunhofer (2021)	Lazard (2021)	IEA (2021)
Solar PV, no storage (US $/MWh, average)	46.31	46.65	34.00	37.00
Solar PV with storage (US $/MWh, average)	*N/A (not provided)*	77.75	70.50	*N/A (not provided as single data point)*
Wind (incl. offshore and onshore), no storage (US $/MWh, average)	52.09	82.93	53.00	47.00
Wind (incl. offshore and onshore) **with storage** (US $/MWh, average)	*N/A (not provided)*	*N/A (provided only for Solar PV)*	89.50	*N/A (not provided as single data point)*
Nuclear (US $/MWh, average)	*N/A (not in scope of the study)*	*N/A (not in scope of the study)*	167.50	128.30
Fossil fuels (incl. solids, oil, and gas fired) (US $/MWh, average)	*N/A (not in scope of the study)*	144.38	113.83	162.50

(*continued on next page*)

Table 3 (*continued*)

LCOEs literature review results				
	IRENA (2022)	Fraunhofer (2021)	Lazard (2021)	IEA (2021)
% of LCOE decrease per year (used in LCOEs sensitivity analysis in case of no projection by 2050)	*5.7% for wind and 8% for solar per year for the period 2010-2021*	*Projections by 2040 for the particular case of Germany are already provided in the report: changing the units of the report to US $/MWh the results for 2040 are 44.5 for Solar PV, 46.65 for Solar PV with storage and 67.1 for wind (average including onshore and offshore)*	*6% for wind and 7.5% for solar per year for the period 2009-2021*	*Projections by 2050 are already provided in the report and are included in all scenarios in the model*
Does the report incorporate LCOE projections that evolve over time at least until 2050?	*No*	*No*	*No*	*Yes*
Does the report include figures to the particular case of Europe?	*Yes*	*No*	*No*	*Yes*
Notes on assumptions in each source	Data with no particular geographical scope. Data in energy storage is provided in Box 3.2 (page 94) of the report but for the particular case of behind-the-meter residential lithium-ion batteries in Europe, contrary to utility scale as the other reports which therefore cannot be compared with other figures.	Data for the particular case of Germany. As for all other cases, we take values for utility-scale PV. In this report, data on the LCOEs is provided only for the case of Solar PV utility scale and not as an independent data point. The values for the different LCOEs are taken as an estimation from the values in Figure 5 of the report (page 17). Nuclearslf is not part of the scope of the report.	Data with no particular geographical scope. For Solar PV, two types are provided: Crystalline Utility Scale and Thin Film Utility Scale - we take the average of the two. For wind, a higher LCOE is given for the particular case of offshore, which is included in the calculation of the average LCOE. For nuclear and fossil fuels, the LCOEs corresponding to fully depreciated assets is not considered. For gas, the case of using green or blue hydrogen reported by Lazard is not considered.	Data taken for the particular case of Europe. Table A3 includes data on battery storage at global level but only for the particular case of transport (EVs). In addition, in Figure 4.18 of IEA electricity system flexibility is considered as well – a large part of the flexibility is provided by a considerable deployment of batteries and demand response systems, but LCOEs on such storage is not provided.

The full code and parameters of the presented model has been made available in Excel format for full disclosure and further use by interested researchers in the following link of the files repository system of the University of Seville: https://idus.us.es/handle/11441/145566.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.enpol.2023.113592.

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Environmental adjustment of the EU27 GDP: an econometric quantitative model

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Abstract
The use of natural resources as an input to economic growth and the interactions between economic and ecological systems have resulted in an accumulation of environmental externalities. This accumulation can negatively affect future levels of welfare and economic growth. In this paper, such dynamics are assessed and quantified by introducing explicit environmental externality variables in a production function. This is performed in an endogenous growth model where cumulative environmental externalities interact with economic growth. Using efficiency analysis, a dynamic econometric model is estimated showing the significance of a negative influence of past levels of use of natural resources on GDP over a broad range of stochastic frontier analysis estimations. The results are applied to propose an alternative specification to the production function of a modelling tool used by the European Commission for the assessment of climate policies in the European Union. The findings show that observed GDP is overestimated when environmental externalities are not considered.

Keywords Economic growth · Climate change · Environmental externalities · Production functions · Stochastic frontier analysis · Natural resources

1 Introduction

Climate change is the most pressing challenge facing the global economy in the coming decades. Whilst the climate emergency gains wider political momentum and public policies shift from targets and roadmaps for climate neutrality (European Commission 2019) to specific policies to reduce greenhouse gas (GHG) emissions (i.e. the "Fit for 55" package in the European Union) (European Commission 2021), new and fundamental questions arise. Will climate policies reduce the dependency of economic growth on natural commodities? Will we be able to maintain the current levels of welfare and living conditions in a decarbonised world? Such questions, even if uncomfortable, need to be addressed when designing credible climate policies. If such policies are not put in place, the maintenance of current living conditions will inevitably result in increased environmental costs that will need to be paid by the current and future generations. This paper aims to quantify these dynamics by including proxy variables for the use of environmental resources (in particular, CO_2 emissions and material extraction) in a production function and by studying their dynamic relationship with the evolution of GDP for the 27 Member States of the European Union from 2000 to 2018. This will be carried out by using the concept of efficiency in production functions, and by analysing whether the accumulation of environmental externalities over time exerts an effect on productivity in economic growth.

Economic growth is often measured by the evolution of Gross Domestic Product (GDP) over time. As shown in Stratford (2020), the production of goods and services that amount to the total GDP in each period is largely reliant on the interplay of economic systems with their surrounding natural environment and on the use of natural capital or environmental goods. The evolution of GDP over time has

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frequently been explained by economists via the concept of the production function. Under this approach, the allocation of different proportions of production factors and their associated productivities constitute the main drivers of change in GDP, with the Cobb–Douglas production function as the cornerstone model (Cobb and Douglas 1928). The production function relies on the premise that the right combination of production inputs produces outputs that are to be considered "desirable", such as economic growth and increased wealth in the form of goods and services, whereas the correlative accumulation of bad outputs (i.e. in the form of increasing environmental damage due to the excessive use of natural goods as input for production processes) tends to be ignored.

Similarly, the Economy-Environment interplay has been largely overlooked in the analysis of economic growth (Mäler 2001; Moretti et al. 2021), despite the evidence that CO_2 increases global temperature and causes major environmental changes (Nordhaus 1991) and the persistent effects of previously emitted CO_2 and its associated environmental disruptions (IPCC 2018). These dynamics, in which economic growth is linked to an extensive use of natural resources, have been amplified by an ever-increasing availability of financial streams (Hagens 2020) that often fail to include the real environmental cost as a shadow price of financial decisions (Bulckaen and Stampini 2009). This has resulted in a parallel accumulation of costs in the form of negative environmental externalities that need to be mitigated by the current and future generations, who will bear most of the cost of climate change (Stern 2007; Tsigaris and Wood 2016).

The interactions between economic growth and material extraction have been explored from a variety of perspectives in the recent literature, including the concepts of eco-efficiency (Zabalza Bribián et al. 2011; Yu et al. 2018), exergy (Dai et al. 2014; Carmona et al. 2021), net primary productivity (Du et al. 2021), and in applications of Hotelling's model in the circular economy (Hoogmartens et al. 2018). All these approaches rely on one principle: economic growth has persistently been driven by an increasing and unsustainable pressure on natural material resources that needs to be considered in modelling applications. Conversely, the integration of these dynamics on production functions remains a largely unexplored line of research. Their inclusion is fundamental since, if environmental costs are not considered in a production function, modelling optimisations applied when designing public policy can lead to misleading outcomes in which an excessive use of environmental goods shows no repercussions on the projected economic growth. As pointed out by Moretti et al. (2021), accounting for these dynamics of environmental externalities is key to designing policy responses more accurately and it has been the focus of recent economic literature for a variety of sectors under different modelling approaches (Mangmeechai 2014; Kiet et al. 2020; Lv et al. 2020; Wang et al. 2020).

This paper assesses the integration of the Economy–Environment interplay in production functions. As a starting point, the following question is posed: Does the unconstrained use of environmental goods over time eventually become a negative determinant of economic growth? The answer, as explained below, requires taking an intermediate stance between macroeconomic and microeconomic levels. In this regard, we consider that Stochastic Frontier Analysis (SFA) provides the most appropriate modelling framework for a variety of reasons. First, SFA enables a deeper understanding of the influence of the accumulation of environmental externalities on economic growth (Wang et al. 2020). Second, SFA takes an intermediate approach between a macroeconomic estimation of production functions and a microeconomic estimation in which the abatement decisions of individual agents can be factored in. This approach aims to fill the gap existing between different modelling techniques, by using a similar rationale to that of Rogna (2020). Finally, by including explicit proxy variables representing environmental externalities in the parameters of the SFA model, a clearer representation is attained of the way in which the economy interacts with the environment, thereby allowing the quantification of the consequences of ignoring these interactions in the estimation of GDP.

The literature on SFA models is vast and has greatly evolved since the seminal papers by Aigner et al. (1977) and Meeusen and Van den Broeck (1977) to include a broad range of sectors and applications (Fernandez and Koop 2005). The added value of SFA lies in its ability to explain heterogeneity in observed values via the concept of distance to an unobserved frontier. When applied to production functions, SFA enables not only assessing the complexity of technical inefficiency for a given set of inputs (Mastromarco 2008), but also including exogenous variables as determinants of efficiency. The latter, however, has rarely been linked to environmental conditions (Wang et al. 2020) and provides opportunities for further research. Additionally, SFA approaches have hitherto been focussed on particular sectors with almost no attempts to estimate technical inefficiency in production functions in a macroeconomic context (de la Fuente-Mella et al. 2020).

Three contributions of this paper can be outlined. First, we propose an alternative specification of GDP that considers the intertemporal influence of negative environmental externalities. Second, this alternative specification is quantified through an SFA estimation of a production function that explicitly considers the macroeconomic impacts of environmental externalities. Finally, our results are applied to the model by Havik et al. (2014), which is a modelling tool for policy design developed for the European Commission. In particular, on the latter, we propose a modification of the Total Factor Productivity (TFP) specification to render the model sensitive to the accumulation of environmental externalities.

The paper is structured as follows. In Sect. 2, the relevant SFA literature and theoretical specification of the model are discussed. The proposed model and EU27 macroeconomic data are described in Sect. 3. Section 4 presents the results obtained for an array of SFA econometric estimations, whilst Sect. 5 covers the implications of the results for EU environmental policy and includes the proposal for a modification on the TFP specification of the model by Havik et al. (2014). Section 6 concludes.

2 Literature review

Empirical explanations of long-term determinants of economic growth using production functions can be traced back to the model by Harrod (1939), where long-term economic growth is explained through a dynamic set of factors that result in an oscillating steady-state equilibrium. The neoclassical growth models of Swan (1956) and Solow (1956) contested this result, arguing that it was built on the notion that production factors intervened in production functions in fixed proportions. This approach claimed that it was the variant combination of capital, labour, technical progress, and especially capital accumulation propelled by technological advancements that drove the economy towards a stable equilibrium. These models became the dominant line of reasoning in the explanation of long-term economic growth in the economic literature until the end of the twentieth century, and still exert decisive influence (Boianovsky and Hoover 2009). Environmental externalities, however, were not included in the analysis of growth.

In the 1990s, a new approach emerged with the models of Lucas (1988) and Romer (1990). This new paradigm paved the way to the estimation of production functions that included elements beyond just the usual production factors. Negative environmental externalities, understood as undesirable outputs of production processes that ultimately affect the path of economic growth in the long run, constituted one of these possible new elements.

A first contemporary approach to the estimation of production functions reflecting externalities is well presented by Burnside et al. (2006), where external effects are captured through the returns of scale of the production function with no explicit representation of undesirable outputs. The influence of external effects over production is considered only implicitly, and the key parameter to estimate is the change in the returns of scale of the production function given a change in the external effects (Basu and Fernald 1995). Conversely, there are contributions in which undesirable outputs are explicitly considered from which three subgroups can be identified, including a first family of "top-down" analyses, where the dynamics of externalities in production are analysed from a general perspective, by considering the economy as a whole and by estimating an environmental production function. A second subgroup of approaches can be referred to as "bottom-up" since they take the perspective of a rational economic agent and its incentives to reduce pollution. Finally, there is stochastic frontier analysis (SFA), which we identify as a middle option between the two aforementioned subgroups.

Within the "top-down" category, we include the approaches given by translog (transcendental logarithmic) and CES (constant elasticity of substitution) production functions. On the one hand, translog functions have been used extensively in the economic literature since they enable variability in the returns of scale of the production function (Boisvert 1982; Heathfield and Wibe 1987; Raihana 2012) and allow for a feasible estimation of environmental production functions (Zhou et al. 2014; Cisco and Gatto 2021). On the other hand, CES functions arise as a Cobb–Douglas extension that permit an elasticity of substitution between inputs other than unity (Heathfield and Wibe 1987), albeit for only a reduced number of production inputs (Henningsen and Henningsen 2011). These approaches enjoy the advantage of taking a broad perspective and aiming to estimate the production function for the entire economy of a country or sector(s); they are criticised, however, on the grounds of failing to take the perspective of the economic agent into consideration (Färe et al. 2007).

The "bottom-up" approaches estimate environmental externalities through their shadow prices. These are defined as the opportunity cost of desirable output to be surrendered by a rational agent in order to comply with environmental regulations and to reduce units of the associated undesirable output of the production process (Färe et al. 1993; Zhou et al. 2014). In other words, valuable production efforts are reallocated to mitigation, thereby causing an opportunity cost. Proponents of this approach argue that the perspective of the rational agent needs to be the viewpoint for the calculation of mitigation pathways, since, in the end, emission reduction efforts are largely carried out by private agents (Zhou et al. 2014). However, climate change remains a public policy issue, especially in Europe, where a public authority (i.e. EU institutions) calibrates targets and adopts regulations, whilst considering the economy as a whole and/or entire sectors.

In short, "bottom-up" approaches appear to be rather limited in their scope and fail to conceive climate change as a policy-driven issue (which is particularly the case in the EU), whereas the "top-down" approaches do not take the perspective of the representative agent into consideration. To overcome these drawbacks, in our understanding, an intermediate stance between these approaches needs to be taken, and this is where SFA can come into play. Therefore, SFA is employed in our estimations to include proxy variables representing environmental externalities (i.e. CO_2 emissions and material extraction) in addition to the usual production factors, together with two sets of control variables. This could be considered a “top-down” approach that takes a general perspective of economic growth and the economy as a whole. However, the use of stochastic frontier analysis as an estimation technique enables the ineffective behaviour of individual observations to be reflected within the sample (Mastromarco 2008), as well as external effects outside the sphere of control of the producer (Daraio and Simar 2005). Additionally, since SFA analyses how such behaviour influences efficiency, it therefore provides the appropriate modelling framework for the estimation of an environmental production function and for the proposal of a modification of TFP in the model by Havik et al. (2014), as presented later.

Stochastic frontier analysis was first proposed by Aigner et al. (1977) and Meeusen and Van de Broeck (1977). By introducing a composite error term that included individual technical efficiency, the authors estimated a frontier production function that explained the variance across individuals. The main benefit of this formulation is that it allows the maximum achievable output to be estimated given a set of inputs, thereby providing a more precise definition of the production function and the determinants of growth (Mastromarco 2008; Rao et al. 2019). The economic rationale of such an approach, as shown by Aigner et al. (1977), relies on considering elements which the individual economic agent can directly manage (such as production factors) together with elements that remain outside the agent’s direct sphere of control.

The economic literature has used efficiency analysis via SFA to study a broad range of policy-oriented fields (Lovell 1995; Fernandez and Koop 2005); this includes efficiency analysis that considers environmental conditions. Most examples of the latter are related to the quantification of environmental externalities on agricultural productivity (Reinhard et al. 1999), analysing the effects of the management of natural resources in development programmes (Bravo-Ureta et al. 2012) or quantifying the influence of externalities on crop yields (Kiet et al. 2020; Wang et al. 2020). However, these studies tend to ignore the accumulation of environmental externalities over time and take only sectoral perspectives. In our case, an SFA-based model is proposed. The model explicitly includes proxy variables that represent environmental externalities (in particular, CO_2 emissions and material extraction) to estimate a production function that accounts for intertemporal environmental effects whilst taking a macroeconomic approach. The contribution of the model consists of explicitly including the effects of environmental externalities in an econometric estimation to quantify their influence on economic growth, and of applying said model to the EU for comparison with observed data. To the best of our knowledge, no study of this kind can be found in the literature.

3 Data, model, and estimation

In this section, our model is presented and estimated for the EU27 data, which will enable implications for environmental policies to be extracted. In recent years, the European Commission has stepped up its policy efforts towards the goal of climate neutrality by 2050, as laid out in the European Green Deal (European Commission 2019) with policy initiatives such as the revised Circular Economy Action Plan (European Commission 2020a), the 2030 Climate Target Plan (European Commission 2020b), and the recent “Fit for 55” package (European Commission 2021). In this context, quantification of environmental externalities and their effect on economic growth constitutes a highly relevant task in the design of credible climate policy, hence the application of our proposed model to the EU.

3.1 Model description

The original SFA model by Aigner et al. (1977) can be expressed as follows:

$$y_{it} = f\left(x_{it}, \beta\right) + u_i + v_i, \tag{1}$$

where “y_{it}” is the production level in each period (t) for a set of individual observations (i), which in our case are the 27 Member States of the European Union. “$f\left[x_{it}(t), \beta\right]$” is the estimated frontier production function, “x_{it}” a vector of production inputs (in our case capital and labour), and “β” a vector of technology parameters. The model takes a composite error measure where “u_i” is a measure of technical inefficiency. “v_i” is a random error term. In the original model, time played no role in the determination of inefficiency (Aigner et al. 1977). This approach has been expanded to accommodate dynamic effects on all variables of the model, as carried out by Greene (2005)[1]:

$$y_{it} = f\left(x_{it}, \beta_{it}\right) + u_{it} + v_{it}, \tag{2}$$

where the variables are the same as in Eq. (1) but are allowed to change both across time and individuals in the sample. Following Kiet et al. (2020) and Wang et al. (2020), determinants of inefficiency linked to environmental externalities

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[1] We omit the firm-specific term of the Greene (2005) model, since the country-specific characteristics of the different Member States are captured by the control variables presented in Sect. 3.3.

can be introduced as additional variables within the inefficiency term, u_{it}. Hence, the following specification of the term is proposed:

$$u_{\mathrm{it}} = \sum_{j=0}^{n} \gamma_j mat_{\mathrm{it}-j} + \sum_{k=0}^{m} \delta_k \mathrm{CO2}_{\mathrm{it}-k} + \varepsilon_{\mathrm{it}}. \quad (3)$$

The specification of the inefficiency term (u_{it}) presented in Eq. (3) incorporates an intertemporal influence of environmental externalities quantified by lags up to a generic "*n*" and "*m*" order for material extraction and CO_2 emissions, respectively. Such intertemporal relation tries to capture the persistent effects of environmental externalities on economic growth, which have been explored in the relevant literature, whereby for instance past levels of emissions reduce the remaining carbon budget and therefore imply negative economic effects (Capellán-Pérez et al. 2014; Friedlingstein et al. 2014). The choice of using lags in Eq. (3) is an attempt to model such effects in a SFA modelling context. $\varepsilon_{\mathrm{it}}$ is a random, white noise error term.

In most of the applied SFA modelling literature, the parameters of interest to be estimated are those contained in the technology vector β in Eq. (2), since they represent the marginal contribution of each production input (Rao et al. 2019). However, in our case, the relevant parameters are those of the variables representing environmental externalities (γ_j and δ_k) since they represent the quantified effect of CO_2 emissions and material extraction on GDP. With the econometric estimation of the model, we intend to test whether a representative lag specification of both variables in the sample range for EU27 exists, which serves as our initial modelling hypothesis.

The model presented in previous equations needs an explicit functional form to be estimated. There are sufficient examples in the literature that point out the utility of using a simple Cobb–Douglas production function for this purpose (Havik et al. 2014). Our function appears as follows:

$$Y_{\mathrm{it}} = A_i \times K_{\mathrm{it}}^{\beta_1} \times L_{\mathrm{it}}^{\beta_2} \times \Phi_{\mathrm{it}}, \quad (4)$$

where Φ_{it} is the intertemporal externality term in Eq. (3) in its exponential form, that is:

$$\Phi_{\mathrm{it}} = \prod_{j=0}^{n} MAT_{\mathrm{it}-j}^{\gamma_j} \times \prod_{k=0}^{m} \mathrm{CO2}_{\mathrm{it}-k}^{\delta_k}. \quad (5)$$

The parameters (to be estimated by SFA) are those in Eqs. (3) and (4). The constant A_i refers to neutral technological change. Equation (2) can be fitted in Eq. (4) by taking logarithms, which will also facilitate the comparison with other modelling approaches and the interpretation of the results in terms of elasticities. The final model to be estimated is therefore the following:

$$y_{\mathrm{it}} = a_i + \beta_1 k_{\mathrm{it}} + \beta_2 l_{\mathrm{it}} + \sum_{j=0}^{n} \gamma_j mat_{\mathrm{it}-j} + \sum_{k=0}^{m} \delta_k \mathrm{CO2}_{\mathrm{it}-k} + v_{\mathrm{it}}. \quad (6)$$

3.2 Sample and measures

The proposed model in Eq. (6) will be applied to a selection of key variables observed in the 27 Member States of the European Union during the latest longest available period in Eurostat: 2000 to 2018. Gross Domestic Product (Y) will be the explained variable of the model and, together with Gross Fixed Capital Formation (K), it is expressed in real terms to prevent price-related distortions. To this end, the Eurostat deflator with base 2015 for every year and Member State has been used (Eurostat 2021). As a proxy for labour (L), people aged between 15 and 64 from the Eurostat Labour Force Survey (Eurostat 2020a) have been considered.

The proxy variable for materials (Mat), Direct Material Inputs, is calculated by Eurostat as the sum of all materials extracted in Europe (known as domestic extraction) and materials imported from non-EU countries for all branches of activity (Eurostat 2020b). This yields a measure of the total extraction generated by economic activity, either inside the economy or in foreign markets, thereby accounting for the total input of materials outsourced from the environment. As for emissions (CO_2), we limit ourselves to the case of carbon dioxide, since it provides better data availability and is the most commonly present particle in air pollution in developed countries (Eurostat 2020c; Stern 2017). Table 1 shows the main variables and descriptive statistics.

3.3 Adjustments to the sample

Several adjustments to the dataset of the key variables shown in Table 1 were implemented prior to the econometric estimations. First, the outlier detection routine by Verardi and Dehon (2010) was applied, which led to the exclusion of Malta from the analysis. Second, cluster-robust standard errors were employed, which have also been implemented by clustering Member States in order to factor in heterogeneity between the different countries. Logs of all variables were also taken, not only to account for the functional form described in Eq. (4), but also to render homogeneous units of measurement of the variables reported in Table 1.

Emissions and resource utilisation tend to show strong correlation with GDP, which can lead to the omitted variable bias and misleading results if a sufficient set of control variables is not included in the econometric estimation. To avoid this, two sets of control variables have been introduced as reported in Table 2. On the one hand, time dummy variables for the years 2008, 2009, and 2010, reflect the effects of the crisis that were still structurally negative during those

Table 1 Descriptive statistics for key variables

Variable name	Unit	Code	Observed values	Mean	Standard deviation	Min. value	Max. value
Gross domestic product	Millions of euros	Y	513	369,274.57	610,653.32	3032.24	3,504,696.19
Gross fixed capital formation	Millions of euros	K	513	80,104.77	127,913.13	721.04	753,744.44
Labour	Thousands of people	L	510	6696.91	8923.85	143.00	40,636.00
Direct material inputs	Thousands of tonnes	Mat	513	320,305.42	381,375.69	3450.17	1,754,895.74
Carbon dioxide emissions	Thousands of TOEs	CO2	513	115,256.46	175,909.89	−3887.52	891,957.83

Individuals in the sample are the Member States of the European Union (without counting Malta, which is omitted after having been identified as an outlier in the sample) with data from 2000 to 2018 inclusive. All data comes from the Eurostat Database (Eurostat 2021)

Table 2 Estimation results

	Time-varying parametric model (Kumbhakar 1990)	Time-varying decay model (Battese and Coelli 1992)	Inefficiency effects model (Battese and Coelli 1995)	Time-invariant model with half-normal distribution (Pitt and Lee 1981)	Time-invariant model with truncated-normal distribution (Battese and Coelli 1988)	True random effects model with half-normal distribution (Greene 2005)	Generalised least squares
Model type	FE; TV; HN	FE: TV; TN	RE; TV; TN	FE; TI; HN	FE; TI; TN	RE; PI; HN	RE; N/A; N/A
Key variables							
$\ln K_t$	0.857*** (0.053)	0.997*** (0.043)	1.006*** (0.046)	0.969*** (0.075)	0.969*** (0.077)	0.906*** (0.079)	0.942*** (0.079)
$\ln L_t$	0.284** (0.093)	0.257** (0.096)	0.245* (0.099)	0.298* (0.161)	0.297* (0.165)	0.364** (0.129)	0.328* (0.172)
$\ln \text{Mat}_t$	−0.589*** (0.111)	−0.907*** (0.173)	−0.894*** (0.208)	−0.858*** (0.138)	−0.858*** (0.137)	−0.515** (0.183)	−0.829*** (0.136)
$\ln \text{Mat}_{t-1}$	0.359** (0.116)	0.585** (0.176)	0.579** (0.201)	0.499** (0.171)	0.499** (0.171)	0.182 (0.142)	0.494*** (0.176)
$\ln \text{CO2}_{t-2}$	−0.040 (0.026)	−0.129* (0.060)	−0.123* (0.071)	−0.131* (0.063)	−0.131* (0.063)	−0.044 (0.064)	−0.141* (0.071)
$\ln \text{CO2}_{t-3}$	0.096* (0.055)	0.166* (0.075)	0.161* (0.084)	0.176* (0.068)	0.176** (0.067)	0.034 (0.058)	0.156* (0.064)
Control variables							
d2008	0.003 (0.027)	−0.176*** (0.031)	−0.182*** (0.029)	−0.167*** (0.038)	−0.167*** (0.038)	−0.133*** (0.028)	−0.161*** (0.038)
d2009	0.042 (0.035)	−0.152*** (0.042)	−0.158*** (0.034)	−0.140*** (0.037)	−0.140*** (0.037)	−0.116*** (0.031)	−0.135*** (0.037)
d2010	0.060* (0.033)	0.008 (0.029)	0.004 (0.024)	0.007 (0.025)	0.007 (0.025)	−0.024 (0.032)	0.011 (0.024)
Middle	−0.129* (0.061)	−0.138* (0.066)	−0.131* (0.071)	−0.149 (0.092)	−0.167 (0.095)	−0.158* (0.095)	−0.187* (0.098)
Low	−0.158* (0.094)	−0.125* (0.070)	−0.107 (0.072)	−0.063 (0.076)	−0.140 (0.092)	−0.086 (0.103)	−0.209* (0.091)
Cons	3.043*** (0.484)	3.022*** (0.570)	3.071*** (0.582)	3.507*** (0.931)	3.506*** (0.945)	3.927*** (0.596)	3.468*** (0.967)
Parameters							
σ_u	0.305*** (0.037)	–	0.687 (0.543)	0.194*** (0.045)	0.194*** (0.048)	0.265*** (0.040)	0.126
σ_v	0.133*** (0.019)	0.036 (0.008)	0.173** (0.053)	0.158*** (0.181)	0.158*** (0.005)	0.024 (0.034)	N/A—Non-SFA model
Log-likelihood	211.848	99.462	99.737	146.681	146.681	173.632	N/A—Non-ML estimation

FE fixed effects, *RE* random effects, *TV* time-varying SFA model, *TI* time-invariant SFA model, *PI* persistent inefficiency model, *HN* half normal distribution for the inefficiency term, *TN* truncated normal, σ_u standard deviation of measured inefficiency, σ_v standard deviation of error term

***, **, *Denote that the coefficients are significant at 1%, 5%, and 10% levels, respectively. The *z*-statistics are given in parentheses years (Altdorfer 2017). On the other hand, structural dummy variables further account for the heterogeneous income distribution across Member States of the European Union (Fredriksen 2012). In Table 2, EU27 has been divided into three groups in terms of income ("high income", "middle income", and "low income") by ranking them according to per capita GDP in Purchase Power Parity from 2018, the latest year for available data (Eurostat 2020d).[2] The data has then been sorted into a stacked time series in terms of Member State and imported into STATA for dynamic panel data SFA analysis using the "sfpanel" STATA code package developed by Belotti et al. (2013).

Thus, the model to be estimated is specified as follows:

$$y_{\text{it}} = a_i + \beta_1 k_{\text{it}} + \beta_2 l_{\text{it}} + \sum_{j=0}^{n} \gamma_j mat_{\text{it}-j} + \sum_{k=0}^{m} \delta_k \text{CO2}_{\text{it}-k} + d2008 + d2009 + d2010 + middle + low + v_{\text{it}}. \tag{7}$$

Although several econometric techniques are available for the estimation of Eq. (7), the Maximum Likelihood Estimation method (MLE) remains as the reference method used across a wide range of applications within the relevant SFA literature (Greene 1982; Mastromarco 2008). For our data, MLE seems to be more appropriate than other available alternatives such as Data Envelopment Analysis (as carried out in Sueyoshi et al. 2017; Yu et al. 2018) and the Generalised Method of Moments (as in Acheampong 2018) for several reasons. On the one hand, our sample is large (27 individuals observed over 19 years covering 5 variables). For large samples, the parametric assumptions underlying the MLE method are more suitable to the observed data, and its results remain largely robust compared to other estimation techniques, such as the Generalised Method of Moments (Behr and Tente 2008).

On the other hand, MLE is related to the incidental parameter problem (Lancaster 2000), under which the number of parameters to be estimated increases with the number of observations (Emvalomatis et al. 2011). This problem, however, arises when the number of individuals observed in the sample is large and the time horizon is relatively short (Belotti et al. 2013). Our panel is sufficiently balanced between individuals and time since 27 individuals are observed over 19 periods.

Regarding the modelling of the lags in the variables representing environmental externalities (material extraction and CO_2 emissions), an initial estimation of lags up to an order of $t-10$ has been tested. Given the length the time horizon ($t=18$), beginning the time series analysis by $t-10$ is considered a sufficient starting point. Several rounds of econometric estimations using different SFA approaches were done, arriving to a parsimonious model where a maximum number of lagged variables were significant. The results are presented in the next section.

4 Results

The results of econometric modelling using SFA are shown in Table 2 across a broad range of SFA estimations and as a GLS-based benchmark, as shown in Greene (2005). The reason for the application across this range of estimations is to ensure that the results obtained from the econometric analysis involve a truly empirical relationship between the variables, specifically regarding the dynamics of the environmental externality variables on GDP in the production function. As explained in Sect. 3, Table 2 shows the distribution of lags in material extraction and CO_2 emissions that obtains a parsimonious model in most estimations.

The reasoning underlying the selection of these particular estimation methods can be summarised as follows. All models presented in Table 2 are panel data models and use maximum likelihood for the estimation of the coefficients. Other approaches, such as those presented in Schmidt and Sickles (1984), Cornwell et al. (1990), and Lee and Schmidt (1993), have been omitted from the analysis since they use other estimation techniques to render the results more comparable. Most of the models presented in Table 2 are based on fixed-effect panel-data estimation techniques since the observed sample of countries remains the same over time. However, random-effect approaches, such as those presented in Battese and Coelli (1995) and in Greene (2005) are also included to render the SFA modelling sample more representative.

It is particularly relevant to estimate the model by Greene (2005), given its potential to consider unobserved heterogeneity when estimating inefficiency (Kumbhakar et al. 2015), although the large number of parameters to be estimated makes the incidental parameter problem an issue for the inference of the results (Belotti et al. 2013). The result of the Greene (2005) specification is therefore to be interpreted cautiously. The fixed-effect models by Kumbhakar (1990) and Battese and Coelli (1992) estimate SFA production frontiers with a lower number of individuals in the sample, but a time horizon similar to our case. However, these approaches estimate a common intercept for all individuals in the sample, thereby leading to problems of misspecification (Belotti et al. 2013). Conversely, in Pitt and Lee (1981) and Battese and Coelli (1988), larger panels of individuals are analysed

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[2] This has resulted in the following categories: A first group of "high-income" Member States includes AT, BE, DE, DK, FI, IE, LU, NL, and SE. This category constitutes the reference group and is therefore not included in the econometric estimations. A second category, classified as "middle-income" countries, includes CZ, CY, ES, FR, IT, LT, SI, and SK. The remaining countries, BG, EE, EL, HR, LV, HU, PO, PT, and RO, are listed under "low-income".

but over shorter times (only three periods), and inefficiency is assumed to be time-invariant.

A second classification across the different SFA estimations can also be made in terms of the way in which time is dealt with in each model, between time-varying (where inefficiency is expected to be largely explained by time rather by the differences between individuals in the sample) and time-invariant, with the opposite assumption. In our case, the observed data regarding the number of individuals ($N=26$) is more prolific than in the number of time periods ($t=19$), but this difference is only slight, hence the presentation of both time-invariant and time-varying approaches appears to be appropriate.

The results from Table 2 suggest a negative correlation of CO_2 emissions and material extraction with GDP. When each of the environmental externality variables approaches $t=0$, their contribution to the overall efficiency changes from a positive to a negative sign. The negative effect of the externality over the overall production efficiency in the frontier is more pronounced in the case of materials than in CO_2 emissions. Importantly, these results hold coherently across all SFA estimations presented in the table with significant results, including the GLS benchmark. The sum of the technology coefficients of the standard production inputs (capital and labour) is roughly equal to 1 across all estimations, which supports the general assumption of constant returns to scale of the production function and greatly simplifies the estimation and interpretation of the results (Havik et al. 2014).

Our results are partially in line with those found by Capello (1998) and Wang et al. (2020), insofar as these authors argue the presence of environmental externalities as a significantly negative factor of change in economic growth that should be modelled in the framework in production functions. Furthermore, our results seem to indicate the existence of a tipping point beyond which environmental externalities generate an intertemporal shadow price on economic growth. Beyond a certain threshold in the past use of environmental commodities, the associated environmental externalities begin to exert negative consequences on economic growth. This can be explained by the current climate policy context: the longer climate action is delayed, the more costly and stringent mitigation and adaptation policies need to become (IPCC 2018).

Importantly, the obtained results also reflect the notion of intergenerational equity: the negative effects of externalities associated to past levels of economic growth (expressed by the coefficients of the model) persist until the present, thereby imposing external costs on the current generation. Policymakers therefore face the trade-off between either surrendering present welfare in order to guarantee the wellbeing of future generations by establishing a strict climate policy or leaving most of the effort to future generations (mostly on climate adaptation) by adopting a more relaxed approach on mitigation at present (Stern 2007). The implications of these dynamics have been assessed by the United Nations as one of the main factors to be considered in cost–benefit analyses of climate policy (United Nations 2013; Skillington 2019).

The notion of intergenerational equity is related to the scarcity of environmental commodities, which also explains the modelling results of Table 2. The successive extraction of materials from the environment and/or the emission of CO_2 over time reduce the availability of their associated environmental goods (Common 1996), that is, remaining materials and air quality, respectively. Economic growth relies on the use of these environmental commodities, but when they become increasingly scarce, a negative influence on economic growth can be observed, hence the values obtained in the coefficients of the model. This assumption uses a similar reasoning to that of the Environmental Kuznets curve (Dinda 2004; Marsiglio et al. 2016; Stern 2017), but applied to environmental externalities: when undesirable outputs are accumulated up to a tipping point, they start affecting economic growth negatively (Selden and Song 1994; Dinda 2004; Yu et al. 2018). Following Moretti et al. (2021), we identify the use of natural resources for the production of economic goods as the determinant of environmental externalities. Under this approach, for the case of material extraction, the increasing need for the production of additional goods stemming from economic growth translates into an ever-increasing scarcity of the materials required, which in turn increases their price and eventually harms economic growth itself. For emissions, the feedback loops are more complicated since they entail the reduction of air quality and associated damage linked to the accumulation of CO_2 emissions. From an economic perspective, and analogously to the case of materials, the increasing need for additional production translates into higher emissions, thereby resulting in increasing environmental damage, thereby also harming economic growth.

The model confirms the initial modelling hypothesis, and provides further insights on the interaction between economic growth and environmental commodities that are coherent with the economic reality. Values closer to the present ($t=0$) can be expected to affect economic growth more negatively (hence the marginally higher values of the obtained coefficients closer to $t=0$), as they have accumulated for a longer period than the same variables observed at a previous moment in time. The effect, however, differs between externalities. Whilst materials become scarce at the very same moment of extraction ($t=0$), CO_2 emissions take longer periods of time to accumulate in the atmosphere and then influence economic growth (Tsigaris and Wood 2016).

All estimations show similar coefficients, both of the technology and the externality parameters, with the exception of the model by Kumbhakar (1990), which shows a downward bias. Except for the case of Greene (2005), all variables show appropriate levels of individual significance. One possible explanation for the differences in the results from the Kumbhakar (1990) model involves its underlying assumptions, which make it fit for any variation (of any sign) on the efficiency in the frontier, whereas in our model this effect is largely of negative sign. Another comparison can be drawn in the results if we distinguish between the random and fixed-effect approaches. Overall, in our case, a fixed-effect modelling approach seems justified from a theoretical standpoint, since the same set of individuals (EU Member States) are observed over the time horizon.

Finally, it can also be noted that time-invariant models show a marginally better fit in terms of log-likelihood than do time-varying models. This is, to a certain extent, coherent with the economic reality. Given the still large and structural differences in income across EU27, better results are achieved by models that estimate inefficiency by granting special importance to these differences that persist over time (Fredriksen 2012). The best results combining significance, log-likelihood, and appropriateness to the data observed are those coming from fixed-effect, time-invariant models such as those proposed by Pitt and Lee (1981) and Battese and Coelli (1988), which yield almost identical results. However, the Pitt and Lee (1981) model in the original paper by the authors is applied to a dataset that is much more similar to our case. The latter, therefore, yields the most relevant result and is hence the one selected for the Discussion section below.

5 Discussion: implications on environmental policy

5.1 Proposed modification to the Havik et al. (2014) model

For the reasons laid out in the section above, we have chosen the Pitt and Lee (1981) estimation results to trace the economic policy implications of our findings. To this end, we apply these results to the production function methodology used by the European Commission for the calculation of potential growth rates and output gaps, as developed by Havik et al. (2014). The production function in this model also features capital and labour, as does ours, although no attention is paid to environmental dynamics and externalities. In this respect, the dynamics captured by Eq. (6), under the Pitt and Lee (1981) estimation shown in Table 2, can be used to render the production function of the Havik et al. model sensitive to such interactions. Since an SFA estimation has been utilised that allows us to reason in efficiency terms, the TFP specification of the model is the appropriate place to include our proposed modification (Kiet et al. 2020; Wang et al. 2020).

The production function in Havik et al. (2014) is a Cobb–Douglas production function with capital and labour adjusted for capacity utilisation and efficiency:

$$Y = L^{\alpha} K^{1-\alpha} \mathrm{TFP}, \tag{8}$$

where total factor productivity (TFP) is defined as:

$$\mathrm{TFP} = \left(E_L^{\alpha} E_K^{1-\alpha}\right)\left(U_L^{\alpha} U_K^{1-\alpha}\right). \tag{9}$$

The first term of TFP accounts for the adjustment on the overall level of efficiency. E_L and E_K account for efficiency of labour and capital respectively, adjusted by a technology parameter (α). The second term captures excess capacity (represented as U_L and U_K, utility coefficients of labour and capital respectively, also adjusted by α) (Havik et al. 2014). Kiet et al. (2020) and Wang et al. (2020) show that environmental externalities can be introduced as additional variables within the inefficiency term in SFA models. The following modification to the specification of TFP can therefore be proposed on the basis of our results:

$$\mathrm{TFP} = \left(E_L^{\alpha} E_K^{1-\alpha} + ENV_{MAT,\mathrm{CO2}}\right)\left(U_L^{\alpha} U_K^{1-\alpha}\right), \tag{10}$$

with $ENV_{MAT,\mathrm{CO2}}$ as an estimated function that accounts for the cumulative effect of environmental externalities, which, in our case, are dependent on material extraction and CO_2 emissions. By considering Eq. (5) and following the Pitt and Lee (1981) estimation reported in Table 2, we can propose the following formulation for the ENV function:

$$\begin{aligned} ENV_{MAT,\mathrm{CO2}} = {} & -0.858 \times \ln mat_{i,t} + 0.499 \times \ln mat_{i,t-1} \\ & - 0.131 \times \ln \mathrm{CO2}_{i,t-2} + 0.176 \times \ln \mathrm{CO2}_{i,t-3}. \end{aligned} \tag{11}$$

With this specification, the estimation of overall efficiency in the production function includes the influence of negative environmental externalities. The result is a production function that captures the presence of environmental dynamics and that can be used as a basis for the calculation of an environmentally balanced GDP series that considers the interactions between economic growth, material extraction, and CO_2 emissions in EU27. We call this an environmentally balanced estimation of GDP.

5.2 Comparison of an environmentally balanced GDP versus observed GDP

We can compare the environmentally balanced estimation of GDP elicited in the previous section with observed GDP to show the consequences of applying the proposed modification in TFP to the model by Havik et al. (2014). Figure 1 shows the differences between observed GDP and

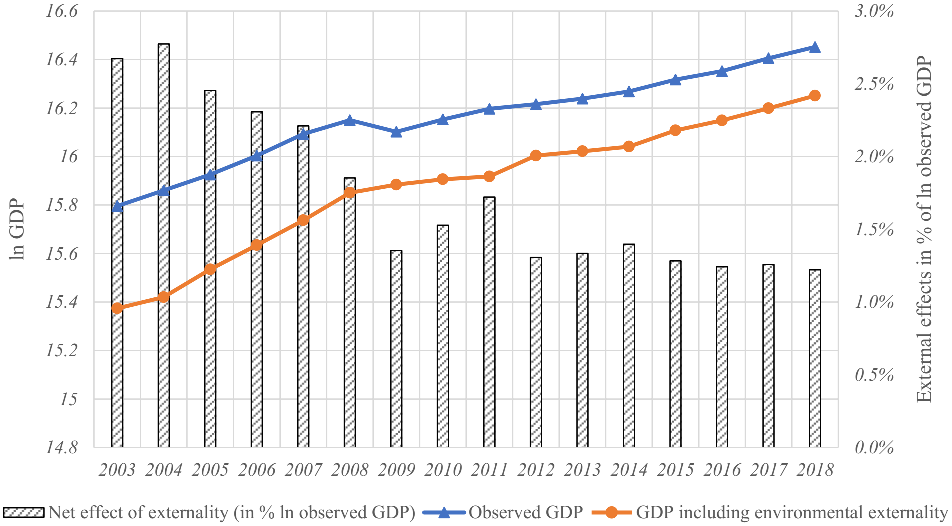

Fig. 1 Observed and estimated GDP with environmental externality

the resulting calculation of GDP using the ENV function in Eq. (11) and the results from the Pitt and Lee (1981) estimation from Table 2. Since the results include lags of up to $t-3$ in the specification of the externality, results for only the period 2003 to 2018 are reported. The data includes all the EU27 countries except Malta, which, as explained in previous sections, was identified as an outlier and therefore removed from the sample. Since the model has been calculated in logarithmic terms, the results are presented likewise.

Figure 1 reveals a negative effect of the accumulation of the environmental externality in all periods. The growth of observed GDP is systematically overestimated when environmental externalities are not taken into consideration. The persistence of undesirable outputs, generated by economic growth in the form of accumulation of CO_2 in the atmosphere and by increased pressure on natural resources caused by material extraction, show a negative influence on GDP. As stated in Sect. 4, this can also be explained in policy terms: the longer society waits to adopt stringent climate policies that can have a tangible effect on CO_2 reduction,[3] the higher the costs that arise in terms of the needed climate mitigation and adaptation (IPCC 2018).

The net effect of the environmental externality (calculated as the difference between observed GDP and calculated GDP with environmental externality) is presented in bars in the graph as an additional indicator and shows that the gap between observed GDP and GDP with environmental effects has reduced over time (from 2.8% of observed GDP in 2004 to 1.2% in 2018). This change could be attributed to the introduction of mores stringent climate policies that has taken place within the European Union in recent years. The gap between the two GDP values represents the opportunity cost in terms of growth in the presence of externalities and can be used as a relevant indicator for policymaking in EU27 to measure the impacts of reducing environmental externalities over time. In the absence of environmental externalities as a by-product of economic growth, the gap between the two variables should equal zero; this should constitute the long-term quantitative objective of EU climate policy.

The results presented in Fig. 1 are also relevant from an economic theory standpoint. The model proposed in this paper is an endogenous growth model that builds on the ideas already presented in the endogenous growth models of Romer (1990) and Lucas (1988). In our model, the environmental externalities resulting from the GDP increase over time which ends up compromising growth itself. Not only does economic growth generate wealth, but it also incurs environmental costs that eventually reduce future levels of wealth. To this end, we aim to present a simple representation of the quantitative consequences of the intergenerational equity dilemma for the EU27 case.

6 Conclusion

In this paper, the quantification of environmental externalities using econometric efficiency analysis has been explored to propose a definition of an environmentally balanced production function for the EU27. We have analysed the determinants of economic growth whilst explicitly considering its associated negative environmental externalities, focussing on CO_2 emissions and material extraction. The proposed model relies on the theoretical framework of endogenous growth models and uses SFA for the quantification of the

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[3] We are aware that climate mitigation extends beyond CO_2 and that an array of Greenhouse Gases and local pollutants must be brought into the picture for it to be complete. Our model focusses on CO_2 only because this is the main indicator targeted in the referred EU climate policies and constitutes the main driver of climate change.

external effects. After controlling for Member State heterogeneity and for the break in the series caused by the years of the economic crisis (2008 to 2010), we estimated the coefficients of an environmentally balanced estimation of GDP growth. Our modelling approach obtains representative results across a broad range of SFA estimations. Moreover, the model proposed presents implications for economic theory and policymaking, since it provides an analytical representation of endogenous economic growth negatively influenced by the accumulation of environmental externalities and an analytical pathway to keep economic growth within environmental boundaries.

The econometric estimation of the model quantifies the influence of CO_2 emissions and material extraction (representing environmental externalities) on economic growth. Both variables show positive signs in past levels and negative signs when approaching $t = 0$ on all SFA estimations. This confirms other findings in the literature, under which environmental externalities become a negative determinant of efficiency in the production function when they accumulate over time (Selden and Song 1994; Yu et al. 2018). The findings also indicate that such a negative influence only takes place after a certain tipping point, beyond which the use of environmental commodities compromises economic growth itself.

The model has been applied in order to propose a modification in the Cobb–Douglas production function modelling tool of the European Commission presented in Havik et al. (2014), in the form of the inclusion of the influence of environmental externalities in the definition of efficiency in total factor productivity. The use of efficiency analysis (SFA) in the econometric estimation provides grounds for the proposal of such a change. The results achieved provide a benchmarking metric between environmentally balanced GDP and observed GDP for both the quantification and a more accurate representation of the impacts of environmental dynamics on economic growth, which can be employed on the evaluation and design of climate change policies in the EU.

With our contribution, we have intended to reply to the research questions posed in the Introduction, since the model proposed provides insights on the quantitative relationship between GDP growth and the accumulation of environmental externalities. Climate policies, which aim at precisely reducing such accumulation of side costs of economic growth, are portrayed in the proposed modelling approach as a way to ensure continuous economic growth kept within environmental boundaries, as shown in Fig. 1 in the GDP series including the environmental externality. Prosperity is possible without compromising the welfare of future generations.

The approach used presents some limitations, especially because environmental externalities go beyond material extraction and CO_2 emissions. On the one hand, economic activities generate pollutants that are not included in our model. On the other hand, there are environmental damages, such as biodiversity loss, that are not captured by the coefficients shown in Table 2. The model and this research are rather aimed at bringing the issue of dynamic environmental externalities to the attention of economic growth modelling.

The model can also be expanded in several ways. Further research is needed as regards the dynamics of the relationship between economic growth and the accumulation of environmental externalities. The use of datasets with a longer time horizon together with an increase in the granularity of the data to observe these interactions on a sectoral level could also yield significant results. Broadening the scope of the environmental externality considered in the model by including local air pollutants and other greenhouse gases such as methane, sulphur dioxide, and nitrogen oxides may also provide meaningful insights into this topic, as may the inclusion of other impacts such as the loss of biodiversity and water use.

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Declarations

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El papel del Sistema de Derechos de Emisión en la transición a la Neutralidad climática

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Número 1 de la colaboración con BCFE

Abstract

El Sistema Europeo de Derechos de Emisión (EU ETS) es una pieza clave de la política climática de la Unión Europea, que actúa de forma directa en los incentivos financieros de sectores emisores. La actual reforma del EU ETS tendrá consecuencias significativas para la economía europea.

The European Emissions Trading Scheme (EU ETS) constitutes a cornerstone climate policy instrument in the European Union, acting directly on the financial incentives of emitting sectors. The current reform of the EU ETS will entail significant consequences for the European economy.

El Sistema Europeu de Drets d'Emissió (EU ETS) és una peça clau de la política climàtica de la Unió Europea, que actua de manera directa als incentius financers de sectors emissors. L'actual reforma de l'EU ETS tindrà conseqüències significatives en l'economia europea.

1. Introducción

El Sistema Europeo de Derechos de Emisión (EU ETS por sus siglas en inglés) es uno de los instrumentos clave en la política climática de la Unión Europea. Basado en un mecanismo de intercambio de permisos que asigna un precio a las emisiones de gases de efecto invernadero (GEI) de sectores altamente emisores, el EU ETS ha conseguido reducciones significativas de emisiones en sectores clave de la economía europea como la generación de electricidad o la producción de materiales esenciales como el cemento o el acero (entre otros). Estas reducciones ascienden a más de 750 millones de toneladas de emisiones GEI desde la adopción del EU ETS en 2003 (Agencia Medioambiental Europea 2022a; Comisión Europea 2022a), un ritmo de reducción anual de emisiones equivalente al volumen anual de emisiones GEI de países como Dinamarca o Bulgaria (Agencia Medioambiental Europea 2022b).

En el contexto actual, donde la emergencia climática convive con las tensiones inflacionistas derivadas de la crisis energética[1], el EU ETS ha cobrado una mayor importancia en la UE como pieza clave para alcanzar los compromisos de neutralidad climática en la UE para 2050, fijados en el Pacto Verde y la Ley Europea del Clima (Comisión Europea 2019; Comisión Europea 2021a; Comisión Europea 2021b; Zaklan, Wachsmuth & Duscha 2021). El futuro del ETS pasa no obstante por encontrar un equilibrio entre una mayor ambición climática y la influencia del mismo en los precios de la electricidad y de materiales fundamentales como el acero, el aluminio o el cemento (Oharenko 2021; Pietzcker, Osorio & Rodrigues 2021). Este artículo presenta el funcionamiento del EU ETS, sus fortalezas como instrumento de política climática y los principales puntos de discusión sobre su futuro.

2. Contexto regulatorio

El EU ETS fue constituido por primera vez en la Directiva del EU ETS de 2003 tras la adopción del Protocolo de Kioto en 1997, que incluía entre sus disposiciones objetivos de reducción de emisiones vinculantes para las economías industrializadas (Comisión Europea 2015; Comisión Europea 2021c). El EU ETS se diseñó para responder a esos compromisos como un sistema de intercambio de derechos de emisión, conocido en inglés como *cap-and-trade*. En este tipo de sistemas se fija un límite, o *cap*, al volumen total de emisiones GEI que ciertos sectores y actividades económicas pueden generar al año y se subastan permisos individuales de emisión, de forma que cada operador económico dentro del ámbito de aplicación del EU ETS debe adquirir a través de subastas o de intercambios con otros operadores suficientes permisos para cubrir su volumen total de emisiones (Comisión Europea 2015).

A través de estas subastas e intercambio de permisos se genera un incentivo financiero para los sectores dentro del EU ETS[2], permitiendo alcanzar un precio de reducción de emisiones GEI al mínimo coste económico y favorecer la inversión hacia tecnologías de reducción de emisiones (Aldi & Stavins 2012; Comisión Europea 2015; Capros et al. 2019; Oharenko 2021; Khan & Johansson 2022). Además, las subastas de permisos generan ingresos económicos sustanciales para el sector público (en este caso, la UE)[3], que entre los años 2012 y 2021 ascendieron a un total de 83,5 mil millones de euros (Comisión Europea 2021d). Estos ingresos se redirigen en su mayor parte hacia los sectores del EU ETS más perjudicados por el sistema para evitar su deslocalización a terceros países[4], mientras que el resto se dedica a financiar proyectos de modernización de infraestructuras energéticas (a

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[1] Este artículo se escribe en los meses de agosto a octubre de 2022, cuando los precios de la energía marcaban máximos históricos en la mayoría de los estados miembros de la UE.

[2] Los sectores económicos incluidos en el EU ETS aparecen definidos en el Anexo I de la Directiva 2003/87/EC y son fundamentalmente industrias intensivas en consumo de energía como la producción de acero o cemento y la generación de electricidad (Comisión Europea 2021c).

[3] Se estima que en los próximos diez años (2021-2030) las subastas del EU ETS generarán un rendimiento económico valorado en más de 1 billón de euros (Sandbag 2022).

[4] Esta compensación se hace en forma de permisos de emisiones GEI dados sin coste a los sectores considerados en mayor riesgo de deslocalización (Marcantonini 2017), fuertemente criticadas por diversas voces (Pellerin-Carlin *et al*. 2022). El resto de los rendimientos del EU ETS se dirigen a iniciativas dirigidas a alcanzar mayores reducciones de emisiones GEI, algunas dirigidas por la UE (como el Fondo de Innovación o el Fondo de modernización) y otras por los estados miembros (Sandbag 2022).

través del denominado Fondo de Modernización) o para encontrar innovaciones que avancen en la descarbonización del sistema energético y la industria europea (a través del Fondo de Innovación) (Marcantonini et al. 2017; Pellerin-Carlin et al. 2022; Sandbag 2022).

El EU ETS ha atravesado diversas reformas (denominadas "fases") que han ido reduciendo el número total de permisos disponibles en el mercado ("cap") y ampliado el número de sectores en el EU ETS (Comisión Europea 2015; Marcantonini 2017; Comisión Europea 2022b). Como puede comprobarse en la figura 1, la próxima fase del EU ETS será la número 4 y se caracterizará por una mayor ambición de reducción de emisiones GEI y un número de sectores cubiertos tras la adopción del paquete "Fit for 55"[5] (Comisión Europea 2021b):

Figura 1. Fases del EU ETS

Fuente: EU ETS Handbook (Comisión Europea 2015)

Las medidas propuestas para la fase 4, todavía en negociaciones entre las instituciones europeas, incluyen, entre otras, reducciones en el EU ETS de entre un 61% y 63% para 2030 con respecto a niveles de 2005, equivalente a una reducción total adicional de más de 760 millones de toneladas de GEI[6] (Comisión Europea 2021b; Comisión Europea 2022b; Parlamento Europeo 2022). Otras medidas incluidas en la propuesta de la Comisión Europea para la fase 4 son la inclusión de nuevos sectores como la aviación, el transporte marítimo y los combustibles para uso en edificios y transporte por carretera, así como la aceleración del ritmo de reducción anual del cap de permisos (Efthymiou & Papatheodorou 2019; Christodoulou et al. 2021; Comisión Europea 2021b; Comisión Europea 2022b). Las medidas también incluyen la posibilidad de utilizar los recursos del ETS para hacer frente a la actual crisis energética y a la financiación de los planes de recuperación de los estados miembros tras la pandemia de Covid-19 (Comisión Europea 2021b; Sandbag 2022).

3. El EU ETS en la transición verde de la UE

El EU ETS es un instrumento clave en la política climática de la UE, esencial para alcanzar cotas de reducción de emisiones GEI en sectores clave a un coste reducido en comparación con otros métodos (Aldi & Stavins 2012; Khan & Johansson 2022). En total, desde 2005 el EU ETS ha conseguido reducir las emisiones GEI de las centrales de generación de electricidad y las industrias intensivas en consumo energético en un 42.8% desde 2005, equivalente a 750 millones de toneladas de emisiones GEI (Comisión Europea 2021b).

El EU ETS se basa en un mecanismo de fijación de precios basado en incentivos financieros, conocido como *cap-and-trade*. Este tipo de sistemas se diferencian de otros instrumentos como los impuestos medioambientales o los sistemas *command and control*, donde las reducciones de emisiones son establecidas de forma más directa por las instituciones públicas (Aldi & Stavins 2012; Comisión Europea 2022a). Las limitaciones de este tipo de enfoques *command and control* se resumen en su menor efectividad para actuar sobre los incentivos de los sectores más contaminantes, mientras que los sistemas *cap-and-trade* se caracterizan precisamente, al menos en el plano teórico, por su habilidad para actuar en dichos incentivos y alcanzar reducciones significativas de emisiones GEI en las actividades y procesos productivos donde cuesta menos hacerlo (Zaklan, Wachsmuth & Duscha 2021; Khan & Johansson 2022; Sato et al. 2022).

La clave para el éxito de un sistema cap-and-trade como el EU ETS reside en que el precio de los permisos de emisiones sea lo suficientemente alto como para que adquirirlos suponga un coste significativo para los sectores emisores (Dominioni 2022). Este ha sido precisamente su principal reto: Como puede comprobarse en la figura 2, las sucesivas fases del EU ETS han ido incrementando el precio de los permisos, pero durante los primeros 20 años del EU ETS el precio de los permisos ha sido relativamente bajo (ICAP 2022; Sato et al. 2022). No ha sido hasta finales de 2020 y en particular a partir de la publicación del paquete Fit for 55 cuando el precio de los permisos ha experimentado incrementos sustanciales (Sato et al. 2022).

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[5] El paquete legislativo "Fit for 55" incluye medidas necesarias para alcanzar una reducción de emisiones del 55% antes de 2030 con respecto a 1990 para el conjunto de la UE como objetivo general (Comisión Europea 2021b; Comisión Europea 2021d; Parlamento Europeo 2022).

[6] Esto supone un incremento de 20 puntos porcentuales con respecto al actual objetivo de reducción del 43% en la fase 3, todavía en aplicación (Comisión Europea 2021b).

Figura 2. Evolución de precios de permisos de emisión del EU ETS

Fuente: ICAP 2022

4. El futuro del EU ETS

La reforma del EU ETS en la fase 4 constituye actualmente uno de los mayores debates de política climática en las instituciones europeas. Preocupa especialmente la influencia que un EU ETS más estricto podría tener en el encarecimiento de bienes fundamentales como la energía[7] o materias primas críticas como el cemento o el acero (Cornago 2022; Gerlagh, Heijmans & Rosendahl 2022). La actual crisis energética provocada por el conflicto bélico entre Rusia y Ucrania ha acrecentado estas preocupaciones (Taylor 2022).

La relación entre la reforma del EU ETS y el contexto actual de crisis energética es particularmente relevante. Para evitar que el incremento del precio de los permisos en un EU ETS más estricto afecte a los precios finales de la energía, una de las más recientes propuestas por parte de la Comisión Europea es aplicar la práctica conocida como frontloading, que consiste en adelantar el calendario de subastas para incrementar los rendimientos económicos para la UE provenientes de las mismas y utilizarlos para financiar el plan de acción de la UE contra la crisis energética (conocido como REPowerEU) (Comisión Europea 2022b; Quemin 2022; Simon 2022).

Otro de los elementos que más preocupan en el futuro del EU ETS es su posible influencia sobre la competitividad global de la Unión Europea al posicionarse como la economía con el sistema de precios de carbono más estricto en la economía mundial (Ismer, Neuhoff & Pirlot 2020). Sin embargo, sistemas similares al EU ETS han ido implantándose[8] en las economías con más peso global (Kapnick 2021; Banco Mundial 2022), reduciendo esos posibles riesgos de divergencia regulatoria entre la Unión Europea y el resto del mundo. Además, con el objetivo de reducir el riesgo de deslocalización y por tanto la pérdida de competitividad europea, la propuesta de la Comisión Europea para la fase 4 del EU ETS incluye el denominado mecanismo de ajuste en frontera (CBAM por sus siglas en inglés) (Comisión Europea 2021b). Este mecanismo trata de evitar la deslocalización de empresas europeas emisoras de GEI a países con regulaciones medioambientales menos estrictas y sustituiría al sistema actual de compensación a través de permisos sin coste (Marcantonini 2017; Comisión Europea 2022c; Sato et al. 2022). El CBAM consistiría en introducir la necesidad de que los productos importados a la UE también tengan que adquirir permisos para cubrir sus emisiones, incluso aunque hayan sido producidos fuera de la UE (Comisión Europea 2022c). La inclusión del CBAM en el EU ETS continúa siendo un foco de debate que influirá decisivamente en el diseño final de la fase 4 (Sandbag 2022).

En cualquier caso, el futuro del EU ETS también pasará por su papel en el ámbito global. El EU ETS es el instrumento fijador de precios de emisiones GEI más grande y consolidado en el mundo. Los acuerdos adoptados en la reciente COP26 de Glasgow incluyeron un hito fundamental: sentar las bases para la implementación del controvertido Artículo 6 del Acuerdo de París para la creación de un mercado global de emisiones GEI (UNFCCC 2016; UNFCCC 2022). En el futuro, la implantación de los acuerdos de la COP, en caso de que ésta sea exitosa, implicará interconectar el EU ETS con estos otros sistemas similares.

5. Conclusiones

En este artículo se ha analizado el papel fundamental del EU ETS como mecanismo fijador de precios de emisiones GEI e instrumento de política climática. La fase 4 del EU ETS, todavía en negociaciones en las instituciones europeas, constituirá un hito decisivo para alcanzar los compromisos de neutralidad climática para la UE en 2050 adquiridos en el Pacto Verde Europeo y la Ley del Clima Europea (Comisión Europea 2019; Comisión Europea 2021a).

Los aspectos a tener en cuenta en el diseño de la Fase 4 del EU ETS son numerosos y complejos. Es necesario encontrar un equilibrio entre un mecanismo de fijación de precios de permisos de emisiones GEI más estricto, que genere suficientes incentivos financieros hacia la descarbonización de sectores contaminantes sin poner en riesgo los precios de bienes esenciales como la energía. Los próximos meses serán clave para diseñar estas reglas, cuya adopción tendrá consecuencias financieras más allá de la política climática europea.

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[7] Recordemos que uno de los sectores incluidos en el Anexo I de la Directiva 2003/87/EC es la generación de electricidad con combustibles fósiles. De ahí la preocupación sobre la influencia del EU ETS en la crisis energética.

[8] Actualmente existen 68 sistemas de fijación de precios de carbono en el mundo en países como China, Indonesia, Chile, Uruguay, Canadá o Sudáfrica, entre otros (Banco Mundial 2022). La lista completa puede consultarse aquí.

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La Protection Environnementale dans les Accords Régionaux de Libre-Échange : une étude comparée

***Luis Galiano Bastarrica*[1]**

Résumé : Cet article examine les différences dans les clauses de protection environnementale d'un échantillon d'accords de libre-échange. Nous avons sélectionné cinq accords (ALENA, CETA, CPTPP, ASEAN et UE-MERCOSUR) pour comparer des variables-clés comme les motivations des parties contractantes, les types de dispositions environnementales ou les systèmes de gouvernance pour la résolution des conflits. L'analyse comparative révèle des différences significatives entre les accords, notamment sur le degré de protection environnementale réalisé dans chacun d'entre eux. La place donnée à la question environnementale dans les négociations commerciales est au cœur de ces différences – des facteurs géopolitiques comme la présence d'un processus plus large d'intégration économique, l'existence d'asymétries économiques et sociales marquées entre les signataires ou la dynamique de la négociation sont identifiés comme facteurs explicatifs des différences observées. La comparaison des accords dévoile aussi une approche fragmentée de l'Union européenne à la protection environnementale, avec des tensions entre les objectifs commerciaux et géopolitiques de l'agenda européen, tels que l'augmentation de l'influence sur des régions stratégiques et l'ambition environnementale du Pacte vert.

Mots-clés : commerce, changement climatique, environnement, développement durable, accord de libre-échange

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Introduction

La multiplication des Accords Régionaux de Libre Échange (ARLEs) dès la fin du XXème siècle est devenue un facteur majeur du changement global dans les processus d'intégration économique. L'immobilisme du système multilatéral de l'Organisation Mondiale du Commerce (OMC) depuis les cycles de négociations à Doha[2] a eu pour conséquence la création, par les principales puissances économiques, du régionalisme (la négociation bilatérale et sélective des accords de libre-échange) comme une opportunité pour concevoir une mosaïque normative à la carte[3] qui sert à mieux protéger les intérêts stratégiques nationaux.

Le régionalisme économique est souvent vu comme un risque pour la cohérence de la gouvernance des relations économiques internationales. En effet, la littérature a défini la dépendance entre les ARLEs et le multilatéralisme de l'OMC comme une relation « compliquée ». La validité de la clause de la nation la plus favorisée est remise en question avec l'établissement de conditions plus privilégiées entre groupes d'États par rapport au reste du monde, posant un risque de discrimination envers les pays non-signataires.[4] Cependant, l'importance des ARLEs est aussi considérée comme une opportunité pour le multilatéralisme, car ils donnent aux États l'opportunité d'atteindre des compromis plus profonds qui ne seraient pas faisables dans le contexte de l'OMC, et qui vont au-delà du plan strictement commercial.[5] De plus, d'autres auteurs reconnaissent le régionalisme comme un élément accélérateur du multilatéralisme, sous la condition que le commerce régional soit ouvert aux pays non-signataires sans discrimination.[6]

Cette relation ambivalente entre régionalisme et multilatéralisme n'est pas passée inaperçue à l'OMC qui, depuis 2002, a mis en place un groupe de travail spécifique appelé "Groupe de Négociation sur les Règles" qui tente d'affirmer la primauté des accords multilatéraux.[7] En revanche, récemment, l'Union européenne (UE), dans sa communication intitulée "Examen de la politique commerciale - Une politique commerciale ouverte, durable et affirmée", a appelé à la nécessité d'une réforme profonde de l'OMC, "y compris par le biais d'accords plurilatéraux ouverts" – un signe clair que le rôle de l'OMC dans le commerce mondial s'est avéré à être profondément révisé.[8]

Également, l'irruption des ARLEs dans les relations commerciales a provoqué un changement d'approche dans les négociations : nous sommes passés d'une conception multilatéraliste centrée presque uniquement sur les réductions des barrières commerciales (tarifaires ou non), où

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[2] Jo-Ann Crawford et Roberto V. Fiorentino, "The Changing Landscape of Regional Trade Agreements", *World Trade Organization Discussion Paper* 8, (2005), p. 6.
[3] Christian Deblock, "Le régionalisme commercial. Y a-t-il encore un pilote dans l'avion ?", *Interventions économiques* 55 (2006): 3.
[4] Crawford & Fiorentino, *op. cit.*, pp. 6-8.
[5] OCDE, "Environment and Regional Trade Agreements: Summary in English", 2007. p. 1.
[6] Jayant Menon, "Building blocks or stumbling blocks? Regional Cooperation Arrangements in Southeast Asia", *Asian Development Bank Institute Discussion Paper* 41 (2005): 8-10.
[7] Organisation mondiale du commerce, "Rules: Regional agreements – Building blocks or stumbling blocks?", 2005.
[8] Commission européenne, "Trade Policy Review - An Open, Sustainable and Assertive Trade Policy", 2021. p. 12.

le progrès est devenu plutôt modeste dans les derniers années,[9] à une approche plus atomisée dans laquelle les États peuvent dépasser le débat sur la libéralisation du commerce et négocier sur des sujets connexes, y compris la protection des ressources environnementales et l'adoption de normes de lutte contre le changement climatique.[10]

De plus, indépendamment de sa forme multilatéral ou régional, la globalisation et le libre commerce ont aussi été fortement critiqués. Les critiques reprochent que le bénéfice de ces accords ne soit parfois pas équitablement partagé entre les pays riches et les pays pauvres. L'accord fonctionnerait comme un mécanisme transférant des rentes des pays pauvres, dont les coûts de main-d'œuvre et de capital sont moins élevés, vers les pays développés.[11] Le sujet étant complexe en nature, certains économistes affirment que les données ne sont pas suffisamment claires pour conclure à un effet négatif de la libéralisation du commerce sur tous les pays moins développés.[12] D'autres économistes, comme le Prix Nobel Joseph Stiglitz, reprochent aux accords d'accroître les inégalités entre les travailleurs et les investisseurs, tant dans les pays riches que dans les pays pauvres.[13]

En ce contexte de mise en question des bénéfices de la libéralisation commerciale et surtout du multilatéralisme, l'UE a accompli un changement profond dans son agenda commercial avec l'adoption du Pacte vert européen.[14] Le chapitre 3 intitulé "L'UE en tant qu'acteur mondial" est consacré à la dimension extérieure de la politique climatique européenne. Dans ce chapitre, la politique commerciale est mentionnée comme un élément clé pour soutenir l'agenda vert européen ; les accords de libre-échange bilatéraux sont conçus comme une opportunité pour renforcer la politique climatique hors Europe. En 2019, ces clauses dans la communication du Pacte vert européen ont établi un nouveau mandat pour la politique commerciale européenne.[15] Les négociations commerciales de l'UE auraient pu devenir un nouvel instrument exécutif de l'UE pour promouvoir la transition climatique dans le monde.[16] Cependant, d'un autre côté, l'agenda commercial européen a souvent montré d'autres motivations, liées à des gains géopolitiques dans certaines régions sans nécessairement avoir l'environnement comme priorité.[17]

L'UE est en train d'élaborer plusieurs initiatives visant à concrétiser ce mandat pour une dimension externe du Pacte Vert en matière de politique commerciale. Les exemples sont nombreux :

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[9] Dale Colyer, "Environmental provisions in free trade agreements", West Virginia University, Department of Agricultural Resource Economics, 2012. pp. 2-3.

[10] OCDE, *op. cit.*, pp. 2-4.

[11] Anup Shah, "Criticisms of Current Forms of Free Trade", *Global Issues,* 2006, https://www.globalissues.org/article/40/criticisms-of-current-forms-of-free-trade.

[12] Emma Aisbett, "Why are the Critics So Convinced that Globalization is Bad for the Poor?", *Globalization and Poverty* (2007): 66-67.

[13] Joseph Stiglitz, "Globalisation: time to look at historic mistakes to plot the future", *The Guardian*, 5 décembre 2017.

[14] Commission européenne, "Pacte vert pour l'Europe", 11 décembre 2019, COM(2019)640 final. pp. 25-27.

[15] Johan Bjerkem, "EU trade policy: Global enforcer for the European Green Deal", *European Policy Centre*, 2019.

[16] *Ibid.*

[17] Beatriz Céu, "Portugal defends 'geopolitical' importance of EU-Mercosur trade deal", *Euractiv*, 10 février 2021, https://www.euractiv.com/section/eu-council-presidency/news/portugal-defends-geopolitical-importance-of-eu-mercosur-deal/, consulté le 26 février 2021.

Le Mécanisme d'Ajustement Carbone aux Frontières (CBAM selon l'acronyme anglais), l'inclusion de chapitres de développement durable (TSD) dans les ARLEs négociés par l'UE et l'inclusion de critères de durabilité dans la stratégie commerciale de l'UE. Le CBAM vise à mettre en place un mécanisme de tarification du carbone pour les marchandises importées par l'UE. Le but de l'instrument est d'agir sur les incitations des acteurs économiques en faveur de produits moins intensifs en carbone et éviter la relocalisation des industries plus polluantes.[18] Toutefois, l'initiative a été fortement critiquée par des partenaires commerciaux clés tels que les États-Unis, qui y voient une mesure unilatérale contraire à l'esprit du libre-échange, qui ne devrait être utilisée qu'en dernier recours.[19] Le Parlement européen a rendu son opinion sur la mesure dans un rapport spécifique, affirmant qu'un CBAM conforme à l'OMC pourrait être possible tant que les tarifs du carbone ne soient ni arbitraires ni discriminatoires.[20]

Quant à l'adoption des chapitres TSD dans les ARLEs, la Commission européenne a donné un nouvel élan avec un document de 2017 intitulé « Trade and Sustainable Development (TSD) chapters in EU Free Trade Agreements (FTAs) ». Le rapport appelle à une utilisation renforcée des clauses de développement durable dans les accords de libre-échange, notamment via comités bilatéraux avec des membres européens et des membres des États signataires (DAGs).[21] Le problème de cette initiative, comme souligné par le Comité économique et social européen dans son avis sur le sujet, a été sa manque de force coercitive et de sanctions en cas de défaillance des chapitres TSD.[22]

La récente communication de la Commission intitulée "Examen de la politique commerciale - Une politique commerciale ouverte, durable et affirmée" est une synthèse précise des principales priorités de la politique commerciale européenne. Le développement durable et l'agenda vert sont cités comme l'un des trois objectifs principaux de la stratégie, ce qui renvoie un message clair sur son importance.[23] En outre, les initiatives qui pourraient être considérées comme unilatérales (comme le CBAM) sont énumérées comme des initiatives "autonomes" dans lesquelles l'UE vise à trouver un équilibre entre la conformité à l'OMC et son objectif de réaliser son agenda politique, avec les chaînes d'approvisionnement durables comme objectif clé.[24] L'exemple européen montre la complexité de trouver un équilibre entre un agenda commercial influent et une ambition écologique marquée. Néanmoins, le nombre d'accords de libre-échange

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[18] Commission européenne, "Carbon Border Adjustment Mechanism – Inception Impact Assessment", 2020. p. 1.

[19] Yuliia Oharenko," An EU Carbon Border Adjustment Mechanism: Can it Make Global Trade Greener While Respecting WTO Rules?", *International Institute for Sustainable Development SDG Knowledge Hub*, 17 mai 2021, https://sdg.iisd.org/commentary/guest-articles/an-eu-carbon-border-adjustment-mechanism-can-it-make-global-trade-greener-while-respecting-wto-rules/.

[20] Parlement européen, "Rapport : Vers un mécanisme européen d'ajustement des émissions de carbone aux frontières compatible avec l'OMC", 15 février 2021, 2020/2043(INI). pp. 7-10.

[21] Commission européenne," Implementation of the Trade and sustainable development (TSD) chapter in trade agreements - TSD committees and civil society meetings", 2020.

[22] Comité économique et sociale européen," Trade and sustainable development chapters (TSD) in EU Free Trade agreements (FTA) (own-initiative opinion)", 2017. p. 9.

[23] Commission européenne," Trade Policy Review", *op. cit.*, pp. 4-5.

[24] *Ibid.*, pp. 12-13.

contenant des dispositions de protection environnementale a fortement augmenté depuis l'année 2000.[25] Or, leur ampleur et leur force juridique divergent en raison d'un ensemble de critères.

Le degré de développement économique des États impliqués est le premier de ces facteurs de divergence, notamment quand il y a des différences importantes entre ceux qui négocient l'accord.[26] Ensuite, les motivations sous-jacentes qui invitent les États à négocier peuvent aussi jouer un rôle sur le résultat de l'accord. Ces motivations peuvent être, par exemple, d'obtenir plus de ressources pour atteindre leurs objectifs de développement durable, de partager certains coûts pour accroître l'efficience dans la production de biens ou d'améliorer la coopération environnementale, parmi d'autres.[27] Finalement, la sévérité et la force contraignante des clauses inclues dans les accords et les systèmes de gouvernance et résolution de conflits prévus jouent aussi un rôle significatif.[28]

Dans cet article, nous utiliserons les quatre critères suivants (États impliqués, motivation, types de provisions et gouvernance) pour examiner et comparer cinq exemples bien divergents[29] : l'Accord de Libre-Echange Nord-Américain (ALENA), l'Accord économique et commercial global entre le Canada et l'Union européenne (CETA), l'Accord de partenariat transpacifique global et progressiste (CTPP), l'Association des Nations de l'Asie du Sud-Est (ASEAN) et finalement le récent accord commercial entre l'Union européenne et le MERCOSUR.[30] Quelle place occupe la protection environnementale dans ces accords venant des différentes régions du monde ? Pour y répondre, nous présenterons les raisons empiriques qui expliquent les similarités et disparités observées entre ces accords.

La première section de l'article présente les critères qui seront utilisés pour analyser l'inclusion des considérations environnementales dans les négociations commerciales. Ensuite, nous analyserons chacun des cas dans l'échantillon proposé : L'ASEAN (Section 2), l'ALENA (Section 3), le CPTPP (Section 4), le CETA (Section 5) et finalement l'accord UE-MERCOSUR (Section 6). La section 7 détaillera les conclusions en touchant sur une série de facteurs explicatives des divergences observées entre les accords.

Le choix de l'échantillon d'accords proposé mérite une explication avant de présenter les résultats. Le principal critère de sélection des accords a été de couvrir une grande variété de cas : soit des accords entre pays en développement (ASEAN), développés (ALENA, CETA), et avec et sans la participation de l'UE (CETA et UE-MERCOSUR pour les premiers ; CPTPP entre autres pour les seconds). Dans chacun d'entre eux, la protection de l'environnement a été abordée de manière différente, soit dans le cadre d'un processus d'intégration plus large (ASEAN) ou comme un point délicat dans le processus de ratification de l'accord (UE-MERCOSUR), pour citer un

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[25] Colyer, *op. cit.*, p.4.

[26] Mehdi Nemati, Wuyang Hu et Michael Reed, "Are Free Trade Agreements Good for the Environment? A Panel Data Analysis", *Review of Development Economics* 23, no. 1 (2019).

[27] OCDE, "Environment and Regional Trade Agreements", 2007. pp. 26-30. Nous irons plus loin dans le reste de l'essai. La liste de possibles motivations des États a été diminuée pour des raisons d'espace dans le texte introductif.

[28] Colyer, *op. cit.*, pp. 4-8.

[29] Nous justifierons cet échantillon dans la section suivante de l'essai.

[30] Nous utiliserons les acronymes anglais pour tous les accords pour faciliter la lecture.

exemple. Nous verrons comment, dans chaque cas, les critères proposés dans la Section 1 ont joué un rôle décisif dans le résultat final. L'environnement est un bien difficile à protéger, et sa protection entre parfois en conflit avec d'autres objectifs des accords commerciaux. Cet article tente de montrer ces tensions et les différentes manières de les traiter dans une gamme diverse de cas.

1. L’environnement comme sujet de négociation dans les ARLEs

L’inclusion des clauses de protection environnementale dans les Accords Régionaux de Libre-Échange (ARLEs) est un phénomène plutôt récent qui a cependant été considéré comme polémique par la littérature économique : dans quelle mesure peut-on s’assurer que le libre échange est positif pour l’environnement ? Cette question, dont la réponse n’est pas évidente, joue un rôle essentiel dans les dynamiques de négociation des accords et notamment dans les résultats finaux des dispositions environnementales.

Les résultats d’études récentes sont divisés quant à la mesure de l’impact des ARLEs sur l’environnement.[31] Il y a cependant depuis 1995 un consensus plus large sur les causes de l’impact des ARLEs sur l’environnement. Il y a trois effets clés à cet égard[32] :

1.1 Effet d’escale

La libéralisation des flux d’échange entraîne une augmentation de l’activité économique entre les États signataires des Traités de Libre Commerce (TLC), et en conséquence les émissions de dioxyde de carbone (CO2) liées au processus de production augmenteront aussi.

1.2 Effet de composition

Quand la concurrence des États membres d’un TLC est basée sur une différence de règlementation environnementale, la libéralisation commerciale peut entraîner des risques pour l’environnement car chaque État sera spécialisé dans les domaines où la règlementation est moins stricte. Par exemple, si deux États (disons A et B) ont des règlementations très différentes dans deux secteurs (agriculture et manufacture), A ayant une législation plus stricte sur la production agricole et B sur la manufacture, une fois que le TLC entre en vigueur les entreprises agricoles de A peuvent être incitées à relocaliser la production vers B où le cadre législatif es plus favorable. La même tendance aura lieu avec les entreprises de la manufacture du pays B. Le TLC risque de faciliter ces mouvements.

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[31] Nemati, Hu et Reed, *op. cit.*, pp. 2-5.

[32] Gene M. Grossman et Alan B. Krueger, “Environmental Impacts of a North American Free Trade Agreement”, National *Bureau of Economic Research Working Paper* 3914 (1991): 3-7; Nemati, Hu et Reed, *loc. cit*.

1.3 Effet technique

Il peut y avoir des transferts de technologie entre les États parties d'un TLC, surtout si l'accord comprend des pays avec des degrés de développement différents. Les États qui sont moins développés peuvent diminuer l'intensité des émissions de CO2[33] en adoptant des technologies plus avancées qui n'étaient pas accessibles avant la libéralisation des relations commerciales.

Ces trois effets (qui peuvent être opposés) sont communs à toutes les négociations des dispositions de protection environnementale dans les ARLEs, mais leur impact final dépend d'une série de critères que nous réduirons à cinq dans cette étude. Nous expliquerons chacun d'entre eux ci-dessous, puis nous les utiliserons pour examiner l'échantillon d'ARLEs proposé. D'autres variables auraient pu être utilisées pour faire une analyse plus complète, mais nous avons décidé de limiter le nombre de critères aux plus importants d'entre eux pour faciliter les comparaisons.

1.4 États impliqués

Nemati, Hu et Reed[34] détectent des différences significatives dans l'impact environnemental des ARLEs en fonction du degré de développement des pays impliqués. Quand les ARLEs sont conclus entre pays développés et en voie de développement, les accords ont tendance à montrer des résultats environnementaux négatifs, alors que dans le cas des accords entre pays en voie de développement, l'effet est contraire.[35] L'une des raisons de ce phénomène est l'effet de composition des ARLEs que l'on vient de mentionner : la diminution des barrières commerciales a pour conséquence une relocalisation des industries plus polluantes qui visent à utiliser des règlementations plus laxistes pour augmenter leurs émissions.[36]

1.5 Motivations

Les États peuvent s'accorder sur l'adoption des clauses de protection environnementale dans les ARLEs pour diverses raisons[37] : contribuer au développement durable, éviter des asymétries règlementaires ou améliorer la coopération politique. Cependant, les dispositions peuvent aussi faire face à des réticences parmi les États pendant les négociations[38] : la cohérence avec les accords multilatéraux déjà en place, la peur de la création de nouvelles barrières au commerce à cause des provisions environnementales ou, tout simplement, l'absence d'un compromis politique en faveur de ces dernières sont des obstacles qui entravent leur inclusion dans les ARLEs.

1.6 Mise en œuvre

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[33] Unités des émissions CO2 par unité de produit intérieur brut (GDP).

[34] Nemati, Hu et Reed, *loc. cit.*

[35] *Ibid.*

[36] Grossman et Krueger, *op. cit.*, p. 6.

[37] OCDE, "Environment and Regional Trade Agreements: Summary in English", *op. cit.*, pp. 2-4.

[38] OCDE, "Environment and Regional Trade Agreements", *op.cit.*, pp. 42-46.

Nous pouvons différencier deux étapes dans la mise en œuvre des dispositions environnementales dans les ARLEs : le placement des compromis environnementaux dans le texte des accords et l'application de ces dispositions. Concernant le premier point, les clauses de protection environnementale peuvent être présentes dans un ARLE de façon diverse[39] : comme une section dans l'accord principal, comme un accord secondaire et séparé ou sous la forme de provisions générales dans le préambule. La manière dont les compromis sont placés dans le texte conditionne leur efficacité finale.[40] En outre, la mise en œuvre finale des mesures peut être conditionnée par les instruments prévus dans les ARLEs et son applicabilité dans la réalité.[41]

1.7 Types de dispositions

Les aspects environnementaux peuvent être reflétés dans les ARLEs de façons vraiment diverses. Pour simplifier l'analyse comparée, nous adopterons la terminologie de l'OCDE pour classifier les dispositions en quatre types [42]: étroites (où l'environnement est traité comme un sujet secondaire par rapport à la réduction tarifaire), générales (les clauses sont désignées pour adresser les problèmes environnementaux que la libéralisation peut entraîner), composantes d'une stratégie d'intégration plus large (les standards environnementaux sont entendus comme un domaine qui doit être harmonisé pour intégrer les économies qui font partie de l'accord) et de coopération (l'environnement est considéré comme un domaine séparé du commerce sur lequel il faut établir des mécanismes ad-hoc pour coordonner les efforts entre pays).

1.8 Systèmes de gouvernance et résolution de conflits

Enfin, il faut aussi considérer les mécanismes institutionnels créés pour assurer une gouvernance efficace ainsi que la mise en application des dispositions environnementales dans les ARLEs.

2. ASEAN: la protection environnementale comme vecteur d'intégration économique

L'ASEAN est l'accord le moins récent de l'échantillon proposé dans cet essai, signé en 1967 à Bangkok. Cependant, ce n'est que dans les années 1990 que ses membres ont commencé à poursuivre une libéralisation substantielle de leurs échanges.[43] Cet effort a abouti à la création de

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[39] Colyer, *op.cit.*, pp. 4-5.

[40] OCDE, "Environment and Regional Trade Agreements: Summary in English", *op. cit.*, p. 2.

[41] Dans l'analyse de chaque accord de l'échantillon et pour des raisons pratiques, nous examinerons la mise en œuvre en même temps que les types de dispositions.

[42] OCDE, "Environment and Regional Trade Agreements", *op. cit.*, pp. 30-34.

[43] Jayant Menon, « Building blocks or stumbling blocks? » (2005), pp. 5-6.

l'AFTA, la zone de libre-échange de l'ANASE entre 2003 et 2004.[44] Dans notre cas, nous parlerons de l'accord complet de l'ASEAN et pas seulement l'AFTA, car il s'agit d'un ARLE qui regroupe les nations du sud-est asiatique autour de mécanismes de coopération qui sont allés plus loin que le plan strictement économique. Il est souvent considéré comme l'exemple le plus prospère d'association économique entre pays en voie de développement.[45]

États impliqués. L'ASEAN comprend la Malaisie, l'Indonésie, le Brunei, le Vietnam, le Cambodge, le Laos, le Myanmar, le Singapour, la Thaïlande et les Philippines. Nous pourrions soutenir que sur le long terme cet accord contribuera à la réduction globale des émissions de CO2 car il n'y a pas d'asymétries fortes entre les pays signataires.[46] Cependant, sur le court terme, les ARLEs créent des incitations à adopter des normes environnementales moins strictes. Les pays signataires peuvent être motivés à déclencher la croissance économique entre eux sans considérer les effets environnementaux, ce qui est aggravé par l'absence de technologies moins polluantes dans ces pays.[47] Dans le cas de l'ASEAN, et outre l'impact environnemental, la mise en œuvre de l'accord a été guidée par des engagements remarquables entre les États membres en matière d'institutionnalisation et de respect des standards environnementaux. Les matières principales sont la préservation des littoraux, le développement urbain durable et les réglementations chimiques, parmi d'autres.[48]

Motivations. Contrairement aux exemples de l'ALENA, du CPTPP et du CETA, les motivations sous-jacentes à l'ASEAN vont au-delà de l'économie et du commerce. Dans une région caractérisée par une extrême diversité de systèmes politiques et de religions, la priorité des États signataires n'était pas uniquement liée a l'élimination des barrières commerciales. Au contraire, la finalité de l'accord était, premièrement, l'établissement d'un cadre durable de coopération pour assurer la stabilité de la région et, deuxièmement, de parler avec une voix unie dans un contexte global (des années 1960 à 1970) de forte concurrence entre le bloc capitaliste et l'URSS.[49] En ce sens, l'ASEAN a été utilisé non seulement comme un accord de libre-échange, mais aussi comme un vecteur d'intégration et de coopération entre les États signataires.

Types de dispositions. L'ASEAN est un exemple de protection environnementale incluse dans un effort d'intégration plus large. Dans cette approche, l'environnement n'est pas considéré comme une matière liée (et secondaire) au commerce, mais comme un domaine avec une identité propre dans l'intégration économique. Plus spécifiquement, les dispositions environnementales sont incluses dans le contexte de l'ASEAN sous l'autorité de la Communauté Culturelle et Sociale

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[44] ASEAN, "ASEAN Free Trade Area (AFTA) Council", https://asean.org/asean-economic-community/asean-free-trade-area-afta-council/, consulté le 05 juillet 2021.

[45] ASEAN, "The Founding of ASEAN", https://asean.org/about-asean/the-founding-of-asean/, consulté le 7 septembre 2021.

[46] Nemati, Hu et Reed, *op. cit.*, p. 17.

[47] Xing Yao et al., "Free Trade Agreements and Environment for Sustainable Development: A Gravity Model Analysis", *Sustainability* 11, no. 3 (2019).

[48] ASEAN Cooperation on Environment, "About ASEAN Cooperation on Environment", https://environment.asean.org/about-asean-cooperation-on-environment/, consulté le 5 juillet 2021.

[49] Kishore Mahbubani et Rhonda Severino, "ASEAN: The Way Forward", *McKinsey*, 1 mai 2014, https://www.mckinsey.com/industries/public-and-social-sector/our-insights/asean-the-way-forward, consulté le 6 juillet 2021.

de l'ASEAN,[50] un organisme qui désigne et met en œuvre des stratégies coordonnées en matière d'environnement et de justice sociale,[51] parmi d'autres. Un exemple pertinent est le Plan Stratégique sur l'Environnement 2016-2025 (ASPEN) qui sert à diriger des actions spécifiques dans une série de priorités stratégiques identifiées par l'ASPEN.[52] Le plan comprend des domaines clés comme le changement climatique ou la conservation des ressources maritimes.[53]

Gouvernance. Les règles environnementales de l'ASEAN sont appliquées en pratique avec une variété de groupes de travail qui surveillent et coordonnent la mise en œuvre de l'ASPEN par les États membres sur les domaines clés identifiés dans le Plan.[54] Des rapports annuels sont publiés pour suivre les progrès accomplis dans la réalisation des objectifs et des actions politiques prévus dans l'ASPEN.[55] Toutes les parties de l'ASEAN sont signataires de l'accord de Paris, et ces rapports d'avancement incluent la corrélation des initiatives de l'ASEAN avec l'agenda des Nations Unies.[56] D'autres accords ont même été conclus grâce à la coopération environnementale, comme la fixation d'objectifs de réduction de l'intensité énergétique entre les signataires.[57]

L'ASEAN est en conséquence un exemple de protection de l'environnement progressiste dans les ARLEs. En 1967, les pays signataires n'ont pas considéré la protection environnementale comme une priorité. Cependant, après un rapprochement prolongé, ils ont décidé de dépasser le cadre purement commercial et de s'engager également en faveur de l'environnement. Toutefois, il est difficile de prévoir si ces engagements seront suffisants pour que les pays signataires soient conformes à l'Accord de Paris.

3. L'ALENA : Les clauses de protection environnementale comme partie intégrante des négociations commerciales

Signé en 1992 entre le Canada, le Mexique et les États-Unis et devenu effectif deux ans plus tard,[58] L'ALENA a été le premier ARLE à contenir des dispositions environnementales dans son texte original. Contrairement à l'ASEAN, les clauses de protection environnementale ont été considérées dès le moment des négociations. L'ALENA constitue aussi un exemple clé des relations entre environnement et commerce car ces dispositions ne sont pas incluses en tant que situations d'exception mais comme partie intégrante du texte de l'accord.[59]

Le 1er juillet 2020, l'ALENA a été remplacé par l'accord États-Unis-Mexique-Canada (USMCA

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[50] ASEAN Socio-Cultural Community, selon l'acronyme en anglais.
[51] ASEAN, "ASEAN Socio-Cultural Community Blueprint 2025", 2016, pp. 1-3.
[52] ASEAN, "ASEAN Cooperation on Environment at A Glance", 2016, pp. 2-6.
[53] ASEAN, "ASEAN Strategic Plan on Environment (ASPEN) 2016-2025", 2016, pp. 8-11.
[54] ASEAN, "Fifth ASEAN State of the Environment Report", 2017, pp. 229-231.
[55] *Ibid.*
[56] *Ibid.*, pp. *233-234.*
[57] ASEAN Magazine, "Climate Change – The Time to Act is Now", Issue 05 (septembre 2020), pp. 6-7.
[58] NAFTA Now, "About NAFTA", https://www.naftanow.org/about/default_en.html, consulté le 05 juillet 2021.
[59] OCDE, "Environment and Regional Trade Agreements", *op. cit.*, p. 40.

selon son acronyme anglais). L'USMCA est considéré comme une renégociation de l'ALENA incitée par l'administration Trump pour protéger davantage les industries américaines en renforçant leurs droits de propriété intellectuelle et en évitant le dumping social vers le Mexique, entre autres.[60]

En ce qui concerne la protection de l'environnement, le nouvel USMCA comprend un chapitre spécifique sur l'environnement (Chapitre 24) qui inclut pour la première fois une liste explicite des accords environnementaux signés par ses membres.[61] En outre, des engagements spécifiques sur l'amélioration de la pollution atmosphérique et la réduction des déchets marins ont aussi été introduits.[62] Ce dernier a été le résultat d'un processus de négociation dans lequel le Canada a fait pression pour inclure des normes environnementales plus strictes sur le texte de l'accord.[63] En conséquence, l'USMCA est censé faire plus en matière de protection de l'environnement que son prédécesseur.[64] Néanmoins, le texte de l'accord ne fait toujours pas référence à l'Accord de Paris et à l'acquis de la Convention des Nations Unies sur le changement climatique.[65] Même si l'USMCA est l'accord le plus récent, dans cette section nous mettrons l'accent sur l'ALENA, car les facteurs explicatifs observés sont très similaires et ce dernier est l'accord qui a déterminé le niveau de protection environnementale entre les trois signataires. Nous soulignerons tout point de comparaison pertinent avec l'USMCA dans le texte.

États impliqués. L'ALENA est un accord commercial établissant une zone de libre-échange entre le Canada, les États-Unis et le Mexique. C'est un accord compréhensif, en ce qu'il essaye d'aborder toutes les problématiques dérivées du libre-échange, y compris l'environnement. Ce qui est pertinent pour l'analyse comparé de cet accord est le fait que l'ALENA intègre deux pays développés (les États-Unis et le Canada) et un pays en voie de développement (le Mexique). C'est pourquoi, au moment des négociations, il y avait des inquiétudes sur les effets environnementaux de l'élimination des barrières commerciales au Mexique vis-à-vis des États-Unis et du Canada. En effet, la relocalisation des industries polluantes vers un pays avec des niveaux d'émissions de CO2 déjà élevés comme le Mexique était un risque réel au moment des négociations. C'est un exemple clair de l'effet de composition énoncé par Grossman et Krueger en 1991.[66]

Motivations. L'article 102 de l'ALENA énumère les objectifs principaux de l'accord, mais il n'y a aucune référence à l'environnement.[67] Les motivations des parties pour initier les négociations

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[60] Office of the United States Trade Representative, "United States-Mexico-Canada Trade Fact Sheet: Modernizing NAFTA into a 21st Century Trade Agreement", https://ustr.gov/trade-agreements/free-trade-agreements/united-states-mexico-canada-agreement/fact-sheets/modernizing, consulté le 05 juillet 2021.

[61] Scott Vaughan, "USMCA Versus NAFTA on the Environment", *International Institute for Sustainable Development*, 3 octobre 2018, https://www.iisd.org/articles/usmca-nafta-environment.

[62] Bashar H. Malkawi et Shakeel Kazmi, "Dissecting and Unpacking the USMCA Environmental Provisions: Game-Changer for Green Governance?", *Jurist Legal News & Commentary*, 5 juin 2020, https://www.jurist.org/commentary/2020/06/malkawi-kazmi-usmca-environment/.

[63] Brice Armel Simeu, "Free trade 2.0: How USMCA does a better job than NAFTA of protecting the environment", *The Conversation*, 24 septembre 2020, https://theconversation.com/free-trade-2-0-how-usmca-does-a-better-job-than-nafta-of-protecting-the-environment-146384.

[64] *Ibid.*

[65] Vaughan, *op. cit.*

[66] Grossman et Krueger, *op. cit.*, pp. 3-6.

[67] NAFTA Now, *op. cit.*

étaient bien différentes[68] : les États-Unis souhaitaient consolider les marchés canadiens et mexicains en réduisant les barrières commerciales et en adoptant une stratégie plus régionaliste que multilatérale pour y arriver. Le Canada avait besoin de réduire la dépendance de ses exportations vis-à-vis du marché américain et se rapprocher du Mexique. Ce dernier, avec un poids économique plus réduit, poursuivait la nécessité d'attirer des investissements pour créer des emplois nationaux et consolider son système productif. La question environnementale est apparue dans les négociations à un stade ultérieur à la suite de la pression de groupes environnementaux,[69] mais au moment de la négociation de l'USMCA, l'environnement est apparu dès le début comme un facteur d'importance majeure du côté canadien.

Types de dispositions. Même si la protection des standards environnementaux n'était pas l'objectif prioritaire des États signataires de l'ALENA, les compromis obtenus ont été remarquables. L'ALENA contient des dispositions environnementales juridiquement contraignantes et un accord supplémentaire en matière de coopération.[70] Il s'agit d'un accord général au sens de l'OCDE[71] car les dispositions adressent des problèmes environnementaux spécifiques qui peuvent être aggravés par la libéralisation du commerce entre les États signataires.

Gouvernance. L'accord supplémentaire a prévu dans ses articles 8 à 19 la création d'une Commission tripartite pour mettre en œuvre les dispositions de l'accord environnemental de l'ALENA, ainsi que pour servir de forum de discussion entre les trois gouvernements et régler les divergences qui peuvent en résulter.[72]

En définitive, l'ALENA est un accord précurseur en ce qui concerne l'institutionnalisation des clauses environnementales. C'est un exemple remarquable en matière de gouvernance et de mise en application des dispositions environnementales dans les ARLEs. Également, l'accord montre l'importance de la pression populaire dans les négociations commerciales : la pression des groupes environnementaux a été fondamentale pour augmenter la crédibilité de la gouvernance environnementale de l'accord.

4. Le CPTPP : Une nouvelle approche encourageante

Le CPTPP est un des plus récents et ambitieux ARLEs. Signé le 8 mars 2018 à Santiago du Chili, il essaye de consolider les échanges et réduire les barrières commerciales entre plus de dix pays des deux côtés du Pacifique.[73]

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[68] Jean Delaneau et Roland du Luart, *L'accord de libre-échange nord-américain: Genèse, résultats et perspectives*, (Paris : Sénat, 1996), 13.

[69] Grossman et Krueger, *op. cit.*, pp. 1-4.

[70] OCDE, "Environment and Regional Trade Agreements", *op. cit.*, p. 27.

[71] *Ibid*, p. 33.

[72] Commission for Environmental Cooperation, "About the CEC", http://www.cec.org/about/, consulté le 6 juillet 2021.

[73] Y compris l'Australie, le Brunei, le Canada, le Chili, le Japon, la Malaisie, le Mexique, la Nouvelle-Zélande, le Pérou, le Singapour et le Vietnam.

États impliqués. D'une façon similaire à l'ALENA, le CPTPP implique à la fois des États développés (l'Australie, le Canada, le Singapour…) et en voie de développement (le Brunei, le Vietnam, le Pérou et d'autres). Néanmoins, dans le CPTPP, les disparités économiques et sociales entre les États impliqués sur les négociations sont plus marquées. De plus, pendant ce processus et après les élections présidentielles de 2016, les États-Unis ont décidé de se retirer de l'accord (initialement appelé TPP, qui comprenait presque 40% de l'économie mondiale) en raison du risque de relocalisation des emplois américains vers les pays membres avec des salaires moins élevés.[74]

Motivations. Le CPTPP a pour objectif d'établir des réductions presque totales des droits de douane entre les États intégrés mais aussi prévoir des mesures spécifiques pour les petites et moyennes entreprises ainsi que des standards en matières connexes comme l'environnement.[75] D'autre part, il y avait aussi des motivations réellement politiques derrière cet accord, notamment les tentatives des États-Unis (au moment de l'administration Obama) d'établir un pouvoir compensateur dans la région du Pacifique pour faire face à la croissance de l'économie chinoise.[76]

Types de dispositions. Le désengagement des États-Unis du TPP original était, paradoxalement, un coup de chance pour les États signataires parce qu'il a nivelé les règles du jeu concernant la participation et la prise des décisions résultant en un accord considéré comme innovant dans un nombre important de matières, y compris l'environnement.[77] En ce qui concerne ce dernier, le CPTPP inclut un chapitre dédié à la protection environnementale, ce qui fait de cet accord un ARLE général au sens de l'OCDE qu'on utilise dans cet article.[78] Les États signataires poursuivent un double objectif dans les dispositions environnementales du CPTPP : créer des mesures contraignantes pour les parties et éviter que la préservation de l'environnement soit réduite en faveur du commerce.[79] Ce dernier objectif a une importance majeure car il situe l'environnement sur un pied d'égalité avec les autres priorités du CPTPP.

Gouvernance. Le CPTPP est aussi innovateur par les moyens institutionnels prévus dans l'accord. Il y a des provisions spécifiques en matière de résolution de disputes et des mécanismes de coopération entre les États, ainsi que des références à des accords internationaux de protection, mais parfois la disposition la plus novatrice est la possibilité d'utiliser des mécanismes volontaires et flexibles pour accroître la protection à condition qu'ils ne posent aucune rigidité au commerce entre les États signataires.

En résumé, le CPTPP constitue un exemple singulier dans l'échantillon proposé. Le changement

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[74] South China Morning Post, "Explained: The CPTPP Trade Deal", *South China Morning Post*, 16 février 2019, https://www.scmp.com/week-asia/explained/article/2186475/explained-cptpp-trade-deal, consulté le 6 juillet 2021.

[75] Pradumma Bickram Rana et Xianbai Ji, "CPTPP: New Key Player in International Trade", *RSIS Commentary* no. 011 (2019): 1-2.

[76] South China Morning Post, *op. cit.*

[77] Rana et Ji, *loc. cit.* ; Takemasa Sekine, "The United States Reasserts Trade Rule-Making through USMCA and Challenges CPTPP", *Asia Pacific Bulletin* no. 448 (2018): 1-2.

[78] OCDE, "Environment and Regional Trade Agreements", *op. cit.*, pp. 32-36.

[79] New Zealand Ministry of Foreign Affairs and Trade, "Environment", https://www.mfat.govt.nz/vn/trade/free-trade-agreements/free-trade-agreements-in-force/comprehensive-and-progressive-agreement-for-trans-pacific-partnership-cptpp/understanding-cptpp/environment/ , consulté le 06 juillet 2021.

de la position des États-Unis dans l’accord a également marqué un changement profond dans la dynamique des négociations. L’accord est passé d’un projet purement commercial à un processus d’intégration plus large, dans lequel l’environnement est situé à égalité avec le commerce.

5. CETA : la référence européenne

Le CETA (l’accord de commerce entre le Canada et l’Union européenne) a été un ARLE controversé dès le début des négociations à cause des doutes et manque d’information sur les effets environnementaux, parmi d’autres. L’un des sujets les plus controversés du CETA est l’inclusion de l’arbitrage en tant que système de résolution des conflits. Sur ce point, la Cour de Justice de l’UE s’est prononcée sur l’intégration de l’arbitrage dans le système juridique européen.[80] Même si la Cour de Justice a jugé les dispositions d'arbitrage de l'accord compatibles avec les traités de l'UE, un contrôle juridique a dû être effectué pour s'assurer que ces dispositions n'enfreignaient pas l'acquis communautaire.[81]

Etats impliqués et motivations. Le CETA réduit les barrières commerciales entre deux des puissances économiques les plus développées du monde. En dépit des résultats variables des études empiriques,[82] nous pourrions espérer que le CETA puisse réduire les émissions futures en favorisant l’efficacité des deux économies vers des solution moins polluantes (ce qu’on appelle l’effet technique).[83] Toutefois, l’accord a trouvé des résistances dans l’opinion publique et la réponse populaire au travers de manifestations a été entendu dans toute l’UE.[84] Il faut en conséquence s’interroger sur le contenu du CETA et pourquoi ses dispositions ont mobilisé citoyens et organisations.

Types de provisions et gouvernance. Il y a deux préoccupations majeures sur les dispositions environnementales du CETA : Premièrement, il manque un compromis réel sur la protection de l’environnement, le chapitre 22 de l’accord[85] ne contient pas d’engagements juridiquement contraignants allant plus loin que l’Accord de Paris, notamment sur le changement climatique.[86] D’autre part, l’ICS (« Investment Court System ») prévu dans l’accord comme instance d’arbitrage entre investisseurs et États est considéré comme un risque d’intrusion d’intérêts privés

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[80] Foodwatch,” The Impact of CETA on the Environment, Climate and Health”, https://www.foodwatch.org/en/campaigns/free-trade-agreements/the-impact-of-ceta-on-the-environment-climate-and-health/, consulté le 06 juillet 2021.

[81] Commission européenne,” European Court of Justice confirms compatibility of Investment Court System with EU Treaties”, *European Commission news archive*, 30 avril 2019, http://trade.ec.europa.eu/doclib/press/index.cfm?id=2014, consulté le 26 février 2021.

[82] Nemati, Hu et Reed, *op. cit.*, pp. 1-4, 17.

[83] Xing Yao et al., *op. cit.*, pp. 1-4.

[84] European Public Service Union, “Protests against CETA continue in advance of vote in European Parliament”, 24 janvier 2017, https://www.epsu.org/article/protests-against-ceta-continue-advance-vote-european-parliament , consulté le 6 juillet 2021.

[85] Commission européenne, “CETA : Chapter by Chapter”, http://ec.europa.eu/trade/policy/in-focus/ceta/ceta-chapter- by-chapter/index_en.htm, consulté le 6 juillet 2021.

[86] Jean-Luc Angot et al., *L’impact de l’Accord Économique et Commercial Global entre l’Union européenne et le Canada (AECG/CETA) sur l’environnement, le climat et la santé* (Paris : Service Public, 2017), 4-7.

des industries polluantes sur les règlementations environnementales de l'UE. Enfin, l'absence dans l'accord d'interdiction des subventions pour les industries polluantes comme les combustibles fossiles est également un facteur préoccupant.

Il semblerait que l'on utilise un critère de comparaison plus exigeant pour examiner les dispositions du CETA qu'avec celles des autres accords de l'échantillon. Cependant, l'UE est un acteur incontournable de la politique environnementale, caractérisée par des mesures ambitieuses contre le changement climatique (parmi d'autres). Par conséquent, le standard d'exigence doit être aussi élevé quand il s'agit de comparer les provisions environnementales des accords entre l'UE et le reste du monde.

En somme, le CETA reste un exemple polémique comme accord commercial en ce qui concerne la protection environnementale. L'intégration commerciale de deux pays développés semble plus complexe que quand il s'agit des pays moins développés (voir l'exemple du CPTPP). Les règles de l'UE en matière environnementale, plus strictes surtout après l'adoption du Pacte vert européen, mettent l'agenda commercial européen sous pression pour qu'il soit cohérent avec l'agenda vert européen. Le système d'arbitrage prévu dans le texte de l'accord, commun dans les juridictions anglo-saxonnes, est vu comme un risque d'assouplissement des mesures du côté européen.

6. UE-MERCOSUR : la dimension globale de la protection environnementale

Nous finissons l'analyse comparée avec une référence au débat plus récent sur la protection environnementale dans les ARLEs : celui qui a lieu au sein des institutions européennes à propos de la mise en œuvre de l'accord entre l'UE et le MERCOSUR. Cet accord est l'un des plus importants de la politique commerciale européenne. Cependant, il a pris une vingtaine d'années à être négocié. Ces clauses ont aussi rencontré le mécontentement de l'opinion publique européenne précisément à cause de ses conséquences environnementales. Après les longues négociations, un accord de principe pour assurer la ratification de l'accord a été atteint en juin 2019.[87] Cet accord de principe est maintenant en question au sein de la commission du commerce international du Parlement européen.

Les représentants européens restent divisés sur un accord qui est vu comme un succès des négociations commerciales pour les uns et une entreprise incompatible avec la dimension extérieure du Pacte vert européen pour les autres.[88] Ce dernier courant de pensée conçoit l'UE comme la référence en termes de croissance économique durable dans le monde et met en doute

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[87] Parlement européen, "Legislative train schedule - EU-MERCOSUR association agreement", https://www.europarl.europa.eu/legislative-train/theme-a-balanced-and-progressive-trade-policy-to-harness-globalisation/file-eu-mercosur-association-agreement, consulté le 26 février 2021.

[88] Parlement européen, "EU-Mercosur: MEPs divided on the trade deal", communiqué de presse, 25 février 2021, pp. 1-2.

que l'accord UE-MERCOSUR soit compatible avec cette idée.[89] En effet, la mise en œuvre de l'accord n'est toujours pas claire et elle a été récemment discutée lors d'une réunion ministérielle informelle à Berlin en 2020 entre les représentants des deux parties.[90] Le résultat de la discussion a été un compromis informel s'accordant à appliquer l'accord en respectant les limites environnementales fixées par l'Accord de Paris. Néanmoins, seulement trois mois plus tard (mars 2021), le parlement autrichien a décidé d'opposer la ratification de l'accord à cause des doutes quant à sa compatibilité avec le Pacte vert européen.[91] C'est un exemple des tensions entre les agendas commercial et vert de l'UE.

Etats impliqués et motivations. Le MERCOSUR est le bloc commercial le plus important de l'Amérique du Sud. Le poids économique de ses quatre membres fondateurs (l'Argentine, le Brésil, le Paraguay et l'Uruguay) et des deux États qui y ont accédé (le Venezuela et la Bolivie) en font la cinquième économie du monde.[92] Les gains du commerce pour les États du MERCOSUR sont significatifs, l'UE étant l'une des régions clés pour les flux commerciaux de ses membres.[93] La motivation pour les pays du MERCOSUR de négocier un tel accord avec l'UE est en conséquence plutôt économique. Du côté européen, il y aurait aussi des implications économiques comme la protection des appellations d'origine protégée ou l'ouverture des marchés publiques aux entreprises européennes.[94] Cependant, l'accord est aussi considéré comme une opportunité pour aller au-delà du commerce et renforcer la présence géopolitique de l'UE dans la région sud-américaine,[95] un aspect souligné par la présidence portugaise du Conseil de l'UE.[96]

Types de provisions et gouvernance. Les clauses environnementales de l'accord UE-MERCOSUR sont regroupées dans un chapitre spécifique lié au développement durable. Ces dispositions ont été incluses sous le principe que le développement commercial ne peut pas empêcher l'application des engagements de l'Accord de Paris. Les parties ont aussi négocié l'inclusion d'une procédure spéciale pour le règlement des litiges comme mécanisme de mise en œuvre.[97] Ce mécanisme a été fortement critiqué pour son manque de force coercitive car il ne fournit pas d'instruments applicables en cas de différend entre les parties.[98]

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[89] Commission européenne, "The external dimension of the Green Deal", https://ec.europa.eu/newsroom/intpa/items/673950, consulté le 26 février 2021.

[90] Commission européenne, "EU-Mercosur statement on Sustainable Development at EU27-LAC Informal Ministerial Meeting", 14 décembre 2020.

[91] EurActiv, "Austria vetoes Mercosur deal saying it goes against EU Green Deal", 8 mars 2021, https://www.euractiv.com/section/economy-jobs/news/austria-vetoes-mercosur-deal-saying-it-goes-against-eu-green-deal/, consulté le 24 avril 2021.

[92] MERCOSUR, "MERCOSUR in brief", https://www.mercosur.int/en/about-mercosur/mercosur-in-brief/, consulté le 26 février 2021.

[93] Max Mendez-Parra et al., *Sustainability Impact Assessment in Support of the Association Agreement Negotiations between the European Union and Mercosur* (London: London School of Economics, 2020), 15.

[94] Parlement européen, "Legislative train schedule", *op. cit.*

[95] Maria Belén Garcia, "The European Union-Mercosur Agreement is Not a Threat to EU Environmental Policy", *Trade Experettes*, https://www.tradeexperettes.org/tradeexperettes-blog/the-european-union-mercosur-agreement-is-not-a-threat-to-eu-environmental-policy, consulté le 27 février 2021.

[96] Céu, *op. cit.*

[97] Commission européenne, "EU-MERCOSUR Trade Agreement - Trade and Sustainable Development", 2020, p. 2.

[98] Francesca Colli, "The EU-Mercosur agreement: towards integrated climate policy?", *EGMONT Royal Institute for International Relations European Policy Brief* no. 59 (2019): 3.

L’enjeu environnemental de l’accord UE-MERCOSUR est surtout lié à la différence, même asymétrique, des structures de production entre les deux parties. Alors que l’UE exporte vers le MERCOSUR principalement des produits hautement élaborés (médicaments, avions, composants pour véhicules automobiles), le MERCOSUR a spécialisé ses exportations dans les produits agroalimentaires tels que le soja ou la viande bovine.[99] C'est précisément l'expansion de ces produits qui suscite le plus d'inquiétudes environnementales. Le soja et la viande bovine sont liés à une consommation élevée de ressources naturelles et à une déforestation accrue[100] : une partie des incendies de forêt en Amazonie a été causée par l'activité humaine visant à libérer des terres pour la production de ces produits.[101]

Au cours des négociations, une évaluation de l'impact sur le développement durable a été menée par la London School of Economics afin de déterminer l'impact environnemental de l'accord. À l'aide de techniques de modélisation macroéconomique, le rapport a conclu que l'accord ne devrait avoir qu'un impact négligeable sur les émissions de CO2.[102] Cependant, le modèle économique utilisé pour prédire les effets environnementaux de l'expansion de ces produits a été également remis en question par des études récentes pour en avoir sous-estimé les conséquences sur l’Amazonie.[103]

Comme nous l’avons montré plus haut, l’accord UE-MERCOSUR est un exemple essentiel à considérer quant aux clauses de protection environnementale dans les accords commerciaux. La raison est claire : il peut être le premier grand accord commercial qui ne sera pas ratifiée par l'UE en raison de ses effets environnementaux. En outre, l'UE est confrontée à un dilemme dans la ratification de cet accord : si elle continue à promouvoir l'accord tel qu'il est actuellement, sa crédibilité en tant qu'acteur du changement dans la diplomatie climatique sera remise en cause. Il y aura aussi un risque élevé de contredire le message d'action extérieure du Pacte vert. En revanche, si l’accord n’est finalement pas ratifié par les États Membres, l’UE risque de perdre sa force comme acteur géopolitique.

Conclusions

L’étude comparée des clauses de protection environnementale de l’ALENA, CPTPP, ASEAN, CETA et UE-MERCOSUR révèle des différences significatives dans les quatre variables proposées : États impliqués, motivations, types de provisions et gouvernance. Il est constaté que les différences d’objectifs des accords et la dynamique des négociations ont une influence significative sur le résultat final des accords.

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[99] Luciana Ghiotto et Javier Echaide, “Analysis of the agreement between the European Union and the Mercosur”, Greens/EFA, 2019, pp. 17-20.

[100] Climate Action Network Europe, “EU-Mercosur: climate costs higher than economic benefits, new report shows”, https://caneurope.org/eu-mercosur-climate-costs-higher-than-economic-benefits-new-report-shows-2/, consulté le 27 février 2021.

[101] Colli, *op. cit.*, pp. 3-4.

[102] Mendez-Parra et al., *op. cit.*, pp. 83-85.

[103] Ghiotto et Echaide, *op. cit.*, pp. 21-24.

L’hétérogénéité des ARLEs dans la protection environnementale dépend aussi de facteurs géopolitiques : les positions individuelles de chaque État et leur prédisposition à coopérer, ainsi que l’histoire même des accords peut conditionner les négociations. En ce sens, l’ASEAN illustre comment l’environnement peut être utilisé comme vecteur d’intégration économique entre États qui appartiennent à un même accord depuis longtemps. Nous avons aussi constaté que l’aspect environnemental prend plus d’importance quand les accords incluent des pays développés avec réglementations environnementales strictes (spécialement l’UE).

Nous avons aussi trouvé des différences importantes dans la chronologie des accords. D’un côté, l’ASEAN a traité la question environnementale à une étape ultérieure de l’intégration commerciale. C’est plutôt logique : ces négociations ont eu lieu dans les années soixante, quand il n’y avait pas une pression aussi significative dans le débat publique sur la question environnementale. Autrement, dans tous les autres accords que nous avons examinés, l’environnement a été traité dès le début des négociations, même avec une importante divergence dans chaque exemple. Dans les cas les plus récents, comme l’accord UE-MERCOSUR, la protection environnementale est devenue un sujet tellement important qu’il risque de faire échouer un accord négocié pendant une vingtaine d’années. L'environnement ne peut plus être ignoré comme facteur décisif à protéger dans le processus de rédaction et négociation des accords commerciaux.

L’environnement, en conclusion, a trouvé sa place dans les ARLEs de l’échantillon proposé de manière particulièrement divergente. Malheureusement, les négociations commerciales entre États semblent encore loin de reconnaître le rôle essentiel de la protection environnementale dans les ARLEs. Le changement climatique et les impacts potentiellement négatifs liés à la libéralisation commerciale de certains produits ne sont pas encore au centre du débat. Comme montré par la problématique de la mise en œuvre de l’accord UE-MERCOSUR, l’UE est confrontée à une ambition géopolitique basée sur la signature d’ARLEs stratégiques qui semblent parfois en contradiction avec ses ambitions climatiques (plus fortes) dans le cadre du Pacte vert. Un équilibre délicat doit être trouvé par les autorités européennes pour assurer la cohérence entre des agendas politiques (commercial et climatique) différents et potentiellement contradictoires. L’agenda commercial doit être effectivement intégré dans l’ambition climatique européenne. Les pouvoirs publics européens doivent s'assurer que le niveau d’ambition mené par les réglementations environnementales au sein de l’UE est aussi respectée dans les actions commerciales de l’UE dans le monde. Il est essentiel pour la crédibilité du projet européen que l’UE continue à être le référent mondial de l’ambition climatique, même si cela entraîne des relations commerciales plus complexes.

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