Understanding the feedbacks between climate change and the global economy: an ecological, post-Keynesian modelling approach for the European Green Deal

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Ignasi Cortés Arbués
Student number: 5134676

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Graduation committee:

Chairperson	:	Prof. dr. J.H. Slinger, Policy Analysis
First Supervisor	:	Dr. S.T.H. Storm, Economics of Technology and Innovation
Second Supervisor	:	Prof. dr. J.H. Slinger, Policy Analysis
External Supervisor	:	Dr. Y. Dafermos, SOAS University of London

Executive Summary

Dealing with the societal and economic consequences of climate change is one of the more complex grand challenges that humanity will face this century. Climate science research suggests that holding global temperature change within 2 °C by 2100 will limit the extent of natural disasters around the world. Moreover, the climate emergency requires revamping the economic system through a green transition, where low-emission or carbon-neutral economic activity replaces the status quo. However, there is uncertainty regarding the economic impact of the policies required to complete the transition, in part because there is no agreement on how to appropriately model these interventions and the economy itself. As a consequence, there is a limited understanding of feedback effects between the environment and the macroeconomy, further complicating the validation of economic policies promoting the green transition.

In this study, we have examined one of the world's more developed green economic strategies, the European Green Deal (EGD), through the lens of a stock-flow consistent model called DEFINE. The purpose of the research is to understand how effective the EGD's policies are in bringing about the green transition, given the temperature and emissions' targets set by climate scientists, and the need to maintain a stable macroeconomy. Hence, the main policies of the EGD, which are expected to raise €1 trillion over ten years for climate action, have been reviewed in detail, including (i) the green public investment strategy, (ii) the cap-and-trade carbon market, and (iii) the role of the financial sector in fostering green private investment.

The next step involved understanding the modelling tool used for the analysis. Inspired by post-Keynesian and ecological macroeconomics principles, DEFINE is an accounting-based, demand-driven macroeconomic model at the global scale with 185 equations that illustrate the behaviour of five main clusters of actors: firms, households, banks, the government and the central bank. It is composed of two main subsystems: the ecosystem and the macroeconomy, which includes a financial sector. These subsystems interact through seven distinct channels, that include the depletion of natural resources, climate damages to the economy, and the impact of green finance on economic activity, amongst others. It outputs a plethora of indicators from both subsystems, allowing us to understand simultaneously how the economy is performing, and how the Earth's environment is affected.

Given the particularities of the model, the policies from the EGD were operationalised to be used as inputs for the model. The policy levers selected were the share of green public investment on GDP, the level of carbon taxation, defined to be equivalent to the EU's cap-and-trade carbon market, and the reduction in green credit rationing, which would emulate the role of the financial sector in the EGD. Moreover, a baseline scenario was selected from previous studies using the model; this scenario is based on the Shared Socioeconomic Pathways (SSP) framework used in climate science. Finally, a scenario tree was developed varying the levers, from an emulation of the EGD to more radical versions of the plan.

It was found that the policies were effective in detaching economic growth from carbon emissions, outperforming the baseline scenario in most relevant metrics. However, the basic policy scenario replicating the EGD did not keep global temperature change within 2°C by 2100, even if it proved to be a major improvement over the status quo. Other policy scenarios, involving a higher level of green public investment and carbon taxation, managed to meet the temperature target while maintaining a high economic growth rate and a stable financial system. The main trade-off in these policy packages was the high fiscal deficit incurred over the first ten years of the plan, as it would require substantial political compromise and bravery.

While these European-based policies were applied on a global model, the added value of this study cannot be overstated. The results cannot be directly translated into quantified policy recommendations for EU policy-making, or for governments of other states, but they can be used to draw a general policy direction that decision-makers around the world can follow. Notably, the level of green public investment should increase to at least 1.5% over the 2021-2030 period, relative to the 0.45% of the EGD, and budget deficit rules should be relaxed to allow for the fiscal stimulus the transition requires. Finally, future work should focus on developing regional modules of DEFINE that analyse a broader range of future scenarios, and provide quantifiable policy recommendations for governments to use.

Acknowledgements

Caminante, no hay camino, se hace camino al andar.

(Antonio Machado)

This thesis represents the end of my two-year period as an Engineering and Policy Analysis student at the TU Delft. Writing a thesis is normally an arduous process with a lot of ups and downs. In the era of COVID-19, the downs were much lower, and the ups were not particularly high. In this environment, the support from those around me has become all the more important, and as such I want to take a moment to thank them.

Firstly, I want to thank my parents, Fermín and Mireia, for their continued emotional and financial support. Despite the distance and the limitations imposed by the pandemic to travel back home, you have always been there when I needed it most. I am very thankful for the financial privileges that your hard work has provided me, notably the ability to study abroad without worries.

Secondly, I want to thank my partner, Weronika, for equally being by my side in the tougher stretches, understanding my struggles and knowing what to do at all times. In all honesty, the prepositions in this report would be constantly wrong without your help.

Thirdly, I want to thank my academic committee for their support over the past few months. To Servaas Storm, thank you for your guidance, your input and above all, for knowing how to motivate me to do my best. To Yannis Dafermos, thank you for trusting me with your model and for altruistically dedicating tens of hours to help me understand it. To Jill Slinger, thank you for accepting to be involved in this project and for all the advice you have given me over the last two years.

Finally, I want to thank my friends from EPA for the fun (albeit strange) times of the last two years. This programme needs social interaction between its students to achieve its full potential, and despite the barriers imposed by the pandemic, we have thrived. Amongst others, I want to thank Sam for suggesting EPA to me over two years ago, Jin for picking up the phone at random times to chat about nothing and everything, and Sahiti for pushing me intellectually to question what others might take for granted.

And thanks to you, the reader, for showing interest in my work. I hope you enjoy it and learn a thing or two about the societal and economic challenge that is climate change, and what we can do about it.

Contents

Acronyms

CTP-A Carbon Tax Pathway A.
CTP-B Carbon Tax Pathway B.

DEFINE Dynamic Ecosystem-FINance-Economy.
DSGE Dynamic Stochastic General Equilibrium.

ECB European Central Bank.
EGD European Green Deal.
EGDIP European Green Deal Investment Plan.
EIB European Investment Bank.
ETS Emissions Trading System.
EU European Union.

GCR Green Credit Rationing.
GDP Gross Domestic Product.
GPI Green Public Investment.

IAM Integrated Assessment Model.
IPCC Intercontinental Panel on Climate Change.

JTM Just Transition Mechanism.

KPI Key Performance Indicator.

RCP Representative Concentration Pathways.

SDG Sustainable Development Goals.
SFC Stock-flow Consistent.

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1 Introduction

Climate change represents, from a policy-making and implementation standpoint, one of the most complex societal challenges humankind has faced (National Research Council, 2011). Its complexity lies in the fact that it worsens other grand challenges that humanity faces, such as the eradication of poverty and access to clean water, amongst other issues highlighted in the UN's Sustainable Development Goals (SDG) (United Nations, 2016). Tackling climate change requires facing interconnected environmental threats (Michaut, 2017), that reinforce harmful social and macroeconomic patterns. Ultimately, climate change is a global problem that knows no borders, and so requires a global solution.

At this point it may be a cliche, but in the same way that human activity is responsible for the climate crisis (Arrow, 2007), it will take human action, in the form of a green transition, economic and otherwise, to achieve sustainable development (Jackson, 2011). This transition requires a broad transformation of modern societies, spanning from changes in agricultural practices to the phasing out of carbon-intensive energy sources, such as fossil fuels (International Renewable Energy Agency, 2020). However, the financing of the transition itself remains a hot topic of discussion. In the political arena, the short-term view has often prevailed: protecting the interests of future generations does not necessarily align well with policies that will help win the next election, even in the most modern democracies (Povitkina, 2018).

Moreover, there are distributional concerns regarding the costs and impacts of climate change (Botzen, Gowdy, & van den Bergh, 2008). Low income economies, mostly in the Global South, will be hit first and more drastically by climate-related disasters, and have limited capacity to finance the transition (Tol, Downing, Kuik, & Smith, 2004). On the opposite end are high income economies in the Global North, which are largely responsible for the post-industrial CO_2 released into the atmosphere (Den Elzen, Schaeffer, & Lucas, 2005), yet will suffer less drastic consequences from the changing climate. Thus, these disparities lead to endless negotiations and burden shifting, promoting inaction and widening global inequalities.

In a hopeful turn of events, some political will to tackle the climate crisis has emerged in recent years, as exemplified by the Paris Agreement (United Nations, 2015), which 189 countries have joined to this day. In this context, a plethora of national climate mitigation plans and initiatives have arisen. Amongst the most aggressive adaptation plans is the European Green Deal, which is a set of ambitious green policies proposed in December 2019 (European Commission, 2019), representing the first step for Europe to reach net-zero greenhouse gas emissions by 2050.

Of course, there are a number of policy challenges related to the implementation of a plan of this magnitude. At a macroeconomic level, the efficient allocation of resources is complex, as the macroeconomy is a convoluted system with many actors. Moreover, climate damage projections are characterised by deep uncertainty (Knight, 1921), as their scale depends on the macroeconomy itself and future events that are hard to predict. As such, forecasting the impact of future policies is an arduous task.

To further complicate matters, underlying this challenge is the nature of economics as a discipline: it is a social science (Frey, 1999). Hence, there are multiple schools of thought making differing interpretations of real-life events (Harvey, 2020), leading to macroeconomic debate and, more importantly for the purposes of this thesis, divergent modelling approaches.

They can be summarised in two large groups. Orthodox, mainstream economists follow a modern interpretation of neoclassical approaches, focused on inflation control through monetary policy, and unemployment reduction through labour deregulation (Storm & Naastepad, 2012). Heterodox economists tend to follow Keynesian principles, which perceive the macroeconomy as demand-driven, and seek to achieve full-employment mostly through fiscal policy (Keynes, 1936). These policy choices are motivated by underlying beliefs and assumptions made about the economy and its agents, such as the assumption of rational expectations made in orthodox approaches. However, despite their disagreements, economists from both sides agree on the tight relationship between economic activity and climate change (Nordhaus, 2008; Rezai, Taylor, & Foley, 2018).

Following this general recognition in the field, a variety of climate-focused macroeconomic models have been developed in recent years. The most recognisable is perhaps an integrated assessment model (IAM) called DICE, which was developed by Nordhaus (2008). It features an optimisation-driven approach, and it has earned the author a Nobel Prize in 2018. However, the model is often criticised for its dependence on rational expectations and perfect foresight by economic agents (Rezai, Taylor, & Mechler, 2013), and in the author's more recent work (Nordhaus, 2018), for ignoring the presence of temperature tipping points beyond 4ºC in its climate damage function. Finally, as a highly aggregated model without a financial sector, it is not a suitable tool to identify policy packages that could finance climate action and keep global warming within reasonable bounds by the end of the century.

Hence, the focus of this thesis shifts away from the assessment of previous models like DICE, and is placed instead on the use of heterodox, Keynesian approaches. These approaches are demand-driven, but also constrained by supply-side factors determined by the Earth's ecosystem, such as the availability of fossil fuels and material resources. The inclusion of planetary and resource boundaries should provide valuable economic insight regarding the limitations of a growth-based economic frame in the context of the climate crisis.

1.1 Academic and societal relevance

This thesis provides insights from both academic and societal perspectives. On the one hand, the academic contributions hinge on the potential of Keynesian approaches to more realistically interact with the biophysical limits of the global economy (Fontana & Sawyer, 2016). On the flip side, ecological economics has often neglected the macroeconomic dimension in its modelling (Spash & Schandl, 2009). This intersection opens up new research possibilities, particularly in the field of modelling and policy analysis, which could result in positive contributions to the economics discipline.

From a societal perspective, contributing to the understanding of the relationship between the macroeconomy and the climate emergency will sharpen the advice given to policymakers in the coming years, particularly as climate becomes a focal component of annual budgets for governments around the globe. The presentation of the European Green Deal facilitates this process, as it can be used as a benchmark for other institutions to follow, as well as a policy input to be analysed. Hence, this thesis is tied to the Engineering and Policy Analysis M.Sc. programme due to its strong focus on the climate crisis as a societal grand challenge, and is located at the intersection between academic and societal relevance.

1.2 Literature review

The purpose of this section is to provide an initial assessment of the state of the art on the subject of economics and climate change. Firstly, the initial review approach is outlined, followed by the definition of some core economic concepts, and a description of the role of the European Union (EU) in the context of this thesis. The analysis of the literature is completed later on, as Chapters 2 and 3 cover the European Green Deal and the chosen modelling method in depth.

1.2.1 Review approach

Given the need to understand the connection between the economics discipline and climate change, the literature search started by exploring academic reviews on recent models in the field of ecological macroeconomics (Ciarli & Savona, 2019; Hafner, Anger-Kraavi, Monasterolo, & Jones, 2020; Hardt & O'Neill, 2017). Following the reviews, the focus shifted towards recent academic articles describing state-of-the-art economic modelling, with a focus on heterodox, post-Keynesian approaches (Dafermos et al., 2017; Nieto, Carpintero, Lobejón, & Miguel, 2020). These approaches were chosen due to their perceived value alignment with ecological economics (i.e., no reliance on a utility maximisation assumption), as highlighted by Rezai et al. (2013).

However, the search also rendered a certain degree of differentiation between post-Keynesian and ecological economics (Spash & Schandl, 2009), notably on the subject of economic growth, not always perceived as desirable on the ecological side. The review conducted by Hardt and O'Neill (2017) specifically targets this gap, as it analyses how different models introduce the policy themes embedded in the post-growth literature. These findings raised a second axis of research within the review, seeking to explore potential gaps between the approaches. Finally, the focus was shifted to the review of EU-specific applications of ecological macroeconomics modelling, such as the work of Nieto et al. (2020), as well as a more detailed inspection of the European Green Deal (European Commission, 2019).

This process was undertaken using the resources available through the TU Delft Library. A snowball method was used to deepen the understanding of specific techniques as well as the normative assumptions populating the discipline; this was quite logical given that the academic reviews were this research's starting point. Upon said review, some of the key works in the field are discussed in more detail.

1.2.2 Relevant previous work

In orthodox economic climate modelling, which follows a neoclassical, optimisation-based approach, the work of Nordhaus (2008) and the creation of his DICE integrated assessment model stand out, particularly due to their impact on US policy-making circles. Other important orthodox approaches to consider are Dynamic Stochastic General Equilibrium (DSGE) models, due to their recent surge in many policy circles, as exemplified by the European Central Bank's (ECB) Smets-Wouters model (Smets & Wouters, 2003). Farmer, Hepburn, Mealy, and Teytelboym (2015) proposed their use in climate-focused applications as successors to IAMs, and they have been used to analyse the impacts of different carbon policies (Chan, 2020; Zhao & Yang, 2019). DSGE models are subject to similar criticism as other approaches based on neoclassical principles, such as the use of flawed microeconomic foundations, including perfect information and the representative agent model, that fail to illustrate key features of economic behaviour (Stiglitz, 2018).

In traditional ecological economics, where post-growth is often discussed, the book "Prosperity without growth? [...]" by Jackson (2009) is central. On analytical post-Keynesian ecological models, Rezai et al. (2018, 2013) provide important insight on the feedback between demand-driven forces and environmental impact, while Dafermos et al. (2017), Bovari, Giraud, and Mc Isaac (2018), and Jackson and Victor (2020) are good examples of stock-flow consistent (SFC) numerical models, at different scales.

1.2.3 Core definitions

As Hardt and O'Neill (2017) point out, there is not yet a mutually agreed definition of **ecological macroeconomics**. However, they mention three academic themes that can emerge when discussing the subject: the need to manage an economy without growth (arising explicitly from the definition of ecological macroeconomics in Jackson (2009)); the development of new tools illustrating dependence between the macroeconomy and the environment (see for example Fontana and Sawyer (2016)); and finally, the combination of ecological and post-Keynesian approaches, upon which this thesis builds. Finally, it is important to point out that some authors analysing from a post-growth perspective view the field as an opportunity to redefine the purpose of the economy (Røpke, 2013).

Another important definition for the purposes of this thesis is that of **stock-flow consistent modelling**. In their recent work, Jackson and Victor (2020) define the method in three axioms. Firstly, each expenditure of an economic sector is also the income of another. Secondly, each sector's financial asset corresponds to a financial liability in at least one other sector, and assets and liabilities add up to zero. Thirdly, changes in stocks of financial assets must be related consistently to flows within and between sectors. Following the original work by Godley and Lavoie (2006), simulation runs are consistent through simple accounting principles derived from these axioms. Moreover, this consistent accounting allows for a reduction in degrees of freedom needed for the economic model (Hafner et al., 2020). Finally, Hafner et al. (2020) further argue that, as a consequence, the main strength of SFC models is their ability to interrelate the financial and real sides of the economy.

1.2.4 Ecological macroeconomics and the EU economy

Undoubtedly, one of the main questions that arises from the literature is whether sustained economic growth is compatible with the challenges that climate change brings (Jackson, 2009), both regarding the financing of the required economic transition and the returning feedback that catastrophic events could have on the global economy. Hence, there is likely an interest in policy-making circles at the EU level to understand whether a growth-powered transition is possible (particularly in the context of the European Green Deal).

There is one specific study that aims to tackle this. In their recent work, Nieto et al. (2020) suggest that the climate targets set by the EU can only be met in a "Post-Growth" scenario, where there is a reduction in GDP growth expectations. They use a model based on system dynamics and input-output analysis, while maintaining the theoretical frameworks from ecological and post-Keynesian economics. It is interesting to explore similar scenarios to theirs using an alternative modelling approach, such as the Dynamic Ecosystem-FINance-Economy (DEFINE) model by Dafermos et al. (2017), which is stock-flow consistent. The integration of financial stocks and flows is a feature that Nieto et al. (2020) openly discuss as to be added in future iterations of their model, something that is already a strength of DEFINE and other similar models. To conclude, the work of Nieto et al. (2020) shows the potential implementation of relevant policies and scenarios in a post-Keynesian model, and so could be used to validate similar analyses.

On a political and societal level, it is important to reflect on the role that high-income economies (in this case, the European Union as a whole) have in spearheading the transition. In a recent "Perspectives" article, Galvin (2020) defends that high-income countries can decarbonise justly and sustainably, and that resistance would come exclusively from the financial sector. His argument is partially backed up, on a more EU-focused level, by the critique of the European Green Deal from Storm (2020), who claims that a more ambitious fiscal spending plan is not only imperative in the face of the challenge, but that it is also politically possible. However, there seems to be a gap between what modellers use as scenarios and the deeper political insights provided by authors like Storm and Galvin. This is likely related to the relative lack of concrete policy actions within the European Green Deal itself, which is more target based (European Commission, 2019); this is discussed in more depth in Chapter 2. Combining what is deemed "politically possible" with economic performance indicators in model outputs, should increase the quality of the advice that could be provided to policymakers.

1.3 Research objectives

In this section, the research question is outlined, followed by 6 related sub-questions. These sub-questions are answered in Chapters 2 through 7 of this thesis, both in the general discussion and explicitly in the last section of each chapter. Following this outline, the research methods are described, including the model that will be used for analysis: the DEFINE model by Dafermos et al. (2017).

1.3.1 Research question

From the literature review, we can conclude that modelling research in ecological macroeconomics is becoming dynamic and commonplace, with post-Keynesian economics having a large influence in heterodox models. There seems to be a relative knowledge gap regarding the application of these models, particularly stock-flow consistent ones, in the context of the European Green Deal and what it means for climate policy globally. Hence, seeking to help define what is "politically possible", the research question is the following:

"How can a stock-flow consistent model grounded in ecological and post-Keynesian economic values further understanding of the macroeconomic and climatic consequences of the European Green Deal?"

1.3.2 Research method

Following the discussion in the introduction, we highlight the assertion by Frey (1999) that economics is in fact a social science. From there, the existence of different schools of thought follows naturally (Harvey, 2020), and so diverging representations of the complex socio-technical system that is the global economy arise. These differences result in the conception of economic models with distinct characteristics, driven by underlying assumptions that bring along a variety of limitations. Hence, economic models act as a double-edged sword, as insightful conclusions can be drawn from the behaviour of the system modelled, but it is essential to acknowledge the limitations embedded in the underlying assumptions in order to recommend robust policies. In conclusion, as George P. Box (1979) famously stated, "all models are wrong, but some are useful".

The research method chosen for this thesis is a modelling approach, specifically a stock-flow consistent model. This approach was originally proposed by Godley and Lavoie (2006), with more contemporary work attributed to authors like Dafermos, Nikolaidi, and Galanis (2018) and Jackson and Victor (2020). The three axioms described in Section 1.2.3 portray the strengths of this "accounting-driven" approach, which features stocks and flows representing, for instance, income and wealth, while maintaining the discrete nature of economic transactions and emphasising the need for (asset-liability) balance, which methods like system dynamics might struggle with.

Upon consultation with one of its authors, who agreed to be an external supervisor to this thesis, **the model used in this study is the DEFINE model** developed by Dafermos et al. (2017). In the words of the authors, DEFINE is a "stock-flow-fund ecological macroeconomic model that analyses the interactions between the ecosystem, the financial system and the macroeconomy" (Dafermos, Galanis, & Nikolaidi, 2018). The DEFINE model is also consistent with the laws of thermodynamics. In their recent review, Hardt and O'Neill (2017) class DEFINE as an SFC model as well as a physical input output model, as it depicts physical stocks and flows, such as waste and resources (see Figure 1).

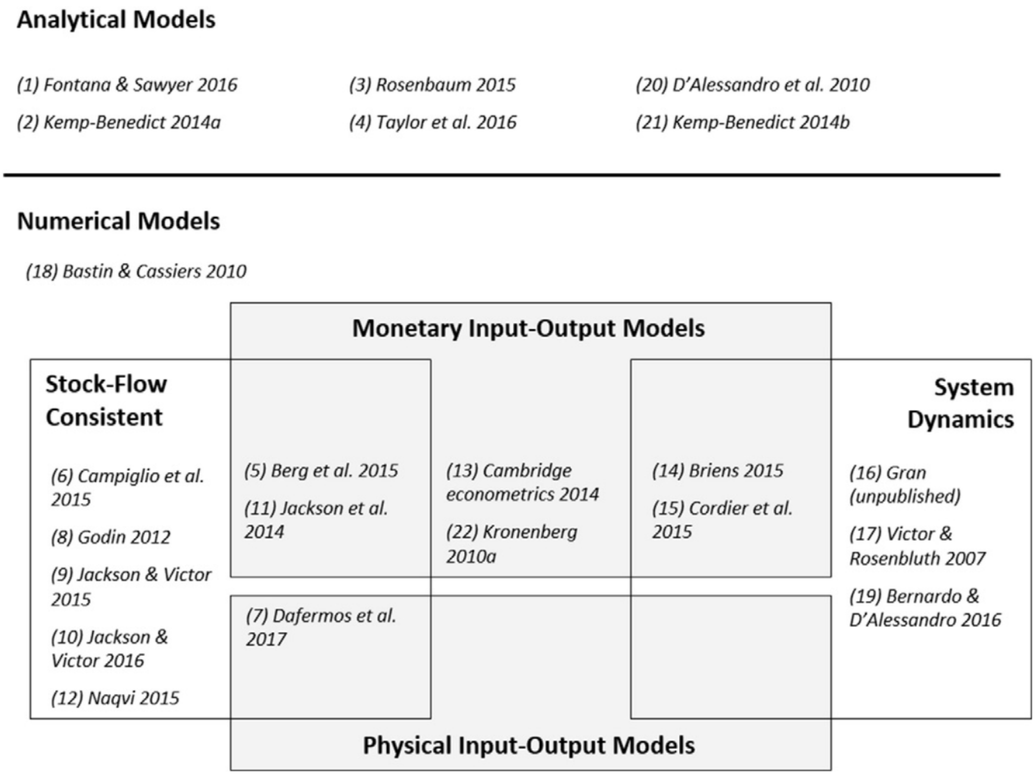


Figure 1: Categorisation of ecological macroeconomics models by modelling technique obtained from Hardt and O'Neill (2017). The DEFINE model is (7), classed as stock-flow consistent and as a physical input-output model.

The main advantages of DEFINE are the embedding of the macroeconomy as an open subsystem within a closed ecosystem, the consideration of supply-side constraints due to climate damages in the context of a demand-driven model, and an emphasis on income and wealth distribution as drivers of the macroeconomy and the financial system (Dafermos, Galanis, & Nikolaidi, 2018).

Given the short length of the thesis project relative to the size and complexity of the model, it was decided that the analysis would be based on introducing a fiscal policy input into the model, to understand its long term implications. For this purpose, the European Green Deal is operationalised to be used as the input. Since DEFINE is a model of the global economy, the policies are scaled up to a global level. Given the lack of concise policy specification in the current version of the Green Deal, a further review of related literature is presented in Chapter 2, in order to establish realistic policy inputs that align with its values.

1.3.3 Research sub-questions

Following from the literature review and choice of model, as well as the policy considerations to be made regarding the European Green Deal, the following sub-questions arise regarding policy operationalisation, model structure and analysis:

Sub-question 1	**What is the European Green Deal and what are its stated aims and policies?**
Sub-question 2	**What are the strengths and weaknesses of the DEFINE model?**
Sub-question 3	**What are relevant policy levers from the European Green Deal which can be included in the DEFINE model?**
Sub-question 4	**What are the long-term results of the European Green Deal's (fiscal) policies based on the model analysis?**

Regarding the presentation of results and the concluding recommendations, the following considerations should be made:

Sub-question 5	**What do the model findings mean for the European Green Deal as the EU's climate mitigation strategy?**
Sub-question 6	**What are the limitations of the analysis and its findings and how should future work in the field be approached?**

1.4 Report structure

The report structure follows the logic of the sub-questions listed above. The report has started with an **Executive Summary** synthesising the thesis process and findings, followed by an introduction in **Chapter 1**. **Chapter 2** covers the European Green Deal in depth, while **Chapter 3** features a description of the DEFINE model and its characteristics. The outcomes of the previous chapters are put together through a policy operationalisation in **Chapter 4**, and results are produced in **Chapter 5**. The main findings are discussed in **Chapter 6**, and the research is concluded in **Chapter 7**, providing policy recommendations and acknowledging the limitations of the analysis.

1.4.1 Research flow

In order to answer the sub-questions posed in Section 1.3.3, a conceptual research flow diagram has been constructed in Figure 2. The first step is to understand the **European Green Deal** at a deeper level, including its aims and the economic significance of its

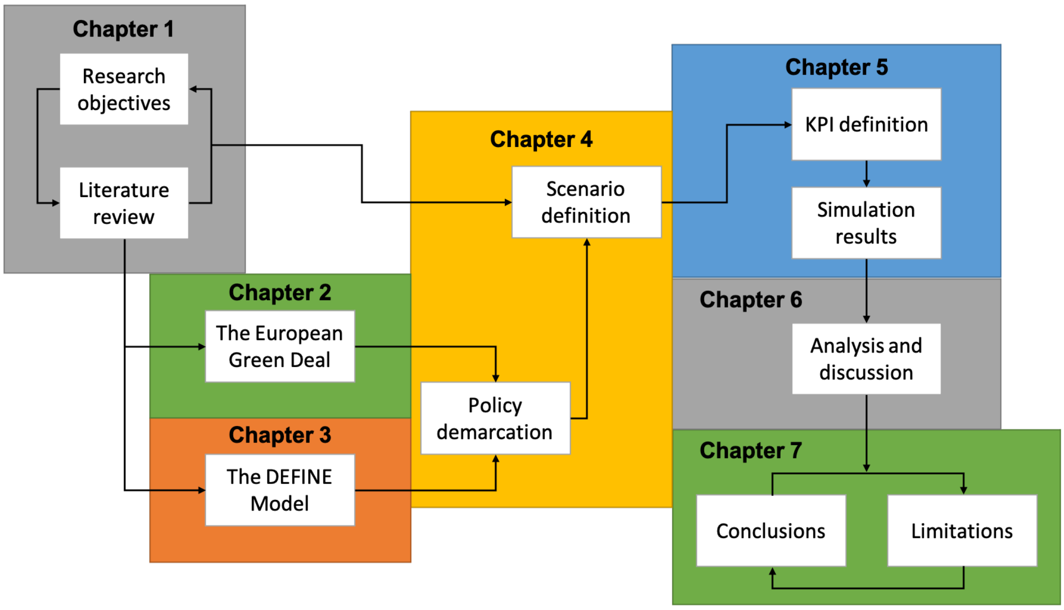


Figure 2: Research flow diagram.

policies. These policies are framed under the potentially catastrophic consequences of climate change and the cost of global inaction. The need for a global policy response is also discussed.

Secondly, the **DEFINE model** is contextualised and its main characteristics are discussed in depth, including its subsystems and the differentiation between green and conventional economic activity. The strengths and weaknesses of the model are discussed in the context of the application proposed in this thesis.

The third step involves the **operationalisation** of the policies discussed within the European Green Deal, in order to define a policy input for the model. Hence, the three main policy inputs are discussed and relevant assumptions are listed. Finally, a scenario tree is developed, setting the stage for model simulation and analysis.

The fourth step is the presentation of the **model simulation and results**. The model settings and general specifications are listed first, followed by a delineation of the key performance indicators (KPI), which are discussed in four thematic clusters. This part of the thesis concludes with the presentation of results and model validation.

The penultimate section is the **analysis of results and discussion** of the general implications. The impact on the KPI clusters is discussed in depth, as well as system-level insights through the behaviour under the different scenarios. This section ends with a discussion on the implications for the European Green Deal, as the model results can illustrate the effectiveness of the Deal's policies at a global level.

In the **conclusions**, the added value of this thesis is presented, along with the limitations of the approach, and some policy recommendations and reflections drawn from the analysis and aided by the literature. Future work avenues are also presented.

2 The Climate Emergency and the European Green Deal

Global warming and climate change have traditionally been the terms used to refer to the environmental consequences of post-industrial greenhouse gas emissions. These terms have a clear scientific connotation, as until recently discussions were mostly started in academic circles. However, the European Parliament, along with other legislating institutions around the globe, declared a **climate emergency** in November 2019, calling on the EU to submit a strategy to reach climate neutrality as soon as possible (European Parliament, 2019), illustrating the need for urgent action at a governmental (regional and national) level as well. In this chapter, this urgency is explained through the cost of global inaction, the need for policy intervention, and finally by answering what the European Green Deal is, and what its aims and significance are.

2.1 The cost of global inaction

Climate change represents an existential threat to human life in its current form. The catastrophic consequences that would follow surpassing certain temperature thresholds defined by climate scientists could displace millions of people, reshaping our society and threatening economic prosperity. These thresholds, known as tipping points, are predicted to trigger non-linear increases in climate-related disasters, and have irreversible effects on the dynamics of the climate system (Heutel, Moreno-Cruz, & Shayegh, 2016). Other relevant thresholds are those related to large ecosystems, such as the Amazon (Nobre & Borma, 2009), as its survival is essential to the Earth's ability to capture carbon. In this context, the Intercontinental Panel on Climate Change (IPCC) stressed the importance of keeping global warming within 1.5°C above pre-industrial levels in its most recent report (Allen, Babiker, Chen, & de Coninck, 2018b).

The same report outlines some of the extreme consequences that would arise under a 2°C warming scenario by the end of the current century. For instance, there would be a sharp increase in the population's exposure to extreme heatwaves; it is estimated that 420 million more people will be exposed to them under a 2°C scenario relative to 1.5°C (Buis, 2019). These differences are illustrated in Figure 3. On a related note, water scarcity will become more prevalent, as droughts will be more widespread. They will be particularly impactful in the Mediterranean, Southern Africa, South America and Australia, with 61 million more people affected in urban areas under a 2°C scenario (Buis, 2019).

On the flip side, some areas will see increased rainfall and flooding, such as North America, Northern Europe, Northern Asia and Southeast Asia (Buis, 2019), with large population centres suffering major material damages. Finally, the melting of the ice caps will increase coastal flooding and generally raise the sea level, rendering many coastal settlements uninhabitable or at least extremely vulnerable. Under one of the more pessimistic representative concentration pathways (RCP), RCP8.5, which are greenhouse gas concentration pathways used by the IPCC, there will be an increase of 52% of the world's population and 46% of global assets at risk of flooding by 2100 (Kirezci et al., 2020).

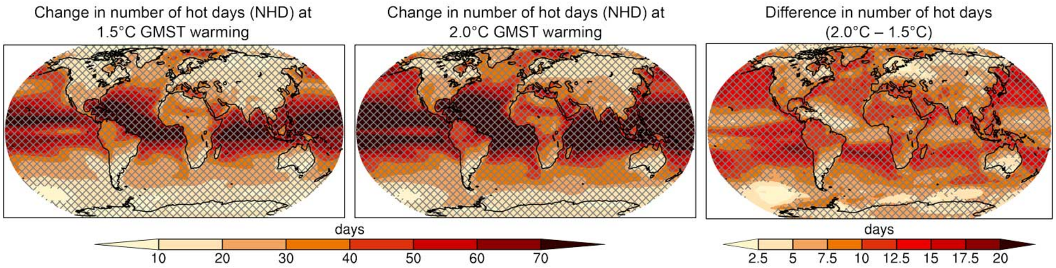


Figure 3: Change in number of hot days between between a 1.5°C scenario and a 2°C scenario, obtained from Allen et al. (2018a). The figures illustrate the increase in prevalence of extreme heatwaves in most regions, particularly in the tropics.

However, the economic damages that result from climate change are not limited to its impact on assets and capital stock, the labour force would be affected as well. Climate disasters can destroy infrastructure and floods can lead to the abandonment of coastal capital (Dietz & Stern, 2015; Taylor, Rezai, & Foley, 2016), while the adverse impacts that climate change has on human health can reduce labour force participation. Finally, both labour and capital will become less productive, as the harmful conditions under which firms could operate will constrain labour productivity (Taylor et al., 2016), creating a hostile environment in which capital is used less effectively (Dietz & Stern, 2015). In these conditions, the financial markets would collapse in an unprecedented manner, due to the high rate of default of firms, and the inability to insure certain assets against climate-related risks (Bolton, Despres, Da Silva, Samama, & Svartzman, 2020). Under these levels of economic and financial uncertainty, the livelihoods of millions would certainly be under threat, creating unpredictable migration away from heavily damaged areas and, ultimately, exacerbating conflict.

2.2 The need for policy intervention

As discussed in Chapter 1, it is both humanity's interest and responsibility to act against the climate crisis in a coordinated and global manner. Action needs to be systemic, and be taken at all levels of government, business and society. On a scientific level, the IPCC concludes that "Strengthening the capacities for climate action of national and sub-national authorities, civil society, the private sector, indigenous peoples and local communities can support the implementation of ambitious actions implied by limiting global warming to 1.5°C" (Allen et al., 2018b). On a political level, climate action needs to take centre stage to avoid major catastrophes, as Barack Obama stressed in his address to COP21: "We are the first generation to feel the impact of climate change, and the last generation that can do something about it" (Obama, 2015).

The need for action follows almost 30 years of UN Climate Talks (Council on Foreign Relations, 2021), which started with some of the first international agreements on climate change at the Rio Earth Summit in 1992. The next major agreement was the Kyoto Protocol (United Nations, 1997), which was the first legally binding treaty requiring high income countries to reduce emissions. The Protocol entered into force in 2005 (Council on Foreign Relations, 2021), and was extended until 2017 due to lack of agreement on more ambitious aims in the midst of the financial crisis.

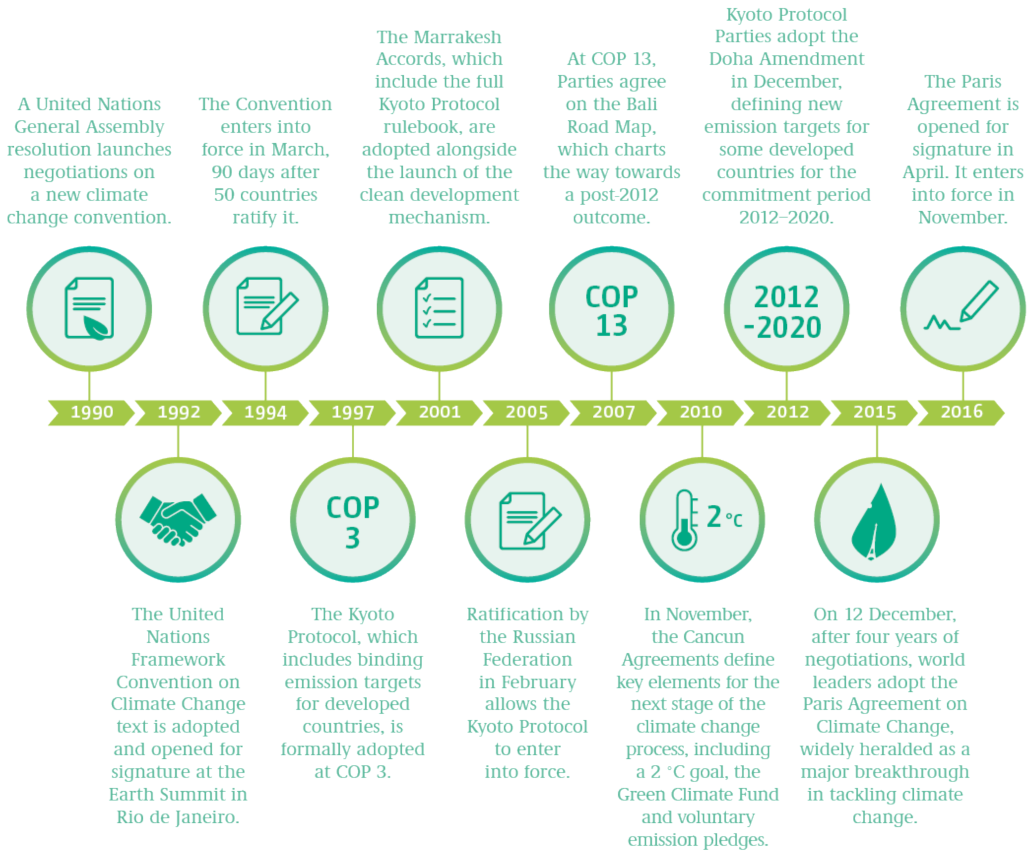


Figure 4: A brief timeline of the history of UN Climate Talks from 1990 to 2016, obtained from United Nations Framework Convention on Climate Change (2017).

The distributional concerns of climate change were on full display in 2013 (Council on Foreign Relations, 2021). The lead negotiators of the G77, a large group of low and middle income countries, walked out of the talks after high-income countries rejected a funding mechanism that would help vulnerable countries deal with climate-related damages. The narrative changed in 2015, when the Paris Agreement was signed (United Nations, 2015), requiring most signing countries to set emissions reduction goals. However, the US's withdrawal under President Trump first (the US recently rejoined the agreement under the Biden administration), and the COVID-19 pandemic later, have stalled further talks and commitments, particularly those related to specific policy actions. A summary of the timeline until 2016 is shown in Figure 4.

Despite the apparent activity over this 30-year period, most climate negotiations have led to standstills, and at best, emission targets set far into the future (Schröder & Storm, 2020). There has been no coordinated policy action at the international level, and so most climate policies have been approved at the national and sometimes, in the case of the EU, at the supranational level. Planned and enacted measures cover a wide range of policy areas and levels, from energy to waste management, from national to local.

Under the umbrella term of green transition, the European Commission (2021a) covers climate action and sets goals for emissions reduction. Under climate action are understood the development of sustainable transport infrastructure, the enhancement of energy efficiency in buildings, and coastal protection measures in areas vulnerable to rising sea levels. There is also a commitment to remove barriers to finance clean energy initiatives, facilitating the rise in renewable energy share. Furthermore, a commitment is made to not leave anyone behind, supporting communities that are heavily reliant on carbon-intensive activities. Finally, public and private financing considerations for green projects are made, using both fiscal and monetary tools. These policies are supported by the EU's green growth strategy, the European Green Deal (European Commission, 2019), which is discussed in depth below.

2.3 The spirit of the European Green Deal

Following the ratification of the Paris Agreement, and the publication of the IPCC's Special Report on the impacts of global warming of 1.5°C above pre-industrial levels (Allen et al., 2018b), the European Commission published a strategic long-term vision for a climate neutral economy, under the title "A Clean Planet for All" (European Commission, 2018). This vision simply proposed a policy direction for the bloc to take, but opened a debate in EU policy-making circles, foreshadowing the publication of the European Green Deal in late 2019.

2.3.1 What is the European Green Deal?

The European Green Deal (EGD) is defined by the European Commission (2019) as the EU's policy response to the challenges of climate change. It is a growth strategy that aims to transform the EU into a modern and fair society, empowered by a resource-efficient and competitive economy. The more specific aim outlined in the Commission's communication is the net zero greenhouse emissions target by 2050, and the decoupling of economic growth from resource use. Moreover, it seeks to achieve these economic targets while conserving and enhancing the EU's natural capital, and protecting the health and well-being of its citizens. Finally, it highlights the need for the transition to be just and inclusive, considering the prevalent inequalities within and across member states, acknowledging regional differences and challenges, and not leaving anyone behind. The main elements of the EGD are presented in Figure 5.

2.3.2 The policy significance of the EGD

The EGD is the defining policy proposal of the von der Leyen Commission. It was presented a few days after the new College of Commissioners took office in late 2019, clearly defining where the main priorities of the new administration would lie. The European Commission recognised in its presentation that the emissions' targets set previously

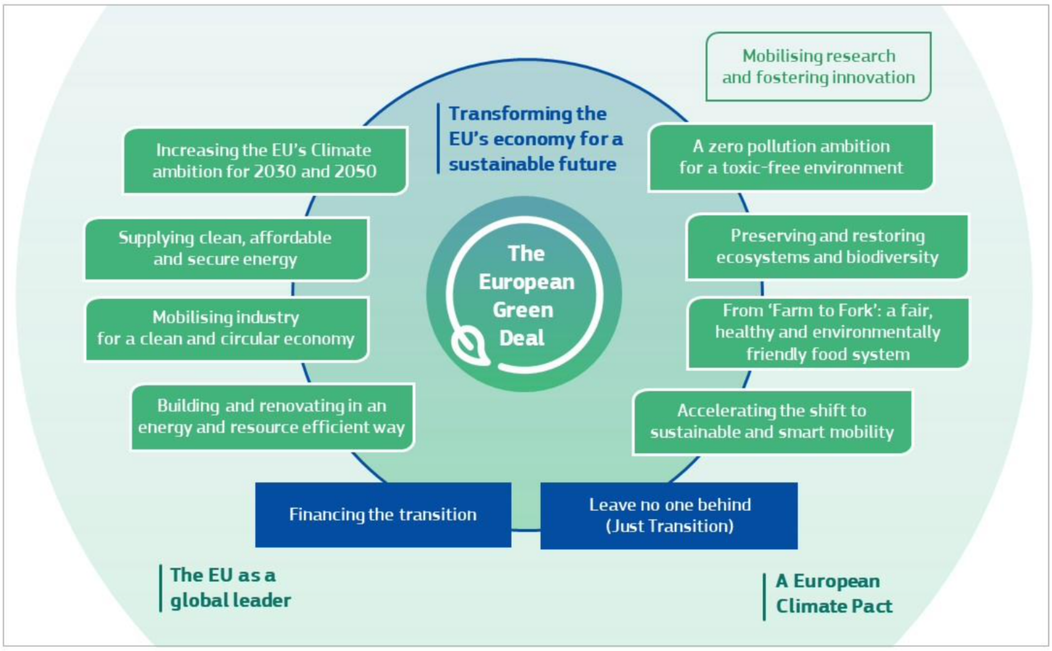


Figure 5: The main policy pillars of the European Green Deal, as summarised by the European Commission (2019).

would only achieve a 60% reduction by 2050 (European Commission, 2019), and so the medium term targets, in this case for the year 2030, had to be more ambitious. Hence, under the EGD, greenhouse gas levels in 2030 are set to be at least 55% lower than in 1990.

In order to achieve this, the Commission committed to the revision of all climate-related policies before July 2021, under a new legal framework called the European Climate Law, introduced in March 2020 (European Commission, 2020b). The law not only includes the new emissions target for 2030, but also addresses the necessary steps the Commission needs to follow to successfully reach the 2050 target. Finally, it requires member states to develop resilient adaptation strategies aimed at reducing vulnerability to the effects of climate change.

The EGD recognises that the challenge we are facing encompasses a variety of sectors, and so policy choices need to be coordinated across the board. For instance, the EGD stresses the need for a new industrial policy, as the transformation of energy-intensive sectors will have a great impact on overall emissions. Hence, the opportunities of the digital transformation, arising in parallel to and in conjunction with the EGD, can be leveraged to keep EU industry competitive while achieving climate objectives.

Finally, the EGD stresses the need to have contingency plans if the EU's international partners do not follow its lead on emissions reduction. The EGD acknowledges the prevalence of carbon leakages in the EU's supply chain, and proposes the creation of a carbon adjustment mechanism to reduce these leakages (European Commission, 2019). This measure is designed to not only meet emission targets, but also to protect greener European alternatives from cheaper, carbon-intensive competition outside the EU. In order to avoid geopolitical tensions, some authors suggest coordinating these adjustment mechanisms with third parties, and engaging oil- and gas-exporting economies to facilitate their diversification towards renewable energy generation (Leonard, Pisani-Ferry, Shapiro, Tagliapietra, & Wolff, 2021).

2.3.3 The economic dimension of the EGD

The main policy pillar of interest in this thesis is the European Green Deal Investment Plan (EGDIP), as it covers the policy inputs that can be operationalised for the analysis. In broad terms, the EGDIP looks to mobilise at least €1 trillion in sustainable investments over the 2021-2030 period (European Commission, 2020a). Besides this direct funding device, the EGDIP aims to create a framework to facilitate sustainable investments for public and private investors, and also to provide support to public administrations and project managers in the identification and execution of sustainable projects.

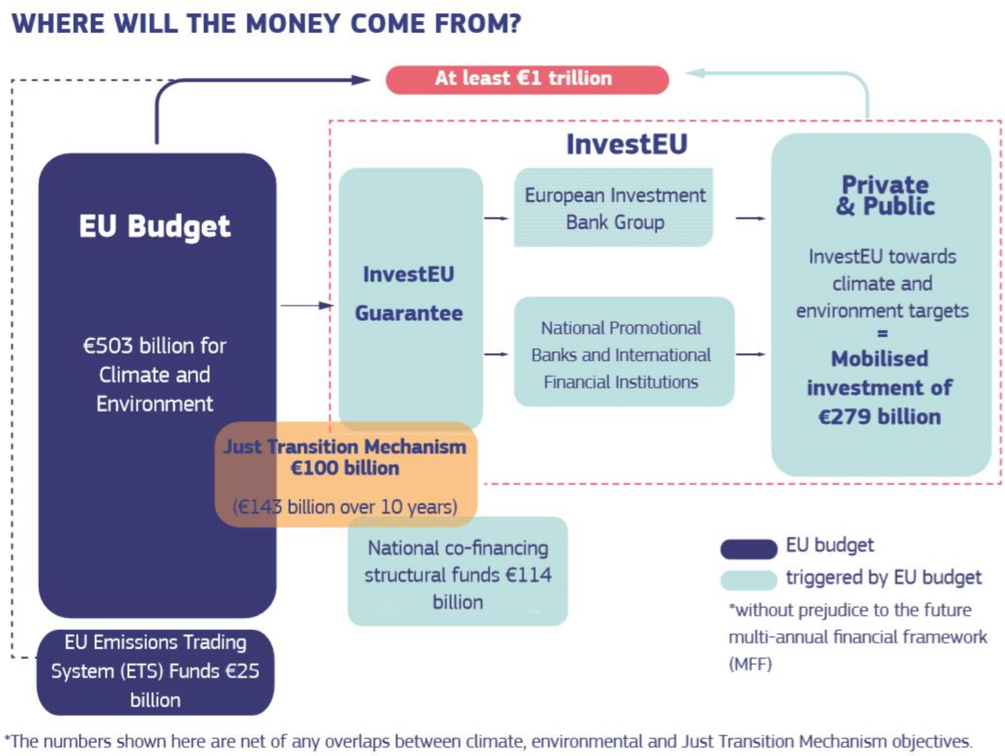


Figure 6: A breakdown of the policy components of the European Green Deal Investment Plan (EGDIP), obtained from European Commission (2020a).

The main components of the investment plan are presented in Figure 6. The main contribution comes from the EU budget, featuring €503 billion dedicated to climate action and the environment. The Commission specifically proposed for 25% of the 2021-2027 budget to be dedicated to these efforts (European Commission, 2020a). Moreover, €114 billion are expected to come via co-financing from member states, triggered by the EU budget, bringing the cumulative green public investment to €617 billion.

The EU is perceived to be leading the charge regarding sustainable finance (Janse & Bradford, 2021). Hence, the second largest contribution to the EGDIP comes from the financial sector, under the guarantees provided by the InvestEU programme. InvestEU is the EU's main investment programme, attracting and mobilising private investment in line with EU policy (European Commission, 2021b). This scheme expects to mobilise at least €279 billion through national banks, international financial institutions and the European Investment Bank (EIB). In fact, the EIB has specifically committed to increase its share of lending activity dedicated to climate action and environmental sustainability to 50% by 2025 (European Investment Bank, 2020). Policymakers hope that these signals sent by the EU's public investment bank are just the beginning, and that the overall levels of mobilised investment are higher than the projected €279 billion.

Furthermore, the EGDIP predicts that €25 billion will come from the EU Emissions Trading System (ETS), which is the EU's cap-and-trade system for carbon emissions. This scheme currently covers around 40% of total greenhouse emissions in the EU (European Commission, 2017b), with its coverage slowly increasing every year. Moreover, according to the ETS directive, at least 50% of revenues, which are received by member states, should be dedicated to climate and energy-related purposes (European Commission, 2017a); in the period 2013-2019, 79% of ETS revenues were recycled for this purpose.

Finally, the EGDIP acknowledges the inequalities embedded in the transition by incorporating the Just Transition Mechanism (JTM) as part of its policies (European Commission, 2020a). To make sure that no one is left behind, €143 billion will be financed using the tools presented above, ensuring that those areas that are heavily dependent on carbon-intensive employment have the funds to transition. These funds partially overlap with the other components of the EDGIP, adding up to the €1 trillion promised in the plan.

2.4 Policy context summary

SQ1: What is the European Green Deal and what are its stated aims and policies?

In Chapter 2, the climate crisis has been discussed in depth, the need for policy intervention has been motivated, and the aims of the European Green Deal as a holistic policy package have been outlined. The societal consequences of climate change clearly encompass a variety of policy areas that are interlinked, and so the policy response needs to be coordinated and compact. The main aim of the EGD, which is to make Europe carbon neutral by 2050, can only be reached through this type of comprehensive response, which is why the economic dimension of the Deal is so important to begin building the required infrastructure and processes to fulfil the green transition. The funding mechanisms presented, embedded within the EGDIP, attempt to transform the European economy from multiple perspectives and involving various actors, committing to the systemic transformation that the climate emergency requires. In upcoming chapters, these mechanisms are operationalised in DEFINE and their impact on the global economy is assessed.

3 The DEFINE Model

The choice of a macroeconomic model as the main tool used to answer the research question acknowledges the uncertain nature of the macroeconomy as a system, and the need to simplify its components to understand its dynamics. Of course, modelling a socio-technical system comes with its own set of difficulties, including conceptualisation, data gathering, and validation. However, the main challenge perhaps resides in making a somewhat correct interpretation of the results, being aware of the limitations of the model and understanding how these play into what the results suggest. In this chapter, the DEFINE model is summarised with a focus on the components that make it useful in the context of this thesis. At the end, the main strengths and weaknesses of the model are discussed in detail.

3.1 An ecological, post-Keynesian macroeconomic model

According to its authors, the DEFINE (Dynamic Ecosystem-FINance-Economy) model is a stock-flow-fund ecological macroeconomic model, that seeks to analyse interactions between the ecosystem, the financial system and the macroeconomy (Dafermos, Galanis, & Nikolaidi, 2018). Its main aim is to examine economic policies that will allow society to live prosperously within the biophysical limits of the planet, following the ecological macroeconomics tradition (Jackson, 2009; Rezai et al., 2013).

The stock-flow-fund elements of the model come from the post-Keynesian tradition, combining the stock-flow-consistent approach of Godley and Lavoie (2006) and the flow-fund model of Georgescu-Roegen (1971). In doing so, DEFINE provides an integrated approach that allows the analysis of physical and monetary stocks and flows (Dafermos, Galanis, & Nikolaidi, 2018). Some of the physical laws and economic principles integrated in the model are the laws of thermodynamics, the relationship between greenhouse emissions and temperature, the material damages due to the changing climate, the endogeneity of money, and the influence of finance in economic activity.

In the past, DEFINE has produced various future scenarios for the economy and the ecosystem under a handful of different policies. It was initially proposed in 2015 (Dafermos, Nikolaidi, & Galanis, 2015), and the first results employing a variety of green finance policies were published in 2017. In more recent iterations, the role of green quantitative easing and financial stability under climate change have been studied (Dafermos, Nikolaidi, & Galanis, 2018). Moreover, green fiscal policies, such as carbon taxes, green subsidies, and green public investment, have also been analysed using DEFINE (Dafermos & Nikolaidi, 2019). Finally, climate-related financial risks were explored in detail in the most recent publication using the model (Dafermos & Nikolaidi, 2021b).

The results and implications presented in this thesis build on this previous work, particularly on the analysis of green fiscal policies, this time using the EGDIP as the main policy input. In order to do so, it is essential to understand the main features of the model, and the different channels through which they interact.

3.2 Characteristics of the DEFINE model

The most recent iteration of the DEFINE model (Version 1.1) is presented in the model's manual, which is the source used throughout this section (Dafermos & Nikolaidi, 2021a). The manual features 185 equations placed in two main subsystems: (i) the ecosystem, and (ii) the macroeconomy and financial sector. Moreover, the manual features 2018 initial values for all endogenous variables and parameters in the baseline scenario; these will be discussed more extensively in Chapter 4. The complete list of equations is available in the Appendix, and the manual can be downloaded from the DEFINE website. The upcoming sections provide a full qualitative overview of the model.

3.2.1 Green and conventional economic activity

Before examining the model structure, it is important to understand why the model distinguishes between green and conventional economic activity. Both public and private investment can be green or conventional, leading to green and conventional capital accumulation. This allows a distinction between green and conventional loans and bonds, which are the main tools that firms can use to finance their activity. By influencing the availability of loans and bonds for green or conventional investments, green financial policies can be enacted supporting the development of a low-emission economy.

Moreover, the model distinguishes four private sectors: 'mining and utilities' (S1), 'manufacturing and construction' (S2), 'transport' (S3) and 'other sectors' (S4). All sectors can accumulate green and conventional capital. The aim of this disaggregation is to identify how 'dirty' the loans given to these sectors are, defined as the ratio between the carbon emissions the sector generates relative to its gross value added. These distinctions allow for further restrictions on dirtier investment projects, facilitating the greening of the economy across the board. For the purposes of this breakdown, the government is treated as a separate sector, that can accumulate both green and conventional capital as well.

3.2.2 Model structure

At the macro-level, the model interactions can be summarised in seven separate channels. By disaggregating the financial system and the macroeconomy (which in DEFINE are portrayed as a common subsystem), the model can be conceptualised as presented in Figure 7. As expected, there is a clear feedback between the macroeconomy and the ecosystem, happening through four separate channels.

The macroeconomy affects the ecosystem through **depletion** and **degradation**. As necessary inputs for the production process, matter and fossil energy are extracted; this process depletes the planet's finite natural resources. Moreover, higher economic activity leads to CO_2 emissions and the generation of hazardous waste, which degrade the ecosystem through rising temperatures and the harmful effects of waste accumulation.

In return, the ecosystem affects the macroeconomy through climate **damages** and **natural resources' constraints**. As discussed in Section 2.1, climate damages can destroy

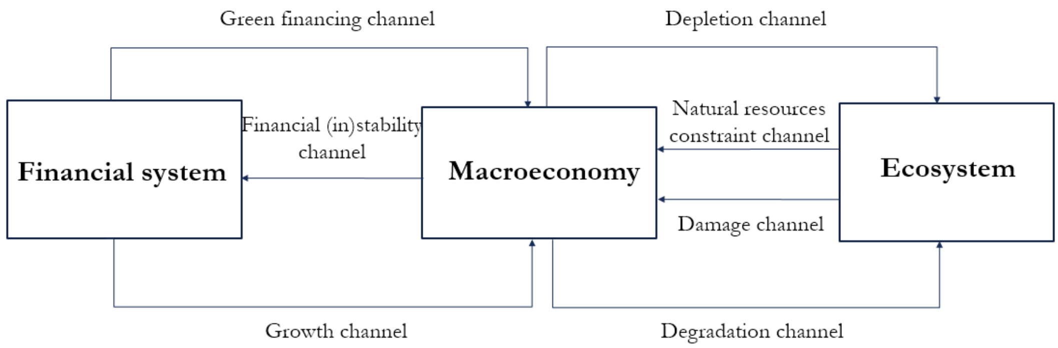


Figure 7: Highly aggregated conceptual model of DEFINE, obtained from Dafermos et al. (2017). The main interactions between the ecosystem, the macroeconomy and the financial sector are presented.

capital and reduce capital and labour productivity. Moreover, they can negatively affect the behaviour of households and firms, reducing consumption and investment expenditure and, ultimately, economic growth. The previous depletion of resources can further deteriorate economic activity, as supply-side resource constraints arise.

Finally, the financial system and the macroeconomy are related through three channels: **green financing**, **growth** and **financial (in)stability**. The financial system can foster economic growth through the provision of credit, increasing investment. By facilitating green financing, banks and central banks can contribute to the green transition and decouple economic growth from environmental issues. In return, the growth of the macroeconomy can expand the financial system, leading to higher financial instability due to higher leverage ratios. Low economic activity could generate debt repayment issues, creating similar instabilities, and so a balance is desired.

3.2.3 The ecosystem

In DEFINE, the ecosystem relies on two accounting matrices looking at physical relationships between stocks and flows. The first is the physical flow matrix (Table 4 in the Appendix), which captures the First and Second Law of Thermodynamics. Thus, in the model, energy and matter cannot be created or destroyed, only transformed during the economic processes, where low-entropy energy (i.e., fossil fuels) is transformed into high-entropy energy (i.e., dissipated heat). Hence, the material and energy balances add up to zero in the model.

The second matrix is the physical stock-flow matrix (Table 5 in the Appendix), which illustrates the changes in physical stocks relevant to human activity, through additions to and reductions of stock. These are the material and fossil energy reserves, the cumulative CO_2 emissions, the socio-economic stock and the cumulative hazardous waste. In this matrix, matter and energy resources are converted to reserves, which are available for use in economic processes; this conversion is relevant for human activities, but does not represent a physical transformation. Note that cumulative CO_2 emissions and hazardous waste do not have outflows in this model.

In the upcoming subsections, the content of the equations in the ecosystem is summarised.

Matter, recycling and waste

The goods produced every year in the global economy require a specific amount of matter to be produced, which can be extracted or recycled. Recycled matter depends on the recycling rate and the amount of discarded socio-economic stock, which is the material content of the sum of all capital goods and durable consumption goods.

Waste is obtained as the residual from the material balance in the physical flow matrix, a small proportion of which is hazardous and accumulates. The mass of carbon used as input in the material balance is estimated from industrial emissions. Finally, material reserves decline when matter is extracted, and increase when resources are converted; a matter depletion ratio is defined based on matter extracted relative to material reserves.

Energy

Energy can be generated either from fossil or non-fossil sources, and is a function of output and energy intensity. Fossil energy reserves change every year based on the conversion of fossil resources and the use of fossil energy. The energy depletion ratio is defined as the fossil energy extracted relative to remaining reserves.

Emissions and climate change

Industrial CO_2 emissions are generated due to the use of fossil fuels (although a proportion does not enter the atmosphere), and due to changes in land use. Atmospheric temperature becomes higher as cumulative carbon emissions increase, using the relationship formulated by Dietz and Venmans (2019).

Ecological efficiency and technology

Overall ecological efficiency of production changes based on a set of efficiency indicators. High material, CO_2 and energy intensities lower overall efficiency, while high recycling and sequestration rates, and high shares of non-fossil energy increase it. CO_2 intensity change is exogenous, while all other indicators change endogenously using logistic functions. These functions assume that their corresponding efficiencies depend on the ratio of green to conventional capital, where more green capital leads to higher overall efficiency. A more nuanced explanation of these indicators can be found in the manual (Dafermos & Nikolaidi, 2021a).

3.2.4 Macroeconomy and financial sector

The macroeconomy and financial sector also rely on two accounting matrices, in this case looking at monetary stocks and flows. The first is the transactions flow matrix (Table 6 in the Appendix), which captures the transactions taking place between the different sectors of the economy (households, firms, banks, government and central banks), including revenues, expenditures and changes in financial assets and liabilities. Current and capital accounts are differentiated, as current accounts register payments made or received while capital accounts portray investment funding in real and financial assets. In this matrix, total monetary inflows are equal to outflows in the aggregate.

The second matrix is the balance sheet matrix (Table 7 in the Appendix), which shows the assets and liabilities of the economic sectors. Following the accounting principles, at the aggregate level, financial assets should equal financial liabilities; these include loans, bonds, government securities, high-powered money and advances. The net worth of the global economy is then the sum of real assets, including firm and government capital stock, and the durable consumption goods of households.

In the upcoming subsections, the content of the equations in the macroeconomy and the financial sector is summarised.

Output determination and climate damages

In DEFINE, potential output is defined as the minimum value of four different types of output: matter-determined, which depends on material reserves; energy-determined, which depends on fossil energy reserves and the renewable share; capital-determined, which depends on capital stock and capital productivity; and labour-determined, which depends on labour productivity and the total hours worked in the economy. On the other hand, actual output is demand-determined, as the sum of private and government consumption and investment. Utilisation and employment rates are obtained from the ratios of actual output to types of potential output, illustrating capital and labour scarcity as they approach a value of 1.

Moreover, climate damages affect both capital and labour productivity and the capital stock and the labour force themselves, in line with the literature (Dietz & Stern, 2015; Taylor et al., 2016). Aggregate demand is affected by the induced investment fears that catastrophes have on entrepreneurs and the increased propensity to save by households for precautionary reasons. Climate damages also affect the four different types of potential output, leading to capital and labour scarcity. Finally, the gross damage function used in this model follows the recent literature on high-temperature damages (Dietz & Stern, 2015).

Firms

As specified in Subsection 3.2.1, firms are split in four different sectors, allowing for different mixes of conventional and green investment, and under green financial regulation, different access to loans. Their total gross profits depend on total output and their costs, including wages, the interest paid on loans, the coupon payments paid on bonds and capital depreciation. A certain percentage is retained by the firms, which also pay profit and carbon taxes, and can receive subsidies from the government.

In the model, firms desire a certain level of investment, which is financed via retained profits and external finance (bonds and loans). However, only a proportion of the new loans are provided, as the model assumes a quantity rationing of credit imposed by banks. Total desired investment is affected positively, in a non-linear manner, by the profit rate and the rate of capacity utilisation, in line with Kaldor (1940). It is also negatively affected by the unemployment rate if it is very low, in line with insights by Kalecki (1945). Finally, resource and energy scarcity can dampen investment at very severe depletion levels. Overall, desired investment relies on the idea that demand declines when it approaches potential output.

Moreover, the share of total desired investment per sector is determined based on their shares in gross value added. The share of desired green investment depends on three factors: (exogenous) changes in environmental preferences and institutional change, the cost of green capital relative to conventional capital, and the borrowing cost to invest in green capital relative to conventional capital.

Once the level of investment has been determined following the rationing of credit, green and conventional capital can accumulate. Capital can also depreciate, both naturally and in an accelerated manner due to climate damages. Labour and capital productivity are also affected by climate damages, while labour productivity specifically can also grow due to exogenous technology factors. Since the wage share is exogenous, the wage rate grows at the same rate as labour productivity.

Households

The gross disposable income of households is composed of wage income, firm and bank distributed profits, interest payments received on bank deposits, on government securities held and on corporate bonds held. After tax, households' consumption depends on lagged income and lagged financial wealth, and can be affected by supply-side constraints due to climate damages.

Moreover, household wealth accumulates every year following asset allocation decisions, which are driven by alterations in the relative rates of return, changes in the transactions demand for money, and climate damages. Finally, the growth rate of population follows UN projections and affects the labour force, which is further affected by the accumulation of hazardous waste and its effect on human health.

Banks

Bank profits are the sum of the interest received on loans and government bonds held by the banks, minus the interest paid on deposits and advances given by the central bank. The change in their capital is equal to their undistributed profits minus the amount of defaulted loans plus any government bailouts.

Moreover, banks impose credit rationing on firms, as they are less willing to lend when the financial position of borrowers worsens. The credit rationing depends specifically on the debt service ratio of firms, and the capital adequacy ratio of banks; by introducing differentiated capital requirements for green and conventional loans, green investment can be favoured.

The risk weights of conventional loans, used to determine the credit rationing, are functions of the degree of dirtiness of each sector. They also determine the lending spread for each sector, which set the interest rate for loans in that sector. The risk weight of green loans equally determines the green spread.

Government sector

Government revenues are the sum of taxes on household income, firms' profits and carbon, as well as profits received from the central bank. Government expenditures include government consumption, green subsidies and interest paid on government issued debt. The difference between current revenues and expenditures constitutes the government net saving. This balance does not include investment spending, which is balanced through government issued securities.

The proportion of public investment spending relative to GDP is set exogenously, both for green and conventional public investment. A degree of carbon revenue recycling can be introduced in the model, whereby a certain percentage of carbon taxes are converted to green subsidies given to firms. Carbon taxes are exogenously determined, and their revenue is linked to industrial emissions.

Central banks

The role of central banks in the model is to determine the base interest rate, provide liquidity to banks, buy government securities and buy corporate bonds through quantitative easing. Their profits are determined based on the revenue streams related to their role, mostly through interest and coupon payments.

3.3 Model application

The DEFINE model was chosen as the main analytical tool used in this thesis partially due to the attention to detail placed on often under-modelled areas of the economy. Moreover, DEFINE offered clear results on a variety of aggregate economic and environmental indicators. However, this high level of aggregation can limit the applicability of the results, particularly when presented to policymakers. In this section, the strengths and weaknesses of DEFINE are discussed in detail, as the considerations made here influence the way in which the policies of the European Green Deal are operationalised.

3.3.1 Strengths

The conceptual model of DEFINE shown in Figure 7 clearly outlines the main strength of the method: the **thoroughly defined feedback channels between the macroeconomy and the ecosystem**. In acknowledging not only the effect of emissions caused by economic activity, but also the depletion of natural resources, the model produces a more complete overview of the damage that uncontrolled dirty economic activity can do to the environment. In addition, the depletion of natural resources imposes supply-side constraints on economic activity, leading to a reduction in potential output, already harmed extensively by economic damage on labour and capital. The integration of all of these channels into a cohesive representation of the system allows us to draw valuable conclusions at an aggregate level, as no significant economic or environmental elements have been assumed away.

In particular, the **inclusion of the financial sector** and its relationship with the rest of the economy is a major strength of the DEFINE model. Most standard IAMs do not incorporate the financial system and simply assume that the funds required to finance (green) investment will be smoothly mobilised out of savings. Doing so, these orthodox approaches define away a major dimension of the macroeconomic system, because they ignore the non-negligible policy problem of how climate action can and should be financed, as well as the non-neutral impacts of different ways of financing climate policy on the economy and the climate system.

Moreover, the distinction between desired investment and actual investment, after the introduction of credit rationing, not only provides a more realistic representation of the challenges that firms face in financing their activity, but also allows us to test different financial policies that can steer economic activity in a green direction. Finally, it allows us to understand whether the financial sector is headed towards the "green swan" events described by Bolton et al. (2020) under climate damage stress, which would have catastrophic effects on the ability of firms to operate, and ultimately affect the livelihoods of millions as firm default rate rises.

In terms of policy implementation, DEFINE can **handle a variety of measures affecting a broad range of economic policy areas**. In the past, the model has been used to analyse the impact of fiscal, financial and monetary policies, through the lens of an economy that differentiates between green and conventional economic activity. Given that the European Green Deal goes beyond an aggregate fiscal plan, the model's versatility and ease of policy implementation allows us to identify the individual and collective effects of the EGD's policies, as well as how they interact with each other. In particular, being able to introduce different carbon tax pathways and exogenously set the level of green public investment makes DEFINE suitable for this policy analysis.

3.3.2 Weaknesses

For all of DEFINE's strengths, its main weakness as a tool for the purposes of this thesis is obvious: **the level of aggregation does not capture regional effects**. Hence, any recommendations made to EU policymakers should be accompanied by an assessment of how the EU fits as a player in the global economy. As a consequence, the analysis is exploratory in nature, and seeks to determine the level of policy intervention that the global economy should undergo. An implementation of the DEFINE model that would focus exclusively on the European economy would require defining regional clusters within the model, that would trade goods and services and financial assets with each other; this level of analysis is beyond the scope of this thesis.

Related to the level of aggregation is the **homogeneous implementation of economic policies**. The green transition will phase out millions of jobs in certain industries, such as coal mining. Hence, certain regions dependent on carbon-intensive industries will require heavy investment in re-training programmes, as well as government support to develop a sustainable business environment. In the EGD, these concerns are tackled by the Just Transition Mechanism, which will allocate funds based on regional needs. However, the global nature of the model prevents us from specifying different policy proposals based on these regional characteristics, and so some distributional nuance of the impact of the policies is lost.

Finally, the breakdown of private industrial sectors and their corresponding emissions still occurs at a high level of aggregation, and so **targeted industrial policies are hard to infer** from the model's results. DEFINE does not identify specific economic activities that should be phased out, or on the contrary encouraged due to their sustainable nature. The model assumes a certain degree of dirtiness for each private sector, and trusts decision makers will allocate funding efficiently within those sectors. Of course, this level of detail would be extremely complex to model and data would be scarce, but it is an important assumption that the model is implicitly making that should be noted.

3.4 Model choice synthesis

SQ2: What are the strengths and weaknesses of the DEFINE model?

In Chapter 3, the DEFINE model has been contextualised in recent literature, its main characteristics have been described and its components conceptually mapped, and its strengths and weaknesses have been identified. In short, DEFINE is an aggregated model of the global economy that captures a plethora of system-level effects between the macroeconomy and the ecosystem, incorporates the financial sector and can handle a variety of economic policies that can steer green growth. Despite the level of aggregation and lack of regional effects, the model features a thorough overview of the decision-making of the economy's main actors (firms, households, banks, government and central bank), which raises the level of confidence placed in the results presented in the upcoming chapters.

4 Policy Operationalisation: The European Green Deal in DEFINE

Translating the policy aims and proposals of the European Green Deal Investment Plan into an input that can be processed by the DEFINE model is not an easy task. As a global model, DEFINE requires inputs that are scaled up from a European level, but in doing so, one must also recognise differences in how the economy is composed. After all, the EU is composed of mostly high- and some middle-income countries, and so its economic composition will diverge from the global average. In this chapter, these complications are identified and a set of assumptions is formulated to convert the policies outlined in the EDGIP into a valid input for the DEFINE model.

4.1 Policy demarcation

In order to operationalise the EDGIP's policies, it is first important to determine which components of the plan can be translated. As discussed in Chapter 3, the global nature of the DEFINE model prevents us from considering regional effects. The Just Transition Mechanism is a policy that seeks to ensure that the transition is fair to all EU citizens, and so allocates project funds unevenly to support regions that are dependent on carbon-intensive industries. Since the JTM can be perceived as a set of transactions within the European economy, it does not need to be explicitly modelled when using a method that analyses aggregate effects. However, policymakers should be aware that conflict between member states and the EU could arise as the JTM is implemented. For instance, lock-in effects (Klitkou, Bolwig, Hansen, & Wessberg, 2015) opposing the green transition are already prevalent in some of these carbon-dependent areas, such as the coal-mining towns in southern Poland (Abnett, 2021). For now, these distributional implications are beyond the scope of this thesis, which focuses on the other aggregate components of the EDGIP.

The rest of the EDGIP can be split in three different policy levers, which are the backbone of the analysis conducted in this thesis. The first one is the **increase in green public investment**, which includes the contribution of the EU budget to climate and environment, as well as the national co-financing structural funds. The second lever relates to the EU's **carbon emissions' reduction system**, which is a cap-and-trade scheme with the same aim as a carbon tax. The final lever relates to the **green lending programmes** backed by the EU under the InvestEU programme. The translation of these three components to model inputs is discussed in detail in the upcoming subsections, including the relevant assumptions made to operationalise them. Finally, it is important to note that the EGP has a policy horizon of ten years (2021-2030), while the model runs until the year 2100 to grasp the environmental and economic consequences at the end of the century. Hence, besides operationalising the EGDIP itself, the following subsections outline the assumptions made after 2030 for the three policy levers. All relevant assumptions are listed in Table 1.

Table 1: List of assumptions associated to the operationalisation of the three main policy levers featured in European Green Deal.

Summary of Policy Assumptions	
Green public investment	EU budget contributions and national co-financing funds are aggregated in a lump sum of €617 billion over 10 years.
	The share of green public investment in GDP for the EGD's period is 0.45%, based on a yearly average of €61.7 billion in green public investment, steady growth, and the EU's GDP in 2019.
	More ambitious scenarios feature a share of green public investment in GDP between 1.5% and 1.75%.
	Green public investment share is kept constant beyond 2030 due to policy uncertainty.
Carbon taxation	The EU ETS is modelled as a carbon tax with associated price and coverage pathways.
	Carbon price pathways are obtained from the EU Reference Scenario and the 2050 long-term strategy, producing two different pathways that plateau at €400/tCO_2.
	Carbon Pathway A: €50/tCO_2 (2030), €100/tCO_2 (2040), €200/tCO_2 (2050), €400/tCO_2 (2070).
	Carbon Pathway B: €100/tCO_2 (2030), €200/tCO_2 (2040), €300/tCO_2 (2050), €400/tCO_2 (2060).
	The average exchange rate from 2018 is used at 1 EUR = 1.1811 USD.
	Emission coverage starts at 40% in 2020, and increases yearly by 0.5% or 1% depending on the scenario.
	The revenue recycling rate is at least 50%; carbon tax revenues are converted to green subsidies for firms.
Green lending	The impact of the InvestEU scheme on the EGD is modelled by a reduction in the green credit rationing.
	The scaling factor between the EU and global economy is 0.1592, using 2019 GDP data.
	The reduction of green credit rationing has been calibrated using Carbon Tax Pathway A and a GDP share of green public investment of 0.45%.
	Green credit rationing has been permanently reduced by 88% to match the €279 billion contribution to the EGD under InvestEU.

4.1.1 Green public investment

In order to model the green public investment (GPI) lever of the EDGIP, the contributions from the EU budget and from national co-financing structural funds are aggregated, adding up to €617 billion over ten years. The main reason for this approach is the global nature of the model, as it does not consider complex institutional arrangements such as those between the EU and its member states, particularly those related to fiscal policy.

In the model, the government acts as a single decision maker, and so it is assumed that the level of investment is set by the sum of both contributions.

In the model, green public investment is defined as an exogenous proportion of GDP, and so the €617 billion should be translated as such. With this level of investment over the next ten years, we obtain an average green expenditure of €61.7 billion per year. Using data from 2019 (World Bank, 2020a), this value is roughly equal to 0.466% of the EU's GDP. Assuming the EU economy grows at a standard pace over the next few years, we round this value down to 0.45%. Here, the assumption is that the proposed level of yearly green public investment is equivalent to 0.45% of GDP in 2025, halfway through the EGD.

However, this value represents the lower bound of green public investment under the EGD's set targets. Some authors, such as Storm (2020), have suggested a more ambitious level of 1.5%, which can be set as a more ambitious public investment level. Interestingly, the European Commission claims that 25% of the next EU budget is to be destined to environmental and climate action (European Commission, 2020a). If EU member states where to follow suit with this commitment, matching 25% of government expenditure to green purposes, the share of green public investment in GDP would be about 1.75% (using the initial value of government investment set in the baseline scenario, defined in Section 4.2).

Beyond 2030, the situation is unclear, as the European Commission (and most policymakers) have relatively short policy horizons. It has been assumed for the most part that the level of green public investment as a percentage of GDP is kept constant beyond 2030, as the transition will require further investment beyond that point. Overall, the green public investment policy lever of the EGDIP is characterised by a substantial spending increase in comparison to the status quo, with varying levels of ambition, and the expectation to at least maintain the current commitment beyond 2030.

4.1.2 Carbon taxation

The EU's Emission Trading System, which collects revenue from large carbon emitters, is an emissions' reduction system that is incompatible with the DEFINE model, which features a standard carbon taxation scheme. Under certain assumptions, the carbon tax and cap-and-trade are equivalent (Goulder & Schein, 2013), and are treated as such in this thesis. In previous studies using DEFINE, the carbon tax is implemented by pricing emissions along a tax pathway, which increases every year. Hence, the only way to model the ETS's contribution to the EGD is by creating an analogous carbon tax pathway, using available projections and coverage data.

In contrast with the green public investment lever, the €25 billion contribution from the ETS listed in the EDGIP cannot be easily converted to a policy input for DEFINE. Thus, potential carbon tax pathways are obtained from the EU Reference Scenario report (Capros et al., 2016) and the analysis report supporting the 2050 long-term strategy (European Commission, 2018), which precede the EGD.

Note that in this thesis, we consider scenarios with a high rate of carbon taxation to be optimistic, as it is viewed from an environmental perspective. Hence, some of the more pessimistic scenarios set the carbon price in 2030 to €50/tCO_2, €100/tCO_2 in 2040, and €200/tCO_2 by 2050 (from here on referred to as *Carbon Tax Pathway A*, or CTP-A). More optimistic scenarios project €100/tCO_2 in 2030, and €200/tCO_2 by 2040 (from here on referred to as *Carbon Tax Pathway B*, or CTP-B). These two trajectories have been linearly interpolated between targets, and beyond the projection they plateau at €400/tCO_2; this occurs in 2070 for CTP-A, and 2060 for CTP-B.

Moreover, since the model uses US dollars as its monetary currency, the carbon prices are converted using the average exchange rate from 2018, 1 EUR = 1.1811 USD (Exchange Rates, 2021). We chose 2018 as it is the starting year for the model run (more on this in Section 4.2). In addition, the ETS does not include all CO_2 emissions in the EU, as its coverage is sector-dependent (European Commission, 2017b). The coverage has been raising steadily in the last few years, at an average rate of about 1% per year. Hence, we assume that, starting at 40% in 2020, the coverage continues to grow at either a 0.5% or 1% clip until the end of the run, depending on the scenario.

Finally, the revenue recycling from carbon taxes is set to at least 50%, in line with European Commission (2017a). However, as mentioned in Section 2.3, member states are recycling carbon tax revenues at a rate closer to 80%. In the model, these revenues are converted to green subsidies for firms, in line with most member states' policies. Overall, this carbon taxation scheme diverges significantly in methodology from the EU ETS and its contribution to the EDGIP, but is compatible with the model's endogeneity and prevents discontinuities in the simulations.

4.1.3 Green lending scheme

Under the InvestEU programme, the European Commission (2019) is hoping to mobilise €279 billion in green investment, notably through the provision of public guarantees aimed at reducing the perception of risk on green projects, and through the EIB's commitment to raise green lending to 50% of its portfolio (European Investment Bank, 2020). Given the endogeneity of DEFINE's investment function, and the fact that the model does not feature a public investment bank, modelling these effects is not straightforward. Moreover, there is no difference in initial values between green and conventional loan interests and bond yields, such that the inherent risk embedded in new green technology is not captured (Mazzucato & Semieniuk, 2018).

Considering all of these challenges and the characteristics of the model, the green lending lever of the EGDIP is modelled by reducing the credit rationing on green loans. With this approach, a larger percentage of desired green loans are approved, leading to an increase in actual green private investment. As the approval of loans is endogenous in the model, we have reduced green credit rationing (GCR) to the point where the global equivalent of €279 billion ($2.07 trillion) is raised over the first ten years of the policy, under the low carbon tax pathway CTP-A and a green public investment share of GDP of 0.45%. The global equivalent is obtained using the average exchange rate from 2018, and the ratio between EU and global GDP from 2019, which is 15.92%. Through trial and error, it was found that green credit rationing needs to be reduced by 88% relative to conventional credit rationing to achieve this level of investment.

In this approach, the main assumption is that all of this new investment occurs in the private sector, and that without the reduction in rationing this funding would not have occurred. Furthermore, note that in this initial approach the desired investment function remains untouched, which might explain the high level of credit rationing required. This level of rationing is kept throughout the entire simulation.

4.2 Scenario definition

Following the demarcation of the three policies, the policy scenarios to be tested are developed to illustrate the impact of the European Green Deal policies relative to a baseline scenario, which is recycled from previous implementations of DEFINE. Some of the key features of all scenarios are the starting year and the presence of a COVID-19 shock. Firstly, the simulations start in 2018 to take advantage of data that is already fully-calibrated with the baseline scenario (Dafermos & Nikolaidi, 2021a). Since we are interested in the long term consequences of the policies, there is very little difference in outcome if 2019 was the starting year, and so given this thesis's time constraints a new calibration was not conducted. Moreover, a COVID-19 shock is introduced in 2020, in line with recent developments in the world economy.

4.2.1 Baseline scenario

The baseline scenario used in this thesis is taken from previous studies using DEFINE (Dafermos & Nikolaidi, 2019, 2021b), and its initial values and parameters can be found in the Appendix (Tables 8 and 9). It is based on the Shared Socioeconomic Pathways (SSP) framework (Riahi et al., 2017), which is commonplace among the climate research community. The scenario created by Dafermos and Nikolaidi draws on features from the SSP2 and SSP3 mitigation scenarios, which both correspond to radiative forcing levels of 6.0 W/m^2, and an atmospheric temperature increase of slightly over 3°C. For reference, in SSP2, there is a moderate growth in global population and social, economic and technological trends do not deviate much from historical patterns. In SSP3, regional conflict driven by renascent nationalism have a negative impact on economic growth. The baseline scenario features characteristics from both pathways, such as moderate economic growth that decays by the end of the century, consistent with SSP2, and the population growth, energy intensity improvement and increase in renewable shares, characteristic of SSP3.

Moreover, the scenario features a COVID-19 shock in 2020, that causes a reduction of economic growth by 5%, consistent with the estimations of the World Bank (2020b). In addition, it assumes that the global economy recovers after 2021, which might not be accurate as the COVID-19 crisis lingers. However, assuming a longer recovery period does not impact long term trends, which are ultimately of more interest in the analysis.

Finally, the carbon tax pathway is consistent with SSP3 for the period 2030-2100, and is consistently below CTP-A and CTP-B defined in this thesis.

All of these factors render a baseline scenario characterised by increasing yearly emissions until 2070, decreasing growth rates of output, slowly increasing unemployment, and a final global temperature change above 3°C. At such high temperatures, the damage channel from the ecosystem activates, harming the macroeconomy and halting growth. Under the stress of climate damage, the financial position of firms deteriorates, mildly raising interest rates and increasing substantially the leverage of banks. In short, as businesses are threatened they become less profitable, requiring a greater proportion of financed investment to stay afloat, leading to financial instability. Moreover, the government sector follows a similar path, as it receives less tax revenue and needs to run a larger budget deficit, raising the public debt well above 100% of GDP. Ultimately, the baseline scenario represents an interpretation of a business-as-usual reality, where the transition to a low-carbon economy is too slow, and climate damages slow down the economy towards the end of the century.

4.2.2 Scenario tree

All developed scenarios in this analysis are compared to the baseline. The purpose of this comparison is to assess how well a policy performs relative to the baseline, as well as how different policy levels compare to one another. As specified in Section 4.1, three different policies are being considered, which can take on different values depending on the assumptions followed. Hence, a scenario tree can be developed based on these value levels. In order to achieve this in a systematic way, each policy is coded using a letter: A for green public investment, B for carbon taxation, and C for the green lending scheme. In addition, each value level considered is assigned a number, such that policy A1 represents a specific increase in green public investment. These policy levels are presented in Table 2.

Table 2: Coded policy levels used in the analysis (A: green public investment, B: carbon taxation, C: green lending scheme). GCR stands for green credit rationing.

A1	GPI as %GDP (2021-): 0.45	**B1**	CTP-A (medium) 0.5%/yr coverage rise Rev. recycling: 80%	**C1**	GCR cut: 88%
A2	GPI as %GDP (2021-): 1.5	**B2**	CTP-B (high) 1%/yr coverage rise Rev. recycling: 80%		
A3	GPI as %GDP (2021-30): 1.75 GPI as %GDP (2030-): 1				

On green public investment, the levels represent the lower bound of the European Green Deal (**A1**), the ambitious GPI-to-GDP share set by some authors (**A2**), and finally a hybrid level that assumes absolute adherence by member states to the Commission's target over the EGD's period, and a middle ground afterwards (**A3**). On carbon taxation, given the behaviour of member states regarding revenue recycling in recent years, both levels feature an 80% recycling rate; they are differentiated by their carbon tax pathway and the rate of increase of the tax's coverage. Finally, the green lending scheme is defined as a switch, with level **C1** representing the calibrated cut in green credit rationing that matches the €279 billion contribution via InvestEU.

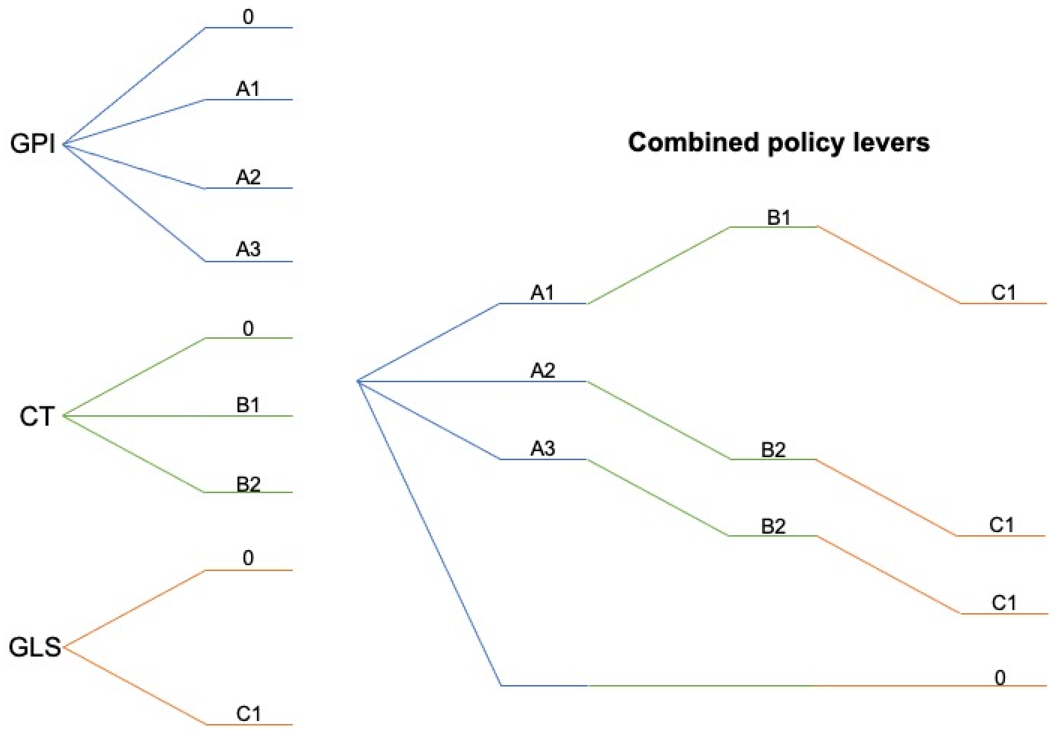


Figure 8: Coded scenario tree including policy-specific and combined policy scenarios. The policy-specific scenarios are on the left, and **0** denotes the baseline scenario.

Following these definitions, the levels are compared against each other within a single policy test. The aim of this step is to determine the general impact of each policy on the system, as well as to assess the relevance of the chosen levels to the analysis. The results of the policy-specific analysis are presented in Section 5.2, and the relevant scenario trees for these runs are shown on the left side of Figure 8.

Finally, three combined policy lever scenarios are built and assessed. Firstly, to replicate the current version of the EGD, the scenario **A1+B1+C1** features low green public investment, a medium carbon tax, and a reduction in green credit rationing. The other two scenarios, **A2+B2+C1** and **A3+B2+C1**, portray more ambitious GPI and carbon taxation policies, and are distinguished by the investment strategy during the EGD's period and beyond. Note that all combined scenarios feature the same reduction in green credit rationing, as we assume that under the basic EGD scenario at least €279 billion are raised through InvestEU, and it is not trivial to model larger increases under a highly endogenous credit system. Overall, these combined policy scenarios provide us with insight on the current version of the EGD, as well as an exploration of more radical policies that could inform policymakers to revise their targets and commitments.

4.3 Scenario setup summary

SQ3: What are relevant policy levers from the European Green Deal which can be included in the DEFINE model?

By identifying some of the limiting characteristics of the DEFINE model, the EGDIP policies have been operationalised in Chapter 4. In short, the features of the investment plan have been summarised into three different policies levers that can be included in the DEFINE model: green public investment, carbon taxation and green lending. These levers are the building blocks of the three main narrative scenarios in this thesis, which illustrate the outcomes associated with the current plan, as well as any improvements that more radical versions of the EGD could render. The results of this scenario analysis are presented in the next chapter.

5 Model Simulation and Results

In this chapter, the main results obtained from the scenario analysis with the DEFINE model are presented and described. Firstly, the key performance indicators that will be assessed are defined, to simplify the discussion and ensure consistency throughout the analysis. Secondly, the three policy levers described in Chapter 4 are assessed individually, to understand their individual impacts on the key performance indicators and how they interact with each other. Thirdly, the three main combined policy scenarios are examined and compared, setting the stage for the discussion in Chapter 6. Finally, the validation process is described.

5.1 Key performance indicators

In order to analyse the results of this exploration consistently, a set of key performance indicators (KPI) is defined, capturing different dimensions of the macroeconomy, financial system and environment. These indicators have been chosen so that both political and economic insights can be drawn from the analysis. Given the plethora of outputs that the DEFINE model provides, the KPI have been grouped in four clusters, illustrating the effects on climate, economic growth, fiscal balance, and finance.

The **climate cluster** features two main indicators: yearly carbon emissions and the change in atmospheric temperature. These effectively summarise the performance of the environmental system under the different policy scenarios. The yearly emissions provide a consistent measure of the dirtiness level of the economy, and provide an effective visualisation of the immediate impact of greener policy packages. The change in atmospheric temperature gives an aggregate overview of the state of the ecosystem, and allows us to easily assess the performance of the policies relative to the temperature targets set by climate science. In this sense, the change in temperature by 2100 is the main subject of interest.

The **economic growth cluster** focuses on the overall performance of the economy by looking at the growth rate of output and unemployment rate. The choice of the growth rate is self-explanatory, as it aggregates the performance of the components of aggregate demand on a yearly basis, and generally illustrates the health of the macroeconomy. On the other hand, the unemployment rate is used as a political indicator, which can be used as a proxy of the population's satisfaction with the policies. We assume that a policy that leads to high unemployment levels can be disrupted by political pressure. Furthermore, we assume following Kalecki (1945) that extremely low unemployment rates can be economically disruptive as well.[1]

The **fiscal balance cluster** is composed of two related indicators: the fiscal balance-to-output ratio and the public debt-to-output ratio. The fiscal balance shows the deficit

[1] The Kaleckian effects referred to in this thesis imply that, at very low rates of unemployment, the bargaining position of workers is strengthened, as there is an effective labour shortage. In turn, this reduces animal spirits and worsens the business climate. The authors of DEFINE have followed the work of Skott and Zipperer (2012) to implement these effects in the model.

incurred by government on a yearly basis to finance its activity; on average, the public sector spends more than it collects in revenue every year. While the fiscal balance can be thought of as a flow in this analysis, the public debt-to-output ratio behaves like a stock variable that measures how indebted the economy is relative to its output. These indicators are economically important as a high debt-to-output ratio can discourage investors and raise the cost of government financing, which can trigger political consequences in the form of deficit rules, for instance.

Finally, the **finance cluster** looks at the overall health of the firm sector and the financial system. In this context, the bank leverage ratio is the prime indicator, as it encapsulates the level of exposure that banks are facing as a consequence of defaulted loans to firms. A related indicator that is also used is the spread on total loans, as it captures the financing cost of firms at different periods of the run. Note that in these results loan spreads are the same for green and conventional loans, as no capital differentiation policies have been tested.

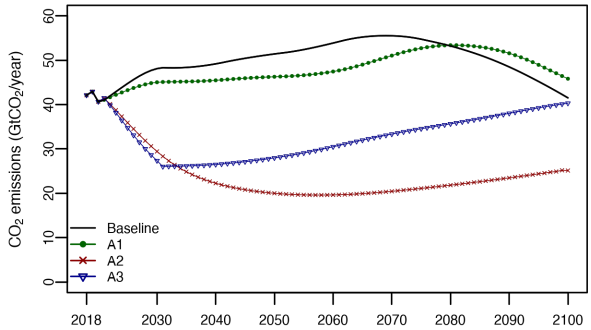
5.2 Policy-specific performance

Using the four clusters defined in Section 5.1, we can assess the impact of each individual policy on the macroeconomy, financial system and ecosystem. With this, we can get a sense of what effect each policy has on the system, with the aim of informing policymakers of economic and environmental impacts of their decision making late into the century.

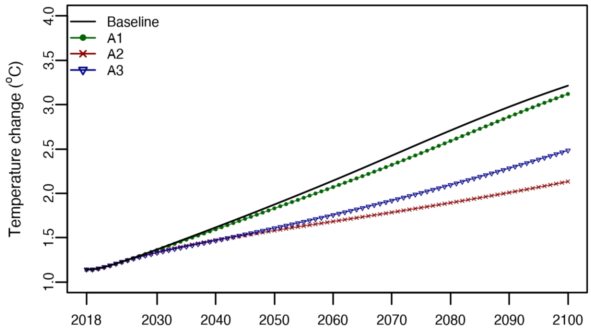
5.2.1 Green public investment

In a post-Keynesian model, an increase in green public investment should initially increase economic growth, as government investment is a component of aggregate demand (using credit from the financial system, the growth and green financing channels are activated). Following the COVID-19 shock, this effect is evident for all policy levels, although **A1** falls below the baseline around 2030 (Figure 10a). The unemployment rate drops following the increase in demand, however it increases under **A1** as the growth rate falls after 2030 (Figure 10b). Under **A2** and **A3**, the economy approaches full employment, with some Kaleckian effects present towards the end of the century in **A2**, causing instability. In addition, it is clear that the change in green public investment share after 2030 under **A3** shocks the system and slows down the macroeconomy, as aggregate demand is lowered.

Moreover, boosting green public investment clearly reduces CO_2 emissions initially, reducing the impact of the degradation channel from the macroeconomy to the ecosystem, particularly at higher rates (Figure 9a). However, as the economy grows relative to the baseline towards the end of the century, and the carbon tax is relatively low, the emissions levels begin to rise and re-converge with the baseline. Ultimately, while these fiscal expansions help reduce the change in temperature, none of the investments can keep the change under 2°C (Figure 9b), as there is no large enough incentive to divest away from conventional economic activity.

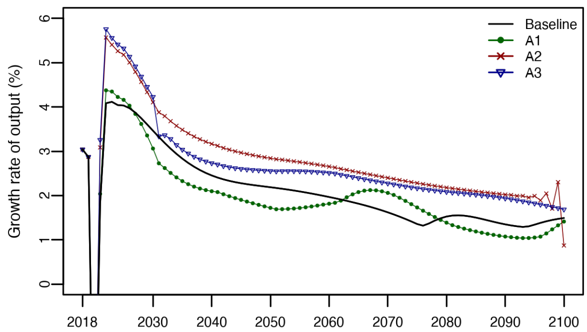


(a) Yearly CO_2 emissions

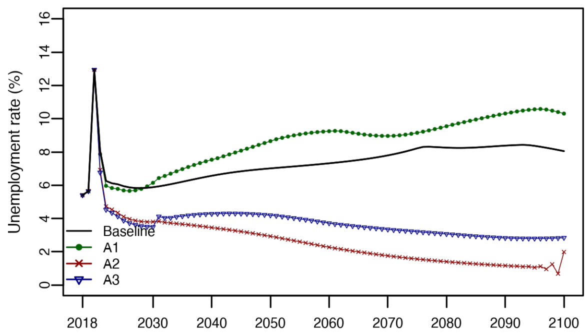


(b) Temperature change

Figure 9: Climate cluster results for Scenarios A# (green public investment).

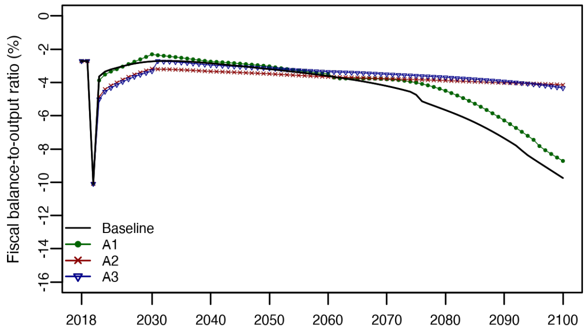


(a) Growth rate of output

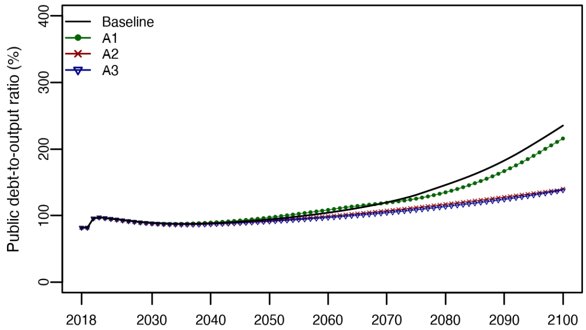


(b) Unemployment rate

Figure 10: Economic growth cluster results for Scenarios A# (green public investment).

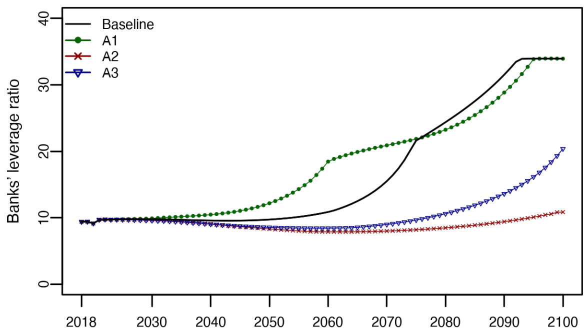


(a) Fiscal balance-to-output ratio

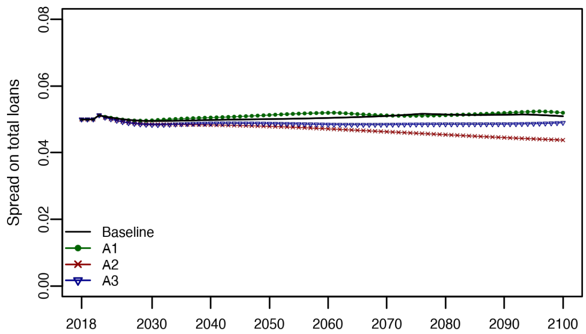


(b) Public debt-to-output ratio

Figure 11: Fiscal balance cluster results for Scenarios A# (green public investment).



(a) Bank leverage ratio



(b) Total spread on bank loans

Figure 12: Finance cluster results for Scenarios A# (green public investment).

The low economic performance of scenario **A1** is partially explained by the fiscal balance and finance clusters of the analysis. **A1** shows a lower fiscal deficit than its counterparts over the first years of the analysis (Figure 11a), which illustrates the lower spending. However, the lower economic activity leads to higher bank leverage ratios, activating the financial instability channel, implying that the economy is proportionally more dependent on financing than at higher GPI levels (Figure 12a).

As a consequence, there is an increase in interest rate spread on total loans in **A1** (Figure 12b), which makes financing economic activity more expensive, placing even more pressure on firms and banks. Under a lower green investment regime and a slowed down economy, there is a severe increase in the fiscal deficit and public debt (Figure 11b) towards the end of the century. Finally, the fiscal balance KPI under scenarios **A2** and **A3** remains relatively stable, although we can observe an increase in the leverage ratio at the end of the run, hinting at the consequences of mild climate damage.

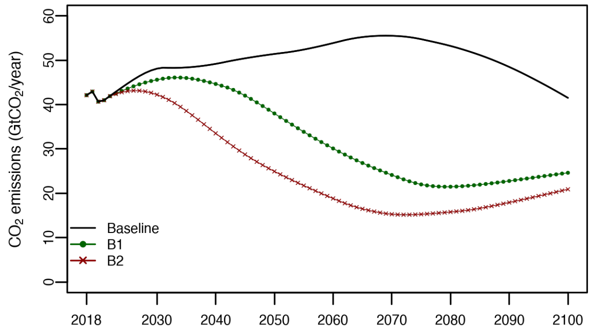
5.2.2 Carbon taxation

Increasing carbon taxation in the economy has the first order effect of reducing firm profits, which then impacts investment and, ultimately, aggregate demand, mostly through the growth channel of the model. However, it strongly discourages conventional economic activity, which has a clear positive effect on the environment via emissions reduction, captured by the model's degradation channel.

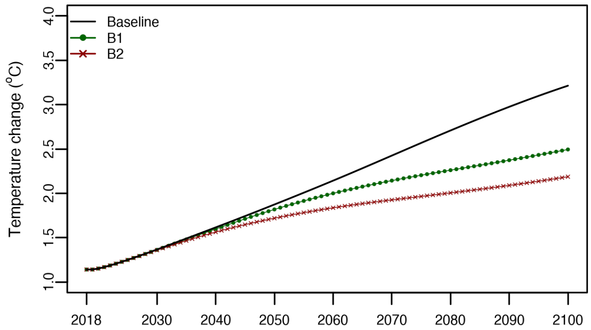
In the simulations, there is a dip in economic growth following the implementation of the tax pathways in 2021 (Figure 14a), while unemployment increases relative to the baseline (Figure 14b). However, there is an improvement in the economic growth indicators at the end of the simulations, as climate damages do not accumulate as fast under these regimes. On the other hand, yearly emissions drop significantly following the implementation of the tax, particularly under the high tax scenario **B2** (Figure 13a). While emissions start to grow again towards 2100, the convergence with the baseline scenario is not as evident as in the A1, 2 & 3 scenarios. However, the tax on its own is not sufficient to keep the planet below a 2°C change under either **B1** or **B2**, although they positively outperform the baseline (Figure 13b).

On measures of fiscal balance, the tax policies perform relatively well, as they represent an increase in revenue for the public sector, keeping public debt under control. However, these features are not evident until after 2060, where the fiscal balance-to-output ratio of the baseline scenario begins to deteriorate as the model's damage channel activates (Figure 15a). The differences between **B1** and **B2** are relatively small, with the higher tax gathering slightly more tax revenue and so having a lower deficit and public debt.

On the financial side, the tax pathways lead to an initial increase in bank leverage relative to the baseline, as firms are hit by lower profit rates and require more external financing, leading to some financial instability (Figure 16a). However, they outperform the baseline past 2070 as climate damages accumulate at a much slower pace, and firms do not default as often. The total spread remains largely unaffected relative to the baseline

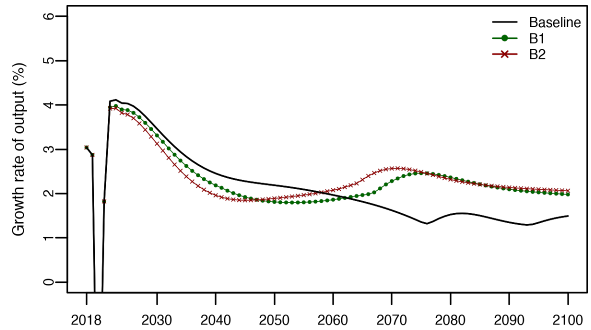


(a) Yearly CO_2 emissions

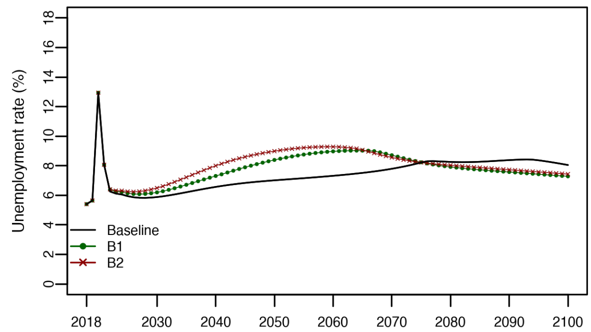


(b) Temperature change

Figure 13: Climate cluster results for Scenarios B# (carbon taxation).

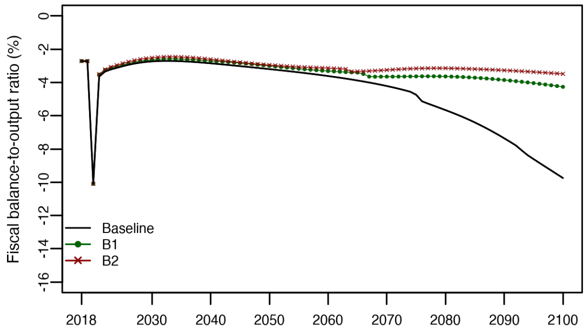


(a) Growth rate of output

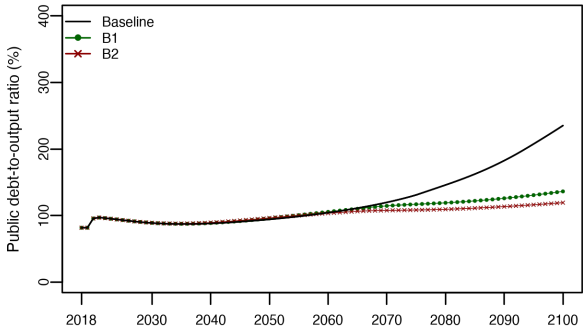


(b) Unemployment rate

Figure 14: Economic growth cluster results for Scenarios B# (carbon taxation).

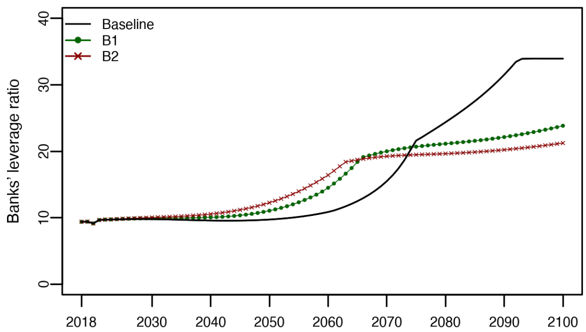


(a) Fiscal balance-to-output ratio

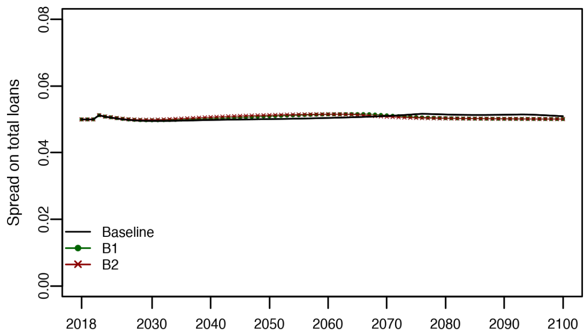


(b) Public debt-to-output ratio

Figure 15: Fiscal balance cluster results for Scenarios B# (carbon taxation).



(a) Bank leverage ratio



(b) Total spread on bank loans

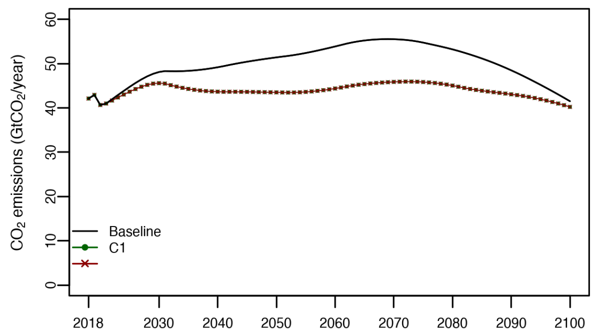
Figure 16: Finance cluster results for Scenarios B# (carbon taxation).

(Figure 16b). Overall, both scenarios show similar performance in this cluster.

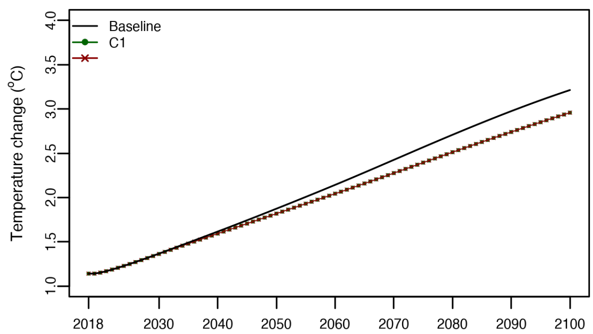
5.2.3 Green lending scheme

The reduction in green credit rationing is the least impactful of the three policies considered on the overall system, as it only affects the proportion of desired private green loans that are approved. These represent a relatively small share of the global economy, and as such the impact of the policy on most indicators can only be perceived after 2050. For instance, the growth rate of output and unemployment profiles (Figures 18a and 18b) only diverge from the baseline after mid-century, while the differences in the fiscal balance cluster are only noticeable after 2070 (Figures 19a and 19b).

Of course, facilitating the expansion of the green economy via reduced credit rationing ultimately reduces emissions (Figure 17a), reducing the threat on the ecosystem through the degradation channel, as the overall share of conventional activity in the economy falls. This divergence makes enough of a dent in the temperature change to keep it below 3°C, as is evident in the results (Figure 17b). Finally, this emissions reduction is sufficient to render a positive change in the bank leverage profile (and thus, promote financial stability) relative to the baseline (Figure 20a), although the climate damages eventually make the curves converge in 2100. Finally, there are no significant changes in the total spread of bank loans, although a minor reduction can be perceived around 2070 (Figure 20b).

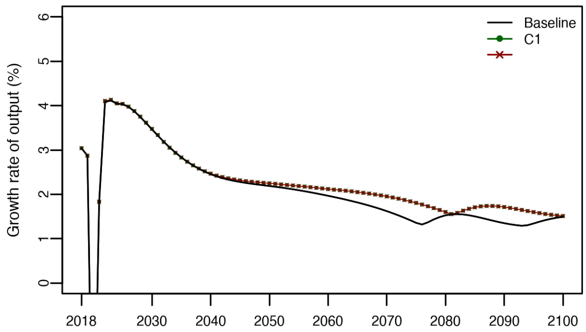


(a) Yearly CO_2 emissions

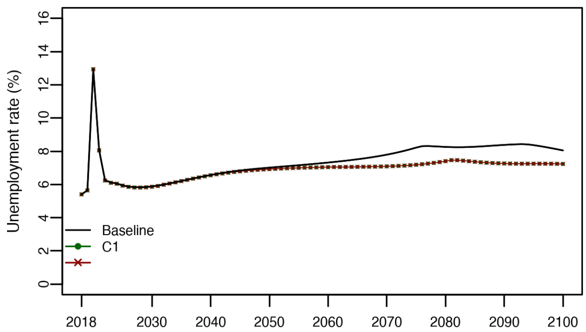


(b) Temperature change

Figure 17: Climate cluster results for Scenario C1 (green lending scheme).

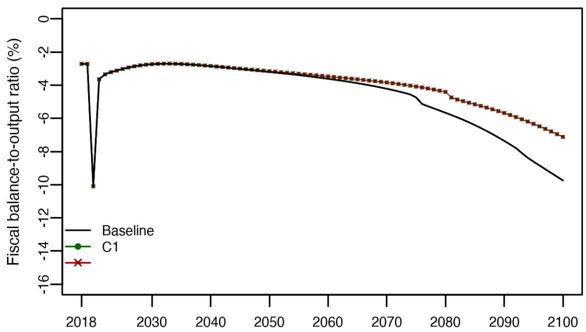


(a) Growth rate of output

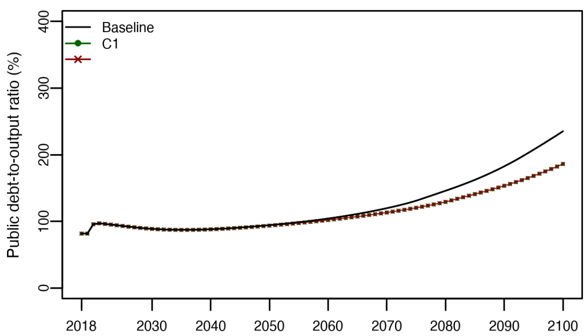


(b) Unemployment rate

Figure 18: Economic growth cluster results for Scenario C1 (green lending scheme)

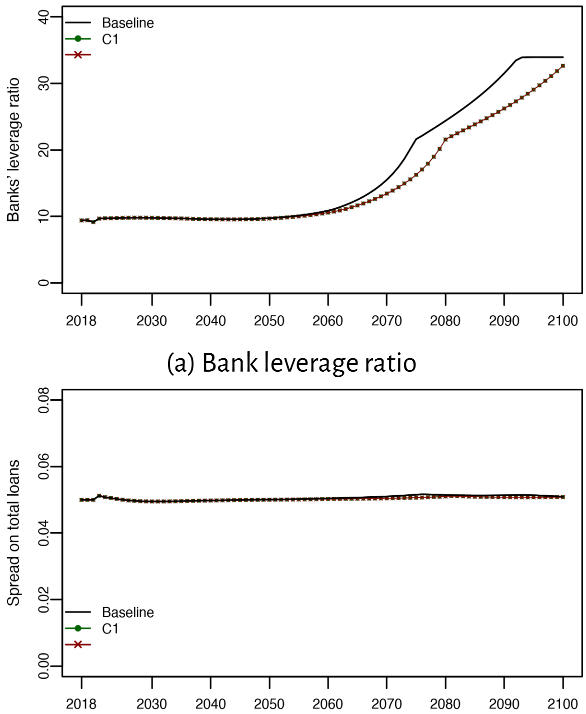


(a) Fiscal balance-to-output ratio



(b) Public debt-to-output ratio

Figure 19: Fiscal balance cluster results for Scenario C1 (green lending scheme).



(a) Bank leverage ratio

(b) Total spread on bank loans

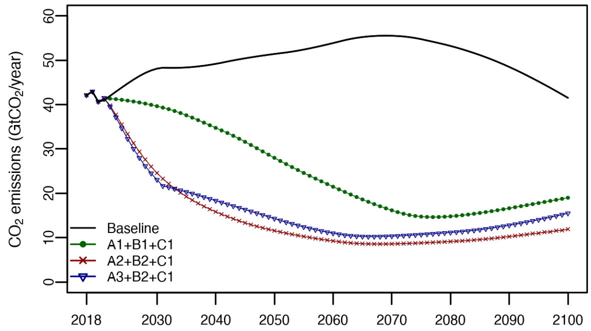
Figure 20: Finance cluster results for Scenario C1 (green lending scheme).

5.3 Combined policy performance

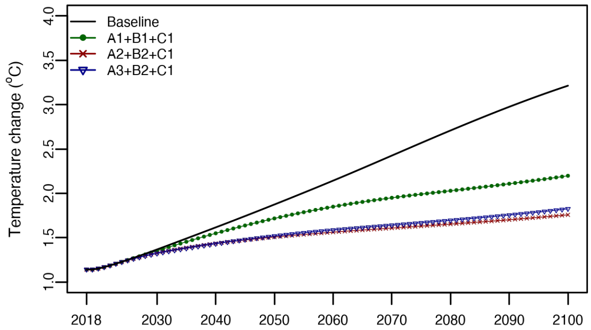
Before reporting on the combined policy performance, it is important to note that policy levels forming each scenario are not additive, as DEFINE is a highly endogenous integrated model. A great example is the exacerbation of the Kaleckian effects on unemployment for high investment scenarios, mentioned earlier in the GPI analysis. Under the **A2+B2+C1** scenario, these effects appear around 2090, which are a few years earlier than in the **A2** scenario, even though they were not present in either the carbon tax or green lending specific curves. Hence, while we can infer some consequences of the combination of policies, they cannot be treated as a simple linear addition, as the nature of the feedbacks present through the model's channels complicate the determination of the combined effect.

In this section, the results are presented through graphs of the 8 KPI, as well as a summary table comparing levels between scenarios at 5 relevant periods (Table 3). These periods are 2018, as the start of the run; 2030, as the end of the EGD's policy horizon; 2050, as the target year for net zero in the EU; 2070, as the start of significant climate damages in the baseline scenario; and 2100, as the final period in the simulation.

Firstly, regarding climate cluster indicators, the three policy scenarios show a serious divergence from the baseline, as no yearly emissions profile continues to rise after the COVID-19 shock (Figure 21a). Clearly, the scenarios with higher levels of investment

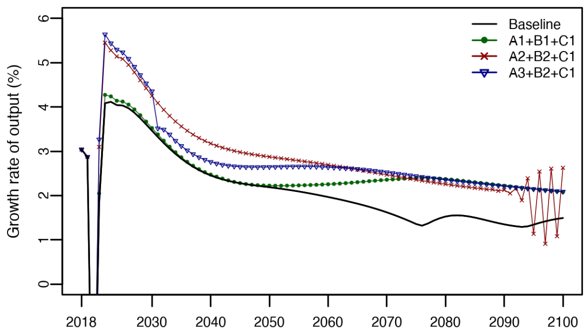


(a) Yearly CO_2 emissions

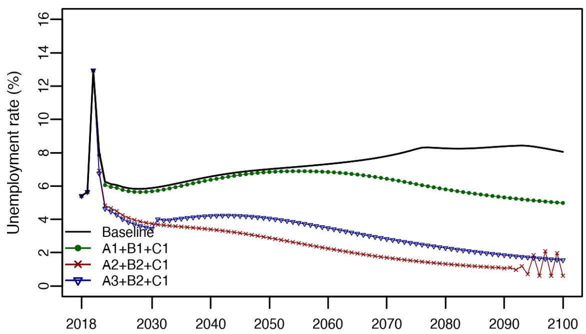


(b) Temperature change

Figure 21: Climate cluster results for the three combined policy scenarios.

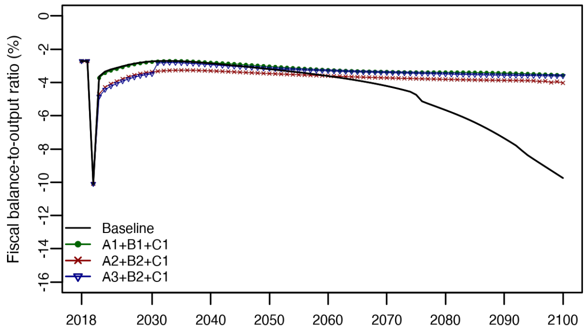


(a) Growth rate of output

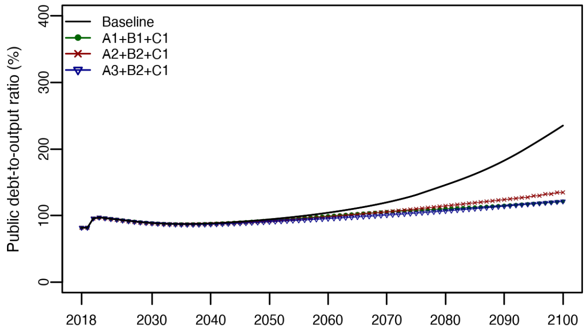


(b) Unemployment rate

Figure 22: Economic growth cluster results for the three combined policy scenarios.

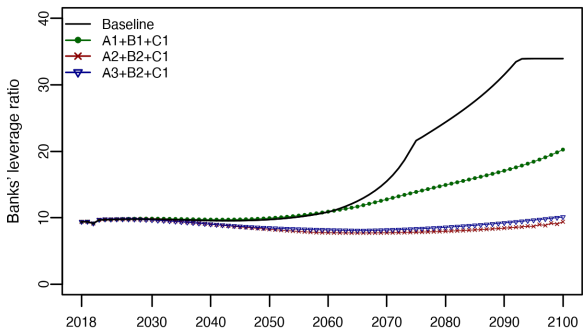


(a) Fiscal balance-to-output ratio

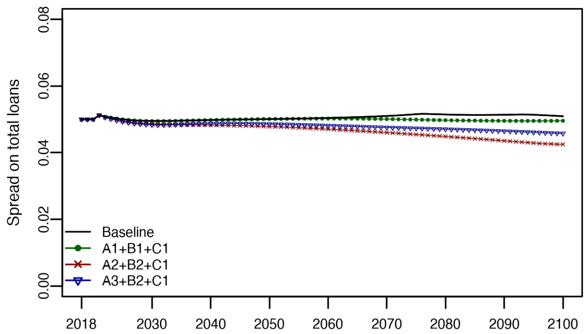


(b) Public debt-to-output ratio

Figure 23: Fiscal balance cluster results for the three combined policy scenarios.



(a) Bank leverage ratio



(b) Total spread on bank loans

Figure 24: Finance cluster results for the three combined policy scenarios.

Table 3: Summary of results of the 8 KPI for the combined policy simulations. The values in bold adjacent to each KPI represent the baseline scenario, while the results in other scenarios are grouped per KPI.

Key Performance Indicator	2018	2030	2050	2070	2100
Yearly CO_2 emissions ($GtCO_2$/year)	**42.13**	**49.91**	**52.48**	**56.41**	**36.94**
A1+B1+C1	42.13	39.65	27.99	16.16	18.99
A2+B2+C1	42.13	24.57	11.56	8.584	11.90
A3+B2+C1	42.13	23.04	14.28	10.32	15.48
Temperature change (°C)	**1.140**	**1.363**	**1.898**	**2.471**	**3.205**
A1+B1+C1	1.140	1.352	1.716	1.949	2.197
A2+B2+C1	1.140	1.325	1.507	1.607	1.757
A3+B2+C1	1.140	1.321	1.518	1.640	1.825
Growth rate of output (%)	**3.040**	**4.783**	**3.834**	**1.379**	**2.338**
A1+B1+C1	3.040	3.523	2.222	2.356	2.080
A2+B2+C1	3.040	4.251	2.874	2.470	2.626
A3+B2+C1	3.040	4.354	2.644	2.525	2.087
Unemployment rate (%)	**5.400**	**4.156**	**5.582**	**7.613**	**7.855**
A1+B1+C1	5.400	5.680	6.839	6.431	4.979
A2+B2+C1	5.400	3.729	2.882	1.692	0.606
A3+B2+C1	5.400	3.437	4.046	2.818	1.544
Fiscal balance-to-output ratio (%)	**-2.713**	**-2.486**	**-3.443**	**-4.530**	**-8.730**
A1+B1+C1	-2.713	-2.767	-3.033	-3.360	-3.562
A2+B2+C1	-2.713	-3.365	-3.466	-3.725	-4.030
A3+B2+C1	-2.713	-3.484	-3.162	-3.411	-3.611
Public debt-to-output ratio (%)	**81.50**	**84.23**	**93.91**	**122.0**	**245.4**
A1+B1+C1	81.50	88.44	92.55	105.3	121.0
A2+B2+C1	81.50	88.00	91.52	105.4	134.6
A3+B2+C1	81.50	88.13	90.43	100.5	121.2
Bank leverage ratio	**9.372**	**10.20**	**9.746**	**17.48**	**33.47**
A1+B1+C1	9.372	9.850	9.922	12.76	20.24
A2+B2+C1	9.372	9.676	8.244	7.722	9.378
A3+B2+C1	9.372	9.636	8.444	8.140	10.09
Total spread on bank loans	**0.0500**	**0.0494**	**0.0507**	**0.0520**	**0.0460**
A1+B1+C1	0.0500	0.0495	0.0501	0.0501	0.0496
A2+B2+C1	0.0500	0.0485	0.0478	0.0460	0.0425
A3+B2+C1	0.0500	0.0484	0.0486	0.0476	0.0458

and carbon taxation return a wider emissions gap relative to the baseline, and successfully keep the change in temperature under 2°C at the end of the century (Figure 21b); this is not true of scenario **A1+B1+C1**, which slightly overshoots the 2°C target. Notably, the difference in temperature change between **A2+B2+C1** and **A3+B2+C1** is relatively minor.

Secondly, the economic growth cluster indicators render some surprising outcomes. On the one hand, the baseline and **A1+B1+C1** scenarios have virtually equivalent profiles for growth rate and unemployment until 2050 (Figures 22a and 22b), where the basic EGD scenario's growth approximately stabilises while the baseline's begins to dip. The commitment to the green transition also results in a reduction in unemployment in the second half of the century. On the other hand, the other two scenarios follow a high growth, low unemployment path that leads to instability in the case of the more extreme **A2+B2+C1**. It is noteworthy that ultimately, despite the negative consequences of the investment reduction in 2030 under the **A3+B2+C1** scenario, both policy sets reach similar macroeconomic positions by 2100.

Thirdly, the fiscal balance cluster results suggest that the three policy scenarios lead to a relatively stable situation in 2100, clearly diverging from the debt crisis caused by climate damages in the baseline scenario. The main difference between scenarios in this area is the high fiscal deficit that **A2+B2+C1** and **A3+B2+C1** incur during the EGD's period (Figure 23a), almost a full point below **A1+B1+C1** and the baseline. This is noteworthy because it would represent a commitment by government to run a large deficit to finance the first years of the transition. In overall terms, all three scenarios have similar public debt profiles (Figure 23b), reaching 100% of GDP around 2070, although **A2+B2+C1** shows a slight deviation towards a more indebted macroeconomy at the end of the century (135%), due to the higher levels of green public investment throughout the simulation.

Finally, the behaviour of the finance cluster indicators is the expected one. Under the high levels of economic growth in **A2+B2+C1** and **A3+B2+C1**, the bank leverage ratio remains low (Figure 24a) and the financial stability channel active, despite the higher levels of borrowing incurred by government. The leverage ratio is higher in **A1+B1+C1**, but largely below the baseline, implying that none of the possible transition policy packages exposes banks more than the business-as-usual scenario. Moreover, under investment friendly scenarios, the total spread on bank loans falls slightly through most of the run (Figure 24b), making credit cheaper for firms and boosting economic activity.

5.4 Validation

The model has been largely validated in previous studies using the DEFINE model. Since the econometrically estimated parameters were determined to suit the baseline scenario, they are assumed to be validated for the purposes of our analysis. Moreover, the accounting nature of stock-flow consistent modelling strengthens our assumptions on the structural consistency of the model, as all stock and flows are effectively accounted for. Hence, in this section, we outline the need to inspect a couple of parameters or mechanisms related to the tested policies in more detail, in order to understand how their underlying assumptions affect the results. Note that a complete sensitivity analysis of parameters relevant to these mechanisms is beyond the scope of this thesis.

The first mechanism of interest relates to the complex relationship between the level of carbon taxation and the share of green private investment in total private investment (in this case, we refer to desired investment). In the Appendix, Equation 57 defines this share per economic sector (β_{it}) based on three contributions: an exogenous development factor that includes institutional changes related to environmental regulation (β_{0it}), the cost of green capital relative to conventional capital (β_{1it}), and the borrowing cost of investing in green capital relative to conventional capital (β_{2it}). For the purposes of this mechanism, β_{1it}, the cost of capital differential, is the focus, and is proxied by the total unit cost of producing renewable energy ($tucr_t$) relative to the total unit cost of producing non-renewable energy ($tucn_t$), even though the authors acknowledge the variety of factors that can influence the capital differential.

From Equation 60, the total unit cost of producing renewable energy, $tucr_t$, falls as the subsidy rate increases, making green investment more attractive. Given the stable and high level of carbon revenue recycling in the simulations, it is clear that higher carbon taxes increase the level of desired green private investment. Clearly, this mechanism has a significant impact on the model results, and could be investigated further. Firstly, the weight of each of the three factors could be determined, to understand their exact relative impact on the share. Secondly, other factors besides differential energy unit costs affecting β_{1it} should be assessed. Given how important this mechanism is to implementing the effect of the carbon tax, a thorough sensitivity analysis would be desirable.

The other model mechanism that merits attention is the relationship between carbon emissions and temperature change. Following the work of Dietz and Venmans (2019), the DEFINE model assumes that global warming is approximately linearly proportional to cumulative carbon emissions. The quasi-linearity of this relationship simplifies the modelling behind it, which in the system is represented by Equation 28. Besides the Transient Climate Response to Cumulative Carbon Emissions factor (φ) defined by the IPCC, the equation features a factor t_1 that captures the timescale adjustment of the climate system to the increase in cumulative emissions, and a constant factor t_2 that captures the effect of non-CO_2 greenhouse gases. However, this relationship has a handful of limitations, including non-linearity at high cumulative CO_2 levels, and the assumption that the impact of non-CO_2 greenhouse gases can be estimated as a fixed fraction of CO_2 emissions. Hence, explicitly integrating these non-linearities and the contribution of other greenhouse gases such as methane and nitrous oxide could provide a sharper estimate of the projected temperature change in future analysis.

5.5 Results' overview

SQ4: What are the long-term results of the European Green Deal's (fiscal) policies based on the model analysis?

In Chapter 5, the macroeconomic and environmental outcomes of applying European

Green Deal policies to the global economy have been presented. It is clear that the three policy levers used contribute to diverging away from the baseline's emissions profile, and overall produce positive macroeconomic results, particularly in the latter half of the century. Regarding the combined policy scenarios, the temperature change is at most slightly over 2°C by 2100 in the more faithful translation of the EGD, and below it under the more radical policy scenarios. The three policy levers synergise with each other, as the increased government revenue from the carbon tax balances the spending from the green public investment lever. In these conditions, the macroeconomy outperforms the baseline and the financial system is not placed under as much pressure. The implications of these results are discussed in detail in the next chapter.

6 Model Analysis and Discussion

In this chapter, the main implications of the analysis are presented and discussed. These findings cover the impact of the policies on the key performance indicators, and how the main mechanisms of the model interact with these policy packages. Finally, the discussion is brought back to the European Green Deal, as the results have provided us with an initial assessment of its effectiveness long-term, providing a basis upon which further policy recommendations can be made. Note that, for simplicity and brevity, the discussion has been conceived largely from the perspective of the government, considering its interests and possible actions, although the positions of other actors are sometimes addressed if relevant.

6.1 Impact on key performance indicators

The choice of key performance indicators is an attempt to provide a wide assessment of the state of the system, as well as to keep track of the variables that climate economic policy, and climate policy in general, tend to use as targets. As mentioned in Chapter 5, all policy scenarios outperform the baseline scenario with regards to temperature change, which is the most important variable when assessing an aggregated climate policy. Hence, while it is trivial in the context of previous climate and economic research, it is important to state that, based on the model results, any attempt to transition towards a greener economy slows down global warming. However, under policy scenario **A1+B1+C1**, which most closely resembles the EGD, these efforts are not sufficient to keep the warming within 2°C, suggesting the need to consider more radical policy scenarios as a serious possibility.

Moreover, the results indicate that detaching economic growth from carbon emissions is possible at the global level, as proponents of green growth suggest. The three combined policy scenarios maintain economic growth rates at least on par with the baseline, and in the latter half of the century they are consistently higher. From the policy-specific analysis, we infer that the increase in green public investment and reduction of green credit rationing are mostly responsible for the expansion, while the carbon taxation schemes have a limited dampening effect. However, under the Kaleckian assumptions of the model at low levels of unemployment, a consistently high level of green public investment can bring the economy to an unstable state by the end of the century, as any scenario involving **A2** shows. Hence, it seems reasonable to cut down on these levels of green public investment once most of the green transition has occurred, following the green public investment path under **A3**, for example.

Cutting down the level of green public investment later in the century also keeps the fiscal balance-to-output ratio at a healthier, more stable level. However, the main finding related to the fiscal balance cluster is undoubtedly the need to increase the deficit in the early years of the transition, as the economy can then fully detach from the baseline's emissions' pathway. Under the more radical policy packages, the global economy should run an average deficit of 4% over the first ten years, which would then stabilise towards

3%. The baseline scenario reaches the 3% deficit level immediately after COVID, but the balance collapses after 2060 due to climate damages. This effect is a perfect illustration of the need to spend heavily now in the transition, to prevent catastrophic macroeconomic consequences in the future.

Finally, the financial indicators epitomise the need to maintain a high level of economic productivity while reducing carbon emissions. Under the baseline scenario and the combined **A1+B1+C1**, the financial system becomes more fragile as banks are more heavily leveraged, and credit becomes more expensive in comparison. Moreover, the difference between the bank leverage ratio profiles of policy-specific and combined policy scenarios spotlights the need to feature multiple policies in any green investment plan. For instance, if only a carbon tax were enacted, the macroeconomy would be financially more fragile than the baseline during the early period of the simulation.

Overall, the main trade-off we have identified in the results is the one between the early fiscal balance of the macroeconomy and green growth, including the reduction of CO_2. Using basic EGD policies, the deficit is kept under control initially, but the growth potential of the economy is dampened, and the financial system is eventually placed under more stress. On the flip side, more ambitious policy packages require a larger, less desirable public deficit initially, but the growth rate of output is on average higher, unemployment lower, and the system is not affected by climate damages.

6.2 System-level insight

The seven channels presented in the conceptual model of DEFINE in Chapter 3 (Figure 7) determine the interactions between the ecosystem, the financial system and the macroeconomy. The policies explored in this analysis act as interventions to the system, and as such vary the impact of the channels on the system's behaviour. Perhaps, the most evident example of this is how the damage channel is not really active when applying the policies, and so we do not observe a serious deterioration of the macroeconomy from 2070 onward. Moreover, the reduction in green credit rationing enhances the effects of the green financing channel, empowering green economic activity. At the system level, we can conclude that the introduction of EGD policies boosts the growth channel, reduces financial instability as the economy remains healthy, and dampens the harmful macroeconomy-ecosystem channels.

Moreover, the influence of each specific policy on the system is important to inspect at an aggregate level. The carbon tax has a great impact on carbon emissions, as it is the one policy that explicitly induces a replacement of conventional for green economic activity, as dirty firms are taxed heavily while green firms receive subsidies from the recycled revenue. In addition, it provides fiscal balance as a revenue stream for the public sector. However, in the current scenarios, its rate plateaus at 400€/tnCO_2, which leads to a small emissions rebound towards the end of the century, as economic growth remains stable. These tax pathways are deeply uncertain however, and so the assumption that the rate plateaus might be too generous, and emissions might continue to fall in reality.

Conversely, green public investment has a clear role in the combined policy package, which is to boost aggregate demand and make the economy grow. On their own, the levels of investment required to keep global temperatures within a 2°C change lead to clear fiscal imbalances early on, which is why they are not achievable if applied individually. However, on the aggregate, these policies benefit households through lower levels of unemployment, and firms through higher profit rates, and should overall be popular. Finding the exact level of public investment, applied during the right time period, is beyond the scope of this exploratory analysis, but the differences between scenarios **A2+B2+C1** and **A3+B2+C1** should point to having variability in the GPI share of GDP, higher in the early years of the transition. Finally, at a system level, the reduction in green credit rationing nudges the economy towards a higher growth path, although this effect is clearly smaller than that produced by GPI, with largely similar implications.

6.3 Implications for the European Green Deal

Politically speaking, the European Green Deal is a policy package of monumental complexity. Firstly, it requires the collaboration of 27 member states and their national governments, as well as downstream coordination with regional and local authorities. Secondly, following the COVID-19 pandemic, allocating funding to projects that do not have an immediate impact on the reactivation of the economy is politically hard to sell. Hence, the narrative around the NextGenerationEU package constantly ties coming out of the pandemic with the green transition (European Commission, 2021c). Finally, it aims to reach emissions' targets that go beyond its policy horizon, and so there is inherent uncertainty as to what happens after 2030.

As mentioned in previous chapters, policy scenario **A1+B1+C1** is the one that most closely resembles the EGD itself. The exogenous share of GPI in GDP is defined based on the EGD's budget contributions, the lower carbon tax pathway aligns well with the small contribution from the ETS, and the reduction in green credit rationing has been determined based on the InvestEU guarantee projections. Throughout the results, we have seen that it is outperformed by its more radical counterparts in most KPI, but still appears as a profound, positive deviation from the baseline scenario. Hence, while the degree to which the targets are met is in doubt, it is undeniable that the European Green Deal takes climate policy in the right direction in the coming years.

Moreover, it is important to remember that the long term assumptions made may not hold as climate action becomes more prevalent, and so it is hard to evaluate the first ten years relative to mid- and end-of-century targets. However, with the knowledge we now have, the current version of the Deal is a good first step, just not enough to keep the planet within a 2°C temperature change. In a way, one of the plan's main weaknesses is that it maintains the economic status quo: moderate growth, moderate unemployment and a fiscal deficit under strict control. Even if the configuration of the economic system is changing to favour green activity, a sluggish macroeconomy will slow down the change, rendering it ultimately fruitless in meeting climate targets and keeping the ecosystem in balance. Thus, the plan should be revised to emphasise green growth further, speeding up the shift from a dirty macroeconomy to a sustainable one.

The main component to be revised in the current plan is the most politically contentious: the level of green public investment. The other two combined policy scenarios considered in this thesis set the GPI-to-GDP level at three to four times the equivalent of the proposed budget, at least during the first ten years. The principal opposition against a more ambitious plan, as it often happens with stimulus packages, comes from those questioning who pays the bill. Despite the prevalence of high-income nations within the EU relative to the global average, there is still a wealth gap between countries in the north and west, who are on average richer, and the south and east, who are poorer. This imbalance lead to the austerity policies of the 2010s, which still have lasting effects today, and have created an uneven starting position for member states with regards to the transition.

A more ambitious EGD completely counters the logic of austerity. Instead of reducing the budget deficit, national economies would be urged to run larger deficits to finance green public investment. As we showed in the results, policy scenarios **A2+B2+C1** and **A3+B2+C1** feature an average budget deficit of 4% over the first ten years, which is high relative to the EU's idea of responsible fiscal management. The Stability and Growth Pact, which dictates the deficit and public debt rules for member states, limits the yearly budget deficit to 3% and the level of public debt to 60% of GDP (European Council, 1997). Its rules are currently suspended due to the COVID-19 pandemic, with the Commission proposing a renewal of this suspension for 2022 (Valero, 2021). However, under normal macroeconomic conditions, the rules clearly conflict with the fiscal imbalance that the high levels of green public investment would create. Hence, it is left to policymakers at the national and supranational level to decide if the rules can be relaxed, and if so whether the relaxation is permanent or a prolonged suspension.

6.4 Overall significance of the model findings

SQ5: What do the model findings mean for the European Green Deal as the EU's climate mitigation strategy?

In Chapter 6, the main implications of the analysis have been discussed. It has been determined that the chosen policies outperform the baseline scenario in virtually every metric, and so the European Green Deal can only be seen as a step in the right direction. However, in its current form, applying the EGD's policies at a global economy level would not be enough to keep global temperature change within 2°C by 2100. Thus, more radical policies are necessary, in line with the other two policy scenarios. In applying these policies, as the level of public investment increases, opposition is likely to come from actors that want to maintain fiscal deficit rules and a frugal status quo. Under a revised EGD, the long-term benefits of running a larger deficit over the next ten years must be highlighted. The final policy recommendations, as well as the perceived added value of this thesis, are presented in the final chapter.

7 Conclusions and Recommendations

In this chapter, the added value of this thesis to the literature and the policy recommendations are presented. Moreover, the limitations of the analysis are discussed, and ideas for future work are proposed. Inherent to the discussion are the conclusions to this thesis, notably the value of a complex macroeconomic model like DEFINE, the need to achieve sustainable growth through substantial fiscal expansions, and the role the EU must have on the global scale to take climate responsibility.

However, in order for the conclusions to be well motivated, and before addressing the subjects listed above, we need to return to and address the research question:

"How can a stock-flow consistent model grounded in ecological and post-Keynesian economic values further understanding of the macroeconomic and climatic consequences of the European Green Deal?"

The DEFINE model has allowed us to project the consequences of the economies policies of the European Green Deal into a planetary-level economic system. Crucially, it has allowed us to assess both the environmental implications that concern climate science, namely the level of carbon emissions and global warming, and the socioeconomic indicators that matter most to macroeconomists, such as the growth rate of output, the fiscal balance and unemployment. In doing so, the analysis using DEFINE has rendered a set of EGD-inspired policy packages that couple the sustainability of the ecosystem with economic prosperity, furthering our understanding of the societal impacts of these policies and their potential to execute the green transition.

7.1 The added value of the analysis

Following the devastating human and economic consequences of the COVID-19 pandemic, bringing back the economic debate to fighting the climate emergency feels timely. As we have seen in this report, assessing the impact of the European Green Deal Investment Plan using the DEFINE model has rendered a handful of interesting outcomes that add value to current research by reinforcing certain arguments made in the ecological and post-Keynesian economics literature. Notably, the need to act fast to avert climate and economic disaster and the role of green growth have been highlighted. Importantly, these conclusions have been reached using a modelling approach that recognises the importance of finance in the green transition, and features a plethora of feedback effects between the ecosystem, the macroeconomy and the financial sector. Thanks to the complexity of DEFINE as a model, a more complete overview of the economic and environmental consequences of the policies has been drawn.

Moreover, we have specifically shown that EDGIP policies are headed in the right direction, but are not sufficient to keep the ecosystem stable, as the temperature change is larger than 2°C under the basic EDGIP policy scenario. In addition, we have provided some initial insight on what the next steps are to meet the climate targets. Notably, we have identified green public investment as the input to be increased in the macroeconomy to sustain economic growth and prevent a large increase in temperature, even if this requires running a large fiscal deficit in the early years to finance the required investment. While our proposed policies need to be analysed further, using fit-for-purpose models that consider the particularities of specific economies, they steer the discussion in a targeted direction for future study.

Finally, the analysis has allowed us to answer our EGD thought experiment, by which its policies were assessed assuming the entire world followed. As mentioned, region-specific analyses should be conducted, but it is important to understand what the average country should do to determine what the richest nations must do. While the climate emergency is a global challenge, both its consequences and the ability to do something about it are distributed unevenly. Generally, the EGDIP policies on their own are not enough to meet the climate targets and achieve sustainable growth, but they are certainly insufficient if we consider the ability to act of EU member states relative to low- and middle-income states in the Global South. Ultimately, the results of this thesis illustrate the need for the EU to take these bold steps and lead by example.

7.2 Policy recommendations

The exploratory analysis conducted in this thesis represents a first step in understanding the quantified impact of specific macroeconomic policies on the environment, and conversely, how environmental effects impact policy in the long run. Hence, the policy recommendations provided in this section do not feature specific, quantified metrics, but rather point relevant actors towards a general policy direction given the conclusions drawn. At the EU level, the recommendations are made to the European Commission, although they often involve convincing or leveraging the participation of national actors. At the global level, the recommendations are made to a generic government sector, following the actor breakdown featured in the DEFINE model (firms, households, banks, government sector, and central banks).

- **Increase the level of green public investment to at least 1.5% share of GDP over the next ten years**. In line with Storm (2020), it has become apparent that the €617 billion aggregation proposed in the EGD is not sufficient to meet climate targets. Given the difficulties in expanding the EU budget in recent years, the European Commission should focus on increasing the provision from national co-financing structural funds (note that in this report the overall level of green public investment in every member state has not been examined). At the global level, to the extent possible, governments should try to follow the EU's lead, particularly those in other high-income nations. A bold increase in GPI in OECD countries and China would facilitate the global green transition and have a substantial impact on CO_2 emissions long-term.
- **Reform (or suspend) current fiscal deficit rules to allow a faster transition.** The COVID-19 pandemic has shown that the rules embedded in the Growth and Stability Pact are outdated, and can prevent a successful economic recovery (this is particularly true given the current low interest rate regime). The analysis shows

that the global economy should run around a 4% budget deficit to finance the transition in a way that keeps global warming within 2°C; the EU's current rules do not allow that kind of budgetary management. At the global level, if there is a coordinated effort to increase government spending, resulting in higher deficits, the burden of debt cannot be shifted around easily, and hence budgets would become easier to manage.

- **Increase carbon market coverage and foster carbon tax revenue recycling.** Carbon taxation has a minor dampening effect on economic growth, as it reduces the profit rate of firms. However, the high level of revenue recycling (80% in our simulations) allows the firm sector to recover most of their lost revenue by promoting green activity. To make this transition in the private sector broader, the coverage level of the ETS (currently set at around 40%) should increase at a steady rate. Globally, involving the private sector in the carbon revenue recycling scheme can have powerful effects in the decarbonisation of the economy, as firms are rewarded for prioritising green activity. Of course, these proposals are to be considered on the aggregate, and should acknowledge the differences between small and medium enterprises, and multinational corporations.

7.2.1 Policy reflections

Following these policy recommendations, it is important to reflect on their meaning relative to previous work, particularly in the context of other modelling approaches. The policies presented in the previous section are drawn from the results of an analysis using heterodox approaches, which clash with the outcomes presented by authors like Nordhaus (2018) using the DICE model. Through the neoclassical production function used in the DICE model, the focus in his work is placed largely on the social cost of carbon and thus the effectiveness of taxing emissions. The policy recommendations made using DEFINE are not as constrained, as the inclusion of the financial sector not only makes the results more realistic through the availability of credit, but also offers more tools to finance the green transition. Moreover, placing no hard restrictions on the budget deficit has allowed us to treat it as a KPI and analyse the trade-offs in the results more freely. Ultimately, the complex nature of the DEFINE model has offered us the opportunity to analyse the impact of a broader range of policies on a more complete abstraction of the economy.

Moreover, another subject to reflect on is the effectiveness of carbon taxes in reducing CO_2 emissions and promoting the green transition. Carbon taxation is viewed as a possible solution across the economic ideological spectrum, as even prominent figures in the American economic right have advocated for it (Smith, 2017). However, leading authors of heterodox traditions are more doubtful of its effectiveness, particularly as the panacea to solve the climate crisis. Taylor (2021) argues that carbon taxation has a limited impact on emissions, in part due to the inelastic nature of demand for gasoline. The main outcome of the study is that carbon taxation, along with the implementation of a broad network of electric vehicles, is not enough to meet the climate goals set by the Biden administration (these ideas are presented largely from an American perspective).

A similar, yet more extensive argument against carbon taxation is made by Rosen (2021), who explores its effectiveness through the lens of both social justice and the impact on different economic sectors. The author argues that carbon taxes can have devastating consequences in low income countries, which produce very little emissions anyway, and cause limited behavioural economic changes in the short and medium term in high income economies. Like Taylor (2021), he insists that other green policies like resource portfolio standards are both necessary to work in conjunction with carbon taxation and more impactful overall. Their policy recommendations clearly diverge from those proposed in this thesis, in part because of the powerful assumption made regarding revenue recycling into green subsidies. Moreover, the levels of carbon taxation they both propose as feasible in the US context of low energy prices, of the order of $\$100/tCO_2$, are lower than those examined in this thesis. Hence, while it is essential to consider the social justice and microeconomic implications of the carbon tax within the European Green Deal, and we have to assume that the revenue generated is put to good use, we can confidently conclude that as part of a policy package the carbon tax is effective in slowing down global warming.

Finally, it is worth discussing these policy recommendations in the context of a growing post-growth movement. The fundamental principle behind post-growth is straightforward: given the current buildup of our economies, lower economic activity and growth lead to fewer carbon emissions. The performance of economies in a post-growth regime is measured by the reduction in environmental impacts and other measures of prosperity, instead of looking at GDP growth (Hardt, Barrett, Taylor, & Foxon, 2020). In order to make up for the increase in unemployment derived from the stalled growth, post-growth authors often suggest reducing the number of worked hours (Jackson & Victor, 2011), as well as promoting a structural change in the economy towards labour-intensive jobs[2] such as those in education and care (Hardt et al., 2020), which are less material-intensive.

Of course, on top of being a transition strategy for the changing climate, the European Green Deal is a growth strategy. By virtue of its nature, policymakers are for now rejecting the general premise of post-growth ideas. However, even when pushing the boundaries of the EGD towards its more radical versions presented in this thesis, the 1.5°C target is not met by 2100. If we are to fully commit to this target, the expansion of green public investment and carbon taxation, and measures to facilitate green private lending might not be enough. In line with what Jackson and Victor (2011) and Hardt et al. (2020) propose, it might be necessary to revise the structure of our economy and its labour practices, with particular focus on the production and consumption of material goods, to prevent the most devastating consequences of a warming planet.

[2] Note that by labour-intensive we do not refer to traditional manufacturing that could be replaced by machinery, but rather to forms of employment where the main production input can only be labour and hence are by definition less material-intensive on average. For further context, consult the work of Hardt et al. (2020).

7.3 Limitations

SQ6: What are the limitations of the analysis and its findings and how should future work in the field be approached?

Given the short research period of this master thesis, there is an abundance of associated limitations that should be considered and contextualised. To begin with, the DEFINE model is an abstraction of reality, featuring a global economy model that has five actors. In addition, the chosen policies are applied at an aggregate level, and fundamentally assume a fixed level of efficiency in implementation. For instance, we freely assume that green investment funds the correct technologies and business projects; notably, we do not specify an industrial policy for the global economy. There are plenty of other factors to consider; hence, a list of the most relevant limitations of our analysis is provided below.

- **A global model with aggregated actors.** The DEFINE model features five actor clusters: firms, households, banks, governments and central banks. These actors interact as if the world was a single economy, which is of course a simplification. For instance, firms of different sizes and sectors operate with different profit margins, are publicly traded or not, and are subject to more or less regulation. Moreover, the inherent investment risk of a specific sector is averaged out into the economy, intrinsically implying that intra-sector risks are not correlated. In general, while the choices each actor is offered are broader than in other models due to the inclusion of the financial sector, the heterogeneous nature of these actors and the economic sectors is not captured.
- **No specialised institutions that can mirror the European economy.** The complex institutional composition of the relationship between the European Union and its member states cannot be captured by the public sector aggregation of the model. Notably, having a centralised supra-governmental actor that can have different budgetary priorities and competences to that of a national government complicates the modelling process, as these differences have to be aggregated. Moreover, DEFINE does not feature a public investment bank such as the European Investment Bank, which is a fundamental actor in the implementation of the InvestEU portion of the European Green Deal.
- **No regional effects, including carbon leakage.** As mentioned in Chapter 4, the Just Transition Mechanism could not be included in the model, as it is a policy measure that requires regional differentiation. However, the lack of regional effects presents other challenges, such as not capturing the balance of payments and its impact on a nation's output and indebtedness. In addition, it prevents us from understanding the consequences of carbon leakage, by which, for instance, the production of capital goods consumed in high-income economies is shifted to other countries with lower environmental and labour standards.
- **Uncertainty of COVID-like shocks.** The simulations feature a COVID-19 shock in 2020 by which the growth rate of output drops to -5%. As mentioned before, there are concerns with the speed of the recovery, although in the long run these make little difference on the KPI. However, future pandemic-like events are not

considered in the scenario analysis, and so the robustness of the policies under those conditions has not been assessed. Under increasing climate pressure, these events are becoming more likely, and so it is important that future studies consider these complications in their setup.

- **Lack of specialised industrial policy.** In the model, the economy is financed via endogenous channels that determine the level of investment provided to firms on the aggregate. In the simulations, the policies tested do not have a specific vision for the industrial make-up of the economy. In short, specifying the level of support that each economic sector would receive under the fiscal expansion underlying the EGD would provide valuable, detailed insight regarding the effectiveness of the plan at a sector level. The current analysis does not produce this type of insight, and so is at risk of leading to erroneous conclusions at the sector level.
- **Limited analysis of distributional factors among households.** Aggregating all households under a single actor cluster prevents us from understanding the impact of our policies on wealth and income inequality, and vice versa. If the EGD's policies were to reinforce inequality, the average propensity to save of households would increase, as higher income individuals tend to save a larger percentage of their income. Hence, economic growth would be dampened, as aggregate demand would fall. These effects are certainly relevant to keep the economy going under the threat of climate damages, as well as to make the transition fair and just.
- **Limited discussion on material depletion of energy and non-energy reserves.** While the DEFINE model provides matter depletion, the level of fuel reserves and waste as outputs, these have not been discussed within this thesis. This was a conscious choice to focus the study on climate targets and macroeconomic indicators. However, a more thorough analysis of the depletion and waste patterns could shed some light into additional constraints to the system, with more punishing supply-side effects if the recycling rate is low, for instance.

7.3.1 Future work

Following the limitations listed, a few avenues for future work arise. We can classify them in different research categories, such as a purely model-based research focused on developing regional models, or a more EGD specific research that digs deeper into its specifications and develops more concise scenarios for analysis. In other words, the research conducted in this thesis has potential to be developed further at all stages, from conceptualisation to results. Hence, what is proposed in this section is by no means a complete overview of future work that can follow this study, but rather a short list of avenues the author would like to highlight.

The first research area where future work is desirable relates to the model itself, specifically its scale. The DEFINE model is a tool with a lot of potential in country-specific analysis. The accounting principles of stock-flow consistent modelling and the inclusion of a financial sector would allow policymakers to draw valuable conclusions at the national level, without having to assume away large components of the economic system. Moreover, a country-specific module could modify the model's five actors to better reflect the region's institutions, which to an extent can influence the economy's behaviour. Overall, introducing regional variations of the model can provide strong and immediately presentable insight to policymakers, streamlining the reporting process and building trust between political institutions and academia.

Moreover, with a more specialised model, the policies of the EGD can be operationalised such that they function in a closer manner to reality. Notably, the green lending scheme affecting the private sector through the InvestEU programme could be modelled in such a way that all relevant actors, including the European Investment Bank, are included. With this, we could reduce uncertainty regarding the financing of the private sector, and obtain much more reliable indicators in the context of financial stability. In addition, the cap-and-trade system could be modelled explicitly, in order to determine whether second order effects arise in the macroeconomy that we have not considered when making the equivalence with the carbon tax.

Finally, analysing the policies under deep uncertainty, with a broader range of scenarios, would allow us to determine their robustness. This thesis has not conducted such work, as the policy study has focused on the 2021-2030 period, due to the EGD's policy horizon. Understanding how well these policies perform with more or less favourable exogenous inputs (such as the development of carbon capture technology or the presence of another global pandemic) would add another dimension in their assessment, raising policymaker confidence in their validity. Hence, it is clear that more detailed quantitative analysis, at lower levels of aggregation, would also be desirable, through the inclusion of targeted industrial policies.

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A Model overview

A.1 Model matrices

Below are the four accounting matrices described in Section 3.2, obtained from Dafermos and Nikolaidi (2021a). The first two matrices cover the ecosystem while the final two cover the macroeconomy and financial system.

Table 4: Physical flow matrix of the ecosystem, reflecting the First and Second Laws of Thermodynamics. The table refers to annual global stocks and flows; matter is measured in Gt and energy is measured in EJ.

	Material balance	Energy balance
Inputs		
Extracted matter	$+M_t$	
Non-fossil energy		$+E_{NFt}$
Fossil energy	$+CEN_t$	$+E_{Ft}$
Oxygen used for fossil fuel combustion	$+O2_t$	
Outputs		
Industrial CO_2 emissions	$-EMIS_{INt}$	
Waste	$-W_t$	
Dissipated energy		$-ED_t$
Change in socio-economic stock	$-\Delta SES_t$	
Total	0	0

Table 5: Physical stock-flow matrix, reflecting changes in physical stocks relevant to human activity. The table refers to annual global stocks and flows; matter is measured in Gt and energy is measured in EJ.

	Material reserves	Fossil energy reserves	Cumulative CO_2 emissions	Socio-economic stock	Cumulative hazardous waste
Opening stock	REV_{Mt-1}	REV_{Et-1}	$CO2_{CUMt-1}$	SES_{t-1}	HW_{CUMt-1}
Additions to stock					
Resources converted into reserves	$+CON_{Mt}$	$+CON_{Et}$			
CO_2 emissions			$+EMIS_t$		
Production of material goods				$+MY_t$	
Non-recycled hazardous waste					$+hazW_t$
Reductions of stock					
Extraction/use of matter or energy	$-M_t$	$-E_{Ft}$			
Demolished/disposed socio-economic stock				$-DEM_t$	
Closing stock	REV_{Mt}	REV_{Et}	$CO2_{CUMt}$	SES_t	HW_{CUMt}

Table 6: Transactions flow matrix, reflecting transactions taking place between different sectors of the economy. The table refers to annual global flows in US$ trillion.

	Households		**Firms**		**Banks**		**Government sector**		**Central banks**		Total
	Current	Capital	Current	Capital	Current	Capital	Current	Capital	Current	Capital	
Private consumption expenditures		$-C_{(PRI)t}$	$+C_{(PRI)t}$								0
Government consumption expenditures			$+C_{(GOV)t}$				$-C_{(GOV)t}$				0
Conventional investment			$+\Sigma I_{C(PRI)it}+I_{C(GOV)t}$	$-\Sigma I_{C(PRI)it}$				$-I_{C(GOV)t}$			0
Green investment			$+\Sigma I_{G(PRI)it}+I_{G(GOV)t}$	$-\Sigma I_{G(PRI)it}$				$-I_{G(GOV)t}$			0
Green subsidies			$+SUB_t$				$-SUB_t$				0
Household disposable income net of depreciation	$-Y_{HDt}$	$+Y_{HDt}$									0
Wages	$+w_t N_t$		$-w_t N_t$								0
Government net saving							$-GNS_t$	$+GNS_t$			0
Taxes	$-T_{Ht}$		$-T_{Ft}-T_{Ct}$				$+T_t$				0
Firms' profits	$+DP_t$		$-TP_t$	$+RP_t$							0
Banks' profits	$+BP_{Dt}$				$-BP_t$	$+BP_{Ut}$					0
Interest on deposits	$+int_D D_{t-1}$				$-int_D D_{t-1}$						0
Depreciation of green capital			$-\delta_t \Sigma K_{G(PRI)it-1}$	$+\delta_t \Sigma K_{G(PRI)it-1}$			$-\delta_t K_{G(GOV)t-1}$	$+\delta_t K_{G(GOV)t-1}$			0
Depreciation of conventional capital			$-\delta_t \Sigma K_{C(PRI)it-1}$	$+\delta_t \Sigma K_{C(PRI)it-1}$			$-\delta_t K_{C(GOV)t-1}$	$+\delta_t K_{C(GOV)t-1}$			0
Interest on conventional loans			$-\Sigma int_{Cit-1} L_{Cit-1}$		$+\Sigma int_{Cit-1} L_{Cit-1}$						0
Interest on green loans			$-\Sigma int_{Gt-1} L_{Git-1}$		$+\Sigma int_{Gt-1} L_{Git-1}$						0
Interest on conventional bonds	$+coupon_{Ct-1} b_{CHt-1}$		$-coupon_{Ct-1} b_{Ct-1}$						$+coupon_{Ct-1} b_{CCBt-1}$		0
Interest on green bonds	$+coupon_{Gt-1} b_{GHt-1}$		$-coupon_{Gt-1} b_{Gt-1}$						$+coupon_{Gt-1} b_{GCBt-1}$		0
Interest on government securities	$+int_S SEC_{Ht-1}$				$+int_S SEC_{Bt-1}$		$-int_S SEC_{t-1}$		$+int_S SEC_{CBt-1}$		0
Interest on advances					$-int_A A_{t-1}$				$+int_A A_{t-1}$		0
Depreciation of durable consumption goods	$-\xi DC_{t-1}$	$+\xi DC_{t-1}$									0
Central bank's profits							$+CBP_t$		$-CBP_t$		0
Bailout of banks						$+BAILOUT_t$		$-BAILOUT_t$			0
Δdeposits		$-\Delta D_t$				$+\Delta D_t$					0
Δconventional loans				$+\Sigma \Delta L_{Cit}$		$-\Sigma \Delta L_{Cit}$					0
Δgreen loans				$+\Sigma \Delta L_{Git}$		$-\Sigma \Delta L_{Git}$					0
Δconventional bonds		$-\bar{p}_C \Delta b_{CHt}$		$+\bar{p}_C \Delta b_{Ct}$						$-\bar{p}_C \Delta b_{CCBt}$	0
Δgreen bonds		$-\bar{p}_G \Delta b_{GHt}$		$+\bar{p}_G \Delta b_{Gt}$						$-\bar{p}_G \Delta b_{GCBt}$	0
Δgovernment securities		$-\Delta SEC_{Ht}$				$-\Delta SEC_{Bt}$		$+\Delta SEC_t$		$-\Delta SEC_{CBt}$	0
Δadvances						$+\Delta A_t$				$-\Delta A_t$	0
Δhigh-powered money						$-\Delta HPM_t$				$+\Delta HPM_t$	0
Defaulted loans				$+DL_t$		$-DL_t$					0
Total	0	0	0	0	0	0	0	0	0	0	0

Table 7: Balance sheet matrix, reflecting the assets and liabilities of the economic sectors. The table refers to annual global flows in trillion US$.

	Households	Firms	Banks	Government sector	Central banks	Total
Conventional capital		+$\Sigma K_{C(PRI)it}$		+$K_{C(GOV)t}$		+K_{Ct}
Green capital		+$\Sigma K_{G(PRI)it}$		+$K_{G(GOV)t}$		+K_{Gt}
Durable consumption goods	+DC_t					+DC_t
Deposits	+D_t		-D_t			0
Conventional loans		-ΣL_{Cit}	+ΣL_{Cit}			0
Green loans		-ΣL_{Git}	+ΣL_{Git}			0
Conventional bonds	+$\bar{p}_C b_{CHt}$	-$\bar{p}_C b_{Ct}$			+$\bar{p}_C b_{CCBt}$	0
Green bonds	+$\bar{p}_G b_{GHt}$	-$\bar{p}_G b_{Gt}$			+$\bar{p}_G b_{GCBt}$	0
Government securities	+SEC_{Ht}		+SEC_{Bt}	-SEC_t	+SEC_{CBt}	0
High-powered money			+HPM_t		-HPM_t	0
Advances			-A_t		+A_t	0
Total (net worth)	+V_{Ht}	+V_{Ft}	+CAP_t	-SEC_t + $K_{C(GOV)t}$ + $K_{G(GOV)t}$	+V_{CBt}	+K_{Ct} + K_{Gt} + DC_t

A.2 Model equations

A.2.1 Matter, recycling and waste

$$MY_t = \mu_t \left(Y_t - C_{(GOV)t}\right) \tag{1}$$

$$M_t = MY_t - REC_t \tag{2}$$

$$REC_t = \rho_t DEM_t \tag{3}$$

$$DEM_t = \mu_t \left(\delta_t K_{t-1} + \xi DC_{t-1}\right) \tag{4}$$

$$SES_t = SES_{t-1} + MY_t - DEM_t \tag{5}$$

$$W_t = M_t + CEN_t + O2_t - EMIS_{INt} - \Delta SES_t \tag{6}$$

$$CEN_t = \frac{EMIS_{INt}}{car} \tag{7}$$

$$O2_t = EMIS_{INt} - CEN_t \tag{8}$$

$$HW_{CUMt} = HW_{CUMt-1} + hazW_t \tag{9}$$

$$hazratio_t = \frac{HW_{CUMt}}{POP_t} \tag{10}$$

$$REV_{Mt} = REV_{Mt-1} + CON_{Mt} - M_t \tag{11}$$

$$CON_{Mt} = con_M RES_{Mt-1} \tag{12}$$

$$RES_{Mt} = RES_{Mt-1} - CON_{Mt} \tag{13}$$

$$dep_{Mt} = \frac{M_t}{REV_{Mt-1}} \tag{14}$$

A.2.2 Energy

$$E_t = \varepsilon_t Y_t \tag{15}$$

$$E_{NFt} = \theta_t E_t \tag{16}$$

$$E_{Ft} = E_t - E_{NFt} \tag{17}$$

$$ED_t = E_{Ft} + E_{NFt} \tag{18}$$

$$REV_{Et} = REV_{Et-1} + CON_{Et} - E_{Ft} \tag{19}$$

$$CON_{Et} = con_E RES_{Et-1} \tag{20}$$

$$RES_{Et} = RES_{Et-1} - CON_{Et} \tag{21}$$

$$dep_{Et} = \frac{E_{Ft}}{REV_{Et-1}} \tag{22}$$

A.2.3 Emissions and climate change

$$EMIS_{INt} = \omega_t \left(1 - seq_t\right) E_{Ft} \tag{23}$$

$$g_{EMISLt} = g_{EMISLt-1} \left(1 - \zeta_9\right) \tag{24}$$

$$EMIS_{Lt} = EMIS_{Lt-1} \left(1 - g_{EMISLt}\right) \tag{25}$$

$$EMIS_t = EMIS_{INt} + EMIS_{Lt} \tag{26}$$

$$CO2_{CUMt} = CO2_{CUMt-1} + EMIS_t \tag{27}$$

$$T_{ATt} = T_{ATt-1} + t_1 \left(t_2 \varphi CO2_{CUMt-1} - T_{ATt-1}\right) \tag{28}$$

A.2.4 Ecological efficiency and technology

$$\omega_t = \omega_{t-1} \left(1 + g_{\omega t}\right) \tag{29}$$

$$g_{\omega t} = g_{\omega t-1} \left(1 - \zeta_1\right) \tag{30}$$

$$\mu_t = \mu^{\max} - \frac{\mu^{\max} - \mu^{\min}}{1 + \pi_1 e^{-\pi_2 \left(K_{GNE_{t-1}} / K_{CNEt-1}\right)}} \tag{31}$$

$$\rho_t = \frac{\rho^{\max}}{1 + \pi_3 e^{-\pi_4 (K_{GNEt-1} / K_{CNEt-1})}} \tag{32}$$

$$\varepsilon_t = \varepsilon^{\max} - \frac{\varepsilon^{\max} - \varepsilon^{\min}}{1 + \pi_5 e^{-\pi_6 (K_{GEt-1} / K_{CEt-1})}} \tag{33}$$

$$\theta_t = \frac{1}{1 + \pi_7 e^{-\pi_8 (K_{GEt-1} / K_{CEt-1})}} \tag{34}$$

$$seq_t = \frac{1}{1 + \pi_9 e^{-\pi_{10} \left(K_{SEQt-1} / \left(K_{CE(PRI)1t-1} + K_{CE(PRI)2t-1}\right)\right)}} \tag{35}$$

A.2.5 Output determination and climate damages

$$Y_{Mt}^{*} = \frac{REV_{Mt-1} + REC_t}{\mu_t} \tag{36}$$

$$Y_{Et}^{*} = \frac{REV_{Et-1}}{(1-\theta_t)\,\varepsilon_t} \tag{37}$$

$$Y_{Kt}^{*} = v_t K_{(PRI)t} \tag{38}$$

$$Y_{Nt}^{*} = \lambda_t h LF_t \tag{39}$$

$$Y_t^{*} = \min\left(Y_{Mt}^{*}, Y_{Et}^{*}, Y_{Kt}^{*}, Y_{Nt}^{*}\right) \tag{40}$$

$$Y_t = C_{(PRI)t} + I_{(PRI)t} + I_{(GOV)t} + C_{(GOV)t} \tag{41}$$

$$um_t = \frac{Y_t - C_{(GOV)t}}{Y_{Mt}^{*}} \tag{42}$$

$$ue_t = \frac{Y_t}{Y_{Et}^{*}} \tag{43}$$

$$u_t = \frac{Y_t}{Y_{Kt}^{*}} \tag{44}$$

$$re_t = \frac{Y_t}{Y_{Nt}^{*}} \tag{45}$$

$$D_{Tt} = 1 - \frac{1}{1 + \eta_1 T_{ATt} + \eta_2 {T_{ATt}}^2 + \eta_3 {T_{ATt}}^{6.754}} \tag{46}$$

$$D_{TPt} = pD_{Tt} \tag{47}$$

$$D_{TFt} = 1 - \frac{1 - D_{Tt}}{1 - D_{TPt}} \tag{48}$$

A.2.6 Firms

$$\begin{aligned} TP_{Gt} = {} & Y_t - w_t N_t - \sum int_{Cit-1} L_{Cit-1} - \sum int_{Gt-1} L_{Git-1} \\ & - \delta_t K_{(PRI)t-1} - coupon_{Ct-1} b_{Ct-1} - coupon_{Gt-1} b_{Gt-1} \end{aligned} \tag{49}$$

$$TP_t = TP_{Gt} - T_{Ft} - T_{Ct} + SUB_t \tag{50}$$

$$RP_t = s_F TP_{t-1} \tag{51}$$

$$DP_t = TP_t - RP_t \tag{52}$$

$$r_t = TP_t / K_{(PRI)t} \tag{53}$$

$$\begin{aligned} I_{(PRI)t}^{D} = {} & \left(\frac{\alpha_{00}\left(1 - D_{Tt-1}\right)}{1 + e^{\left(\alpha_{01} - \alpha_1 u_{t-1} - \alpha_2 r_{t-1} + \alpha_{31} ur_{t-1}^{-\alpha_{32}} + \alpha_{41}(1-ue_{t-1})^{-\alpha_{42}} + \alpha_{51}(1-um_{t-1})^{-\alpha_{52}}\right)}} K_{(PRI)t-1} \right) \\ & + \delta_t K_{(PRI)t-1} \end{aligned} \tag{54}$$

$$I^D_{(PRI)it} = sh_{(GVA)i} I^D_{(PRI)t} \tag{55}$$

$$I^D_{G(PRI)it} = \beta_{it} I^D_{(PRI)it} \tag{56}$$

$$\begin{aligned}\beta_{it} = \beta_{0it} - \beta_1 sh_{(EMIS_{IN})i}\left(tucr_{t-1} - tucn_{t-1}\right) \\ - \beta_2\left[sh_{Lt-1}\left(int_{Gt-1} - int_{Cit-1}\right) + \left(1 - sh_{Lt-1}\right)\left(yield_{Gt-1} - yield_{Ct-1}\right)\right]\end{aligned} \tag{57}$$

$$\beta_{0it} = \beta_{0it-1}\left(1 + g_{\beta 0t}\right) \tag{58}$$

$$g_{\beta 0t} = g_{\beta 0t-1}\left(1 - \zeta_2\right) \tag{59}$$

$$tucr_t = ucr_t\left(1 - gov_{SUBt}\right) \tag{60}$$

$$tucn_t = ucn_t + \tau_{Ct}\omega_t\left(1 - seq_t\right) \tag{61}$$

$$ucn_t = ucn_{t-1}\left(1 + g_{ucnt}\right) \tag{62}$$

$$g_{ucnt} = g_{ucrt-1}\left(1 - \zeta_8\right) \tag{63}$$

$$ucr_t = ucr_{t-1}\left(1 - g_{ucrt}\right)\frac{1 - \theta_t}{1 - \theta_{t-1}} \tag{64}$$

$$g_{ucrt} = g_{ucrt-1}\left(1 - \zeta_7\right) \tag{65}$$

$$I^D_{C(PRI)it} = I^D_{(PRI)it} - I^D_{G(PRI)it} \tag{66}$$

$$NL^D_{Git} = I^D_{G(PRI)it} - sh_{(GVA)i}\beta_{it}RP_t + repL_{Git-1} - \delta_t K_{G(PRI)it-1} - sh_{(GVA)i}\bar{p}_G\Delta b_{Gt} \tag{67}$$

$$NL^D_{Cit} = I^D_{C(PRI)it} - sh_{(GVA)i}\left(1 - \beta_{it}\right)RP_t + repL_{Cit-1} - \delta_t K_{C(PRI)it-1} - sh_{(GVA)i}\bar{p}_C\Delta b_{Ct} \tag{68}$$

$$I_{G(PRI)it} = sh_{(GVA)i}\beta_{it}RP_t + \Delta L_{Git} + \delta_t K_{G(PRI)it-1} + sh_{(GVA)i}\bar{p}_G\Delta b_{Gt} + def_t L_{Git-1} \tag{69}$$

$$I_{C(PRI)it} = sh_{(GVA)i}\left(1 - \beta_{it}\right)RP_t + \Delta L_{Cit} + \delta_t K_{C(PRI)it-1} + def_t L_{Cit-1} + sh_{(GVA)i}\bar{p}_C\Delta b_{Ct} \tag{70}$$

$$\begin{aligned}I_{C(PRI)S4t} = RP_t + \Delta L_{Ct} + \Delta L_{Gt} + \delta_t K_{(PRI)t-1} - I_{G(PRI)t} - I_{C(PRI)S1t} \\ - I_{C(PRI)S2t} - I_{C(PRI)S3t} + \bar{p}_G\Delta b_{Gt} + \bar{p}_C\Delta b_{Ct} + DL_t\end{aligned} \tag{71}$$

$$I_{G(PRI)t} = \sum I_{G(PRI)it} \tag{72}$$

$$I_{C(PRI)t} = \sum I_{C(PRI)it} \tag{73}$$

$$I_{(PRI)t} = I_{C(PRI)t} + I_{G(PRI)t} \tag{74}$$

$$\kappa_t = I_{G(PRI)t}/I_{(PRI)t} \tag{75}$$

$$L_t = L_{Ct} + L_{Gt} \tag{76}$$

$$K_{G(PRI)it} = K_{G(PRI)it-1} + I_{G(PRI)it} - \delta_t K_{G(PRI)it-1} \tag{77}$$

$$K_{C(PRI)it} = K_{C(PRI)it-1} + I_{C(PRI)it} - \delta_t K_{C(PRI)it-1} \tag{78}$$

$$K_{G(PRI)t} = \sum K_{G(PRI)it} \tag{79}$$

$$K_{C(PRI)t} = \sum K_{C(PRI)it} \tag{80}$$

$$K_{(PRI)t} = K_{C(PRI)t} + K_{G(PRI)t} \tag{81}$$

$$K_{GE(PRI)it} = \gamma_{Ei} K_{G(PRI)it} \tag{82}$$

$$K_{GNE(PRI)it} = (1 - \gamma_{Ei}) K_{G(PRI)it} \tag{83}$$

$$K_{CE(PRI)it} = \gamma_{Ei} K_{C(PRI)it} \tag{84}$$

$$K_{CNE(PRI)it} = (1 - \gamma_{Ei}) K_{C(PRI)it} \tag{85}$$

$$K_{SEQ(PRI)it} = \gamma_{SEQi} K_{GE(PRI)it} \tag{86}$$

$$K_{GEt} = \sum K_{GE(PRI)it} + \gamma_E K_{G(GOV)t} \tag{87}$$

$$K_{GNEt} = \sum K_{GNE(PRI)it} + (1 - \gamma_E) K_{G(GOV)t} \tag{88}$$

$$K_{CEt} = \sum K_{CE(PRI)it} + \gamma_E K_{C(GOV)t} \tag{89}$$

$$K_{CNEt} = \sum K_{CNE(PRI)it} + (1 - \gamma_E) K_{C(GOV)t} \tag{90}$$

$$K_{SEQt} = \sum K_{SEQ(PRI)i} \tag{91}$$

$$\delta_t = \delta_0 + (1 - \delta_0)(1 - ad_K) D_{TFt-1} \tag{92}$$

$$v_t = v_{t-1} [1 - (1 - ad_P) D_{TPt-1}] \tag{93}$$

$$g_{\lambda t} = \sigma_{0t} + \sigma_1 + \sigma_2 g_{Yt-1} \tag{94}$$

$$\sigma_{0t} = \sigma_{0t-1} (1 - \zeta_3) \tag{95}$$

$$\lambda_t = \lambda_{t-1} (1 + g_{\lambda t}) [1 - (1 - ad_P) D_{TPt-1}] \tag{96}$$

$$w_t = s_W \lambda_t h \tag{97}$$

$$N_t = \frac{Y_t}{h \lambda_t} \tag{98}$$

$$ur_t = 1 - re_t \tag{99}$$

$$b_{Ct} = b_{Ct-1} + \frac{x_{1t} \sum I^D_{C(PRI)it}}{\bar{p}_C} \tag{100}$$

$$b_{Gt} = b_{Gt-1} + \frac{x_{2t} \sum I^D_{G(PRI)it}}{\bar{p}_G} \tag{101}$$

$$x_{1t} = x_{10} - x_{11} yield_{Ct-1} \tag{102}$$

$$x_{2t} = x_{20} - x_{21} yield_{Gt-1} \tag{103}$$

$$x_{20t} = x_{20t-1} (1 + g_{x20t}) \tag{104}$$

$$g_{x20t} = g_{x20t-1}\left(1-\zeta_4\right) \tag{105}$$

$$yield_{Ct} = \frac{coupon_{Ct}}{p_{Ct}} \tag{106}$$

$$yield_{Gt} = \frac{coupon_{Gt}}{p_{Gt}} \tag{107}$$

$$coupon_{Ct} = yield_{Ct-1}\bar{p}_C \tag{108}$$

$$coupon_{Gt} = yield_{Gt-1}\bar{p}_G \tag{109}$$

$$B_{Ct} = B_{CHt} + B_{CCBt} \tag{110}$$

$$B_{Gt} = B_{GHt} + B_{GCBt} \tag{111}$$

$$p_{Ct} = \frac{B_{Ct}}{b_{Ct}} \tag{112}$$

$$p_{Gt} = \frac{B_{Gt}}{b_{Gt}} \tag{113}$$

$$B_t = B_{Ct} + B_{Gt} \tag{114}$$

$$DL_t = def_t L_{t-1} \tag{115}$$

$$def_t = \frac{def^{\max}}{1 + def_0 e^{\left(def_1 - def_2 illiq_{t-1}\right)}} \tag{116}$$

$$illiq_t = \frac{\sum\left(int_{Cit-1}+rep\right)L_{Cit-1} + \sum\left(int_{Gt-1}+rep\right)L_{Git-1} + coupon_{Ct-1}b_{Ct-1}}{Y_t + \sum\left(1-CR_{Cit}\right)NL^D_{Cit} + \sum\left(1-CR_{Gt}\right)NL^D_{Git} + \bar{p}_C\Delta b_{Ct} + \bar{p}_G\Delta b_{Gt}}$$
$$\frac{+coupon_{Gt-1}b_{Gt-1} + w_tN_t + T_{Ft} + T_{Ct} - SUB_t + \delta_t K_{(PRI)t-1}}{Y_t + \sum\left(1-CR_{Cit}\right)NL^D_{Cit} + \sum\left(1-CR_{Gt}\right)NL^D_{Git} + \bar{p}_C\Delta b_{Ct} + \bar{p}_G\Delta b_{Gt}} \tag{117}$$

$$dsr_t = \frac{\sum\left(int_{Cit-1}+rep\right)L_{Cit-1} + \sum\left(int_{Gt-1}+rep\right)L_{Git-1}}{TP_t + \sum int_{Cit-1}L_{Cit-1} + \sum int_{Gt-1}L_{Git-1}}$$
$$\frac{+coupon_{Ct-1}b_{Ct-1} + coupon_{Gt-1}b_{Gt-1}}{+coupon_{Ct-1}b_{Ct-1} + coupon_{Gt-1}b_{Gt-1}} \tag{118}$$

A.2.7 Households

$$Y_{HGt} = w_tN_t + DP_t + BP_{Dt} + int_D D_{t-1} + int_S SEC_{Ht-1} + coupon_{Ct-1}b_{CHt-1} + coupon_{Gt-1}b_{GHt-1} \tag{119}$$

$$Y_{Ht} = Y_{HGt} - T_{Ht} \tag{120}$$

$$C_{(PRI)Nt} = \left(c_1 Y_{Ht-1} + c_2 V_{HFt-1}\right)\left(1 - D_{Tt-1}\right) \tag{121}$$

$C_{(PRI)t} = C_{(PRI)Nt}$ if $C_{(PRI)Nt} + I_{(PRI)t} + I_{(GOV)t} + C_{(GOV)t} < Y_t^*$; otherwise

$$C_{(PRI)t} = pr\left(Y_t^* - I_{(GOV)t} - I_{(PRI)t} - C_{(GOV)t}\right) \tag{122}$$

$$V_{HFt} = V_{HFt-1} + Y_{Ht} - C_{(PRI)t} + b_{CHt-1}\Delta p_{Ct} + b_{GHt-1}\Delta p_{Gt} \tag{123}$$

$$\frac{SEC_{Ht}}{V_{HFt-1}} = \lambda_{10}+\lambda'_{10}D_{Tt-1}+\lambda_{11}int_S+\lambda_{12}yield_{Ct-1}+\lambda_{13}yield_{Gt-1}+\lambda_{14}int_D+\lambda_{15}\frac{Y_{Ht-1}}{V_{HFt-1}} \tag{124}$$

$$\frac{B_{CHt}}{V_{HFt-1}} = \lambda_{20}+\lambda'_{20}D_{Tt-1}+\lambda_{21}int_S+\lambda_{22}yield_{Ct-1}+\lambda_{23}yield_{Gt-1}+\lambda_{24}int_D+\lambda_{25}\frac{Y_{Ht-1}}{V_{HFt-1}} \tag{125}$$

$$\frac{B_{GHt}}{V_{HFt-1}} = \lambda_{30t}+\lambda'_{30}D_{Tt-1}+\lambda_{31}int_S+\lambda_{32}yield_{Ct-1}+\lambda_{33}yield_{Gt-1}+\lambda_{34}int_D+\lambda_{35}\frac{Y_{Ht-1}}{V_{HFt-1}} \tag{126}$$

$$\frac{D_t}{V_{HFt-1}} = \lambda_{40}+\lambda'_{40}D_{Tt-1}+\lambda_{41}int_S+\lambda_{42}yield_{Ct-1}+\lambda_{43}yield_{Gt-1}+\lambda_{44}int_D+\lambda_{45}\frac{Y_{Ht-1}}{V_{HFt-1}} \tag{127n}$$

$$D_t = D_{t-1} + Y_{Ht} - C_{(PRI)t} - \Delta SEC_{Ht} - \bar{p}_C\Delta b_{CHt} - \bar{p}_G\Delta b_{GHt} \tag{127}$$

$$\lambda_{30t} = \lambda_{30t-1}\left(1 + g_{\lambda 30t}\right) \tag{128}$$

$$g_{\lambda 30t} = \zeta_{10}g_{bGt-1} \tag{129}$$

$$b_{CHt} = \frac{B_{CHt}}{p_{Ct}} \tag{130}$$

$$b_{GHt} = \frac{B_{GHt}}{p_{Gt}} \tag{131}$$

$$DC_t = DC_{t-1} + C_{(PRI)t} - \xi DC_{t-1} \tag{132}$$

$$g_{POPt} = g_{POPt-1}\left(1 - \zeta_5\right) \tag{133}$$

$$POP_t = POP_{t-1}\left(1 + g_{POPt}\right) \tag{134}$$

$$LF_t = \left(lf_{1t} - lf_2 hazratio_{t-1}\right)\left(1 - \left(1 - ad_{LF}\right)D_{TFt-1}\right)POP_t \tag{135}$$

$$lf_{1t} = lf_{1t-1}\left(1 - \zeta_6\right) \tag{136}$$

A.2.8 Banks

$$BP_t = \sum int_{Cit-1}L_{Cit-1}+\sum int_{Gt-1}L_{Git-1}+int_S SEC_{Bt-1}-int_D D_{t-1}-int_A A_{t-1} \tag{137}$$

$$CAP_t = CAP_{t-1} + BP_{Ut} - DL_t + BAILOUT_t \tag{138}$$

$$BP_{Ut} = s_B BP_{t-1} \tag{139}$$

$$BP_{Dt} = BP_t - BP_{Ut} \tag{140}$$

$$HPM_t = h_1 D_t \tag{141}$$

$$SEC_{Bt} = h_2 D_t \tag{142}$$

$$A_t = A_{t-1}+\Delta HPM_t+\Delta L_{Gt}+\Delta L_{Ct}+\Delta SEC_{Bt}+DL_t-\Delta D_t-BP_{Ut}-BAILOUT_t \tag{143}$$

$$CR_t = \frac{CR^{\max}}{1 + r_0 \exp\left(r_1 - r_2 dsr_{t-1} + r_3\left(CAR_{t-1} - CAR^{\min}\right)\right)} \tag{144}$$

$$CR_{Gt} = \left[1 + l_1\left(w_{Gt-1} - w_{LTt-1}\right)\right] CR_t \tag{145}$$

$$CR_{Cit} = \left[1 + l_1\left(w_{Cit-1} - w_{LTt-1}\right)\right] CR_t \tag{146}$$

$$CR_{CS4t} = \frac{CR_t - sh_{(NLG)t-1}CR_{Gt} - sh_{(NLC)S1t-1}CR_{CS1t}}{sh_{(NLC)S4t-1}} \\ \frac{-sh_{(NLC)S2t-1}CR_{CS2t} - sh_{(NLC)S3t-1}CR_{CS3t}}{sh_{(NLC)S4t-1}} \tag{147}$$

$$L_{Cit} = L_{Cit-1} + \left(1 - CR_{Cit}\right) NL_{Cit}^{D} - repL_{Cit-1} - def_t L_{Cit-1} \tag{148}$$

$$L_{Git} = L_{Git-1} + \left(1 - CR_{Gt}\right) NL_{Git}^{D} - repL_{Git-1} - def_t L_{Git-1} \tag{149}$$

$$L_{Ct} = \sum L_{Cit} \tag{150}$$

$$L_{Gt} = \sum L_{Git} \tag{151}$$

$$lev_{Bt} = \left(L_{Ct} + L_{Gt} + SEC_{Bt} + HPM_t\right) / CAP_t \tag{152}$$

$$CAR_t = CAP_t \Big/ \left[w_{Gt} L_{Gt} + \sum w_{Cit} L_{Cit} + w_S SEC_{Bt} + w_H HPM_t\right] \tag{153}$$

$$w_{LTt} = sh_{(LG)t-1} w_{Gt} + \sum sh_{(LC)it-1} w_{Cit} \tag{154}$$

$$int_{Gt} = spr_{Gt} + int_A \tag{155}$$

$$int_{Cit} = spr_{Cit} + int_A \tag{156}$$

$$spr_t = spr_0 - spr_1\left(CAR_{t-1} - CAR^{\min}\right) + spr_2 dsr_{t-1} \tag{157}$$

$$spr_{Gt} = \left[1 + spr_3\left(w_{Gt-1} - w_{LTt-1}\right)\right] spr_t \tag{158}$$

$$spr_{Cit} = \left[1 + spr_3\left(w_{Cit-1} - w_{LTt-1}\right)\right] spr_t \tag{159}$$

$$spr_{CS4t} = \frac{spr_t - sh_{(LG)t-1}spr_{Gt} - sh_{(LC)S1t-1}spr_{CS1t}}{sh_{(LC)S4t-1}} \\ \frac{-sh_{(LC)S2t-1}spr_{CS2t} - sh_{(LC)S3t-1}spr_{CS3t}}{sh_{(LC)S4t-1}} \tag{160}$$

A.2.9 Government sector

$$GNS_t = T_t + CBP_t - C_{(GOV)t} - SUB_t - int_S SEC_{t-1} - \delta_t K_{(GOV)t-1} \quad (161)$$

$$SEC_t = SEC_{t-1} + I_{(GOV)t} - GNS_t - \delta_t K_{(GOV)t-1} + BAILOUT_t \quad (162)$$

$$I_{G(GOV)t} = gov_{IG} Y_{t-1} \quad (163)$$

$$I_{C(GOV)t} = gov_{IC} Y_{t-1} \quad (164)$$

$$I_{(GOV)t} = I_{G(GOV)t} + I_{C(GOV)t} \quad (165)$$

$$K_{G(GOV)t} = K_{G(GOV)t-1} + I_{G(GOV)t} - \delta_t K_{G(GOV)t-1} \quad (166)$$

$$K_{C(GOV)t} = K_{C(GOV)t-1} + I_{C(GOV)t} - \delta_t K_{C(GOV)t-1} \quad (167)$$

$$K_{(GOV)t} = K_{C(GOV)t} + K_{G(GOV)t} \quad (168)$$

$$K_t = K_{(PRI)t} + K_{(GOV)t} \quad (169)$$

$$K_{Gt} = K_{G(PRI)t} + K_{G(GOV)t} \quad (170)$$

$$K_{Ct} = K_{C(PRI)t} + K_{C(GOV)t} \quad (171)$$

$$C_{(GOV)t} = gov_C Y_{t-1} \quad (172)$$

$$SUB_t = T_{Ct} \quad (173)$$

$$gov_{SUBt} = \frac{SUB_t}{E_{NFt-1} ucr_{t-1}} \quad (174)$$

$$T_{Ht} = \tau_H Y_{HGt-1} \quad (175)$$

$$T_{Ft} = \tau_F TP_{Gt-1} \quad (176)$$

$$T_{Ct} = \tau_C EMIS_{INt-1} \quad (177)$$

$$T_t = T_{Ht} + T_{Ft} + T_{Ct} \quad (178)$$

A.2.10 Central banks

$$CBP_t = coupon_{Ct-1} b_{CCBt-1} + coupon_{Gt-1} b_{GCBt-1} + int_A A_{t-1} + int_S SEC_{CBt-1} \quad (179)$$

$$B_{GCBt} = s_G B_{Gt-1} \quad (180)$$

$$B_{CCBt} = s_C B_{Ct-1} \quad (181)$$

$$b_{CCBt} = \frac{B_{CCBt}}{p_{Ct}} \quad (182)$$

$$b_{GCBt} = \frac{B_{GCBt}}{p_{Gt}} \quad (183)$$

$$SEC_{CBt} = SEC_t - SEC_{Ht} - SEC_{Bt} \quad (184)$$

$$SEC_{CBt} = SEC_{CBt-1} + \Delta HPM_t - \Delta A_t - \bar{p}_C \Delta b_{CCBt} - \bar{p}_G \Delta b_{GGBt} \quad \text{(185-red)}$$

B Baseline Scenario

Table 8: Symbols and initial values for endogenous variables in the baseline scenario (Dafermos & Nikolaidi, 2021a).

Symbol	Description	Value	Remarks/sources
A	Advances (US$ trillion)	9.5	Calculated from the identity $CAP=L_C+L_G+HPM+SEC_B-A-D$ using the initial values of CAP, L_C, L_G, HPM, SEC_B and D
B	Value of total corporate bonds (US$ trillion)	12.6	Based on S&P Global Ratings (2019)
$BAILOUT$	Bailout funds provided to the banking system from the government sector	0	No bailout is assumed in 2018 since $lev_B<lev_B^{max}$ and $CAR>CAR^{min}$
B_C	Value of conventional corporate bonds (US$ trillion)	12.2	Calculated from Eq. (114) using the initial values of B and B_G
b_C	Number of conventional corporate bonds (trillions)	0.122	Calculated from Eq. (112) using the initial values of p_C and B_C
B_{CCB}	Value of conventional corporate bonds held by central banks (US$ trillion)	0.2	Calculated from the identity $B_{CCB}=B_{CB}-B_{GCB}$ where B_{CB} is the estimated amount of corporate sector holdings
b_{CCB}	Number of conventional corporate bonds held by central banks (trillions)	0.002	Calculated from Eq. (182) using the initial values of p_C and B_{CCB}
B_{CH}	Value of conventional corporate bonds held by households (US$ trillion)	12.0	Calculated from Eq. (110) using the initial values of B_{CCB} and B_C
b_{CH}	Number of conventional corporate bonds held by households (trillions)	0.1	Calculated from Eq. (130) using the initial values of p_C and B_{CH}
B_G	Value of green corporate bonds (US$ trillion)	0.40	Based on Climate Bonds Initiative (2017, 2018); we use the value of the climate-alligned bonds that has been issued by the financial and the non-financial corporate sector
b_G	Number of green corporate bonds (trillions)	0.004	Calculated from Eq. (113) using the initial values of p_G and B_G
B_{GCB}	Value of green corporate bonds held by central banks (US$ trillion)	0.03	Calculated from the identity $B_{GCB}=prop_{GCB}*B_{CB}$ where $prop_{GCB}$ is the proportion of green bonds in the total corporate banks held by central banks and B_{CB} is the estimated amount of corporate sector holdings
b_{GCB}	Number of green corporate bonds held by central banks (trillions)	0.0003	Calculated from Eq. (183) using the initial values of p_G and B_{GCB}
B_{GH}	Value of green corporate bonds held by households (US$ trillion)	0.38	Calculated from Eq. (111) using the initial values of B_G and B_{GCB}
b_{GH}	Number of green corporate bonds held by households (trillions)	0.0038	Calculated from Eq. (131) using the initial values of p_G and B_{GH}
BP	Profits of banks (US$ trillion)	3.40	Calculated from Eq. (137) using the initial values of int_{CI}, int_G, L_{CI}, L_{GI}, SEC_B, D and A
BP_D	Distributed profits of banks (US$ trillion)	0.76	Calculated from Eq. (140) using the initial values of BP and BP_U
BP_U	Retained profits of banks (US$ trillion)	2.64	Calculated from Eq. (139) using the initial value of BP
$C_{(GOV)}$	Government expenditures (US$ trillion)	14.2	Calculated from Eq. (172) using the initial value of Y
$C_{(PRI)}$	Consumption (US$ trillion)	51.1	No supply-side constraints are assumed in 2018 since $C_{(PRI)N}+I_{(PRI)}+I_{(GOV)}+C_{(GOV)}<Y^*$; therefore $C_{(PRI)}=C_{(PRI)N}$
$C_{(PRI)N}$	Consumption when no supply-side constraints exist (US$ trillion)	51.1	Calculated from Eq. (41) using the initial values of Y, $C_{(GOV)}$, $I_{(PRI)}$ and $I_{(GOV)}$ (since $C_{(PRI)}=C_{(PRI)N}$)
CAP	Capital of banks (US$ trillion)	9.5	Calculated from Eq. (152) using the initial values of lev_B, L_C, L_G, SEC_B and HPM
CAR	Capital adequacy ratio	0.1	Calculated from Eq. (153) using the initial values of CAP, L_C, L_G, w_C, w_G, SEC_B and HPM
CBP	Central banks' profits (US$ trillion)	0.4	Calculated from Eq. (179) using the initial values of $coupon_C$, b_{CCB}, $coupon_G$, b_{GCB}, A and SEC_{CB}
CEN	Carbon mass of fossil energy sources (Gt)	10.0	Calculated from Eq. (7) using the initial value of $EMIS_{IN}$
$CO2_{CUM}$	Cumulative CO_2 emissions ($GtCO_2$)	2210	Calculated from the formula $CO2_{CUM}=T_{AT}/(t_2*\varphi)$ using the initial value of T_{AT}
CON_E	Amount of fossil energy resources converted into reserves (EJ)	1650.5	Calculated from Eq. (20) using the initial value of RES_E
CON_M	Amount of material resources converted into reserves (Gt)	227	Calculated from Eq. (12) using the initial value of RES_M
$coupon_C$	Fixed coupon paid per conventional corporate bond (US$)	5	Calculated from Eq. (108) using the initial values of p_C and $yield_C$
$coupon_G$	Fixed coupon paid per green corporate bond (US$)	5	Calculated from Eq. (109) using the initial values of p_G and $yield_G$
CR	Degree of total credit rationing on loans	0.2	Calculated from Eq. (144) using the initial values of dsr and CAR
CR_{CS1}	Degree of credit rationing on conventional loans of the 'mining and utilities' sector	0.2	Calculated from Eq. (146) using the initial values of w_{C1}, w_{LT} and CR
CR_{CS2}	Degree of credit rationing on conventional loans of the 'manufacturing and construction' sector	0.2	Calculated from Eq. (146) using the initial values of w_{C2}, w_{LT} and CR
CR_{CS3}	Degree of credit rationing on conventional loans of the 'transport' sector	0.2	Calculated from Eq. (146) using the initial values of w_{C3}, w_{LT} and CR
CR_{CS4}	Degree of credit rationing on conventional loans of the 'other sectors'	0.2	Calculated from Eq. (147) using the initial values of sh_{NLG}, sh_{NLCi}, CR, CR_G, CR_{CS1}, CR_{CS2} and CR_{CS3}
CR_G	Degree of credit rationing on green loans	0.2	Calculated from Eq. (145) using the initial values of w_G, w_{LT} and CR
D	Deposits (US$ trillion)	70.0	Based on Brandmeir et al. (2017)
DC	Stock of durable consumption goods (US$ trillion)	1415	Calculated from Eq. (4) using the initial values of K, DEM, δ and μ

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Symbol	Description	Value	Remarks/sources
def	Firms' rate of default	0.037	Based on World Bank
DEM	Demolished/discarded socio-economic stock (Gt)	17.7	Taken from Wiedenhofer et al (2019); the figure refers to the end-of-life waste from stocks
dep_E	Energy depletion ratio	0.012	Calculated from Eq. (22) using the initial values of E_F and REV_E
dep_M	Matter depletion ratio	0.020	Based on World Bank Group (2017)
DL	Amount of defaulted loans (US$ trillion)	2.4	Calculated from Eq. (115) using the initial values of L and def
DP	Distributed profits of firms (US$ trillion)	19.8	Calculated from Eq. (52) using the initial values of TP and RP
dsr	Debt service ratio of firms	0.46	Calculated from Eq. (118) using the initial values of int_{Cl}, int_G, L_{Cl}, L_{Gl}, $coupon_C$, b_C, $coupon_G$, b_G and TP
D_T	Total proportional damage caused by climate change	0.0039	Calculated from Eq. (46) using the initial value of T_{AT}
D_{TF}	Part of damage that affects directly the fund-service resources	0.0035	Calculated from Eq. (48) using the initial values of D_T and D_{TP}
D_{TP}	Part of damage that reduces the productivities of fund-service resources	0.0004	Calculated from Eq. (47) using the initial value of D_T
E	Energy used for the production of output (EJ)	590	Based on IEA (International Energy Agency); total primary energy supply is used
ED	Dissipated energy (EJ)	590	Calculated from Eq. (18) using the initial values of E_F and E_{NF}
$EMIS$	Total CO_2 emissions ($GtCO_2$)	42.1	Calculated from Eq. (26) using the initial values of $EMIS_{IN}$ and $EMIS_L$
$EMIS_{IN}$	Industrial CO_2 emissions ($GtCO_2$)	36.6	Taken from CDIAC (Carbon Dioxide Information Analysis Center)
$EMIS_L$	Land-use CO_2 emissions ($GtCO_2$)	5.5	Taken from CDIAC (Carbon Dioxide Information Analysis Center)
E_F	Energy produced from fossil sources (EJ)	501.5	Calculated from Eq. (17) using the initial values of E and E_{NF}
E_{NF}	Energy produced from non-fossil sources (EJ)	88.5	Calculated from Eq. (16) using the initial values of θ and E
GNS	Government net saving (US$ trillion)	0.2	Calculated from Eq. (161) using the initial values of $C_{(GOV)}$, SUB, T, SEC, CBP, δ and $K_{(GOV)}$
g_{EMISL}	Growth rate of land emissions	0.016	Taken from SSP3, 6.0 W/m^2 (see Riahi et al., 2017)
g_{POP}	Growth rate of population	0.011	Taken from SSP3, 6.0 W/m^2 (see Riahi et al., 2017)
gov_{SUB}	Green subsidy rate	0.01	Calculated from Eq. (174) using the initial values of SUB, E_{NF} and ucr
g_{ucn}	Growth rate of pre-taxes levelised cost of generating non-renewable energy	0.005	Selected from a reasonable range of values
g_{ucr}	Growth rate of pre-subsidies levelised cost of generating renewable energy	0.010	Selected from a reasonable range of values
g_{x20}	Growth rate of the autonomous proportion of desired green investment funded via bonds	0.020	Calibrated such that the model generates the baseline scenario
g_Y	Growth rate of output	0.030	Based on IMF
$g_{\beta o}$	Growth rate of the autonomous share of green investment in total investment	0.001	Calibrated such that the model generates the baseline scenario
g_λ	Growth rate of labour productivity	0.021	Calculated from Eq. (94) using the initial values of g_Y and σ_o
$g_{\lambda 30}$	Growth rate of the households' portfolio choice parameter related to the autonomous demand for green bonds	0.005	Calculated from Eq. (129) using the initial value of g_{bG}
g_ω	Growth rate of CO_2 intensity	-0.004	Calibrated such that the model generates the baseline scenario
$hazratio$	Hazardous waste accumulation ratio (tonnes per person)	1.92	Calculated from Eq. (10) using the initial values of HW_{CUM} and POP
HPM	High-powered money (US$ trillion)	12.60	Calculated from Eq. (141) using the initial value of D
HW_{CUM}	Cumulative hazardous waste (Gt)	14.6	Calculated assuming a constant ratio of hazardous waste to GDP since 1960
$I_{(GOV)}$	Investment of the government sector (US$ trillion)	5.77	Calculated from the identity $I_{(GOV)}=(1\text{-}prop)*(I/Y)*Y$ where $prop$ is the proportion of private investment in total investment (based on data from IMF), I/Y is the proportion of total investment in GDP (taken from World Bank) and Y is the initial value of output
$I_{(PRI)}$	Investment of the private sector (US$ trillion)	14.85	Calculated from the identity $I_{(PRI)}=prop*(I/Y)*Y$ where $prop$ is the proportion of private investment in total investment (based on data from IMF), I/Y is the proportion of total investment in GDP (taken from World Bank) and Y is the initial value of output
$I_{C(GOV)}$	Conventional investment of the government sector (US$ trillion)	5.58	Calculated from Eq. (165) using the initial values of $I_{(GOV)}$ and $I_{G(GOV)}$
$I_{C(PRI)}$	Conventional investment of the private sector (US$ trillion)	14.34	Calculated from Eq. (74) using the initial values of $I_{(PRI)}$ and $I_{G(PRI)}$
$I_{C(PRI)S1}$	Conventional investment of the 'mining and utilities' sector (US$ trillion)	0.54	Calculated from the identity $I_{C(PRI)S1}=I_{(PRI)S1}\text{-}I_{G(PRI)S1}$; we use the initial values of $I_{(PRI)S1}$ and $I_{G(PRI)S1}$
$I_{C(PRI)S2}$	Conventional investment of the 'manufacturing and construction' sector (US$ trillion)	3.36	Calculated from the identity $I_{C(PRI)S2}=I_{(PRI)S2}\text{-}I_{G(PRI)S2}$; we use the initial values of $I_{(PRI)S2}$ and $I_{G(PRI)S2}$
$I_{C(PRI)S3}$	Conventional investment of the 'transport' sector (US$ trillion)	1.23	Calculated from the identity $I_{C(PRI)S3}=I_{(PRI)S3}\text{-}I_{G(PRI)S3}$; we use the initial values of $I_{(PRI)S3}$ and $I_{G(PRI)S3}$
$I_{C(PRI)S4}$	Conventional investment of the 'other' sectors (US$ trillion)	9.22	Calculated from the identity $I_{C(PRI)S4}=I_{(PRI)S4}\text{-}I_{G(PRI)S4}$; we use the initial values of $I_{(PRI)S4}$ and $I_{G(PRI)S4}$

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Symbol	Description	Value	Remarks/sources
$I_{G(GOV)}$	Green investment of the government sector (US$ trillion)	0.196	Calculated from the identity $I_{G(GOV)}$ =(1-*prop*)**green investment* ; *prop* is the proportion of private investment in total investment based on data from IMF; *green investment* refers to total green investment based on CPI (2019); we use a higher value than the one reported in CPI (2019) since green investment in our model is not confined to investment in energy efficiency and renewables (it also includes investment in recycling and material efficiency)
$I_{G(PRI)}$	Green investment of the private sector (US$ trillion)	0.5	Calculated from the identity $I_{G(PRI)}$ =*prop* **green investment*; *prop* is the proportion of private investment in total investment based on data from IMF; *green investment* refers to total green investment based on CPI (2019); we use a higher value than the one reported in CPI (2019) since green investment in our model is not confined to investment in energy efficiency and renewables (it also includes investment in recycling and material efficiency)
$I_{G(PRI)S1}$	Green investment of the 'mining and utilities' sector (US$ trillion)	0.2	Calculated from the identity $I_{G(PRI)S1}=sh_{(GREEN)S1}*I_{G(PRI)}$; we use the initial value of $I_{G(PRI)}$
$I_{G(PRI)S2}$	Green investment of the 'manufacturing and construction' sector (US$ trillion)	0.04	Calculated from the identity $I_{G(PRI)S2}=sh_{(GREEN)S2}*I_{G(PRI)}$; we use the initial value of $I_{G(PRI)}$
$I_{G(PRI)S3}$	Green investment of the 'transport' sector (US$ trillion)	0.10	Calculated from the identity $I_{G(PRI)S3}=sh_{(GREEN)S3}*I_{G(PRI)}$; we use the initial value of $I_{G(PRI)}$
$I_{G(PRI)S4}$	Green investment of the 'other sectors' (US$ trillion)	0.12	Calculated from the identity $I_{G(PRI)S4}=sh_{(GREEN)S4}*I_{G(PRI)}$; we use the initial value of $I_{G(PRI)}$
$I^{D}_{(PRI)}$	Desired total investment (US$ trillion)	17.6	Calibrated such that the model generates the baseline scenario
$I^{D}_{(PRI)S1}$	Desired total investment of the 'mining and utilities' sector (US$ trillion)	0.9	Calculated from Eq. (55) *using* the initial value of $I^{D}_{(PRI)}$
$I^{D}_{(PRI)S2}$	Desired total investment of the 'manufacturing and construction' sector (US$ trillion)	4.04	Calculated from Eq. (55) *using* the initial value of $I^{D}_{(PRI)}$
$I^{D}_{(PRI)S3}$	Desired total investment of the 'transport' sector (US$ trillion)	1.58	Calculated from Eq. (55) *using* the initial value of $I^{D}_{(PRI)}$
$I^{D}_{(PRI)S4}$	Desired total investment of the 'other sectors' (US$ trillion)	11.09	Calculated from Eq. (55) *using* the initial value of $I^{D}_{(PRI)}$
$I^{D}_{C(PRI)S1}$	Desired conventional investment of the 'mining and utilities' sector (US$ trillion)	0.64	Calculated from Eq. (66) using the initial values of $I^{D}_{(PRI)S1}$ *and* $I^{D}_{G(PRI)S1}$
$I^{D}_{C(PRI)S2}$	Desired conventional investment of the 'manufacturing and construction' sector (US$ trillion)	4.0	Calculated from Eq. (66) using the initial values of $I^{D}_{(PRI)S2}$ *and* $I^{D}_{G(PRI)S2}$
$I^{D}_{C(PRI)S3}$	Desired conventional investment of the 'transport' sector (US$ trillion)	1.46	Calculated from Eq. (66) using the initial values of $I^{D}_{(PRI)S3}$ *and* $I^{D}_{G(PRI)S3}$
$I^{D}_{C(PRI)S4}$	Desired conventional investment of the 'other sectors' (US$ trillion)	10.95	Calculated from Eq. (66) using the initial values of $I^{D}_{(PRI)S4}$ *and* $I^{D}_{G(PRI)S4}$
$I^{D}_{G(PRI)S1}$	Desired green investment of the 'mining and utilities' sector (US$ trillion)	0.29	Calculated such that it is reasonably higher than $I_{G(PRI)S1}$
$I^{D}_{G(PRI)S2}$	Desired green investment of the 'manufacturing and construction' sector (US$ trillion)	0.05	Calculated such that it is reasonably higher than $I_{G(PRI)S2}$
$I^{D}_{G(PRI)S3}$	Desired green investment of the 'transport' sector (US$ trillion)	0.12	Calculated such that it is reasonably higher than $I_{G(PRI)S3}$
$I^{D}_{G(PRI)S4}$	Desired green investment of the 'other sectors' (US$ trillion)	0.14	Calculated such that it is reasonably higher than $I_{G(PRI)S4}$
illiq	Firms' illiquidity ratio	0.74	Calculated from Eq. (117) using the initial values of int_{Ci}, int_{G}, L_{Ci}, L_{Gi}, $coupon_{C}$, b_{C}, $coupon_{G}$, b_{G}, w, N, T_{F}, T_{C}, SUB, δ, $K_{(PRI)}$, Y, CR_{Ci}, NL_{Ci}^{D}, CR_{G} and NL_{Gi}^{D}
int_{CS1}	Interest rate on the conventional loans of the 'mining and utilities'	0.08	Calculated from Eq. (156) using the initial value of spr_{CS1}
int_{CS2}	Interest rate on the conventional loans of the 'manufacturing and construction' sector	0.08	Calculated from Eq. (156) using the initial value of spr_{CS2}
int_{CS3}	Interest rate on the conventional loans of the 'transport' sector	0.08	Calculated from Eq. (156) using the initial value of spr_{CS3}
int_{CS4}	Interest rate on the conventional loans of the 'other sectors'	0.08	Calculated from Eq. (156) using the initial value of spr_{CS4}
int_{G}	Interest rate on green loans	0.08	Calculated from Eq. (155) using the initial value of spr_{G}
K	Total capital stock	275.6	Calculated from the identity $K=(K/Y)*Y$; we use the initial value of Y and the capital-to-output has been selected such that the model generates the baseline scenario
$K_{(GOV)}$	Capital stock of the government	77.2	Calculated from the identity $K_{(GOV)}$ =(1-*prop*) *K where *prop* is the proportion of private investment in total investment (based on data from IMF); we use the initial value of K
$K_{(PRI)}$	Capital stock of firms (US$ trillion)	198.4	Calculated from the identity $K_{(PRI)}$ =*prop* *K where *prop* is the proportion of private investment in total investment (based on data from IMF); we use the initial value of K
K_{C}	Conventional capital stock (US$ trillion)	266.3	Calculated from Eq. (171) using the initial values of $K_{C(PRI)}$ and $K_{C(GOV)}$
$K_{C(GOV)}$	Conventional capital stock of the government sector (US$ trillion)	74.6	Calculated from Eq. (168) using the initial values of $K_{(GOV)}$ and $K_{G(GOV)}$
$K_{C(PRI)}$	Conventional capital stock of firms (US$ trillion)	191.7	Calculated from Eq. (81) using the initial values of $K_{(PRI)}$ and $K_{G(PRI)}$

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Symbol	Description	Value	Remarks/sources
$K_{C(PRI)S1}$	Conventional capital stock of the 'mining and utilities' sector (US$ trillion)	10.1	Calculated from the identity $K_{C(PRI)S1}=sh_{(GVA)S1}*K_{C(PRI)}$; we use the initial value of $K_{C(PRI)}$
$K_{C(PRI)S2}$	Conventional capital stock of the 'manufacturing and construction' sector (US$ trillion)	43.9	Calculated from the identity $K_{C(PRI)S2}=sh_{(GVA)S2}*K_{C(PRI)}$; we use the initial value of $K_{C(PRI)}$
$K_{C(PRI)S3}$	Conventional capital stock of the 'transport' sector (US$ trillion)	17.2	Calculated from the identity $K_{C(PRI)S3}=sh_{(GVA)S3}*K_{C(PRI)}$; we use the initial value of $K_{C(PRI)}$
$K_{C(PRI)S4}$	Conventional capital stock of the 'other sectors' (US$ trillion)	120.5	Calculated from the identity $K_{C(PRI)S4}=sh_{(GVA)S4}*K_{C(PRI)}$; we use the initial value of $K_{C(PRI)}$
K_{CE}	Conventional energy capital stock (US$ trillion)	111.7	Calculated from Eq. (89) using the initial values of $K_{CE(PRI)}$ and $K_{C(GOV)}$
$K_{CE(PRI)S1}$	Conventional energy capital stock of the 'mining and utilities' sector (US$ trillion)	9.8	Calculated from Eq. (84) using the initial value of $K_{C(PRI)S1}$
$K_{CE(PRI)S2}$	Conventional energy capital stock of the 'manufacturing and construction' sector (US$ trillion)	7.5	Calculated from Eq. (84) using the initial value of $K_{C(PRI)S1}$
$K_{CE(PRI)S3}$	Conventional energy capital stock of the 'transport' sector (US$ trillion)	15.0	Calculated from Eq. (84) using the initial value of $K_{C(PRI)S1}$
$K_{CE(PRI)S4}$	Conventional energy capital stock of the 'other sectors' (US$ trillion)	26.1	Calculated from Eq. (84) using the initial value of $K_{C(PRI)S1}$
K_{CNE}	Conventional non-energy capital stock (US$ trillion)	154.6	Calculated from Eq. (90) using the initial values of $K_{CNE(PRI)}$ and $K_{C(GOV)}$
$K_{CNE(PRI)S1}$	Conventional non-energy capital stock of the 'mining and utilities' sector (US$ trillion)	0.3	Calculated from Eq. (85) using the initial value of $K_{C(PRI)S1}$
$K_{CNE(PRI)S2}$	Conventional non-energy capital stock of the 'manufacturing and construction' sector (US$ trillion)	36.4	Calculated from Eq. (85) using the initial value of $K_{C(PRI)S1}$
$K_{CNE(PRI)S3}$	Conventional non-energy capital stock of the 'transport' sector (US$ trillion)	2.1	Calculated from Eq. (85) using the initial value of $K_{C(PRI)S1}$
$K_{CNE(PRI)S4}$	Conventional non-energy capital stock of the 'other sectors' (US$ trillion)	94.4	Calculated from Eq. (85) using the initial value of $K_{C(PRI)S1}$
K_G	Green capital stock (US$ trillion)	9.3	Calculated from Eq. (170) using the initial values of $K_{G(PRI)}$ and $K_{G(GOV)}$
$K_{G(GOV)}$	Green capital stock of the government sector (US$ trillion)	2.6	Calibrated such that the model generates the baseline scenario
$K_{G(PRI)}$	Green capital stock of firms (US$ trillion)	6.7	Calculated from the formula $K_{G(PRI)}=x*K_{(PRI)}$ using the initial values of x and $K_{(PRI)}$
$K_{G(PRI)S1}$	Green capital stock of the 'mining and utilities' sector (US$ trillion)	3.3	Calculated from the identity $K_{G(PRI)S1}=sh_{(GREEN)S1}*K_{G(PRI)}$; we use the initial value of $K_{G(PRI)}$
$K_{G(PRI)S2}$	Green capital stock of the 'manufacturing and construction' sector (US$ trillion)	0.5	Calculated from the identity $K_{G(PRI)S2}=sh_{(GREEN)S2}*K_{G(PRI)}$; we use the initial value of $K_{G(PRI)}$
$K_{G(PRI)S3}$	Green capital stock of the 'transport' sector (US$ trillion)	1.4	Calculated from the identity $K_{G(PRI)S3}=sh_{(GREEN)S3}*K_{G(PRI)}$; we use the initial value of $K_{G(PRI)}$
$K_{G(PRI)S4}$	Green capital stock of the 'other sectors' (US$ trillion)	1.5	Calculated from the identity $K_{G(PRI)S4}=sh_{(GREEN)S4}*K_{G(PRI)}$; we use the initial value of $K_{G(PRI)}$
K_{GE}	Green energy capital stock (US$ trillion)	6.7	Calculated from Eq. (87) using the initial values of $K_{GE(PRI)}$ and $K_{G(GOV)}$
$K_{GE(PRI)S1}$	Green energy capital stock of the 'mining and utilities' sector (US$ trillion)	3.2	Calculated from Eq. (82) using the initial value of $K_{G(PRI)S1}$
$K_{GE(PRI)S2}$	Green energy capital stock of the 'manufacturing and construction' sector (US$ trillion)	0.1	Calculated from Eq. (82) using the initial value of $K_{G(PRI)S1}$
$K_{GE(PRI)S3}$	Green energy capital stock of the 'transport' sector (US$ trillion)	1.2	Calculated from Eq. (82) using the initial value of $K_{G(PRI)S1}$
$K_{GE(PRI)S4}$	Green energy capital stock of the 'other sectors' (US$ trillion)	0.3	Calculated from Eq. (82) using the initial value of $K_{G(PRI)S1}$
K_{GNE}	Green non-energy capital stock (US$ trillion)	2.7	Calculated from Eq. (88) using the initial values of $K_{GNE(PRI)}$ and $K_{G(GOV)}$
$K_{GNE(PRI)S1}$	Green non-energy capital stock of the 'mining and utilities' sector (US$ trillion)	0.1	Calculated from Eq. (83) using the initial value of $K_{G(PRI)S1}$
$K_{GNE(PRI)S2}$	Green non-energy capital stock of the 'manufacturing and construction' sector (US$ trillion)	0.4	Calculated from Eq. (83) using the initial value of $K_{G(PRI)S2}$
$K_{GNE(PRI)S3}$	Green non-energy capital stock of the 'transport' sector (US$ trillion)	0.2	Calculated from Eq. (83) using the initial value of $K_{G(PRI)S3}$
$K_{GNE(PRI)S4}$	Green non-energy capital stock of the 'other sectors' (US$ trillion)	1.2	Calculated from Eq. (83) using the initial value of $K_{G(PRI)S4}$
K_{SEQ}	Sequestration capital (US$ trillion)	0.0	Calculated from Eq. (91) using the initial values of $K_{SEQ(PRI)S1}$ and $K_{SEQ(PRI)S2}$
$K_{SEQ(PRI)S1}$	Sequestration capital of the 'mining and utilities' sector (US$ trillion)	0.011	Calculated from Eq. (86) using the initial value of $K_{G(PRI)S1}$
$K_{SEQ(PRI)S2}$	Sequestration capital of the 'manufacturing and construction' sector (US$ trillion)	0.002	Calculated from Eq. (86) using the initial value of $K_{G(PRI)S2}$
L	Total loans of firms (US$ trillion)	65.9	Calculated from the identity $L=(credit-B/Y)*Y$; *credit* is the credit to the non-financial corporations in percent of GDP taken from BIS (Bank for International Settlements); it is assumed that *credit* includes both loans and bonds
L_C	Conventional loans (US$ trillion)	63.7	Calculated from Eq. (76) using the initial values of L and L_G
L_{CS1}	Conventional loans of the 'mining and utilities' sector (US$ trillion)	3.4	Calculated from the identity $L_{CS1}=sh_{(GVA)S1}*L_C$; we use the initial value of L_C

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Symbol	Description	Value	Remarks/sources
L_{CS2}	Conventional loans of the 'manufacturing and construction' sector (US$ trillion)	14.6	Calculated from the identity $L_{CS2}=sh_{(GVA)S2}*L_C$; we use the initial value of L_C
L_{CS3}	Conventional loans of the 'transport' sector (US$ trillion)	5.7	Calculated from the identity $L_{CS3}=sh_{(GVA)S3}*L_C$; we use the initial value of L_C
L_{CS4}	Conventional loans of the 'other sectors' (US$ trillion)	40.0	Calculated from the identity $L_{CS4}=sh_{(GVA)S4}*L_C$; we use the initial value of L_C
L_G	Green loans (US$ trillion)	2.2	Calculated by assuming that $L_G/L=K_{G(PRI)}/K_{(PRI)}=x$; we use the initial values of x and L
L_{GS1}	Green loans of the 'mining and utilities' sector (US$ trillion)	0.1	Calculated from the identity $L_{GS1}=sh_{(GVA)S1}*L_G$; we use the initial value of L_G
L_{GS2}	Green loans of the 'manufacturing and construction' sector (US$ trillion)	0.5	Calculated from the identity $L_{GS2}=sh_{(GVA)S2}*L_G$; we use the initial value of L_G
L_{GS3}	Green loans of the 'transport' sector (US$ trillion)	0.2	Calculated from the identity $L_{GS3}=sh_{(GVA)S3}*L_G$; we use the initial value of L_G
L_{GS4}	Green loans of the 'other sectors' (US$ trillion)	1.4	Calculated from the identity $L_{GS4}=sh_{(GVA)S4}*L_G$; we use the initial value of L_G
lev_B	Banks' leverage ratio	9.4	Based on World Bank
LF	Labour force (billion people)	3.43	Taken from World Bank
lf_1	Autonomous labour force-to-population ratio	0.45	Calculated from Eq. (135) using the initial values of LF, POP, $hazratio$ and D_{TF}
M	Extraction of new matter from the ground, excluding the matter included in fossil energy sources (Gt)	47.4	Calculated from Eq. (2) using the initial values of M and REC
MY	Matter necessary for the production of output (Gt)	52.2	Taken from Wiedenhofer et al. (2019); the figure refers to primary plus secondary stock-building inputs
N	Number of employees (billion people)	3.2	Calculated from the definition of the rate of employment ($re=N/LF$) using the initial values of re and LF
$NL_{CS1}{}^D$	Desired new amount of conventional loans of the 'mining and utilities' sector (US$ trillion)	0.43	Calculated from Eq. (68) using the initial values of $I_{CS1}{}^D$, θ_{S1}, RP, L_{CS1}, δ, K_{CS1} and b_C
$NL_{CS2}{}^D$	Desired new amount of conventional loans of the 'manufacturing and construction' sector (US$ trillion)	3.03	Calculated from Eq. (68) using the initial values of $I_{CS2}{}^D$, θ_{S2}, RP, L_{CS2}, δ, K_{CS2} and b_C
$NL_{CS3}{}^D$	Desired new amount of conventional loans of the 'transport' sector (US$ trillion)	1.08	Calculated from Eq. (68) using the initial values of $I_{CS3}{}^D$, θ_{S3}, RP, L_{CS3}, δ, K_{CS3} and b_C
$NL_{CS4}{}^D$	Desired new amount of conventional loans of the 'other sectors' (US$ trillion)	8.30	Calculated from Eq. (68) using the initial values of $I_{CS4}{}^D$, θ_{S4}, RP, L_{CS4}, δ, K_{CS4} and b_C
$NL_{GS1}{}^D$	Desired new amount of green loans of the 'mining and utilities' sector (US$ trillion)	0.13	Calculated from Eq. (67) using the initial values of $I_{GS1}{}^D$, θ_{S1}, RP, L_{GS1}, δ, K_{GS1} and b_G
$NL_{GS2}{}^D$	Desired new amount of green loans of the 'manufacturing and construction' sector (US$ trillion)	0.07	Calculated from Eq. (67) using the initial values of $I_{GS2}{}^D$, θ_{S2}, RP, L_{GS2}, δ, K_{GS2} and b_G
$NL_{GS3}{}^D$	Desired new amount of green loans of the 'transport' sector (US$ trillion)	0.07	Calculated from Eq. (67) using the initial values of $I_{GS3}{}^D$, θ_{S3}, RP, L_{GS3}, δ, K_{GS3} and b_G
$NL_{GS4}{}^D$	Desired new amount of green loans of the 'other sectors' (US$ trillion)	0.19	Calculated from Eq. (67) using the initial values of $I_{GS4}{}^D$, θ_{S4}, RP, L_{GS4}, δ, K_{GS4} and b_G
$O2$	Oxygen used for the combustion of fossil fuels (Gt)	26.6	Calculated from Eq. (8) using the initial values of $EMIS_{IN}$ and CEN
p_C	Market price of conventional corporate bonds (US$)	100	The price has been normalised such that it is equal to US$100 (the par value of bonds) in 2018
p_G	Market price of green corporate bonds (US$)	100	The price has been normalised such that it is equal to US$100 (the par value of bonds) in 2018
POP	Population (billions)	7.63	Taken from the SSP3 6.0 W/m^2 scenario (see Riahi et al., 2017)
r	Rate of total profits	0.105	Calculated from Eq. (53) using the initial values of TP and $K_{(PRI)}$
re	Rate of employment	0.95	Calculated from Eq. (99) using the initial value of ur
REC	Recycled socio-economic stock (Gt)	4.8	Taken from Wiedenhofer et al (2019); the figure refers to end-of-life waste from stocks minus final waste, after recycling
RES_E	Fossil energy resources (EJ)	550183	Taken from BGR (2019, p. 39)
RES_M	Material resources (Gt)	151305	Calculated by assuming $RES_M/REV_M=63.8$ (based on UNEP, 2011)
REV_E	Fossil energy reserves (EJ)	40237	Taken from BGR (2019, p. 39)
REV_M	Material reserves (Gt)	2371	Calculated from Eq. (14) using the initial values of M and dep_M
RP	Retained profits of firms (US$ trillion)	1.0	Calculated from Eq. (51) using the initial value of TP
SEC	Total outstanding amount of government securities	70.0	Calculated from the identity *general government debt-to-GDP* $=SEC/Y$ using the initial value of Y and the value of the *general government debt-to-GDP* ratio (taken from IMF)
SEC_B	Government securities held by banks (US$ trillion)	10.5	Calculated by assuming that $SEC_B/SEC=0.15$ based on Abbas et al. (2014)
SEC_{CB}	Government securities held by central banks (US$ trillion)	2.8	Calculated from the identity $SEC_{CB}=HPM+V_{CB}-\bar{p}_C b_{CCB}-\bar{p}_G b_{GCB}-A$ using the initial values of V_{CB}, b_{CCB}, b_{GCB}, A and HPM

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Symbol	Description	Value	Remarks/sources
SEC_H	Government securities held by households (US$ trillion)	56.7	Calculated from Eq. (184) using the initial values of SEC, SEC_{CB} and SEC_B
seq	Proportion of carbon that is sequestrated	0.002	Based on GCCS (2019, p. 20)
SES	Socio-economic stock (Gt)	1230.5	Calculated from the identity $SES=\mu(K+DC)$ using the initial values of μ, K and DC
$sh_{(NLG)}$	Share of desired green loans in total desired loans	0.03	Calculated from the formula $sh_{(NLG)}=\Sigma NL_{GI}^{D}/(\Sigma NL_{GI}^{D}+\Sigma NL_{CI}^{D})$ using the initial values of NL_{GI}^{D} and NL_{CI}^{D}
$sh_{(NLC)S1}$	Share of desired conventional loans in total desired loans, 'mining and utilities' sector	0.05	Calculated from the formula $sh_{(NLC)S1}=NL_{CS1}^{D}/(\Sigma NL_{GI}^{D}+\Sigma NL_{CI}^{D})$ using the initial values of NL_{GI}^{D} and NL_{CI}^{D}
$sh_{(NLC)S2}$	Share of desired conventional loans in total desired loans, 'manufacturing and construction' sector	0.22	Calculated from the formula $sh_{(NLC)S2}=NL_{CS2}^{D}/(\Sigma NL_{GI}^{D}+\Sigma NL_{CI}^{D})$ using the initial values of NL_{GI}^{D} and NL_{CI}^{D}
$sh_{(NLC)S3}$	Share of desired conventional loans in total desired loans, 'transport' sector	0.09	Calculated from the formula $sh_{(NLC)S3}=NL_{CS3}^{D}/(\Sigma NL_{GI}^{D}+\Sigma NL_{CI}^{D})$ using the initial values of NL_{GI}^{D} and NL_{CI}^{D}
$sh_{(NLC)S4}$	Share of desired conventional loans in total desired loans, 'other sectors'	0.61	Calculated from the formula $sh_{(NLC)S4}=1-sh_{(NLG)}-sh_{(NLC)S1}-sh_{(NLC)S2}-sh_{(NLC)S3}$
$sh_{(L)}$	Share of loans in total firm liabilities	0.84	Calculated from the formula $sh_{(L)}=L/(L+B)$ using the initial values of L and B
$sh_{(LC)S1}$	Share of conventional loans in total loans, 'mining and utilities' sector	0.05	Calculated from the formula $sh_{(LC)S1}=L_{CS1}/L$ using the initial values of L and L_{CS1}
$sh_{(LC)S2}$	Share of conventional loans in total loans, 'manufacturing and construction' sector	0.22	Calculated from the formula $sh_{(LC)S2}=L_{CS2}/L$ using the initial values of L and L_{CS2}
$sh_{(LC)S3}$	Share of conventional loans in total loans, 'transport' sector	0.09	Calculated from the formula $sh_{(LC)S3}=L_{CS3}/L$ using the initial values of L and L_{CS3}
$sh_{(LC)S4}$	Share of conventional loans in total loans, 'other sectors'	0.61	Calculated from the formula $sh_{(LC)S4}=L_{CS4}/L$ using the initial values of L and L_{CS4}
$sh_{(LG)}$	Share of green loans in total loans	0.03	Calculated from the formula $sh_{(LG)}=L_G/L$ using the initial values of L and L_G
spr	Spread on total loans	0.05	Based on World Bank
spr_G	Spread on green loans	0.05	Calculated from Eq. (158) using the initial values of w_G, w_{LT} and spr
spr_{CS1}	Spread on conventional loans of the 'mining and utilities' sector	0.05	Calculated from Eq. (159) using the initial values of w_{CS1}, w_{LT} and spr
spr_{CS2}	Spread on conventional loans of the 'manufacturing and construction' sector	0.05	Calculated from Eq. (159) using the initial values of w_{CS2}, w_{LT} and spr
spr_{CS3}	Spread on conventional loans of the 'transport' sector	0.05	Calculated from Eq. (159) using the initial values of w_{CS3}, w_{LT} and spr
spr_{CS4}	Spread on conventional loans of the 'other sectors'	0.05	Calculated from Eq. (160) using the initial values of sh_{LG}, spr, spr_G and spr_{CS1}, spr_{CS2} and spr_{CS3}
SUB	Green government subsidies	0.044	Calculated from Eq. (173) using the initial value of T_C
T	Total taxes (US$ trillion)	19.4	Calculated from Eq. (178) using the initial values of T_H, T_F and T_C
T_{AT}	Atmospheric temperature change from the pre-industrial period (°C)	1.14	Taken from European Environment Agency/NOAA
T_C	Revenues from carbon taxes (US$ trillion)	0.044	Taken from World Bank Group (2019)
T_F	Taxes on firms' profits (US$ trillion)	3.6	Calculated from Eq. (176) using the initial value of TP_G
T_H	Taxes on households' disposable income	15.8	Calculated from Eq. (175) using the initial value of Y_{HG}
TP	Total profits of firms (US$ trillion)	20.8	Calculated from Eq. (50) using the initial values of TP_G, T_F, T_C and SUB
TP_G	Total gross profits of firms (US$ trillion)	24.4	Calculated from Eq. (49) using the initial values of Y, w, N, L_{CI}, L_{GI}, int_{CI}, int_G, δ, $K_{(PRI)}$, $coupon_C$, b_C, $coupon_G$ and b_G
$tucn$	Total unit cost of producing renewable energy	0.03	Calculated from Eq. (61) using the initial values of ucn, τ_C, ω and seq
$tucr$	Total unit cost of generating non-renewable energy	0.03	Calculated from Eq. (60) using the initial values of ucr and gov_{SUB}
u	Rate of capacity utilisation	0.72	Based on World Bank, Enterprise Surveys
ucn	Pre-taxes levelised cost of generating non-renewable energy (US$ trillion/Gt)	0.028	Based on IRENA (2019)
ucr	Pre-subsidies levelised cost of producing renewable energy (US$ trillion/Gt)	0.034	Based on IRENA (2019)
ue	Rate of energy utilisation	0.01	Calculated from Eq. (43) using the initial values of Y and Y_E^*
um	Rate of matter utilisation	0.02	Calculated from Eq. (42) using the initial values of Y, $C_{(GOV)}$ and Y_M^*
ur	Unemployment rate	0.05	Based on World Bank
v	Capital productivity	0.60	Calculated from Eqs. (38) and (44) using the initial values of Y, u and $K_{(PRI)}$
V_{CB}	Wealth of central banks (US$ trillion)	0	It is assumed that there are no accumulated capital gains for the central banks
V_H	Wealth of households (US$ trillion)	1553.8	Calculated from the identity $V_H=DC+D+\bar{p}_C b_{CH}+\bar{p}_G b_{GH}+SEC_H$ using the initial values of SEC_H, b_{CH}, b_{GH}, DC and D
V_{HF}	Financial wealth of households (US$ trillion)	139.1	Calculated from the identity $V_{HF}=D+p_C b_{CH}+p_G b_{GH}+SEC_H$ using the initial values of SEC_H, p_C, b_{CH}, p_G, b_{GH} and D
w	Annual wage rate (US$ trillion/billions of employees)	14.30	Calculated from Eq. (97) using the initial value of λ
W	Waste (Gt)	12.87	Calculated from the identity $W=DEM-REC$ using the initial values of DEM and REC

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Symbol	Description	Value	Remarks/sources
w_{CS1}	Risk weight on conventional loans provided to the 'mining and utilities' sector	1	Based on BCBS (2006)
w_{CS2}	Risk weight on conventional loans provided to the 'manufacturing and construction' sector	1	Based on BCBS (2006)
w_{CS3}	Risk weight on conventional loans provided to the 'transport' sector	1	Based on BCBS (2006)
w_{CS4}	Risk weight on conventional loans provided to the 'other sectors'	1	Based on BCBS (2006)
w_G	Risk weight on green loans	1	Based on BCBS (2006)
w_{LT}	Risk weight on total loans	1	Calculated from Eq. (154) using the initial values of w_G, w_{CI}, $sh_{(LG)}$, $sh_{(LC)S1}$, $sh_{(LC)S2}$ and $sh_{(LC)S3}$
x_1	Proportion of desired conventional investment funded via bonds	0.02	Calibrated such that the model generates the baseline scenario
x_2	Proportion of desired green investment funded via bonds	0.02	Calibrated such that the model generates the baseline scenario
x_{20}	Autonomous proportion of desired green investment funded via bonds	0.03	Calculated from Eq. (103) using the initial values of $yield_G$ and x_2
Y	Output (US$ trillion)	85.9	Taken from World Bank (2018 prices)
Y^*	Potential output (US$ trillion)	90.8	Calculated from Eq. (40) using the initial values of Y_M^*, Y_E^*, Y_K^* and Y_N^*
Y_E^*	Energy-determined potential output (US$ trillion)	6894.4	Calculated from Eq. (37) using the initial values of REV_E, θ and ε
Y_H	Disposable income of households (US$ trillion)	54.9	Calculated from Eq. (120) using the initial values of Y_{HG} and T_H
Y_{HD}	Household disposable income net of depreciation (US$ trillion)	43.7	Calculated from the identity $Y_{HD}=Y_H-\xi DC$ using the initial values of Y_H and DC
Y_{HG}	Gross disposable income of households (US$ trillion)	70.7	Calculated from Eq. (119) using the initial values of w, N, DP, BP_D, D, SEC_H, $coupon_C$, b_{CH}, $coupon_G$ and b_{GH}
$yield_C$	Yield on conventional corporate bonds	0.05	Based on FTSE Russell (2018)
$yield_G$	Yield on green corporate bonds	0.05	Based on FTSE Russell (2018)
Y_K^*	Capital-determined potential output (US$ trillion)	119.3	Calculated from Eq. (38) using the initial values of v and $K_{(PRI)}$
Y_M^*	Matter-determined potential output (US$ trillion)	3263.6	Calculated from Eq. (36) using the initial values of REV_M, REC and μ
Y_N^*	Labour-determined potential output (US$ trillion)	90.8	Calculated from Eq. (39) using the initial values of λ and LF
β_{S1}	Share of desired green investment of the 'mining and utilities' sector in total investment	0.32	Calculated from Eq. (56) using the initial values of $I^D_{(PRI)S1}$ and $I^D_{G(PRI)S1}$
β_{S2}	Share of desired green investment of the 'manufacturing and construction' sector in total investment	0.01	Calculated from Eq. (56) using the initial values of $I^D_{(PRI)S2}$ and $I^D_{G(PRI)S2}$
β_{S3}	Share of desired green investment of the 'transport' sector in total investment	0.08	Calculated from Eq. (56) using the initial values of $I^D_{(PRI)S3}$ and $I^D_{G(PRI)S3}$
β_{S4}	Share of desired green investment of the 'other sectors' in total investment	0.01	Calculated from Eq. (56) using the initial values of $I^D_{(PRI)S4}$ and $I^D_{G(PRI)S4}$
β_{0S1}	Autonomous share of desired green investment of the 'mining and utilities' sector in total investment	0.37	Calculated from Eq. (57) using the initial values of β_{S1}, $tucn$, $tucr$, sh_L, int_G, int_{LCS1}, $yield_G$ and $yield_C$
β_{0S2}	Autonomous share of desired green investment of the 'manufacturing and construction' sector in total investment	0.03	Calculated from Eq. (57) using the initial values of β_{S2}, $tucn$, $tucr$, sh_L, int_G, int_{LCS2}, $yield_G$ and $yield_C$
β_{0S3}	Autonomous share of desired green investment of the 'transport' sector in total investment	0.11	Calculated from Eq. (57) using the initial values of β_{S3}, $tucn$, $tucr$, sh_L, int_G, int_{LCS3}, $yield_G$ and $yield_C$
β_{0S4}	Autonomous share of desired green investment of the 'other sectors' in total investment	0.02	Calculated from Eq. (57) using the initial values of β_{S4}, $tucn$, $tucr$, sh_L, int_G, int_{LCS4}, $yield_G$ and $yield_C$
δ	Depreciation rate of capital stock	0.05	Calculated from Eq. (92) using the initial value D_{TF}
ε	Energy intensity (EJ/US$ trillion)	6.87	Calculated from Eq. (15) using the initial values of E and Y
θ	Share of non-fossil energy in total energy	0.15	Based on IEA (International Energy Agency); total primary energy supply is used
κ	Ratio of green capital to total capital	0.03	Calculated from Eq. (75) using the initial values of $I_{G(PRI)}$ and $I_{(PRI)}$
λ	Hourly labour productivity (US$ trillion/(billions of employees*annual hours worked per employee))	0.01	Calculated from Eq. (98) using the initial values of Y and N
λ_{30}	Households' portfolio choice parameter related to the autonomous demand for green bonds	0.01	Calculated from Eq. (126) using the initial values of B_{GH}, V_{HF}, D_T, $yield_C$, $yield_G$ and Y_H
μ	Material intensity (kg/$)	0.73	Calculated from Eq. (1) using the initial values of MY, $C_{(GOV)}$ and Y
ρ	Recycling rate	0.27	Calculated from Eq. (3) using the initial values of REC and DEM
σ_0	Autonomous growth rate of labour productivity	-0.01	Calibrated such that the model generates the baseline scenario
τ_C	Carbon tax	0.001	Calculated from Eq. (177) using the initial values of $EMIS_{IN}$ and T_C
ω	CO_2 intensity of fossil energy ($GtCO_2$/EJ)	0.07	Calculated from Eq. (23) using the initial values of $EMIS_{IN}$, E_F and seq

Table 9: Symbols and values for parameters and exogenous variables in the baseline scenario (Dafermos & Nikolaidi, 2021a).

Symbol	Description	Value	Remarks/sources
ad_K	Fraction of gross damages to capital stock avoided through adaptation	0.80	Selected from a reasonable range of values
ad_{LF}	Fraction of gross damages to labour force avoided through adaptation	0.95	Selected from a reasonable range of values
ad_P	Fraction of gross damages to productivity avoided through adaptation	0.95	Selected from a reasonable range of values
c_1	Propensity to consume out of disposable income	0.83	Calibrated such that the model generates the baseline scenario
c_2	Propensity to consume out of financial wealth	0.05	Based on econometric estimations for a panel of countries over the period 1995-2018 (available upon request)
CAR^{min}	Minimum capital adequacy ratio	0.08	Based on the Basel III regulatory framework
con_E	Conversion rate of fossil energy resources into reserves	0.003	Selected from a reasonable range of values
con_M	Conversion rate of material resources into reserves	0.0015	Selected from a reasonable range of values
CR^{max}	Maximum degree of credit rationing	0.5	Selected from a reasonable range of values
dd_{S1}	Degree of dirtiness of the 'mining and utilities' sector	8.84	Calculated from the formula $dd_{S1} = (carbon_{S1}/GVA_{S1})/(carbon/GVA)$ where $carbon_{S1}$ denotes the carbon emissions of sector S1, *carbon* denotes the total carbon emissions (taken from IEA), GVA_{S1} is the gross value added of sector S1 and *GVA* is the total gross value added (taken from UN)
dd_{S2}	Degree of dirtiness of the 'manufacturing and construction' sector	0.81	Calculated from the formula $dd_{S2} = (carbon_{S2}/GVA_{S2})/(carbon/GVA)$ where $carbon_{S2}$ denotes the carbon emissions of sector S2, *carbon* denotes the total carbon emissions (taken from IEA), GVA_{S2} is the gross value added of sector S2 and *GVA* is the total gross value added (taken from UN)
dd_{S3}	Degree of dirtiness of the 'transport' sector	2.73	Calculated from the formula $dd_{S3} = (carbon_{S3}/GVA_{S3})/(carbon/GVA)$ where $carbon_{S3}$ denotes the carbon emissions of sector S3, *carbon* denotes the total carbon emissions (taken from IEA), GVA_{S3} is the gross value added of sector S3 and *GVA* is the total gross value added (taken from UN)
dd_{S4}	Degree of dirtiness of the 'other sectors'	0.16	Calculated from the formula $dd_{S4} = (carbon_{S4}/GVA_{S4})/(carbon/GVA)$ where $carbon_{S4}$ denotes the carbon emissions of sector S4, *carbon* denotes the total carbon emissions (taken from IEA), GVA_{S4} is the gross value added of sector S4 and *GVA* is the total gross value added (taken from UN)
def^{max}	Maximum default rate of loans	0.2	Selected from a reasonable range of values
def_0	Parameter of the default rate function	4.41	Calculated from Eq. (116) using the initial value of *illiq*
def_1	Parameter of the default rate function	6.12	Calibrated such that the model generates the baseline scenario
def_2	Parameter of the default rate function (related to the sensitivity of the default rate to the illiquidity ratio of firms)	8.29	Selected from a reasonable range of values
gov_C	Share of government expenditures in output	0.17	Based on World Bank; the figure includes only the consumption government expenditures
gov_K	Share of conventional public spending in output	0.07	Calculated from Eq. (164) using the initial values of Y and $I_{C(GOV)}$
gov_G	Share of green public spending in output	0.0023	Calculated from Eq. (163) using the initial values of Y and $I_{G(GOV)}$
h	Annual working hours per employee	1900	Based on Penn World Table 9.1 (see Feenstra et al., 2015)
h_1	Banks' reserve ratio	0.18	Based on World Bank
h_2	Banks' government securities-to-deposits ratio	0.15	Calculated from Eq. (142) using the initial values of SEC_B and D
haz	Proportion of hazardous waste in total waste	0.04	EEA (2012, p. 22) reports a figure equal to 3.7% for EU-27
int_A	Interest rate on advances	0.03	Based on Global Interest Rate Monitor
int_D	Interest rate on deposits	0.025	Based on World Bank
int_S	Interest rate on government securities	0.025	Based on FTSE Russell (2018)
l_1	Parameter in the function of the credit rationing on green/conventional loans (related to the sensitivity of credit rationing to the difference between the weight on green/conventional loans and total loans)	1.00	Selected from a reasonable range of values
lev_B^{max}	Maximum leverage ratio	33.33	Based on the Basel III regulatory framework (the Basel III bank leverage can be proxied by the capital-to-assets ratio and its minimum value is 3%; since in our model the bank leverage is defined as the assets-to-capital ratio, the maximum value used is equal to 1/0.03)
lf_2	Sensitivity of the labour force-to-population ratio to hazardous waste	0.001	Selected from a reasonable range of values
p	Share of productivity damage in total damage caused by climate change	0.1	Selected from a reasonable range of values
$\bar{p}_C$	Par value of conventional corporate bonds (US$)	100	The par value of bonds is assumed to be always equal to US$100
$\bar{p}_G$	Par value of green corporate bonds (US$)	100	The par value of bonds is assumed to be always equal to US$100
pr	Ratio of demand-determined output to supply-determined output under the existence of supply-side constraints	0.99	Selected such that it is reasonably close to 1

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Symbol	Description	Value	Remarks/sources
r_0	Parameter in the function of the credit rationing on total loans	1.50	Calibrated such that the initial value of credit rationing is 20%. This figure is slightly higher than the one implied by the results in ECB (2017) that rely on the Survey on Access to Finance of Enterprises (SAFE) that covers EU countries. This is because credit rationing is expected to be higher in emerging and developing countries
r_1	Parameter in the function of the credit rationing on total loans	5.06	Calibrated such that the initial value of credit rationing is 20%. This figure is slightly higher than the one implied by the results in ECB (2017) that rely on the Survey on Access to Finance of Enterprises (SAFE) that covers EU countries. This is because credit rationing is expected to be higher in emerging and developing countries
r_2	Parameter in the function of the credit rationing on total loans (related to the sensitivity of credit rationing to the debt service ratio)	13.03	Based on econometric estimations for a panel of countries over the period 1995-2018 (available upon request)
r_3	Parameter in the function of the credit rationing on total loans (related to the sensitivity of credit rationing to the capital adequacy ratio of banks)	14.01	Based on econometric estimations for a panel of countries over the period 1995-2018 (available upon request)
rep	Loan repayment ratio	0.1	Selected from a reasonable range of values
s_B	Banks' retention rate	0.80	Calibrated such that the model generates the baseline scenario
s_C	Share of conventional corporate bonds held by central banks (US$ trillion)	0.02	Calculated from Eq. (181) using the initial values of B_{CCB} and B_C
s_F	Firms' retention rate	0.05	Calibrated such that the model generates the baseline scenario
s_G	Share of green corporate bonds held by central banks (US$ trillion)	0.06	Calculated from Eq. (180) using the initial values of B_{GCB} and B_G
s_W	Wage income share	0.54	Based on Penn World Table 9.1 (see Feenstra et al., 2015)
$sh_{(EMISIN)S1}$	Share of industrial emissions of the sector 'mining and utilities' to total industrial emissions	0.47	Calculated from the equation $carbon_{S1}/\Sigma carbon_{Si}$ where $carbon_{Si}$ denotes the industrial emissions of the i sector taken by IEA
$sh_{(EMISIN)S2}$	Share of industrial emissions of the sector 'manufacturing and construction' to total industrial emissions	0.19	Calculated from the equation $carbon_{S2}/\Sigma carbon_{Si}$ where $carbon_{Si}$ denotes the industrial emissions of the i sector taken from IEA
$sh_{(EMISIN)S3}$	Share of industrial emissions of the sector 'transport' to total industrial emissions	0.24	Calculated from the equation $carbon_{S3}/\Sigma carbon_{Si}$ where $carbon_{Si}$ denotes the industrial emissions of the i sector taken from IEA
$sh_{(EMISIN)S4}$	Share of industrial emissions of the 'other sectors' to total industrial emissions	0.10	Calculated from the equation $carbon_{S4}/\Sigma carbon_{Si}$ where $carbon_{Si}$ denotes the industrial emissions of the i sector taken from IEA
$sh_{(GREEN)S1}$	Share in green investment, 'mining and utilities' sector	0.49	Based on CPI (2019)
$sh_{(GREEN)S2}$	Share in green investment, 'manufacturing and construction' sector	0.08	Based on CPI (2019)
$sh_{(GREEN)S3}$	Share in green investment, 'transport' sector	0.21	Based on CPI (2019)
$sh_{(GREEN)S4}$	Share in green investment, 'other sectors'	0.23	Based on CPI (2019)
$sh_{(GVA)S1}$	Share in total gross value added, 'mining and utilities' sector	0.05	Calculated from the equation $GVA_{S1}/\Sigma GVA_{Si}$ where GVA_{Si} denotes the gross value added of the i sector taken from UNCTAD
$sh_{(GVA)S2}$	Share in total gross value added, 'manufacturing and construction' sector	0.23	Calculated from the equation $GVA_{S2}/\Sigma GVA_{Si}$ where GVA_{Si} denotes the gross value added of the i sector taken from UNCTAD
$sh_{(GVA)S3}$	Share in total gross value added, 'transport' sector	0.09	Calculated from the equation $GVA_{S3}/\Sigma GVA_{Si}$ where GVA_{Si} denotes the gross value added of the i sector taken from UNCTAD
$sh_{(GVA)S4}$	Share in total gross value added, 'other sectors'	0.63	Calculated from the equation $GVA_{S4}/\Sigma GVA_{Si}$ where GVA_{Si} denotes the gross value added of the i sector taken from UNCTAD
spr_0	Parameter in the function of the spread on total loans	0.04	Calculated from Eq. (157) using the initial values of CAR and dsr
spr_1	Parameter in the function of the spread on total loans (related to the sensitivity of spread to the capital adequacy ratio of banks)	0.03	Based on econometric estimations for a panel of countries over the period 1995-2018 (the econometric estimations are available upon request)
spr_2	Parameter in the function of the spread on total loans (related to the sensitivity of spread to the debt service ratio of firms)	0.02	Based on econometric estimations for a panel of countries over the period 1995-2018 (the econometric estimations are available upon request)
spr_3	Parameter in the function of the spread on green/conventional loans (related to the sensitivity of spread on green/conventional loans to the difference between the weight on green/conventional loans and total loans)	1.00	Selected from a reasonable range of values
t_1	Coefficient capturing the timescale of the initial adjustment of the climate system to an increase in cumulative emissions	0.500	Taken from Dietz and Venmans (2019)
t_2	Coefficient that captures the global warming that stems from non-CO_2 greenhouse gas emissions	1.1	Taken from Dietz and Venmans (2019)
w_H	Risk weight on high-powered money	0	Based on BCBS (2006)
w_S	Risk weight on government securities	0	Based on BCBS (2006)
x_{10}	Autonomous proportion of desired conventional investment funded via bonds	0.03	Calculated from Eq. (102) using the initial values of $yield_C$ and x_1
x_{11}	Sensitivity of the proportion of desired conventional investment funded via bonds to the conventional bond yield	0.25	Selected from a reasonable range of values

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Symbol	Description	Value	Remarks/sources
x_{21}	Sensitivity of the proportion of desired green investment funded via bonds to the green bond yield	0.25	Selected from a reasonable range of values
α_{00}	Parameter in the desired investment function	0.19	Calibrated such that the model generates the baseline scenario
α_{01}	Parameter in the desired investment function	0.30	Calibrated such that the model generates the baseline scenario
α_{1}	Parameter in the desired investment function (related to the sensitivity of investment to the capacity utilisation)	1.03	Based on econometric estimations for a panel of countries over the period 1950-2017 (available upon request)
α_{2}	Parameter in the desired investment function (related to the sensitivity of investment to the rate of profit)	1.19	Based on econometric estimations for a panel of countries over the period 1950-2017 (available upon request)
α_{31}	Parameter in the desired investment function (related to the sensitivity of investment to the unemployment rate)	0.08	Based on econometric estimations for a panel of countries over the period 1950-2017 (available upon request)
α_{32}	Parameter in the desired investment function (related to the sensitivity of investment to the unemployment rate)	0.5	Selected from a reasonable range of values
α_{41}	Parameter in the desired investment function (related to the sensitivity of investment to the energy utilisation rate)	0.1	Selected from a reasonable range of values
α_{42}	Parameter in the desired investment function (related to the sensitivity of investment to the energy utilisation rate)	0.99	Selected from a reasonable range of values
α_{51}	Parameter in the desired investment function (related to the sensitivity of investment to the matter utilisation rate)	0.1	Selected from a reasonable range of values
α_{52}	Parameter in the desired investment function (related to the sensitivity of investment to the matter utilisation rate)	0.99	Selected from a reasonable range of values
β_{1}	Autonomous share of desired green investment in total investment	20	Calibrated such that the model generates the baseline scenario
β_{2}	Sensitivity of the desired green investment share to the interest rate differential between green loans/bonds and conventional loans/bonds	1	Selected from a reasonable range of values
γ_{E}	Proportion of energy government capital in total government capital	0.714	Based on CPI (2019)
γ_{E1}	Proportion of energy capital in the total capital of the sector S1	0.969	Based on CPI (2019)
γ_{E2}	Proportion of energy capital in the total capital of the sector S2	0.170	Based on CPI (2019)
γ_{E3}	Proportion of energy capital in the total capital of the sector S3	0.875	Based on CPI (2019)
γ_{E4}	Proportion of energy capital in the total capital of the sector S4	0.217	Based on CPI (2019)
γ_{SEQ1}	Proportion of sequestration capital in the green energy capital of the sector	0.003	Based on IEA
γ_{SEQ2}	Proportion of sequestration capital in the green energy capital of the sector	0.018	Based on IEA
δ_{0}	Depreciation rate of capital stock when there are no climate damages	0.048	Based on Penn World Table 9.1 (see Feenstra et al., 2015)
ε^{max}	Maximum potential value of energy intensity (EJ/US$ trillion)	12	Selected such that it is reasonably higher than initial ε
ε^{min}	Minimum potential value of energy intensity (EJ/US$ trillion)	2	Selected such that it is reasonably higher than 0
ζ_{1}	Rate of decline of the (absolute) growth rate of ω	0.0001	Calibrated such that the model generates the baseline scenario
ζ_{2}	Rate of decline of the growth rate of β_0	0.100	Calibrated such that the model generates the baseline scenario
ζ_{3}	Rate of decline of the autonomous (absolute) growth rate of λ	0.01	Calibrated such that the model generates the baseline scenario
ζ_{4}	Rate of decline of the growth rates of x_{20}	0.40	Calibrated such that the model generates the baseline scenario
ζ_{5}	Rate of decline of the growth rate of population	0.0160	Calibrated such that the model generates the baseline scenario
ζ_{6}	Rate of decline of the autonomous labour force-to-population ratio	0.0003	Calibrated such that the model generates the baseline scenario
ζ_{7}	Rate of decline of the growth rate of ucr	0.1000	Calibrated such that the model generates the baseline scenario
ζ_{8}	Rate of decline of the growth rate of ucn	0.0500	Calibrated such that the model generates the baseline scenario
ζ_{9}	Rate of decline of the growth rate of $EMIS_L$	0.0140	Calibrated such that the model generates the baseline scenario
ζ_{10}	Parameter linking the demand for green bonds with their supply	0.18	Calibrated such that the model generates the baseline scenario
η_{1}	Parameter of the damage function	0	Based on Dietz and Stern (2015); D_T=50% when T_{AT}=4°C
η_{2}	Parameter of the damage function	0.00284	Based on Dietz and Stern (2015); D_T=50% when T_{AT}=4°C
η_{3}	Parameter of the damage function	0.00008	Based on Dietz and Stern (2015); D_T=50% when T_{AT}=4°C
λ_{10}	Parameter of households' portfolio choice	0.42	Calculated from Eq. (124) using the initial values of SEC_H, V_{HF}, D_T, $yield_C$, $yield_G$ and Y_H
λ_{10}'	Parameter of households' portfolio choice	0.10	Selected from a reasonable range of values
λ_{11}	Parameter of households' portfolio choice	0.03	Calculated from the constraint λ_{11}=-λ_{21}-λ_{31}-λ_{41}
λ_{12}	Parameter of households' portfolio choice	-0.01	Selected from a reasonable range of values
λ_{13}	Parameter of households' portfolio choice	-0.01	Selected from a reasonable range of values
λ_{14}	Parameter of households' portfolio choice	-0.01	Selected from a reasonable range of values
λ_{15}	Parameter of households' portfolio choice	-0.01	Selected from a reasonable range of values
λ_{20}	Parameter of households' portfolio choice	0.09	Calculated from Eq. (125) using the initial values of B_{CH}, V_{HF}, D_T, $yield_C$, $yield_G$ and Y_H
λ_{20}'	Parameter of households' portfolio choice	-0.20	Selected from a reasonable range of values
λ_{21}	Parameter of households' portfolio choice	-0.01	Calculated from the constraint λ_{21}=λ_{12}

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Symbol	Description	Value	Remarks/sources
λ_{22}	Parameter of households' portfolio choice	0.03	Calculated from the constraint $\lambda_{22}=-\lambda_{12}-\lambda_{32}-\lambda_{42}$
λ_{23}	Parameter of households' portfolio choice	-0.01	Selected from a reasonable range of values
λ_{24}	Parameter of households' portfolio choice	-0.01	Selected from a reasonable range of values
λ_{25}	Parameter of households' portfolio choice	-0.01	Selected from a reasonable range of values
λ_{30}'	Parameter of households' portfolio choice	0.00	Climate damages are assumed to have no impact on the holdings of green bonds
λ_{31}	Parameter of households' portfolio choice	-0.01	Calculated from the constraint $\lambda_{31}=\lambda_{13}$
λ_{32}	Parameter of households' portfolio choice	-0.01	Calculated from the constraint $\lambda_{32}=\lambda_{23}$
λ_{33}	Parameter of households' portfolio choice	0.03	Calculated from the constraint $\lambda_{33}=-\lambda_{13}-\lambda_{23}-\lambda_{43}$
λ_{34}	Parameter of households' portfolio choice	-0.01	Selected from a reasonable range of values
λ_{35}	Parameter of households' portfolio choice	-0.01	Selected from a reasonable range of values
λ_{40}	Parameter of households' portfolio choice	0.48	Calculated from the constraint $\lambda_{40}=1-\lambda_{10}-\lambda_{20}-\lambda_{30}$
λ_{40}'	Parameter of households' portfolio choice	0.10	Calculated from the constraint $\lambda_{40}'=-\lambda_{10}'-\lambda_{20}'-\lambda_{30}'$
λ_{41}	Parameter of households' portfolio choice	-0.01	Calculated from the constraint $\lambda_{41}=\lambda_{14}$
λ_{42}	Parameter of households' portfolio choice	-0.01	Calculated from the constraint $\lambda_{42}=\lambda_{24}$
λ_{43}	Parameter of households' portfolio choice	-0.01	Calculated from the constraint $\lambda_{43}=\lambda_{34}$
λ_{44}	Parameter of households' portfolio choice	0.03	Calculated from the constraint $\lambda_{44}=-\lambda_{14}-\lambda_{24}-\lambda_{34}$
λ_{45}	Parameter of households' portfolio choice	0.03	Calculated from the constraint $\lambda_{45}=-\lambda_{15}-\lambda_{25}-\lambda_{35}$
μ^{max}	Maximum potential value of material intensity (kg/US$)	1.5	Selected such that it is reasonably higher than initial μ
μ^{min}	Minimum potential value of material intensity (kg/US$)	0.3	Selected such that it is reasonably higher than 0
ξ	Proportion of durable consumption goods discarded every year	0.008	Selected such that the initial growth of *DC* is equal to the growth rate of output
π_1	Parameter linking the green to conventional non-energy capital ratio with material intensity	0.66	Calibrated such that the model generates the baseline scenario
π_2	Parameter linking the green to conventional non-energy capital ratio with material intensity	9.86	Calibrated such that the model generates the baseline scenario
π_3	Parameter linking the green to conventional non-energy capital ratio with recycling rate	2.76	Calibrated such that the model generates the baseline scenario
π_4	Parameter linking the green to conventional non-energy capital ratio with recycling rate	20.20	Calibrated such that the model generates the baseline scenario
π_5	Parameter linking the green to conventional energy capital ratio with energy intensity	4.40	Calibrated such that the model generates the baseline scenario
π_6	Parameter linking the green to conventional energy capital ratio with energy intensity	25.72	Calibrated such that the model generates the baseline scenario
π_7	Parameter linking the green to conventional energy capital ratio with the share of non-fossil energy	14.59	Calibrated such that the model generates the baseline scenario
π_8	Parameter linking the green to conventional energy capital ratio with the share of non-fossil energy	15.85	Calibrated such that the model generates the baseline scenario
π_9	Parameter linking the sequestration to conventional energy capital ratio with the sequestration rate	1288.63	Calibrated such that the model generates the baseline scenario
π_{10}	Parameter linking the sequestration to conventional energy capital ratio with the sequestration rate	1446.97	Calibrated such that the model generates the baseline scenario
ρ^{max}	Maximum potential value of recycling rate	0.8	Selected such that it is reasonably lower than 1
σ_1	Autonomous growth rate of labour productivity	0.0095	Calibrated such that the model generates the baseline scenario
σ_2	Sensitivity of labour productivity growth to the growth rate of output	0.825	Based on econometric estimations for a panel of countries over the period 1991-2018 (available upon request)
τ_F	Firms' tax rate	0.15	Selected from a reasonable range of values
τ_H	Households' tax rate	0.23	Calibrated such that the model generates the baseline scenario
φ	Transient Climate Response to cumulative carbon Emissions (TCRE) ($^{\circ}C/GtCO_2$)	0.0005	Based on MacDougall et al. (2017)