University of Cyprus

DEPARTMENT OF ACCOUNTING AND FINANCE

MASTER'S THESIS

CLIMATE IMPACT ON SOVEREIGN DEBT USING BLANCHARD'S MODEL

AUTHOR : ELENA PAPADIOFANTOUS
SUPERVISOR : PROFESSOR STAVROS A. ZENIOS

January 18, 2023

University
of Cyprus

January 18, 2023

Graduate School Coordinator
Department of Accounting and Finance

CERTIFICATE

This is to certify that the thesis submitted by Elena Papadiofantous, entitled CLIMATE IMPACT ON SOVEREIGN DEBT USING BLANCHARD'S MODEL, in fulfilment for the award of the Master's of Science Degree, succeeded in the oral defend of her thesis that took place on 22nd December 2022. The student submitted her thesis on 18th January 2023.

The Committee,

Professor
Stavros A.Zenios
Committee President
/ Supervisor

Associate Professor
Andreas Milidonis
Committee Member

ABSTRACT

Climate change is without a doubt a subject of great concern and the connection between sovereign debt and climate vulnerability is clear. The purpose of this study is to demonstrate the effect of climate change on the sovereign debt of two European countries, Italy and Netherlands. The Netherlands is an example of a low-debt country, while Italy represents a high-debt country. The purpose of this thesis is twin-fold. In the first part of this thesis, the study is focused on Debt Sustainability Analysis. I employ a simple stochastic debt sustainability model, constructed in a similar manner as the stylized model Olivier Blanchard suggested in the Debt Sustainability chapter of his forthcoming book ”Fiscal Policy Under Low Interest Rates”. The idea is to use simple debt dynamics configuration to see if I can reproduce a good estimate of what a more complex model can calculate. Then, I compare my results with the ones obtained from the model of S. A. Zenios et al. (2021), which involves optimization methods and risks boundaries. Comparing the two, I have found that the simple model can give us rough estimates for debt to GDP ratio, however there are several drawbacks. In the second part of the thesis, I follow the approach of S. Zenios (2022) to include the effects of climate change in Blanchard's model. I obtained climate data for Italy's and Netherlands' GDP under CP and NDC climate policies from IIASA's AR6 Database[1], the debt sustainability is tested under some climate burdens. In the case, debt is deemed unsustainable, I adjust primary balance to stabilize debt. Netherlands debt seems to impacted at a higher degree than Italy, however the annual fiscal adjustment needed by Italy ranges between 0.35-0.50 %GDP in the long term.

---

[1] [*IPCC's sixth Assessment Report (AR6) Database* n.d.]

ACKNOWLEDGMENTS

Through these few words, I would like to express my gratitude to my thesis supervisor Prof. Stavros Zenios for teaching and supporting me through this journey. I have definitely gained new experiences and knowledge through the time that I have worked under his guidance.

On a personal level, I would like to thank my family for their unconditional support in this journey. Without their support, I couldn't have done this. Furthermore, I would like to thank my mathematician friend Dr. Somayyeh Lotfi for always believing in me and keeping always her office door open for me.

Contents

List of Figures 2

List of Tables 3

Glossary 4

1 Introduction 5
- 1.1 Literature Review . . . 6
- 1.2 Data Sources . . . 8

2 Debt Sustainability Analysis 9
- 2.1 Debt Sustainability Analysis - DSA . . . 9
- 2.2 Stochastic DSA - SDSA . . . 10
- 2.3 SDSA with Optimization Modeling . . . 10
- 2.4 Debt Analysis under Low Interest Rates . . . 14

3 Climate Finance 17
- 3.1 Key Institutions . . . 18
  - 3.1.1 International Panel on Climate Change - IPCC . . . 18
  - 3.1.2 International Institute for Applied Systems Analysis- IIASA . . . 18
  - 3.1.3 Integrated Assessment Model Consortium - IAMC . . . 18
- 3.2 Representative Concentration Pathways - RCP . . . 19
- 3.3 Socio - Economic Pathways - SSP . . . 19
- 3.4 The scenario matrix architecture . . . 20
- 3.5 Climate Impact Chanels . . . 21
- 3.6 Mitigation Policies . . . 21
- 3.7 Adaptation Costs and Policies . . . 22
- 3.8 Climate Modeling . . . 24
- 3.9 Integrated Assessment Models - IAMs . . . 24
- 3.10 Social Cost of Carbon . . . 25
- 3.11 Disputes on ex-ante IAM models . . . 25
- 3.12 Climate Impact Function . . . 26
- 3.13 DICE . . . 26

3.14 Criticism on Damage Function . . . 28
3.15 RICE50+ . . . 28

4 Analysis **31**
4.1 A replication of Zenios et al. with Blanchard's model . . . 31
4.2 Debt analysis with climate burdens . . . 34

5 Conclusions **39**

Appendix A Climate Finance **41**
A.1 Socio - Economic Pathways (SSP) . . . 41
A.2 The Representative Concentration Pathways (RCPs) . . . 42
A.3 CP and NDC Climate Policies . . . 43
  A.3.1 CP Price scenarios . . . 44
  A.3.2 CP Intensity scenarios . . . 44
  A.3.3 NDC Price and NDC Intensity scenarios . . . 45
  A.3.4 ICES-XPS 1.0 . . . 45
  A.3.5 NEMESIS 5.0 . . . 46
A.4 RICE50+: Alternative Impact Function . . . 47

Appendix B Supplementary Material **48**
B.1 Debt Analysis under Low Interest Rates . . . 48
B.2 Risk and Term Premia calibration factors . . . 48
B.3 Correlation Matrix . . . 49
B.4 Debt average maturities . . . 49
B.5 DSA under climate burdens . . . 50
B.6 Model's Inputs . . . 50
B.7 Debt Analysis under Climate burdens . . . 52

Bibliography **54**

List of Figures

1 General structure of a scenario tree. 11

2 Declining interest rates.See B.1 for the declining trend of EU and US long term interest rates. 14

3 Cost of the most frequent natural disasters in Europe (floods/storms) from 1925-2021. Source: https://public.emdat.be/data 17

4 Natural Disasters' frequency in Europe between 1903-2022.(aggregated natural disaster type like floods, wildfires, droughts, extreme temperatures) The mean frequency has moved the last 50 years. Source: https://public.emdat.be/data. 17

5 A conceptual map of the five families of IPCC Shared Socioeconomic Pathways (SSP), in relation to the strength of mitigation and adaptation challenges posed by each scenario. 20

6 EU ETS Alowances Futures (EUA, EUAA) spot prices. Source: Refinitiv Eikon. 22

7 Total annual costs of adaptation for NCAR scenario as share of GDP, by decade and region (percent, at 2005 prices, no discounting)^2. Source: EACC study 2010 World Bank. 23

8 Real GDP 2100 to real GDP 2020, as computed by RICE50+ under SSP2-RCP2.6 scenario. Source :S. Zenios (2022). Green dots represent country's resilience to climate change. Source: ND-GAIN index data. 24

9 Figure borrowed from Nordhaus Nobel Prize lecture in 2018 [W. Nordhaus 2019]. T$<$ 2.0 (200 yr) notation stands for temperature limited to $2.0°C$ for 200-year average ^{3}. 27

10 Netherlands' debt dynamics as reproduced with Blanchard's model using different maturity bonds, comparing them with the results of S. A. Zenios et al.(2021). 32

11 Italy's debt dynamics as reproduced with Blanchard's model using different maturity bonds, comparing them with the results of S. Zenios(2022). 32

12 Debt dynamics under a climate scenario (SSP2-2.6, RICE50+). 34

13 CP Price Debt/GDP (%), stabilized when $c = 5\%$ 35

14 Primary balance under CP Price Policy for 2020-2050. 36

15 Historical Primary Balance for Italy ($\%GDP$). Source: IMF 36

16 NDC Price Debt/GDP, stabilized when $c = 5\%$ 37

17 Primary balance without and under NDC Price Policy for 2020-2050. . 37

18 Debt/GDP ratio (%)WITH CLIMATE BURDENS AND C=40% 37
19 Historical Primary Balance for Netherlands ($\%GDP$). Source: IMF . . 38
20 Carbon price forecast under the scenario SSP2-2.6 and different IAM models. The prices displayed are for OECD countries in dollars of 2010. There is a great deviation between models. Source IIASA, SSP Database. 40
21 Declining EU and US 10 year bond rates. 48
22 Risk Premium as a Smooth Approximation of a Piecewise Debt Function 48
23 Italy's and Netherland's Total (amortization and interest cost) Legacy debt. 49
24 Debt/GDP (%) under CP Intensity. 52
25 Debt/GDP (%) under NDC Intensity. 52
26 Debt/GDP ratio (%) without and with NDC Price Climate Policy, stabilized when $c = 35\%$ 53
27 Primary balance without and under NDC Price Policy for 2016-2050. . 53
28 GDP discount factor as obtained from NEMESIS model under CP and NDC Price policies computed with NEMESIS model. Source :AR6 Database [*IPCC's sixth Assessment Report (AR6) Database* n.d.]. . . . 53

List of Tables

2 Scenario Matrix formed by RCPs and SSPs combinations. Source : Rogelj et al. (2018). 20
3 Climate Risk Channels 21
4 Summary of the main differences between the two models. 33
5 Shared Socio-Economic Pathways (SSP) 41
6 Representative Concentration Pathways (RCP) 42
7 CP and NDC Policies 43
8 Calibrated coefficients for Eq. (8) 49
9 Calibrated coefficients for Eq. (9) 49
10 Correlation Matrix for the main quantities used in debt stock calculation. 49

Glossary

Notation	Description	Page
AR5	Fifth Assessment Report of the Intergovernmental Panel on Climate.	19
AR6	Sixth Assessment Report of the Intergovernmental Panel on Climate.	18
Disordered Default	A situation where creditors are not willing to discuss debt restructuring and the sovereign defaults on its debts. That is a messy or disorderly default because banks shut down and it is triggered a chain of business defaults and supply chain disruptions, sinking the country into deep recession. Example : Argentina, Greece.	12
DSA	The Debt Sustainability Analysis is the main tool for multilateral institutions and other creditors to assess risks to debt sustainability.	5
GHG	GreenHouse Gas Emissions. It refers to a group of gases that trap heat in earth's atmosphere instead of let it diffuse in space.	42
IAM	Integrated Assessment Model.	4, 24
IAMC	Integrated Assessment Model Consortium.	4, 18
IPCC	The Intergovernmental Panel on Climate Change is the United Nations body for assessing the science related to climate change.	2, 4, 18–20
MACC	Marginal abatement cost curves seek to convert the cost of different greenhouse gas (GhG) emissions abatement measures into comparable units (i.e $\$/tCO_2$)	25
MPK	Marginal product of capital equals to $\frac{\Delta Y}{\Delta K}$. It is defined as the additional output you produce with one more unit of capital.	16
Neutral Interest Rate	The neutral rate of interest, previously called the natural rate of interest, is the real interest rate that supports the economy at full employment/maximum output while keeping inflation constant.	14
RCP	Representative Concentration Pathways describe four different pathways of greenhouse gas (GHG) emissions and atmospheric concentrations, air pollutant emissions and land use.	20
Safe Interest Rate	The rate of return on a low-risk investment. Examples of investments with safe rates include U.S. Treasury securities and investment grade bonds.	14
SSP	Shared Socio-Economic Pathways are scenarios of projected socioeconomic global changes up to 2100. They are used to derive greenhouse gas emissions scenarios with different climate policies.	19, 20

1 Introduction

Over the past decades, economists have engaged in debates surrounding climate change, with the need for action becoming more urgent in recent years. Climate scientists and economists collaborate closely to estimate the future costs of climate change on society, government, and market. Integrating asset models (IAM) and empirical studies help to assess future costs of climate change on society, government, and markets. IAM models provide valuable insights into future climate damages, and it is an important risk to be considered in particular in the context of debt sustainability, which is the subject of this thesis.

Debt Sustainability Analysis(DSA) has always been a vital tool used in forming future expectations of the debt-repayment capacities of the debtor. ECB, IMF and other major organizations use this DSA analysis regularly to identify whether a country is eligible to receive financial aid. They also developed the debt sustainability framework to assist in debt sustainability analysis for low-income countries. After the 2008 global financial crisis, many countries found themselves struggling to repay their debts. Southern European countries were the most affected by this crisis, leaving them with high sovereign debt and a trembling economy. As with the COVID crisis, climate crisis aftermath would be an increase in mitigation and adaptation spending. Moreover, climate disasters do not impact only spending but also the GDP of a country. In such a case, many questions arise. Given this status quo, countries with high debt are able to sustain their debt? How probable is a debt explosion of an already high sovereign debt? and how much fiscal space a country needs to withstand climate crisis? Those are the major questions that governments and policy makers are called to answer and take decisions.

The first chapter provides an overview of the current literature on sovereign bonds under climate burdens and Debt Sustainability (DSA) analyses under climate impacts. Additionally, the data sources used throughout the thesis are also provided in a short paragraph[4]. In the second chapter, I elaborate on the Theoretical background on debt sustainability analysis. Some key equations are presented, as well as the the stochastic approach to debt sustainability analysis. A more elaborate discussion is based on S. A. Zenios et al. (2021) work, which is used later on to compare the trade-offs between a simplistic model and a more complex like S. A. Zenios et al. (2021) model. The section ends with a brief discussion of Blanchard's ideas. Finally, I present the stylized model that Blanchard uses in his recent book "Fiscal Policy Under Low Interest Rates" for demonstration purposes. The goal is to demonstrate that by tailoring a sim-

---

[4] Additional data sources may be found under the figures or numbers provided throughout the text.

ple model like this to a more realistic approach, it can replicate up to a fair degree the debt dynamics, without the need to run an expensive, complex DSA model.

The third chapter provides information on the climate models, emphasizing on DICE and RICE50+ models. The IAM structure presented through these models is similar across the macroeconomic IAM models and thus I use these two models for demonstration purposes. Aside from that, the chapter presents the terminology that one frequently encounters when working in the field of climate finance. In the next chapter the study's main results are presented. In the first part of this chapter I compare Blanchard's stylized model with Zenios's complex model. For comparison purposes two countries are chosen based on their debt obligations, one with high debt (Italy) and one with low debt levels (Netherlands). Following that, the second part of the results' analysis involve the exploitation of Blanchard's simplistic model when GDP is enhanced with climate burdens. We will take a look on how the dynamics work, as well as how much primary balance is needed to maintain the debt stable in the long run. Finally, the fifth chapter summarizes the main conclusions drawn from the previous chapter analysis, as well as providing some thoughts for some future research.

1.1 Literature Review

Climate finance or climate economics is still considered a new multidisciplinary field of study. It lies at the intersection of economics and climate studies and calls for collaboration between them. Unfortunately, at the moment, the financial community falls quite short of methodologies that allow the successful assessment of climate risks on financial analyses. However, as the problem with the rising temperature became evident, professionals started taking notice of the climate risks and efforts to understand and quantify them intensified. Big corporations have also started to choose carefully their portfolio, based on environmental friendly investments. Most notably, Black Rock's CEO Larry Fink in the annual letter to chief executives, stated that the company will withdraw their investments away from assets related with high climate sustainability risk like such as those in coal producers. In addition, earlier this year, the IMF began incorporating climate risks into its key surveillance and monitoring exercises, including its Debt Sustainability Analysis (DSA).

In the following paragraphs, some notable efforts into studying climate risks in relation damage costs, bonds and government debt. During 1992 to 2016, the International Monetary Fund (IMF) analyzed 11 ”natural disasters” that affected the Gross Domestic Product (GDP) of developing countries by at least 20%. According to the results, public debt increased from 68% of GDP in the year of the climate extreme event to 75% of

GDP three years afterwards [Fund 2019].

Another significant contribution to the field came from Cevik and Jalles (2020), when they published their work concerning the bond yields of 98 economies from 1995 to 2017. They found that countries that are more resilient to climate change have lower bond yields and spreads relative to countries with greater vulnerability, that is their cost of borrowing is lower. Further, S. Zenios (2021) addressed the debt sustainability analysis under climate burdens. The author integrated the outputs of IAM models like WITCH and RICE50+ into Stochastic DSA, in order to assess climate risks to sovereign debt dynamics and estimate the probability the debt to be sustainable. In this paper, Italy is used as a case study, which has a high debt-to-GDP ratio. It is shown that with RICE50+, the climate risks begin to take effect from about 2050, whereas with WITCH, the debt starts to build up by 2035. The study concludes that this increase is part due to the increasing adverse effects on growth, but also in part due to the nonlinear increase in risk premia with increasing debt ratio. As part of this thesis, I use the results of the latter study for comparison purposes as I aim also to compare simple and complex debt dynamics under climate burdens.

Another significant study is the one by Battiston and Monasterolo (2019). The authors study the climate policy shocks on individual assets of the Austrian's central bank's portfolio under a milder and a tighter climate scenario. Although they may find that impacts looked small and central banks are pretty robust, they have raised concerns about commercial banks. In fact, many sovereign bonds issued by OECD countries and mainly by those who are affected by the largest shocks are easily found in the portfolios of commercial banks with leverage equal to or higher than 30. With such a leverage, a shock of 1.3% on the value of the bond would lead to at least 30% capital losses, and that can disturb the financial stability of the bank.

Another paper, binding physical risks and financial stability, is the one by Lamperti et al. (2019), who indicated that climate change will increase the frequency of banking bailouts (average per decade - 9.1 without climate change to 22.6 when labor and capital are damaged by climate change). It is estimated that a non-negligible 20% of such effects are caused by the deterioration of banks' balance sheets induced by climate change.

This study also elaborates the debt sustainability analysis under climate burdens using simple debt sustainability analysis. All the previous studies, produced useful results for climate costs on sovereign debt examining the problem by different angles (bonds analysis, frequency of bank bailouts, or complex sustainability analysis). In this thesis we focus, on simple debt dynamics and I aim obtain a rough estimate of how much fiscal space high debt countries like Italy or low debt countries like Netherlands may need, depending also on their vulnerability on climate change. Rather than a more complex analysis, I suggest that one can obtain quick, inexpensive and reliable estimates of debt paths using a more simple model.

1.2 Data Sources

Data about legacy debt of Netherlands are retrieved from DTSA[5], as well as other variables implemented into debt dynamics, like GDP growth, primary balance, and risk-free rate data. For Italy GDP and primary balance are given by IMF, the Italian Ministry of Finance and the European Commission (EC), converging to Italy's long-term averages[6]. The five-year forward rate is derived from 5-year euro area government bond spot rate curve (all ratings bonds).

As it concerns, the adjustment factor for adjusting GDP according to climate policy impact, it's calculated as the ratio of GDP at t = 0 with GDP projected at t. RICE50+ model is used under SSP2-RCP2.6 scenarios for the GDP projections[S. Zenios 2022]. GDP data projections under CP and NDC climate policies are downloaded from IPCC's sixth Assessment Report (AR6) Database [*IPCC's sixth Assessment Report (AR6) Database* n.d.], under climate econometric models ICES (for Italy) and NEMESIS (for Netherlands). Any additional data sources that may be omitted in this section can be found as footnotes in the relevant figures or data tables.

---

[5] Dutch State Treasury Agency (DTSA)

[6] Data are borrowed from S. A. Zenios et al. (2021)

2 Debt Sustainability Analysis

2.1 Debt Sustainability Analysis - DSA

Debt is incurred by countries borrowing money. Borrowing can enable countries to develop and grow their productivity but unsustainable debt can overwhelm a country's finances, at worst leading to default. Public debt is considered sustainable if the government is able to meet its current and future obligations without significant financial assistance. Debt Sustainability Analysis (DSA) is the main tool used to assess risks and vulnerabilities to the sovereign's debt trajectory, providing policy makers and national authorities with vital insides. The key question a DSA attempts to answer is whether traditional debt relief mechanisms are sufficient to allow a country to service its debt under plausible assumptions about future output growth. In a DSA, key economic indicators such as output growth, export growth, exchange rates, and budget aggregates are projected forward in a fixed time horizon and behavior of public debt stock and debt service is examined.

DSA aims to give estimates for an appropriate debt threshold and a primary balance that enables the country to achieve the desired debt targets. Debt evolves as a function of its lagged values and the current primary balance and can be scaled by the capacity to pay (nominal GDP).

$$D_t = (1 + i_t)D_{t-1} - PB_t \tag{1}$$

$$d_t = \frac{(1 + r_t)}{(1 + g_t)} d_{t-1} - pb_t \tag{2}$$

where r is the real interest rate, i is nominal interest rate and g is the real GDP growth, while $d_t = \frac{D_t}{Y_t}$, $d_{t-1} = \frac{D_{t-1}}{Y_{t-1}}$ and $pb_t = \frac{PB_t}{Y_t}$.

Using this equation, it is possible to analyze the factors that drive debt dynamics. For example, high surpluses tend to reduce the debt stock. Similarly, higher growth rates lower debt levels, since they improve the ability to pay. However, a high initial debt, leads to even higher debt for the next period. Finally, higher real interest rates inflate interest expenditure payments, resulting in higher debt.

Debt sustainability can be approached under different risks. A credit risk occurs when the promised future cash flows are not paid in full. Liquidity risk is another possible risk and it is the case there is not enough liquidity to fulfill their payments. Governments should maintain access to financial markets, as an exit plan in case they do not have sufficient cash or other liquid assets, ensuring their ability to service all upcoming obligations in the short term. However, a debtor's liquidity may be compromised if there are not enough liquid assets and that leads to insolvency risk.

Moreover, the length of the maturity period determines the liquidity of the debt, and the shorter the maturity term, the more liquid the securities become. The government borrows in various maturities, but they can shorten this period by repurchasing the stakes in the market or wait until the date of payoff. However, as the debt maturity becomes short is accompanied by other risks, like refinancing risks. These kind of risk can be constrained by the introduction of Gross financing needs variable into DSA.

GFNs, is used as a complement in the standard DSA by major organizations like the IMF and the Commission. As a flow variable, GFNs focuses on the flow dimension of debt sustainability, while a typical DSA examines the debt to GDP ratio, which is a stock variable. GFNs measures the amount of debt that is falling due and a government needs to refinance in a given year. It encapsulates the risk of the change of market sentiment or the charge of higher interest rates.

2.2 Stochastic DSA - SDSA

Stochastic Debt Sustainability (SDSA) is a relatively new adding to the standard DSA. The method, provides an empirical rather than narrative analysis. Thus, it is a complementary tool to deterministic debt sustainability analyses. The stochastic DSA captures the uncertainty associated with the deterministic debt paths. Many international institutions implement SDSA when assessing fiscal policy. ECB and IMF have published various papers describing in detail Stochastic DSA ([Bouabdallah et al. 2017],[Chalk and Hemming 2000]). While the deterministic projections reflect a single outcome for the debt trajectory following the impact of either policy or pre-determined shock scenarios, the stochastic projections reflect a probabilistic approach. SDSA results a distribution of debt trajectories reflecting the impact on the baseline value of shocks to the debt drivers drawn from their historical probability distribution.

2.3 SDSA with Optimization Modeling

In light of the recent global financial crisis of 2008, followed by Greece's default, SDSA has become an essential tool for financial institutions and policy makers in assessing tail risk measures. S. A. Zenios et al. (2021) applied a financial decision optimization model under macroeconomic, financial and fiscal uncertainty on data from a highly leveraged country (Italy), a country (Netherlands) with low debt levels, and a representative eurozone crisis country. The model is used as a foundation by the European Stability Mechanism (ESM) [Gabriele et al. 2017] to carry debt sustainability analysis. Below, I briefly discuss the general structure of their model model. I only use part of the results of this study for comparison purposes in the result section, however is important to explain the main idea of the model, in order to be able to exploit key differences between this model and a simple debt dynamics model.

The model's main axis is the scenario tree, which represents the introduction of uncertainty in the analysis. The tree idea is borrowed from portfolio optimization management theory. The nodes represent plausible evolutions (states n) of the random parameters during a horizon, while decisions are taken at a given moment based the known information and anticipated uncertain information (tree nodes). For more information on the scenario generation procedures and more details on the scenario tree structure, one can be referred to the book of S. Zenios (2007).

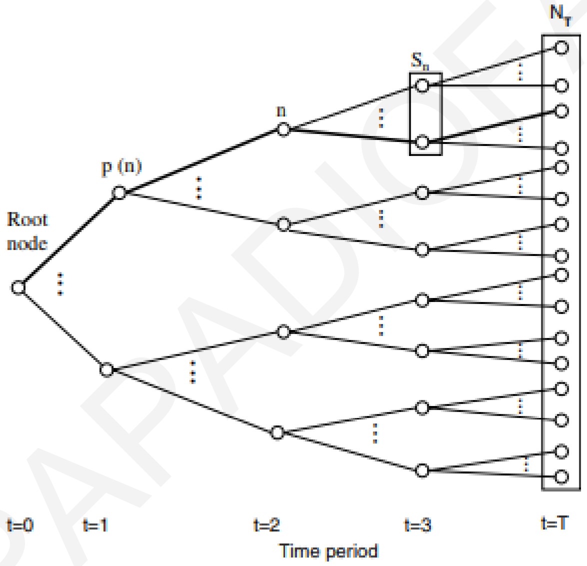


Figure 1: General structure of a scenario tree.

Let us assume a sovereign that at gross output Y_t, runs a primary balance PB_t, and owes a stock of debt D_{t-1}.Then, the sovereign's flow dynamics (Gross Financing Needs-GFN) and stock dynamics (D) are given by the two equations below.

$$GFN_t = i_{t-1}D_{t-1} + A_t - PB_t \tag{3}$$

where i_{t-1} is the effective nominal interest rate on debt at $t-1$, and A_t denotes the amortization schedule corresponding to D_{t-1}. The main variable of the model is the amount of debt to be issued at each state n at each time period t.

$$D_t = (1 + i_{t-1})D_{t-1} - PB_t \tag{4}$$

The debt-financing decisions (X) satisfy the equation:

$$\sum_{j=1}^{J} X_t(j) = GFN_t \tag{5}$$

Financing decision, X, denotes the amount of debt issued using instrument type j at state n. The interest rate for instrument j is given as the sum of the risk free rate and ρ, which endogenizes risk and term premia for different maturities j.

$$r_t(j) = r_{ft} + \rho(d_t, j) \tag{6}$$

The interest rate (r_t) and financing decision (X_t) determine the effective interest rate, used in equations (3), (4).

$$i_t = \frac{i_{t-1}(D_{t-1} - A_t) + \sum_{j=1}^{J} r_t(j) X_t(j)}{D_t} \tag{7}$$

The risk and term premia are defined according to the equation,

$$\rho(d_t, j) = a_j + (1 + b_j)\hat{\rho}(d_t) \tag{8}$$

where a_j and b_j are maturity-specific constants (term premia), and $\hat{\rho}(d)$ is the effect of debt stock on interest rates[7]

$$\hat{\rho}(d) = [\frac{d_{max} - d}{1 + exp(d_{max} - d)} - \frac{d_{min} - d}{1 + exp(d_{min} - d)}] \tag{9}$$

In most analyses, debt stock dynamics matters the most. However, according to the authors, the key question when assessing a country's debt sustainability is whether the country has enough funds to cover its financing needs over the medium and long term. Only the amount of borrowed money is accurately reflected in the stock of debt, not the flow of obligations to be fulfilled.

Though this approach addresses growth and roll-over risks, it focused on debt levels and the policy recommendations regarding the sustainability of debt (i.e the stock of debt should decline to level D by year T). A different structure of debt, can impose very different repayment flows and refinancing risks. A significantly lower debt level can significantly reduced both the cost of financing the debt stock and the need to roll it over, reducing the risk of a Disordered Default for a given debt level.

As the goal is to prevent debt financing shortages, Gross financing needs (GFN) is the variable of interest.It is a flow metric that measures a country's forthcoming financing needs. GFN is defined in Equation (3) as the sum of interest payments, principal repayments, and the primary deficit. Consequently, the net interest payments

---

[7] More information about the function and coefficients of equation 9 can be found in Appendix .

(NIP) are minimized. The reason that NIP is the objective function is because Net interest payments minus interest on legacy debt is what the sovereign controls through financing decisions. Moreover, NIP/D is the effective interest rate of debt (7), where D is debt stock. Interest payments consist of interest on legacy debt I_t^n plus interest on debt created by the financing decisions.

$$NIP_t^n = I_t^n + \sum_{m \in \mathcal{P}(n)} \sum_{j=1}^{J} X_{\tau(m)}^m(j) CF_t^n(j, m) \tag{10}$$

The goal is to find the (weights-w) financing decisions X that minimize expected costs of debt (sum interest payments).

$$w_t^n = \frac{X_t^n}{GFN_t^n} \tag{11}$$

where $\sum_{j=1}^{J} w_t^n(j) = 1$. The objective function is defined as follows:

$$\min_{X} \qquad \sum_{n \in \mathcal{N}_t, t=0,1,2,\ldots T} p^n NIP_t^n \tag{12}$$

with constraints:

$$\psi(\text{gfn}) < \omega \tag{13}$$

$$\frac{\partial d}{\partial t} \leqslant \delta \tag{14}$$

To track service payments on endogenously created debt on a path leading to n , it is achieved with the tree structure. In Equation (10), $CF_t^n(j; m)$ is defined as the nominal amount of interest payment due at state n of period t, per unit of debt $X_{\tau(m)}^m(j)$ issued at state m of period $\tau(m)$ on the path P(n). This amount is computed from scenarios of the term structure of interest rates, the terms of the issued instrument, and the premia (Equation (6)). In the objective function p denotes the probability, while in Equation (13), the random variable gfn equals GFN/Y, where Y is the nominal GDP.

Moreover, the model constrains flow and stock dynamics by exogenous thresholds, ω and δ. The flow risks are constrained by a tail measure of the flow distribution, and for insolvency risks, the stock is constrained to converge. In other words, DSTA[8] and the Italian Treasury would like to finance government borrowing at the lowest cost, against acceptable risks to the budget, with a medium and long term view.

Summarizing this short model overview, the model contributes to the literature in three ways. Firstly, the model exploits a decision tree algorithm to optimize debt financing decisions and thus, modeling the uncertainty around debt path. Further, it is

---

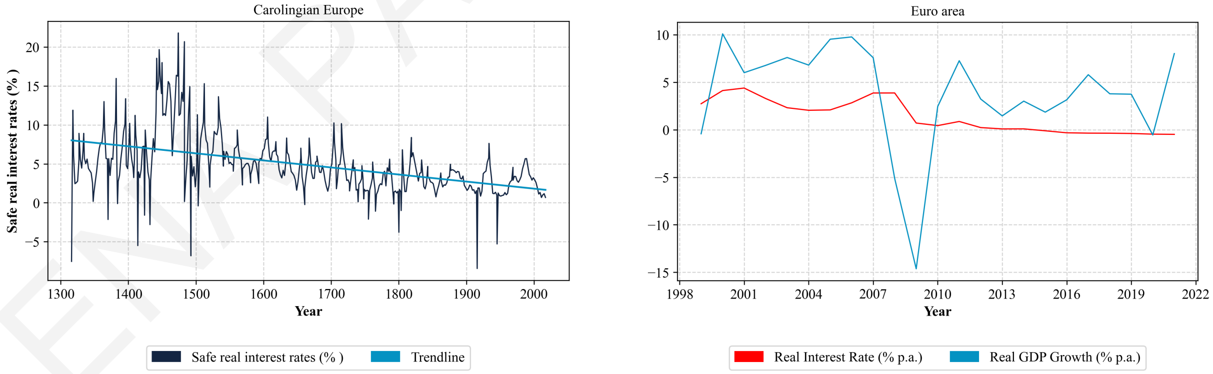
[8] Dutch State Treasury Agency

the first study that exploits risk measure for flow debt dynamics (Conditional Flow at Risk (CFaR)) and endogenizes interest rates as provided by Equations(8), (9). Essentially, the model creates a feedbackloop starting with a debt service structure, consisting of financing decisions X, and then optimizes the distribution of those debt loads. Debt stock determines risk and term premia, which, in turn, influence the maturities to be issued. One can observe a feedback loop that starts with X $\longrightarrow$ D $\longrightarrow$ r $\longrightarrow$ X.

The model of Zenios et al. is presented very briefly here, because further analysis is beyond the scope of this study. This thesis uses only the results of the S. A. Zenios et al. (2021) for Netherlands and from paper S. Zenios (2022) for Italy only for comparison purposes with the simple debt dynamics. The purpose of the comparison is to see if a more simplistic model can replicate up to a satisfactory degree a more complex model like this. If the reader is eager to understand the model in a deeper level, they are prompted to read the published paper of S. A. Zenios et al. (2021).

2.4 Debt Analysis under Low Interest Rates

As real interest rates have fallen, since over the last decade, fiscal policy's role and scope needs to be revised. Actually, the safe real interest rates follow a declining trend since 14th century, but the recent decline has been much more bold. The decline in safe real interest rates drives lower the Neutral Interest Rate as well, reflecting strong saving and weak investment, together with a strong demand for safe assets. This situation is secular stagnation [Summers 2014].



(a) The figure shows the declining trend of the Carolingian European Safe Interest Rate from 1300-2018. Source: Schmelzing (2019).

(b) EONIA interest rate compared with real GDP growth.[9].

Figure 2: Declining interest rates.See B.1 for the declining trend of EU and US long term interest rates.

O. Blanchard sparked this debate back in 2019 with his work "Public Debt and Low Interest Rates". Recently he completed his book titled "Fiscal Policy Under Low

---

[9] Data retrieved from ECB Statistical Data Warehouse. EONIA was Europe's benchmark interest rate which is computed as a daily index of overnight interbank lendings. Since January 2022, it has been replaced by €STR- Europe short-term, which is now the new Europe's benchmark near risk-free interest rate.

Interest Rates" published by MIT press in April 2022[10].

The core of Blanchard's proposal is to replace the current 'preventive arm' of the Stability and Growth Pact (SGP), which was originally adopted by member states in the 1990s. Currently, SGP is a confusing tangle of rules that attempt to link debt and deficit levels to adjustment requirements. The requirements are hard to satisfy nowadays by most of the European countries, since debt levels are generally high. The idea is to argue that austerity economics are not always the solution to weak economies, when the correct constraints are imposed (i.e. deficits shall be allowed to expand up to a limit) and circumstances allow it (i.e when $r < g$). Instead, the proposed solution is to update those policies with a medium-term adjustments guided by debt sustainability analysis (DSA). The requirements for countries to keep debt within 60% of GDP and deficits within 3% of GDP would be maintained, since it is very complex to alter the protocol but they would be embedded into an entirely new framework.

Blanchard states in his book that lower than GDP growth interest rates imply lower fiscal costs of debt. To make this statement more clear, let us assume that the government spends on a large, debt-financed, public investment. If taxes are not raised, debt continues to increase with the interest rate, but at the same time g¿r, so after an initial jump, the debt-to-GDP ratio will decrease over time, with no change in taxes.

However, as the primary deficit increases steadily due to excessive spending, the debt will eventually blow up. As the equality implies, $pb_t = \frac{r-g}{1+g} \cdot d_{t-1}$, if the primary deficit becomes more negative than this number, the debt ratio will quickly increase. However, if the primary deficit remains within those limits, theoretically, the country can run forever a primary deficit and the debt-to-GDP ratio will still stabilize.

The concept of debt sustainability is fundamentally probabilistic. When the probability of the debt ratio exploding is very low, debt can be considered sustainable.

Consequently, a simple demonstration of Blanchard's ideas about debt sustainability is by implementing the classical debt evolution equation. He lets GDP growth, interest rate and primary balance fluctuate around their annual mean and he adjusts primary balance by a factor of the amount needed to stabilize debt. Blanchard's stylized debt dynamics model can be found in the Chapter 4 of his book [Blanchard 2022].

$$r_t = r_t^* + er \tag{15}$$

$$g_t = g_t^* + eg \tag{16}$$

$$pb_t = {pb_t}^{11} + es + c \cdot \frac{r-g}{1+g} \cdot d_{t-1} \tag{17}$$

$$d_t = \frac{1+r}{1+g} \cdot d_{t-1} - pb_t \tag{18}$$

---

[10] The book release is scheduled for early 2023. Currently is openly available an online draft version [Blanchard 2022].

[12] where r is the real interest rate and g the real GDP growth. eg, er, es are normally distributed around zero using the correlation matrix and standard deviations, given in the Appendix B.3. Moreover, the shocks introduced to the interest rates and GDP growth are assumed to be temporary.

After one has calculated the debt ratio, Blanchard suggests that one should compute the distribution of debt over the next n years, (i.e. $d_{10} - d_0$). This is a simplistic form of SDSA. If debt explodes with high probability after n years, then the government must decide today policies that would prevent such a case. Once a new policy is implemented, debt ratio should be tested again for sustainability.

Debt rollovers are feasible in a world where $r < g$ and they come with little to no fiscal costs. In other words government can raise debt without a later increase in taxes. However that doesn't mean that they are desirable and they come with no welfare costs. High levels of debt crowds out capital, capital that otherwise would be saved or invested, thus it is widely perceived by policymakers and the general public as mortgaging the future and burdening future generations. The fact that r now is less than g forces a reconsideration of this proposition. According to growth theory, an increase in debt can actually increase welfare for all generations when r is less than g. When r is less than g, the marginal product of capital (MPK) falls below the investment needed to maintain the capital at rate g. Although lower capital does mean lower future output, the reduction in investment required allows higher future consumption.

However, up to this moment, this simplistic model hasn't taken into account the interaction of debt and interest rates. Indeed, as debt increases and capital accumulation decreases, the rate of return on all assets, and by implication the rate on government bonds, will increase. It is possible that the interest rate will surpass the growth rate at a certain point. As a result, all the previous discussion turns around, the fiscal deficit becomes a problem and a positive fiscal adjustment is now required in order to prevent a debt explosion.

In the previous decade, many factors contributed to low safe interest rates and consequently low neutral interest rates. Especially after the last financial crisis, people became more risk averse, turning to saving rather than investment, and liquidity became more important. Those factors are not likely to turn around any time soon. However, the forth coming consequences of climate change might be the reason to turn around this environment of low interest rates and high GDP growth. Depending on how the efforts to battle climate change are financed, and how big public and private investments would be, this could lead to higher neutral rates.

---

[12]* r_t, g_t, pb_t are constant in Blanchard's model used for educational/demonstration purposes in his book. In our case they change over time, since I approach a real-world problem.

3 Climate Finance

As the efforts intensified the last years to battle climate change, the research to calculate costs and impacts from climate change became necessary. Climate finance refers to the funding needed for the efforts to combat climate change, using either private funds or public funds. Climate finance is needed both to mitigate emissions and to help communities and economies adapt to the changes that are now inevitable.The effects of climate changes have become more bold and obvious the last decade.

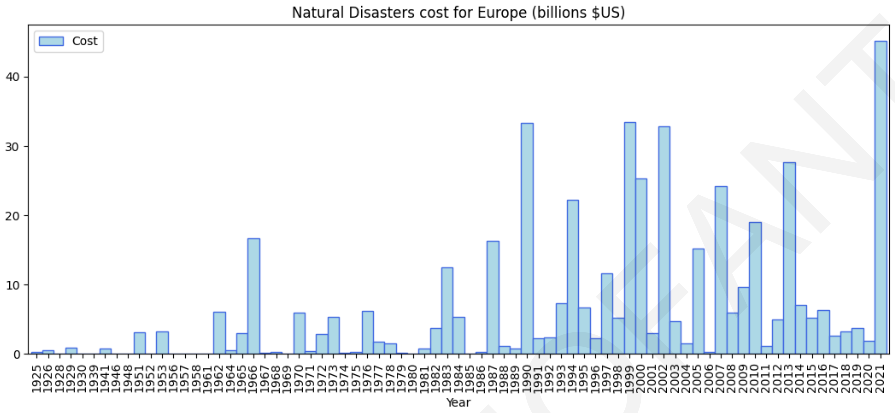


Figure 3: Cost of the most frequent natural disasters in Europe (floods/storms) from 1925-2021. Source: https://public.emdat.be/data

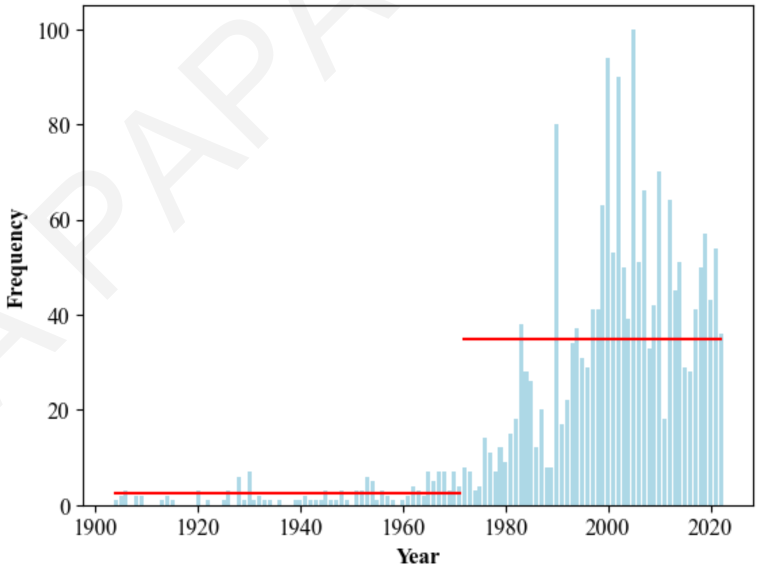


Figure 4: Natural Disasters' frequency in Europe between 1903-2022.(aggregated natural disaster type like floods, wildfires, droughts, extreme temperatures) The mean frequency has moved the last 50 years. Source: https://public.emdat.be/data.

Paris Agreement signed on April 16, 2016 sets a solid foundation for policy actions on climate change that include mitigation, adaptation, and financial commitments. The main goal of the agreement is to limit global warming to well below 2° C, even to 1.5°C.

However, that target needs immediate action in order to be achievable, otherwise we might surpass the critical point that ecosystem damage is reversible.

3.1 Key Institutions

In the following lines, I briefly introduce the names of some key organizations responsible for organizing global efforts against climate change.

3.1.1 International Panel on Climate Change - IPCC

The Intergovernmental Panel on Climate Change (IPCC) was jointly established in 1988 by the World Meteorological Organisation (WMO) and the United Nations Environment Programme (UNEP) to assess scientific, technical and socio-economic information relevant to climate change. Since its inception, the IPCC has produced a series of Assessment Reports on the state of understanding of causes of climate change, its potential impacts, and response strategies. IPCC assessment reports have become standard reference works and are widely used by policymakers, scientists, and other experts. The most recent report, the 6^{th} Assessment Report (AR6) [Pörtner et al. n.d.] was finalized on 4 April 2022, since Working Group III completed its contribution. The report was written by three distinct groups: Working Groups I, II, III.

3.1.2 International Institute for Applied Systems Analysis- IIASA

IIASA is the abbreviation of the International Institute for Applied Systems Analysis. Since 1972, the institute has conducted policy-orientated research into problems that are too large or complex to be solved by a single country or academic discipline like global environmental crisis, economic issues or technological, and social changes.

3.1.3 Integrated Assessment Model Consortium - IAMC

Founded in 2007 in response to the Intergovernmental Panel on Climate Change (IPCC) calling for a research organization to lead the integrated assessment modeling community in the development of new scenarios that could be used by climate modelers in the development of numerical experiments for both the short and long term.

Scenarios are available to the scientific community, policy makers, or the public via online databases. IIASA hosts those databases on behalf of the IAMC which has been formalized in a cooperation agreement between the Working Group III of the IPCC, IAMC and IIASA. The most recent database is the AR6 database, which contains 1,389 quantitative scenarios derived from 188 unique models with data on socio-economic development, greenhouse gas emissions, and sectorial transformations in energy, land use, transportation, buildings, and industry.

3.2 Representative Concentration Pathways - RCP

Radiative forcing is a measure of the change in energy flux in the atmosphere caused by climate change and is measured in W per m^2. Researchers created four different levels of representative concentration pathways (IPCC - AR5) and these pathways cover the full range of emission scenarios. The relevant radiative forcing levels for the Paris Agreement are 2.6 W/m^2 leading to a warming well below 2°C and 1.9 W/m^2 limiting the warming to 1.5 ° C or below. This is captured by RCP2.6 and RCP1.9. As shown in Subsection ”The Scenario Matrix Architecture”, RCPs can be combined with the SSPs to derive emissions and concentration scenarios. Climate policy makers based on these assumptions to form policies to meet climate targets by the end of the century. More information about each RCPs can be found in the Appendix A.2.

3.3 Socio - Economic Pathways - SSP

Shared Socioeconomic Pathways (SSP) have been developed over the last years as a joint community effort by an international team of climate scientists, economists, and energy systems’ modelers. This set of scenarios aims to provide a common set of world interpretations to facilitate multidisciplinary research and analysis. SSPs consist of five alternative scenarios characterized by sustainable development, regional rivalry, inequality, fossil-fuel development, and middle-of-the-road development [Riahi, Van Vuuren, et al. 2017]. SSP narratives [O’Neill et al. 2017] were carefully developed using expert teams that designed the narratives to ensure their internal consistency. SSPs are defined along two axes, as they vary in socioeconomic challenges to mitigation and socioeconomic challenges to adaptation. More information about each SSP can be found in the Appendix A.1.

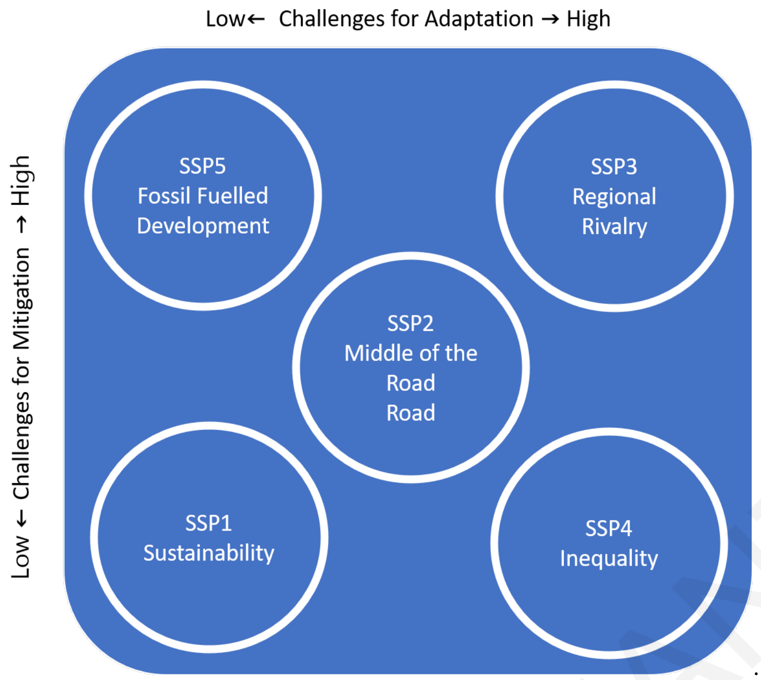


Figure 5: A conceptual map of the five families of IPCC Shared Socioeconomic Pathways (SSP), in relation to the strength of mitigation and adaptation challenges posed by each scenario.

3.4 The scenario matrix architecture

In 2014, Van Vuuren, Kriegler, et al. (2014) proposed a matrix architecture to represent scenarios in a more compact and efficient way. Cells form a combination of a level of climate forcing RCP with a SSP pathway. Naturally, not all combinations of SSP and RCP are feasible, for example, SSP3 with radiative forcing of 1.9 and 2.6 W/m^2 was found to be infeasible in IAMs due to regional rivalries, which impair global coordination of deep mitigation efforts.

	SSP1	SSP4	SSP2	SSP3	SSP5
RCP8.5	■	■	6/6	4/4	4/4
RCP6.0	6/6	3/3	6/6	4/4	4/4
RCP4.5	6/6	3/3	6/6	4/4	4/4
RCP2.6	6/6	3/3	6/6	■	3/4
RCP1.9	6/6	1/3	4/6	■	2/4

■	Infeasible
□	Feasible for some IAMs
🟩	Feasible by all IAMs.

Table 2: Scenario Matrix formed by RCPs and SSPs combinations. Source : Rogelj et al. (2018).

3.5 Climate Impact Chanels

There are two main impact chanels: the physical risks and the transition risks. The table below summarizes the impacts on economy stemming from the two channels of risk.

Climate Risks	
Physical Risks	**Transition Risks**
Temperature, precipitation, agricultural productivity, sea levels.	Policy and Regulation, Technology development, Consumer preferences
Direct Impacts: Capital stock destruction. Shifts in prices from supply shock.	Direct Impacts: Shifts in prices from structural changes. Carbon stranded assets.

Table 3: Climate Risk Channels

Other indirect impacts involve :

- Households: Loss of income, Property Damages.
- Macro: Capital Depreciation, Productivity Changes, Inequality Gap.
- Businesses: Business disruption from weather conditions,Stranded Assets, Legal liabilities.

3.6 Mitigation Policies

Mitigation involves all efforts aimed to reduce the flow of heat-trapping greenhouse gases into the atmosphere, either by reducing sources of these gases (for instance: burning of fossil fuels) or enhancing the 'sinks' that accumulate and store these gases (such as the oceans, forests, and soil). European Environment Agency publishes all the recent policies implemented or planned to be implement in the future for all European countries [EEA 2022]. The policies might vary in scope and type, they could be economic, fiscal, educational and many more. It is true though that mitigation policies for climate change can result in transition risks that arise from (a) changes to policies, rules, and regulations governing a path to low carbon intensities; (b) potential disruptions to technology; or (c) changes in consumer/investor preferences.

European trading system (EU ETS) established in 2005 and it was the world's first international emissions trading system. It is responsible to apply and maintain 'cap and trade' policy. A cap is set on the total amount of certain greenhouse gases that can be emitted by the installations covered by the system. The cap shall be reduced over time so that total emissions fall. Within the cap, installations can trade with one another as needed. In addition a carbon tax would be a strong disincentive measure for carbon emissions. With regard to climate change, the ECB has committed to managing and mitigating financial risks, facilitating a smooth transition towards a low-carbon economy, and sharing expertise information to encourage further economic changes. Many important financial institutions in attempt to hedge from future losses are in track to decarbonise their corporate bond portfolio and enhance it with more green investments. Moreover, the Eurosystem will be more reluctant to accept collateral assets issued by entities with a high carbon footprint risk. Rating agencies will also be required to provide greater transparency, as well as governments and corporations to disclose climate risks and progress.

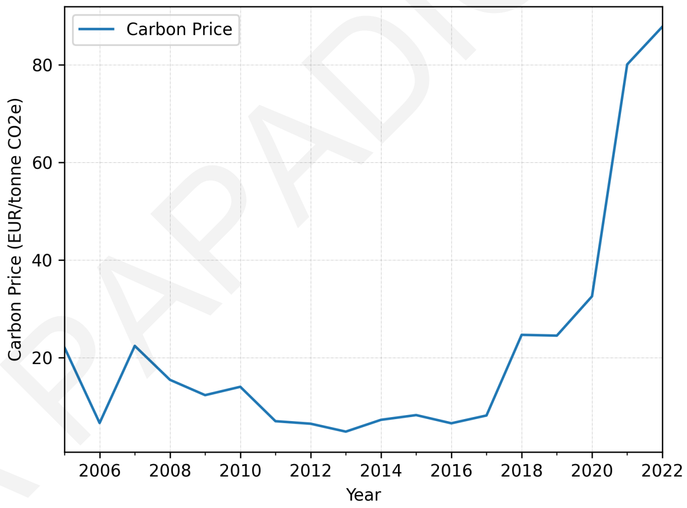


Figure 6: EU ETS Alowances Futures (EUA, EUAA) spot prices. Source: Refinitiv Eikon.

3.7 Adaptation Costs and Policies

The notion of adaptation is used to describe the adjustment efforts of society and systems in response to actual or expected climate changes. Well-implemented adaptation strategies may reduce the country's vulnerability to climate change and probably also create the conditions for having competitive advantage compared to less prepared countries. Despite all the potential benefits, adaptation cannot replace mitigation.

The objective of adaptation to climate change is to reduce the damage caused by it on a local level, whereas the objective of mitigation is to reduce the damage caused by it on a global scale. In the absence of global coordination, mitigation efforts will fail if too many or large countries opt out. Local adaptation, however, can usually succeed (or fail) independently of global adaptation efforts.

Climate-ADAPT is the authoritative European platform for adaptation information [climate-ADAPT 2022]. For example Weather derivatives can be used as risk management tool to hedge against possible climate disasters. Moreover governments need to decide on a resilient macro-fiscal policy and reserve a budget for adaptation investments by weighing costs, benefits, and distributional effects.

Additional adaptation policies include (a) building up financial resilience by protecting financial capacity and ensuring that it can cope with more frequent supply-side shocks and price changes, and (b) building up physical resilience.

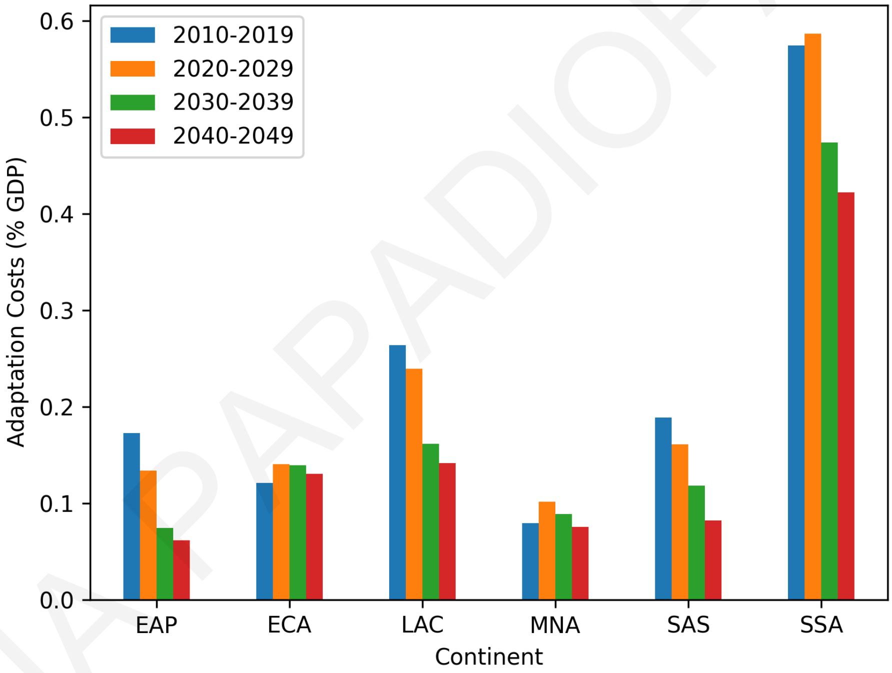


Figure 7: Total annual costs of adaptation for NCAR scenario as share of GDP, by decade and region (percent, at 2005 prices, no discounting)[13]. Source: EACC study 2010 World Bank.

As it obvious from the graph, highest adaptation costs burden the southern and poorer countries like SSA, Sub-Saharan Africa and LAC, Latin America. The following graph shows the ND-gain index in terms of resiliance for different countries. It comes to confirm the previous figure that countries like Brazil, Argentina are very much vulnerable to climate impacts. Even, Italy that is a developed country, looks less prepared to face climate damages than their counterparts.

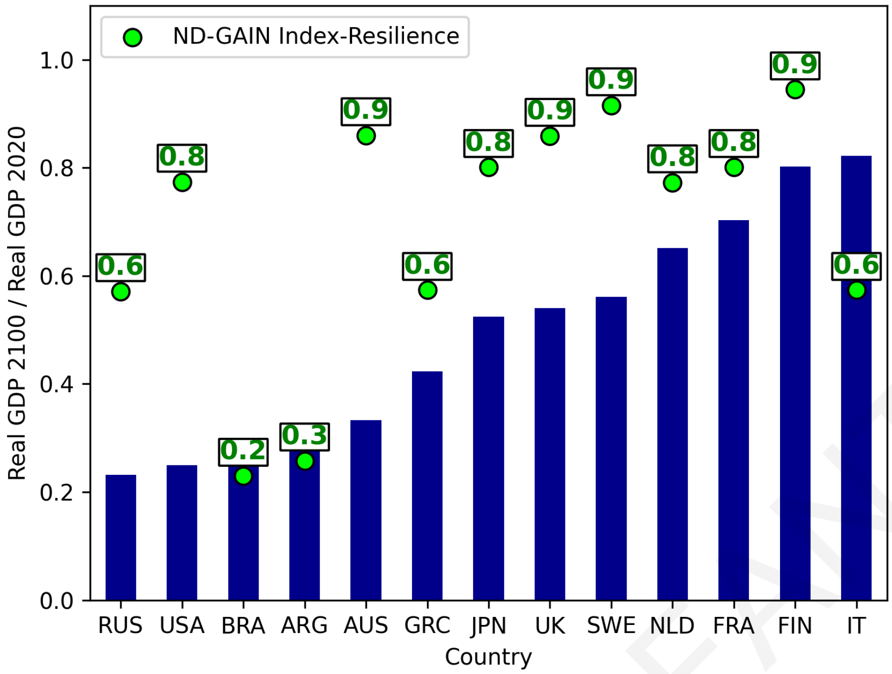


Figure 8: Real GDP 2100 to real GDP 2020, as computed by RICE50+ under SSP2-RCP2.6 scenario. Source :S. Zenios (2022). Green dots represent country's resilience to climate change. Source: ND-GAIN index data.

3.8 Climate Modeling

3.9 Integrated Assessment Models - IAMs

Scientists and economists have developed a suite of tools known as Integrated Assessment Models (IAMs), which are used to analyze long-term global climate pathways through several what-if assumptions on countries' socio-economic status. They divide into two broad categories: the ”benefit-cost” (BC) models, and the more complex, ”detailed process” (DP) IAMs [Weyant 2017], often mirroring the benefit-cost and cost-effective approaches. Despite the fact that both IAM types include projected greenhouse gas emissions and costs of various mitigation measures (changes in production processes, fuel switching, etc), they handle climate change impacts differently.

DP-IAMs, as the name suggests, are disaggregated and have a detailed representation of sectors and processes that are important for climate mitigation, primarily energy and the land use systems. They mainly simulate biophysical impacts like reduced crop growth, land flooded by sea level rise, and additional deaths from heat stress to estimate cost-efficient mitigation pathways for reaching a given climate target. Moreover, DP models outcomes are extensively used in the calibration of marginal abatement costs

---

[13] EAP, East Asia and Pacific; ECA, Europe and Central Asia; LAC, Latin America and Caribbean; MNA, Middle East and North Africa; SAS, South Asia; SSA, Sub-Saharan Africa.

curves (MACC). However, when a high level of aggregation is applied, their region-specific characteristics diminishes [Weyant 2017]. Examples of process-based IAMs include AIM-Enduse [Selvakkumaran and Limmeechokchai 2015], GCAM [K. Calvin et al. 2019], IMACLIM [Sassi et al. 2010], IMAGE [Vuuren et al. 2015], MESSAGE-GLOBIOM [Krey et al. 2016], and REMIND [Klein et al. 2014].

BC-IAMs, on the other hand, provide an aggregated representation of climate change mitigation costs and impacts by sector and region. They are comparing benefits of avoided climate damages to costs of mitigation policies, by optimizing aggregating welfare in order to determine economically “optimal” climate policies. Examples of cost-benefit integrated assessment models include DICE [W. D. Nordhaus 1992b], PAGE [Hope 2006], FUND [Anthoff and Tol 2013], WITCH [Bosetti, Massetti, and Tavoni 2007] and RICE50+ [Gazzotti 2022].

A comparison of the two categories in terms of accessibility indicates that DP-IAMs are often complex ”black boxes” requiring high levels of technical skill for interpretation, thus raising questions regarding transparency. Comparatively, processes encoded in cost-benefit models are simpler and more widely available. However, these modeling families, have been becoming more connected in recent years ([Dellink, Lanzi, and Chateau 2019], [Matsumoto 2019],[Z.-J. Zhao et al. 2020]).

3.10 Social Cost of Carbon

Social cost of carbon (SCC) is defined as the incremental damage that an additional ton of CO2 caused on outcomes, converted into dollars. Notable estimations on SCC of different countries accross the world has been carried by Tol (2019). It is a key number to policymakers, because it indicates how much society benefits from reducing CO2 emissions; It shows that climate policies will pay for themselves as long as the economic sacrifices involved don’t exceed the social cost of carbon.

3.11 Disputes on ex-ante IAM models

However, the estimated values of SCC coming from different studies varies widely from a few dollars to hundreds of dollars per tone CO_2 ([W. Nordhaus 2014], [N. Stern and N. H. Stern 2007]). An IAM model contains various exogenous parameters, which substantially influence the model’s estimation of a time series of SCCs. Pindyck criticized IAM models in several publications throughout the years ([Pindyck 2013],[Pindyck 2017]). He argued that there is no consensus regarding the ”correct” discount rate for estimating the SCC, but different rates will lead to drastically different estimates of the SCC and optimal levels of abatement.

Pindyck also underlines the ignorance that exists on climate sensitivity, i.e., the temperature increase that would eventually result from a doubling of the atmospheric carbon dioxide concentration. Physical mechanisms are described by multiple feedback loops and it is unknown how this system is sensitive to climate change [Freeman, Wagner, and Zeckhauser 2015].

In addition, IAMs do not provide information on tail risks that is how extreme climate events, like a temperature increase over $5°C$ impact economy. Then, the policy-makers are not in the position to decide for a stringent abatement policy in the case of such an event. Apart from Pindyck, other economists like Weitzman (2011) raised concerns over the uncertainties in the economics of extreme climate change. However, the most extensively discussed deficiency of IAM models is the damage function, which we are going to discuss in the next section. There is still long way into concluding to a functional form for the key relationship of the damages.

Finally, to sum up this section, In order to determine plausible outcomes and probabilities, economists need to work closely with climate scientists. Rather than dispute over IAMs, a better approach is to discuss with climate experts in order to find a consensus on at least a range of answers to the questions and connect through empirical studies or based on climate science the form of key model relationships and inputs.

3.12 Climate Impact Function

Economic climate damage is defined as the fractional loss in annual economic output at a given level of warming compared to output in the same economy with no warming. For most IAMs, the damage curve is calibrated based on global temperatures, like the equation implemented for DICE model Equation (19).

3.13 DICE

In 1992, W. Nordhaus pioneered the field of Climate Finance when he first presented his DICE (Dynamic Integrated Climate-Economy) model ([W. D. Nordhaus 1992a], [W. D. Nordhaus 1994]). DICE models has a simple structure and it is an integrated assessment model (IAM) that uses cost-benefit analysis. The model's objective is to optimize aggregate Welfare (W) in regards to inter-temporal consumption, population and discount on welfare. Throughout the years, the model used as a basis for other models and itself updated in several versions [W. D. Nordhaus 2017]. In 2018, W.Nordhaus was awarded the Nobel Prize in Economics for his contributions to the macroeconomics of climate change.

In this study, I will elaborate on the damage function used in the model, and how it influences factor's used as input in Blanchard's model like GDP. To calculate the model's damage function, DICE model considers global mean temperature changes ΔGMT. Equation (19) assumes that damages can be reasonably well approximated by a quadratic function of temperature change.

$$D\left(T(t)\right) = a_{1i} \cdot \Delta\mathrm{GMT}(t) + a_{2i} \cdot \Delta\mathrm{GMT}(t)^2 \tag{19}$$

where a_{i1} , a_2 are calibrated coefficients.
In the DICE specification of the gross output net of damages and abatement costs, $Y_{NET}(t)$.

$$Y_{NET,\ i}(t) = \Omega_i(t) \cdot [1 - \Lambda(t)] \cdot Y_{GROSS,i}(t) \tag{20}$$

$$\Omega(t) = 1 - \frac{1}{1 + D(t)} = \frac{D(t)}{1 + D(t)}$$

The abatement costs are implemented into the damages to show a trade-off between abatement costs and damages. As it is shown in the figure, abatement costs to keep the temperature below $2°C$ in the next 100 years is suboptimal, since abatement costs exceed future damages.

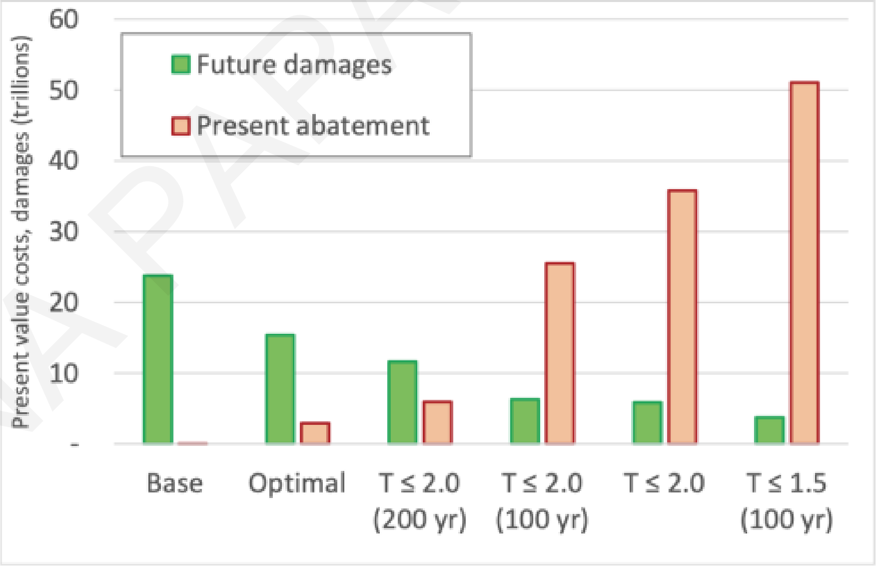


Figure 9: Figure borrowed from Nordhaus Nobel Prize lecture in 2018 [W. Nordhaus 2019]. T< 2.0 (200 yr) notation stands for temperature limited to $2.0°C$ for 200-year average [14].

Total output is divided between total consumption and total gross investment. Capital accumulates at an optimized savings rate, while labor accumulates proportionally

---

[14] IPCC Special Report on Global Warming of $1.5\circ C$ uses the reference period 1850–1900 to represent pre-industrial temperature. So when it is referenced 200 year average, it means that the average temperature from 1900 to 2100, should not exceed the temperature calculated in pre-industrial period.

to the population.

$$Y_{GROSS,\ i}\ (t) =\ TFP_i(t) \cdot K_i(t)^{\alpha} \cdot L_i(t)^{1-\alpha} \tag{21}$$

$$I_i(t) = S_i(t) \cdot Y_i(t) \tag{22}$$

$$K_i(t+1) = (1-d_k)^{\Delta t} \cdot K_i(t) + \Delta t \cdot I_i(t) \tag{23}$$

Net output is gross output reduced by damages and abatement costs.

$$Y_{NET,\ \ i}(t) = \Omega(t) \cdot [1 - \Lambda(t)] \cdot Y_{GROSS}(t) = C(t) + I(t) \tag{24}$$

3.14 Criticism on Damage Function

Nevertheless, the DICE damage function definition has a number of problems. As we have discussed before in the section ”Disputes on ex-ante IAM models”, the same concerns apply on the damage function fomrulation. DICE-like damage functions are aggregated, simplified and lacking both scientific and economic basis. They tend to exclude a number of factors like biodiversity, ocean acidification, and political reactions.

According to Pindyck(2017), fundamental parameters of the climate, such as climate sensitivity, are subject to significant uncertainty. Although significant progress has been made in estimating historical damages from climate change (e.g., [Burke, Hsiang, and Miguel 2015]), we know very little about the damage function. Anthoff and Tol (2013) and Gillingham et al. (2015) describe parameters of the climate-economy nexus, which include significant uncertainties, while W. D. Nordhaus and Moffat (2017) and Hassler, Krusell, and Olovsson(2018) discuss in detail how uncertainty impacts climate sensitivity. However, climate change seems to be characterized by deep uncertainty , rather than just risk. Meinshausen et al.(2009), for example, present a set of densities associated with climate sensitivity which raises the issue of which one a regulator will choose to incorporate into the coupled model of economy and climate. Such a choice goes beyond choice under risk and enters the realm of deep uncertainty [Barnett, Brock, and Hansen 2020].

3.15 RICE50+

Gazzotti(2022) decided to update the classical DICE formulation. Firstly, RICE50+ can assign climate impacts and costs to multiple distinct countries and regions. The authors have also used historical GDP and temperature data to derive an empirical damage function, based on the empirical studies of ([Dell, Jones, and Olken 2012], [Burke, Hsiang, and Miguel 2015]).

In 2015, Burke, Hsiang, and Miguel (2015) studied the effect of climatic conditions on economic activity. Particularly, they examined whether country-specific deviations from growth trends are non-linearly related to country-specific temperature deviations, after accounting for shocks common to all countries.

According to the study, there is evidence that rich countries may be less affected by rising temperatures, as previously hypothesized, however this result is also uncertain since there are few hot, rich countries in their sample. Based on their findings, all countries (rich and poor) show a non-linear bell-shaped relationship between economic productivity and temperature with annual average temperatures peaking at $13°C$ and declining strongly at higher temperatures. The study concludes that unmitigated warming is expected to reduce the average global income by almost 23$\%$ by 2100, under a global warming scenario.

Getting now back to the RICE50+, damage function has the same format as DICE (see Equation (19)) and the net of damages output Y_NET is found as in Equation (20).

Gazzotti, following Burke's suggestion, adds an impact also on GDP growth, which is determined from specification impact $\delta_{i,spec}(t)$ on GDP per-capita growth rate $g_i(t)$. In RICE50+, three specifications (δ_{spec}) are tested. The authors implemented δ specification, coming from the empirical study of Burke, Hsiang, and Miguel(2015), as δ_{BMH}.[15] and then other two coming from Dell, Jones, and Olken (δ_{DJO}) Khan et al. (δ_{Kahn}).

$$GDP_{CAP,i}(t+1) = GDP_{CAP,i}(t)(1 + g_i(t) + \delta_{i,spec}(t)) \tag{25}$$

In this way, both growth (Eq. (25)) and level (Eq. (20)) impact assumptions are taken into account. Conceptually, direct damage on infrastructure (from e.g., more-extreme cyclones or floods) is represented by the enhanced depreciation rate of physical capital with increased global temperature and all other pathways of economic damage (e.g., reduced worker productivity, investments, etc.) are represented via a reduction in the background growth rate.

This class of impact functions assumes that climate change permanently impacts economic activity, whereas the previous one (i.e DICE damage function) assumes economic growth can recover. The difference is that the level effect eventually reverses itself as the weather returns to its prior state. For example, a temperature shock may reduce agricultural yields, but once temperature returns to its average value, agricultural yields bounce back. By contrast, the growth effect appears during the weather shock and is not reversed: a failure to innovate in one period leaves the country permanently further behind.

---

[15] BMH : Burke, Hsiang and Miguel

Then using the definition GDP per capita $GDP_{CAP} = \frac{Y_{NET,i}(t)}{L_i(t)}$ and the classical DICE impact (Eq. (19)), as well as the DICE equations (21), (23), (22), it is obtained a new recursive formula for impacts $\Omega_i(t)$:

$$\Omega_i(t+1) = \frac{\mathrm{TF}P_i(t+1)}{\mathrm{TF}P_i(t)} \cdot \left(\frac{L_i(t+1)}{L_i(t)} \right)^{-a} \cdot Y_i(t)^a \cdot \frac{1+\Omega_i(t)}{\left(1+g_i(t)+\delta_{i,spec}(t)\right)^{\Delta t}} - 1 \tag{26}$$

where,

$$Y_i = (1+\delta_k)^{\Delta t} + \Delta t \cdot S_i(t) \cdot TFP_i(t) \cdot \left(\frac{L_i(t)}{K_i(t)} \right)^{1-a} \cdot \frac{1}{1+\Omega_i(t)}$$

This implementation is perfectly consistent with the growth-rate empirical impact estimation of Eq. (25). However, Eq. (26) is giving some numerical issues for endogenous savings definition, so through some approximations, it is obtained a damage function free of this issue.

$$\widetilde{\Omega}_i(t+1) = \left(1 + \widetilde{\Omega}_i(t)\right) \cdot \frac{1}{\left(1+\delta_{i,spec}(t)\right)^{\Delta t}} - 1 \tag{27}$$

So when the exogenous savings option is enabled Eq.(26) is preferred, otherwise the latter definition should be used. Proof is carried out in the Appendix A.4.

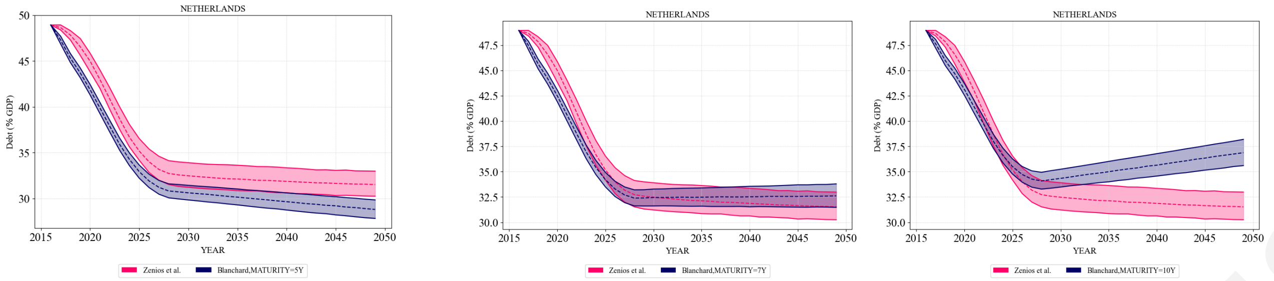
4 Analysis

This section is dedicated to discuss and analyze the findings of this study. The aim of the thesis is explore debt dynamics for two countries : Netherlands and Italy, without and with climate burdens. The result's analysis is divided into two subsections; The comparison of the DSA output carried out by a simple model with the results of another study using a complex model, in an effort to see if a simple model can capture a good estimate of what the complex model can give us. The second part of the thesis, integrates climate burdens to the debt analysis using simple debt dynamics with the aim to assess the primary balance needed to stabilize debt when a climate policy is applied.

4.1 A replication of Zenios et al. with Blanchard's model

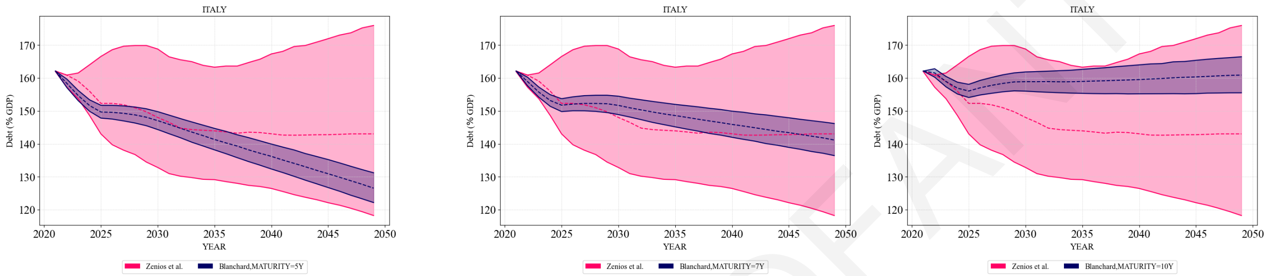
In the first part, I compare the output for the debt dynamics of the Blanchard's stylized model(for reference see Section 2.4 and Blanchard's book [Blanchard 2022], Chapter 4) with the sophisticated model of **consiglio2015risk** (**consiglio2015risk**). As a reference for comparison purposes, in the case of Netherlands, I use the results of S. A. Zenios et al.(2021). In the case of Italy, I try to replicate the results from S. Zenios(2022).

By doing an empirical comparison, I modify Blanchard's model, to apply it to the real data of the two sovereigns' case study. Applying the Debt Equation (18), along with Equations (15),(16), (17), I obtained the grey-blue curve as shown in the Figures (10) and (11). As an alternative to using a constant plus a noise for the indepedent variables of debt equation, I use projections of interest rates, gdp growth and primary balance in order to be able to formulate a more realistic approach. For comparison purposes, I use the same input data with S. A. Zenios et al. (2021) (for Netherlands) and S. A. Zenios et al. (2021) (for Italy). For Netherlands, the growth and primary balance projections are taken from the DSTA Outlook 2019 (Dutch State Treasury Agency), extrapolated to their historical averages in the long term. Meanwhile, the five-year forward rate is derived from the 5-year ECB's Euro area government bond spot rate curve for AAA-rated bonds. For Italy, gdp and fiscal projections are obtained from the IMF World Economic Outlook for 2021 and they converge to Italy's long term average. The five-year forward rate is derived from 5-year euro area government bond spot rate curve (all ratings bonds). Further I use S. A. Zenios et al. (2021) calibration to adjust 5-year rates to higher maturities (table given in Appendix B.2). Lastly, correlation and errors are given in the Appendix B.3.



(a) Maturity 5 years (b) Maturity 7 years (c) Maturity 10 years

Figure 10: Netherlands' debt dynamics as reproduced with Blanchard's model using different maturity bonds, comparing them with the results of S. A. Zenios et al.(2021).



(a) Maturity 5 years (b) Maturity 7 years (c) Maturity 10 years

Figure 11: Italy's debt dynamics as reproduced with Blanchard's model using different maturity bonds, comparing them with the results of S. Zenios(2022).

From these figures we observe that for long-term bonds the debt trajectories short upwards, while 5-year bond trajectory is declining. The reason this is happening is because Blanchard's model can assess only one cost of debt, meaning the sovereign continuously finances its debt with 10-year bonds for instance, which are expensive. In contrast, Zenios' model uses different instruments to finance debt each period and thus the cost of debt is different. The cost of debt can also inflated by the refinancing risk. However, what is missing in this case is the fact that refinancing risk is normally increasing, when one chooses short-term debt, something that we don't see in Blanchard's model output. Refinancing risk is part of the optimization criterion of Zenios et al. but is not part of Blanchard's equations. As a result of these two observations, borrowing short-term is always cheaper according to Blanchard. Additionally, among the three maturities displayed the most appropriate to replicate the debt analysis of Zenios is the 7 year bonds, as the average maturity debt of Netherlands is 7 years and Italy's 6.3 years (Appendix 23).

A second reason why we cannot precisely replicate Zenio's results is because of the endogeneity of the interest rates he uses in his algorithm. According to the equation (7), the debt stock, the amortization payment and the mixture of financing decisions define the effective interest rate that applies as the cost of the debt. Debt also determines term and risk premia as the equation (9) describes. There is a continuous feedback loop between financing decisions, debt stock and cost of debt ($X \rightarrow D \rightarrow R \rightarrow X$).

Another difference between the two models is the range of uncertainty they can specify. Blanchard's model seems more narrow, while Zenio's model accounts for wider uncertainty range. Blanchard's model misses the tail risks, while Zenio's traces the debt stock-flow trade-off, as they impose sustainability thresholds on the conditional value-at-risk (CVaR) measure of tail risks. A tail measure such as CVaR is well suited for DSA since unsustainability is a rare event that can be captured by a tail measure, ensuring a high level of probability for sustainability assessment, as recommended by international organizations.

For Italy, the same process of thought and analysis can be applied. As one can observe from Italy's figures, I repeated the same excersice for Italy's debtfor the same three bond maturities of 5-,7-,10- years in a period from 2021-2050. Finally, the two model's differences can be found summarized in the table below.

Zenios et al.	**Blanchard's model**
Term structure and a mixture of financing instrument	Uses only one maturity to finance debt.
Includes gross financing needs (debt flow) as a variable to measure refinancing risk.	No consideration of refinancing risk.
Endogenous interest rates. A feedback loop$X \rightarrow D \rightarrow R \rightarrow X$.	No dependence between debt and interest rates.
Tail risks	No tail risks

Table 4: Summary of the main differences between the two models.

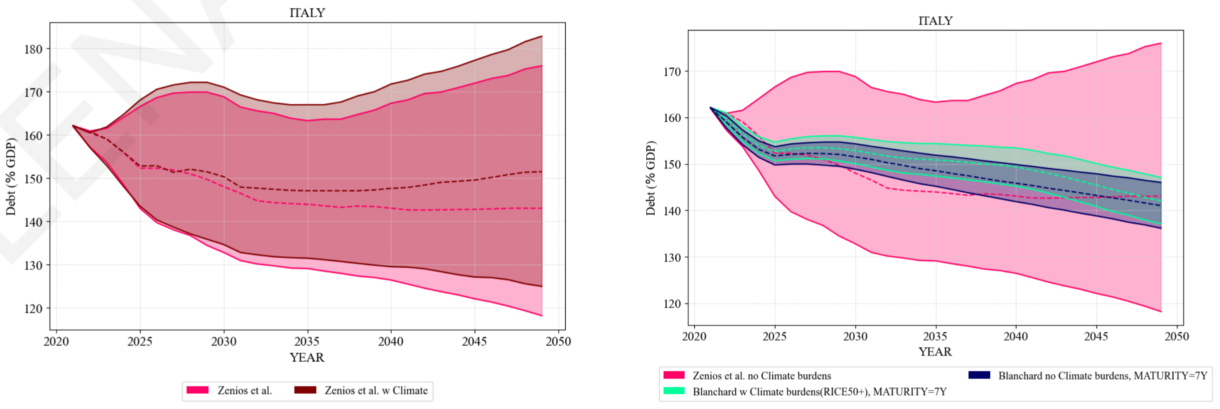
4.2 Debt analysis with climate burdens

Currently, DSA analysis dismiss climate risks. As we discussed in the previous chapters, climate risks can be translated into significant expenditures for the government, who should anticipate for funding reserves and impactful policies in place.

Italy

In the next section, debt sustainability analysis under the effects of climate change is discussed. The analysis follows the method defined in paper of S. Zenios (2022). The author uses as a case study Italy and defines a climate impact on all the main variables of debt dynamics (interest rates, gdp growth, primary balance and amortization). In this study only the GDP climate discount is implemented. Thus, it is defined a climate adjustment factor cf_t^s as the ratio of t = 0 GDP to the time t projections by an IAM.

Below you can find the two plots; The left plot shows the results by S. Zenios without climate burdens (bright red) and under an SSP2-2.6 scenario (using RICE50+ model)(dark red), meaning confiding temperature rise below 2°. Additionally, the figure on the right hand side shows the output of Blanchard without climate burdens (dark blue) comparing to Zenios debt trajectory again with no climate burdens (red); However, the green line shows Blanchard's model output when adjusting GDP for climate impact (SSP2-2.6, RICE50+). As, in Zenios' result (Figure (12), Panel A), the debt trajectory under climate burdens is slightly shifted. Tracing the dark red line, we can see that after 2030, the line diverges significantly from the bright red line and continues to increase until the end. Similarly, the green line also diverging, especially after 2025, but keeps a slightly declining trend since the model does not account for several factors mentioned in the previous subsection. More specifically, it is not optimal that all debt is financed with one maturity bond (either too cheap, or too expensive) as in the case of Blanchard's model.



(a) Zenios' debt dynamics with (SSP2-2.6, RICE50+) and without climate burdens.[S. Zenios 2022]

(b) Zenios' result with no climate burden, comparing with Blanchard's output for w/without climate burdens for seven year maturity interest rates.

Figure 12: Debt dynamics under a climate scenario (SSP2-2.6, RICE50+).

Next, I consider climate effects under CP (current policies) and NDC (nationally determined contributions[16]) scenarios under two different models ICES-XPS (Italy) and NEMESIS (Netherlands)[17]. Further, CPs and NDCs can be applied under two different methods, price scenario and intensity scenario. Current policies price scenario assumes current policies upto 2030. Post-2030, carbon equivalent prices are imposed and current policies are kept constant or as minimum effort in order to ensure no backtracking on technology and sectorial current standards. Additionally, CP Intensity scenario assumes also current policies in place upto 2030. After 2030, the method implies that current policies remain in place as constant or minimum effort and assumes rates of emissions-intensity (emissions per GDP) reductions. The NDC price scenario and NDC intensity scenario are implemented in a similar manner, except in regions where emissions exceed the national determine contributions. In that case, additional mitigation efforts are applied to meet the nationally determined emission targets. CP and NDCs are implemented as increasingly stringent constraints on baseline emissions in each region, taking into account overachievement.

The first case study is Italy, where I am using the same inputs as in Analysis-Part A, while I introduce the GDP climate impact factor (cf) and I compare the debt analysis output with and without this damage. I use Blanchard's model and financing my debt with 7-year bonds. The blue fan chart represents the debt dynamics without climate burdens and the green fan chart shows the shift in the debt trajectory caused by the implementation of CP Price policy. As it is expected, we observe a significant shift after 2030 and even higher after 2040 where policies take further effect. Then we aim to find how much fiscal effort we need to stabilize the debt given the climate burdens. The dark blue line represents a gradual fiscal adjustment by a factor c as proposed by Blanchard in Equation (17).

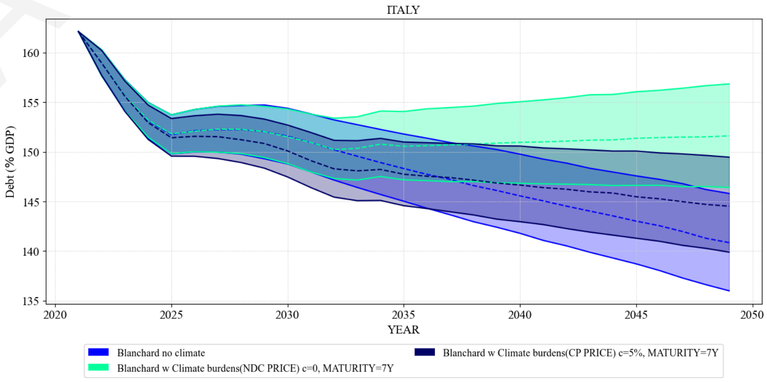


Figure 13: CP Price Debt/GDP (%), stabilized when $c = 5\%$

The figures below show the adjustment Italy needs per year upto 2050 to stabilize

---

[16] As set by Paris Agreement

[17] Data from AR6 Database

the debt, according to the stylized Blanchard's model. As we observe in the Figure 19, Italy historically runs a primary deficit and the projections account for around 1.5% of GDP. The green bar chart suggests that under CP Price policy Italy will need an increasingly additional Primary balance upto 0.35%. Other things equal, this seems an insignificant impact and Italy with of two standard deviations will be able achieve this primary surplus by 2050.

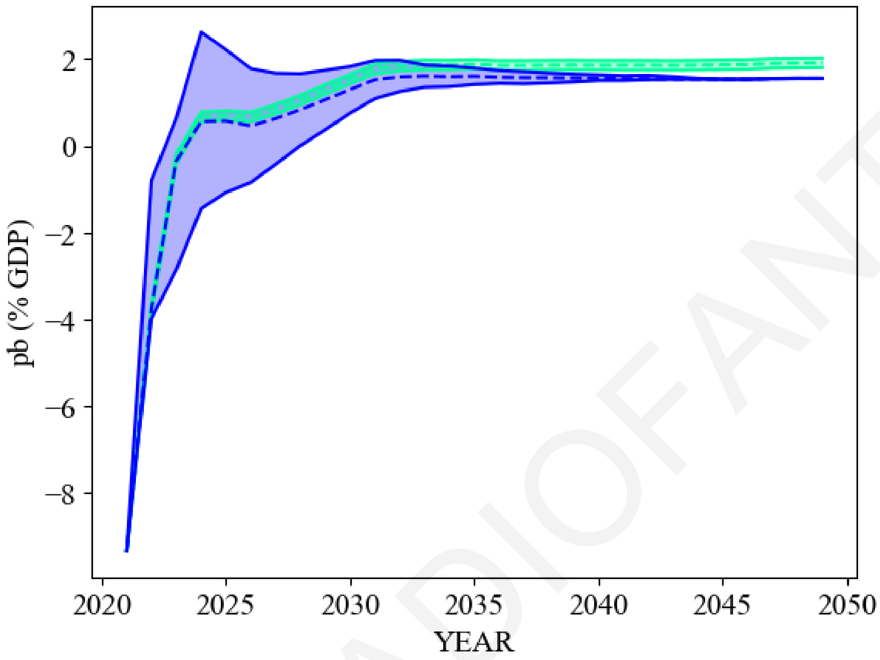


Figure 14: Primary balance under CP Price Policy for 2020-2050.

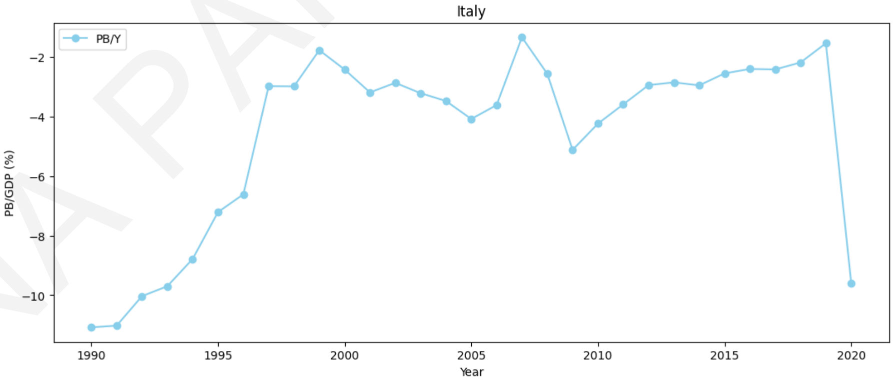


Figure 15: Historical Primary Balance for Italy ($\%GDP$). Source: IMF

A NDC Price Policy is also used to test. There is very little difference between the effects of the CP Price policy and the NDC Price policy. Moreover, CP, NDC Intensity Policies applied to debt dynamics but since Intensity seems to be a milder policy, the debt was already declining and thus no Primary balance adjustment was meaningful (Figures found in Appendix B.7).

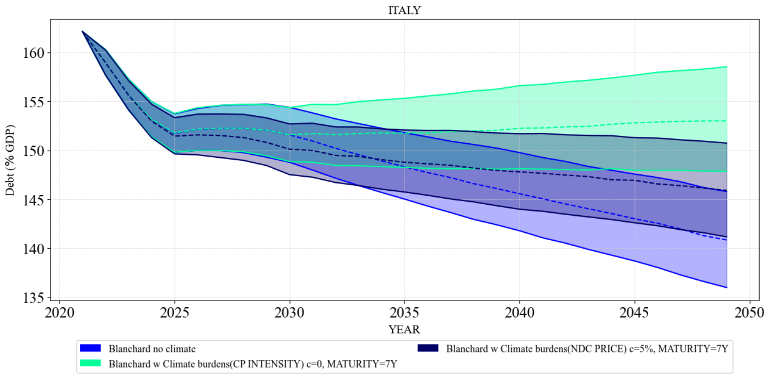


Figure 16: NDC Price Debt/GDP, stabilized when $c = 5\%$

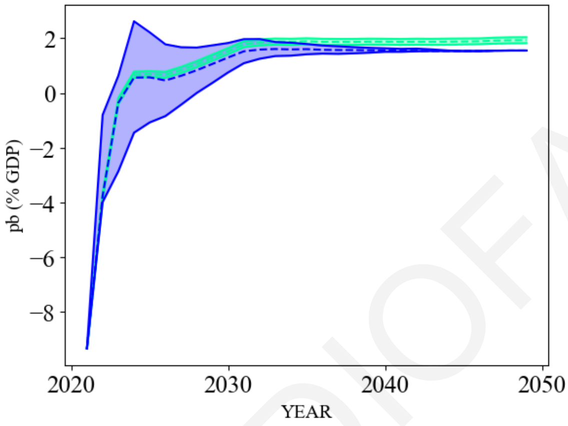


Figure 17: Primary balance without and under NDC Price Policy for 2020-2050.

NETHERLANDS

In this section , the climate impact on the case of Netherlands was exploited. Firstly, we test debt sustainability under Current Policies scenario. Under certainty, the debt of Netherlands explodes especially after 2030 (bright green line).

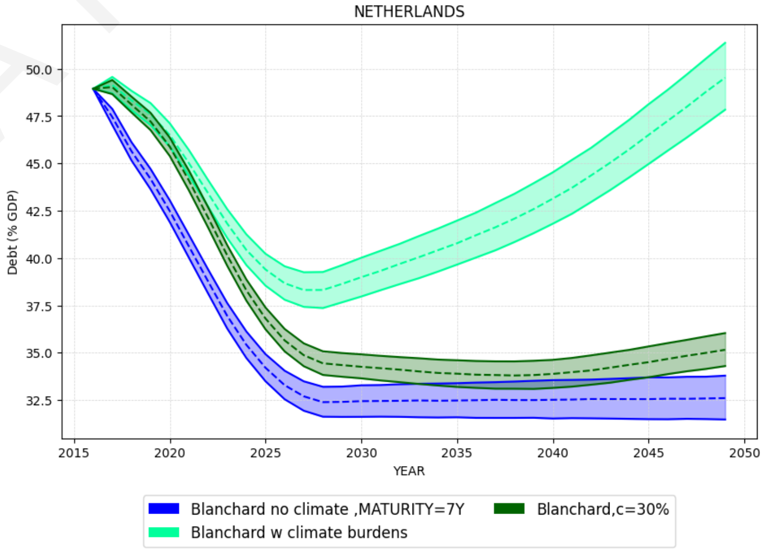
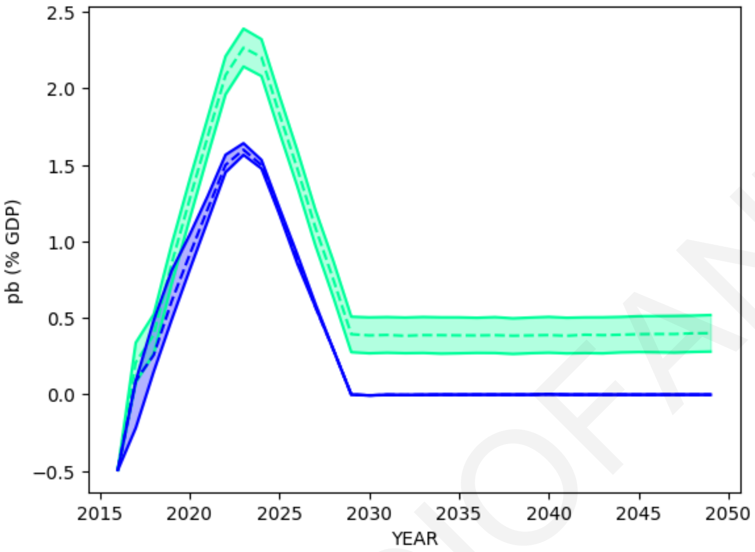


Figure 18: Debt/GDP ratio (%)WITH CLIMATE BURDENS AND C=40%

In order to stabilize debt, Blanchard's model suggests an additional fiscal funding of $0.7\%GDP$ in 2025 and around 0.5%GDP in the long-term. As per historical data, the highest primary Balance for Netherlands in the last 20 years was 2%GDP. Under climate policy, the primary balance needed to stabilize debt is 2.5% of GDP in 2025. That seems a bit high for the standard fiscal balance of Netherlands and seems that additional tax policies should be implied given also the rising interest rates.



(a) Primary balance without and under CP Price Policy for 2016-2050.

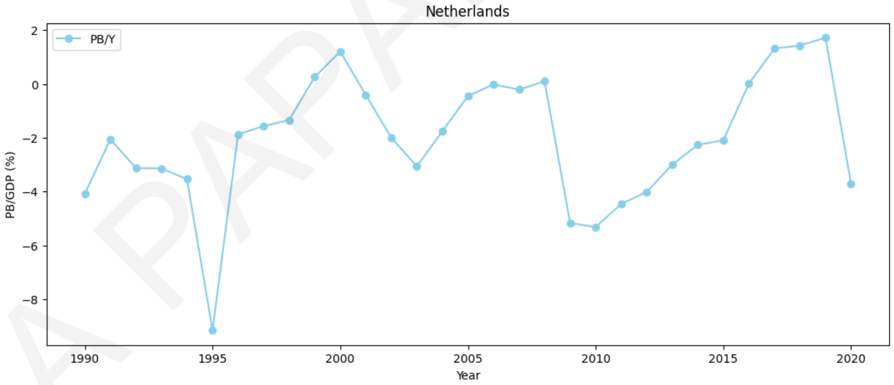


Figure 19: Historical Primary Balance for Netherlands $(\%GDP)$. Source: IMF

The test was repeated with NDC Climate Policy, which gave us similar results; Thus, the figures can be found in Appendix B.7. For CP and NDC Intensity policies the data were not available on the database and thus there is not relevant analysis. Overall, this chapter suggests that Netherlands needs a bit more GDP to stabilize its debt than Italy. Italy, overall seems fine also in the long run since the primary balance adjustment projections are not exceptionally high.

5 Conclusions

Debt sustainability depends on many factors, from the stochastic behavior of interest rates and growth rates to other uncertainty factors like inflation or political influence. Long-term projections always hide a lot of uncertainty and it is very difficult task to predict the future of the debt trajectory. However, the projections give us a good sense how the debt evolves and a good understanding of risks and vulnerabilities. Thus, the DSA is an essential tool for governments and policymakers. As part of this thesis project, I examined the debt dynamics of Italy and the Netherlands. Netherlands is an example of a country that has a low debt-to-GDP ratio, while Italy has a high debt-to-GDP ratio. According to the simple debt dynamics model, debt in both cases is stable over the long run, and the results are consistent with Zenios et al.'s debt sustainability analysis. Comparing the two models, as it is expected the simple model can only catch a rough estimate of the output of the complex model. Overall, the simple model fall behind because (i) it lacks a term structure and a mixture of financing instruments, (ii) it does not optimize the financial decisions, (iii) the effective interest rate doesn't change as debt changes, and (iv) it does not take tail risks into account. Although the Blanchard's model can give us a good estimate of the debt trajectory cannot be used for research purposes or any serious sustainability assessment. A full scale stochastic model, taking into account various risks and various financing instruments it is recommended. However, one can use the model to get a rough estimate where debt is headed or how much fiscal adjustment is required. In that case, the result can be obtained quick without expensive and complex calculations, while the outcome would be reliable in average.

In the second part of the thesis, I have accounted for GDP impacts from climate policy effects. Again, I examined Italy and Netherlands as two case studies. The results are most striking for CP and NDC Price policies for both countries. We have found that Italy's debt does not impacted highly and the fiscal adjustment that will need ranges between 0.2-0.35% GDP beyond and above its current Primary Balance. The results for CP and NDC policies were similar. While CP and NDC intensity policies were milder and their effect on the debt trajectory was small. In the case of Netherlands the shock was higher. According to the model's predictions the country might need a 0.7% GDP fiscal adjustment in 2025 to stabilize its debt. There after this adjustment falls to 0.5%GDP and not below 0.4%GDP upto 2050. Summing up, climate burdens affect more the Netherlands, rather than Italy, in terms debt dynamics. Calculations, show that Netherlands needs more fiscal adjustment under climate burdens to keep its debt ratio from explotion. However, there might be a discrepancy between the results, since for the calculation of the climate adjustment factor have been used two different models. Italy's calculations have been carried out by ICES model and Netherlands by NEMESIS model. As we see in the figure below, different IAM model can give significantly different results. For demonstration purposes, the figure shows carbon price ($2010).

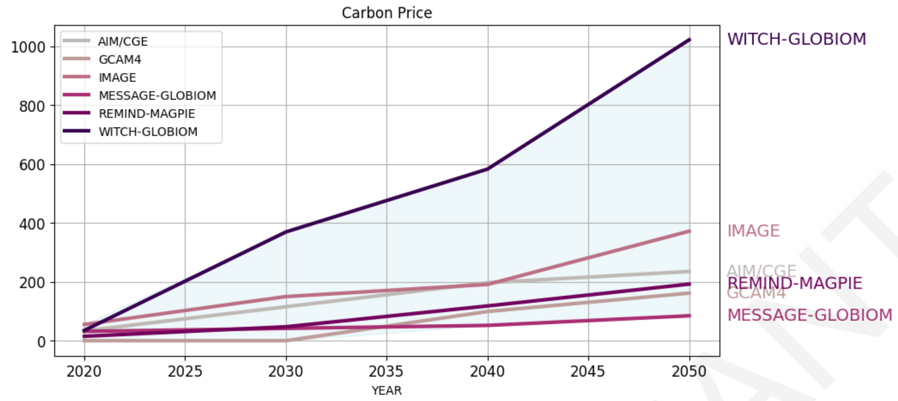


Figure 20: Carbon price forecast under the scenario SSP2-2.6 and different IAM models. The prices displayed are for OECD countries in dollars of 2010. There is a great deviation between models. Source IIASA, SSP Database.

Indeed, in order to have more solid conclusions, a solid basis of comparison must be constructed. Economists and climate scientists must come together to coordinate their efforts into economic modeling with climate interactions. Moreover, this thesis accounts only for damage costs, and more specifically damages on GDP. In a future assessment, one can account also for the impact on government expenditure and the interplay between damage costs, mitigation and adaptation costs. It is true that the more one spends early to mitigate the problem, or to adapt to it, it is expected to have positive effect and less damage on GDP or fiscal balance in the future. However, the more mitigation spending and adaptation expenses may not decrease future damage costs equally. Thus, It would be interesting, in a future assessment to see the impact of adaptation and mitigation expenditure on debt levels and fiscal reserves. This analysis would be especially important for countries that suffer from high debt or are susceptible to physical disasters, or for countries that suffer from both. Additionally, the integration of mitigation and adaptation costs in DSA would be also significant, during times of transition when fossil fuels are still used around the world but are slowly being replaced by greener methods. Concluding, I would like to underline that the field of climate finance is still new and rich. There is a lot of space for improvement in the models and techniques used to assess climate risks. Moreover, I believe that it is not a temporary risk assessment exercise. In the near future, the climate risk assessment would be an essential part for debt sustainability analyses.

Appendix A Climate Finance

A.1 Socio - Economic Pathways (SSP)

SSP1	Sustainability: SSP1 refers to a sustainable and well-developed world in terms of both mitigation and adaptation.
SSP2	Middle of the Road: SSP2 is an intermediate case between SSP1 and SSP3, where future dynamics follow historical trends. The world population is continuously increasing at a rate lower than SSP4; However it is expected intermediate levels of economic development, and less rapid technological change and mitigation actions than SSP1 and SSP4.
SSP3	Regional Rivalry: SSP3 is the worst possible scenario from all the other 5, since the world faces both adaptation and mitigation challenges. Unmitigated emissions are high due to moderate economic growth, the population is growing rapidly and technological change in the energy sector is making mitigation difficult. Moreover investments in human capital are low, inequality is high and institutional development is unfavorable. Many people are left vulnerable to climate change.
SSP4	Inequality: SSP4 has large mitigation capacity due to fast technological development in low carbon energy sources in key emitting regions. However, inequality remains high, and economies are relatively isolated, leaving the rest of the regions highly vulnerable to climate change with limited adaptive capacity.
SSP5	Fossil-Fuelled Development: SSP5 describes a world, where investments in clean energy technologies are low, and available options for mitigation are limited. Nonetheless, the resources are equally distributed due to improved human capital, and slower population growth. As a result the populations can adapt more easily.

Table 5: Shared Socio-Economic Pathways (SSP)

A.2 The Representative Concentration Pathways (RCPs)

Scenario	**Description**	**Avg. Temperature Increase**	**Reference**
RCP2.6	RCP2.6 is representative of a scenario that aims to keep global warming below 2 above pre-industrial temperatures.	1.8°C - 2°C	[Van Vuuren, Stehfest, et al. 2011]
RCP4.5	A stabilization scenario where temperature increase is stabilized before 2100 by employing a a range of technologies to reduce GHG emissions.	2.7	[A. M. Thomson et al. 2011]
RCP6.0	It can be considered a baseline scenario	3.6	[Van Vuuren, Edmonds, et al. 2011]
RCP8.5	Non-existent efforts to constrain emissions. It is also considered the ”baseline scenario” or BAU (Business as Usual).	4.4	[Riahi, Rao, et al. 2011]

Table 6: Representative Concentration Pathways (RCP)

A.3 CP and NDC Climate Policies

Firstly, it is important to note the Paris Agreement's design around nationally determined contributions (NDCs) means mitigation effort will vary between countries and over time. The following policies are deisigned to assume mitigation efforts in line with current policies (CPs) and NDCs to 2030 and more intense levels of effort thereafter. Bellow, the reader can find more analytical information about the policies and the models used for the data downloaded from AR6 Database.

Scenario	2030 target	Post-2030 assumption	Description
CP Intensity	CP	Constant rate of emissions intensity[18].	Scenario exploring where emissions are headed assuming CP to 2030 and constant rates of emissions-intensity reductions thereafter.
CP Price	CP	Carbon price[19]increasing with per capita GDP.	Scenario exploring where emissions are headed assuming CP to 2030 and carbon prices increasing with per capita GDP thereafter.
NDC Intensity	NDCs	Constant rate of emissions intensity.	Scenario exploring where emissions are headed assuming NDCs to 2030 and constant rates of emissions-intensity reductions thereafter.
NDC Price	NDCs	Carbon price increasing with per capita GDP.	Scenario exploring where emissions are headed assuming NDCs to 2030 and carbon prices increasing with per capita GDP thereafter.

Table 7: CP and NDC Policies

A.3.1 CP Price scenarios

1. Current policies are implement upto 2030. Emissions in 2030 are recorded in all modeled regions.
2. The run of the model is repeated without current policies, using regional economy-wide carbon prices to reach the levels of emissions in 2030 recorded in step 1. The ”equivalent carbon prices” (ECPs) in 2030 are the carbon prices that reproduce the emissions caused by current policies to 2030 in each region (i.e. the emissions recorded in step 1).
3. The model is executed again from 2030 until end (2050 or 2100, depending on model time horizon) with the ECPs growing with GDP per capita in every region. The starting point should be the end point of the scenario run in step2 (not the end point of the scenario run in step1). The emissions trajectories are obtained (to 2050 or 2100) for all modeled regions.
4. Then the model is ran once again from the beginning, with:(i) Current policies to 2030, kept as constant or minimum levels after 2030.(ii) The emissions trajectories in step, as regional emissions caps.

A.3.2 CP Intensity scenarios

1. Current policies are implmemented upto 2030. The resulting emissions are recorded in every region in the modelled period and the annualised rate of change of emissions intensity(emissions per GDP) are computed in every region to 2030.
2. Starting with regional emissions in 2030 recorded in step 1, regional emissions pathways are estimated to the end of the modelling period (2050 or 2100) by applying the annualised rate of change of emissions intensity computed in step 1 beyond 2030. Unlike in the case of CP Price scenario, this step does not involve re-running the model.
3. Lastly, the model is re-executed from the beginning, with: (i) Current policies to 2030, kept as constant or minimum levels after 2030. (ii) The emissions trajectories in step 2, as regional emissions caps.

---

[14] Emissions per GDP.

[15] Carbon prices may vary by model.

A.3.3 NDC Price and NDC Intensity scenarios

Up to 2030, there are two cases:

- For regions where emissions in CP Price scenarios are equal to or below NDC targets, NDC Price scenarios are set equal to CP Price scenarios.
- For regions where emissions in CP Price scenarios are above NDC targets, additional mitigation efforts are implemented in NDC Price scenarios to ensure NDC targets are met in 2030.

Post 2030:

- The scenarios are extended post-2030 using two different methods: (i) The first method is based on continuing rates of emissions-intensity reductions (emissions per unit gross domestic product (GDP)) and (ii) the second on increasing carbon prices in line with per capita economic growth.

A.3.4 ICES-XPS 1.0

The Intertemporal Computable Equilibrium System (ICES) is a recursive-dynamic multi-regional Computable General Equilibrium (CGE) model developed to assess economy-wide impacts of climate change on the economic system and to study mitigation and adaptation policies.

The economics

The CGE framework makes it possible to account for economic interactions of agents and markets within each country (production and consumption) and across countries (international trade). Within each country the economy is characterised by multiple industries, a representative household, and the government. Industries are modelled as representative, cost-minimising firms, taking input prices as given. In turn, output prices are given by average production costs. Each commodity is sold domestically or abroad without any substitution degree. In addition, the household is taxed and receives transfers from the government and the rest of the world (i.e. interest repayments). Then, income is split between consumption and saving in fixed shares. Government income derives mainly from direct and indirect taxes, but a small fraction comes from transfers from other governments (i.e. grants). The difference between revenues and expenditures is the budget deficit, which is primarily financed through borrowing from the capital market. ICES- XPS is solved as a series of equilibriums. The dynamic of the model is led by two accumulation processes for capital and government debt. Capital accumulation is modelled endogenously, with current-period investment generating new capital stock for the subsequent period. Accumulation of government debt builds the public debt stock that is served at a fixed interest rate both to domestic and foreign households. The public debt stock is split between domestic and foreign debt according to base year shares.

A.3.5 NEMESIS 5.0

NEMESIS is a multi-country macro-sectoral econometric model which can be used for assessment of structural policies, mainly environmental and $R\&D$ policies. It closely links energy and environmental policy to economic outcomes, making it a suitable tool for analysis of the response measures. In particular it can be used to model the impacts of additional taxes on emissions or energy use.

The economics

On the supply side, each sector is modelled as a representative firm determining its production level and the use of production factors (Capital, low- and high-qualified labour, energy and other intermediate consumptions) given its expectations on demands and prices. Price setting is defined under monopolistic competition, with constant margin rates, different among sectors and inter-sectoral exchanges are captured by conversion matrices that allocate the intermediate consumption and investment demands to economic activities producing the required goods and services. The labour market is modelled on the basis of the demand for labour, depending on the optimisation of production levels done by firms, and its supply, which is based on population's age and qualification levels (approximated using education levels). Wages are determined by augmented Philipps curves, and they are calculated separately for high- and low-qualified workers. As for international trade, each EU country exports to (and imports from) two groups of trade partners: intra-EU and extra-EU countries. The determinants of trade are the relative prices of domestic and foreign goods and services, capturing the competitiveness effect, and the volume of exchanges, which is approximated by sectoral demand for goods and services.

A.4 RICE50+: Alternative Impact Function

Proof:

Gazzotti defines the following Lemma:
"In an economic growth model with a Cobb-Douglas production function, stable capital-labor ratios, and 'small' exogenous annualized growth rates g_t, the Burke, Hsiang, and Miguel(2015) or similar damage function based on temperature-dependent annual growth impacts δ_t is approximately equivalent to using a damage function for a model with time step of Δt if Ω_t is computed as:"
(The region index, i, is omitted for simplicity.)

Given that: $g_{GDP\ perCAP} = \frac{Y_{GROSS}}{L}$
$Y_{GROSS,\ t} = TFP_t \cdot K_t^{\alpha} \cdot L_t^{1-\alpha}$
Then,

$$\frac{Y_{GROSS,\ t} \backslash L_t}{Y_{GROSS,\ t-\Delta t} \backslash L_{t-\Delta t}} = \frac{TFP_t}{TFP_{t-\Delta t}} \cdot \frac{\cancel{(K \backslash L)^{\alpha}}}{\cancel{(K_{t-\Delta t} \backslash L_{t-\Delta t})^{\alpha}}}$$

and $\quad (1 + g_t)^{\Delta t} \approx \frac{TFP_t}{TFP_{t-\Delta t}}$

Then,
$Y_{NET,\ t} = \frac{Y_{GROSS,\ t}}{1+\Omega_t}$

$$\frac{Y_{NET,\ t} \backslash L_t}{Y_{NET,\ t-\Delta t} \backslash L_{t-\Delta t}} = \frac{1 + \Omega_{t-\Delta t}}{1 + \Omega_t} \cdot \frac{TFP_t}{TFP_{t-\Delta t}}$$

$$\frac{Y_{NET,\ t} \backslash L_t}{Y_{NET,\ t-\Delta t} \backslash L_{t-\Delta t}} = \frac{1 + \Omega_t - \Delta t}{1 + \Omega_t} \cdot (1 + g_t)^{\Delta t}$$

Also, $\quad \frac{Y_{NET,\ t} \backslash L_t}{Y_{NET,\ t-\Delta t} \backslash L_{t-\Delta t}} = 1 + g_t + \delta_t$

To ensure equivalence, it must be satisfied,

$$(1 + g_t + \delta_t)^{\Delta t} = \frac{1 + \Omega_{t-\Delta t}}{1 + \Omega_t} \cdot (1 + g_t)^{\Delta t}$$

and $(1 + g_t + \delta_t)^{\Delta t} = ((1 + g_t)(1 + \delta_t))^{\Delta t}$

$$\rightarrow \Omega_t = (1 + \Omega_{t-\Delta t}) \cdot \frac{1}{(1 + \delta_t)^{\Delta t}} - 1$$

Appendix B Supplementary Material

B.1 Debt Analysis under Low Interest Rates

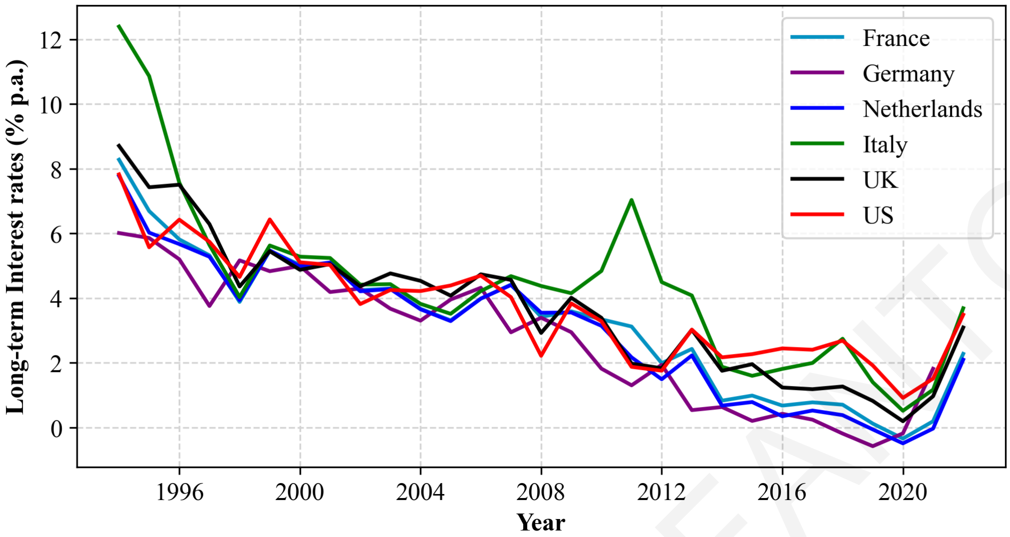


Figure 21: Declining EU and US 10 year bond rates.

B.2 Risk and Term Premia calibration factors

S. A. Zenios et al.(2021) defines the risk and term premia as follows. A piecewise function is defined as ρ and is plotted in the figure below.

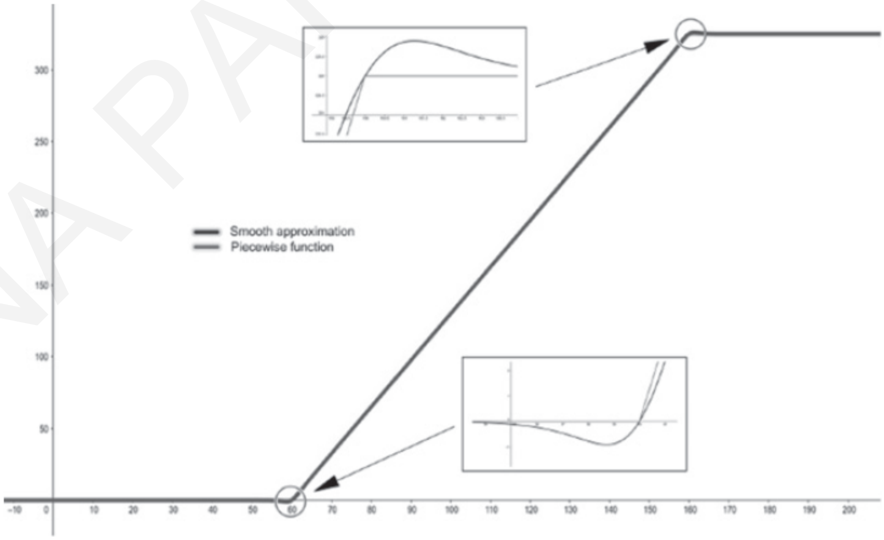


Figure 22: Risk Premium as a Smooth Approximation of a Piecewise Debt Function

According to the Stability and Growth Pact no premium is needed for debt ratios below 60%. For a higher debt the premium grows linearly with slope 3.25 up to a ceiling of 325 basis points (set by the authors and explained in their paper). The first two piecewise segments are calibrated using panel data from 23 European Union (EU) countries over the period 1995–2016 [Gabriele et al. 2017], with baseline the 5-year yield.

Coefficients for Equations (8) and (9) can be found in the following tables.

Coefficient	Bond Maturity		
	3	5	10
α_j	-35	0	72
b_j	-0.13	0	0.13

Table 8: Calibrated coefficients for Eq. (8)

Coefficient	Value
$\hat{\rho}$	3.25
d_{min}	60
d_{max}	160

Table 9: Calibrated coefficients for Eq. (9)

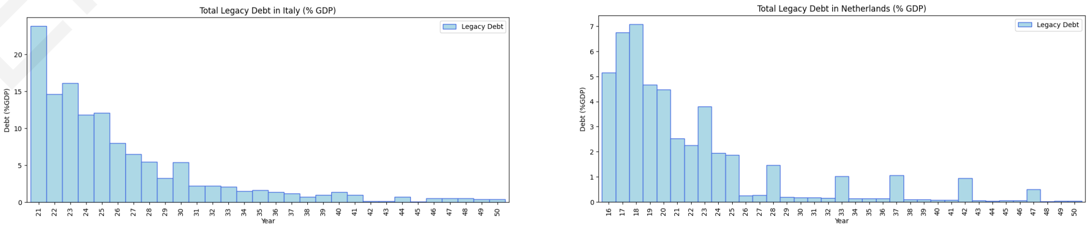
B.3 Correlation Matrix

	Growth	Five-year rates	Primary Balance
	Correlations		
Growth	1.00		
Five-year Rates	-0.20	1.00	
Primary Balance	0.25	-0.03	1.00
Standard Deviation	0.75	0.85	0.15
Mean Values			
Long-term mean (Netherlands)	3.8	3.40	0.0
Long-term mean (Italy-IMF)	2.3	3.25	1.5

Table 10: Correlation Matrix for the main quantities used in debt stock calculation.

Data for Netherlands are taken form DSTA GDP growth, primary balance, and risk-free rate. And for Italy it is used the 5-year eurozone forward rate,, while gdp growth and primary balance projections are taken from the 2018 IMF World Economic Outlook, with alternative projections from the Italian Ministry of Finance and the EC, converging to Italy's long-term averages. Further information can be found in S. A. Zenios et al.(2021).

B.4 Debt average maturities



(a) Average maturity found to be 6.3 years.

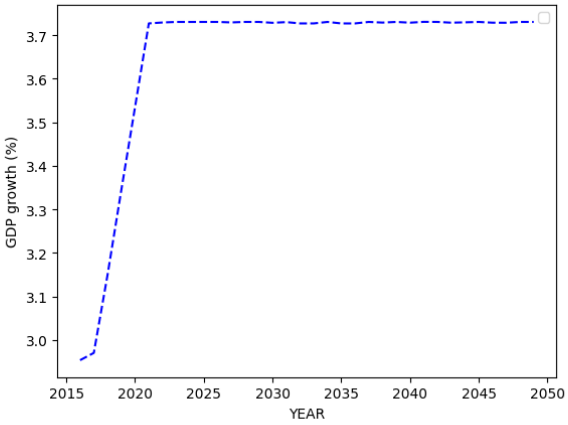
(b) Average maturity found to be 7 years.

Figure 23: Italy's and Netherland's Total (amortization and interest cost) Legacy debt.

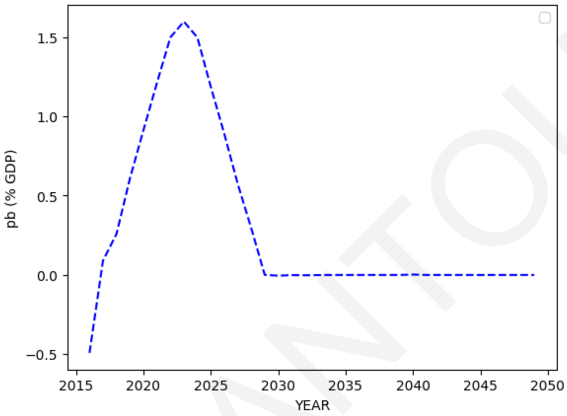
B.5 DSA under climate burdens

B.6 Model's Inputs

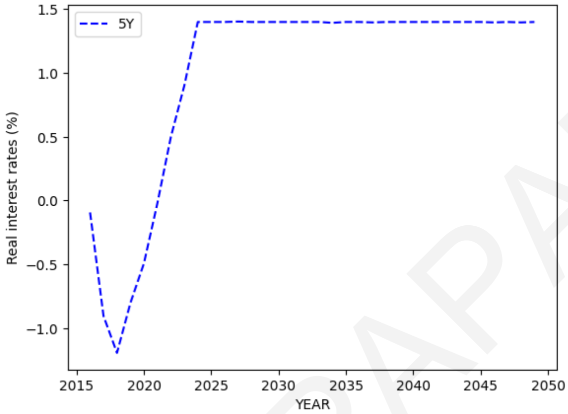
NETHERLANDS:



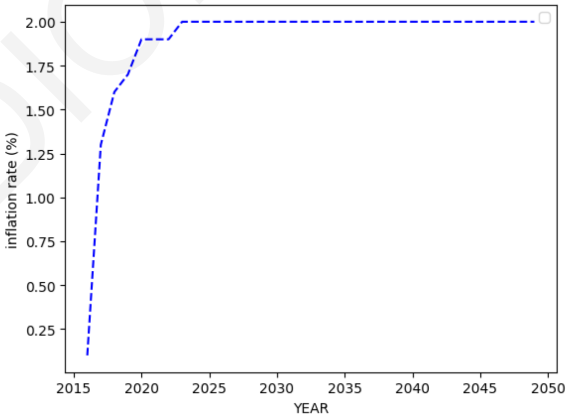
(a) nominal GDP growth (%)



(b) Primary Balance (% GDP)

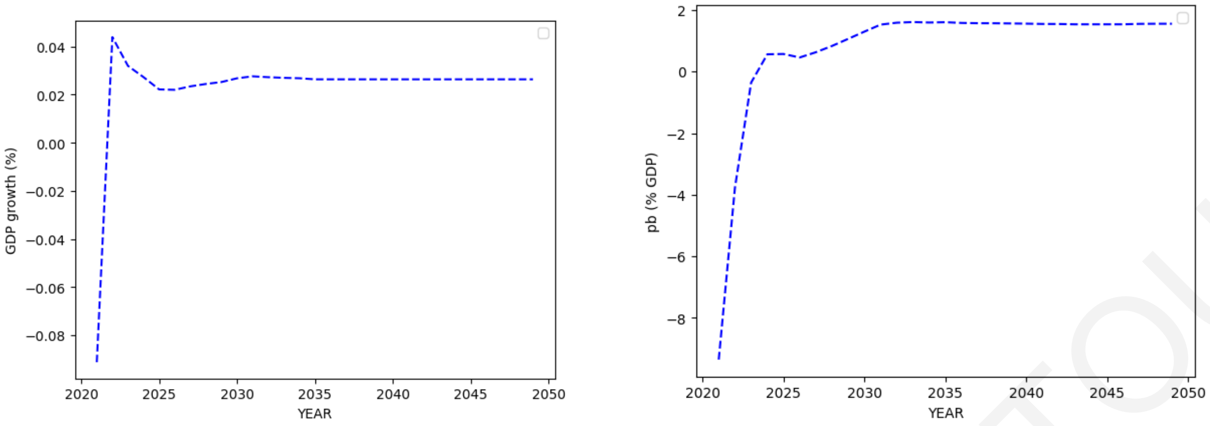


(c) Real interest rate (%)



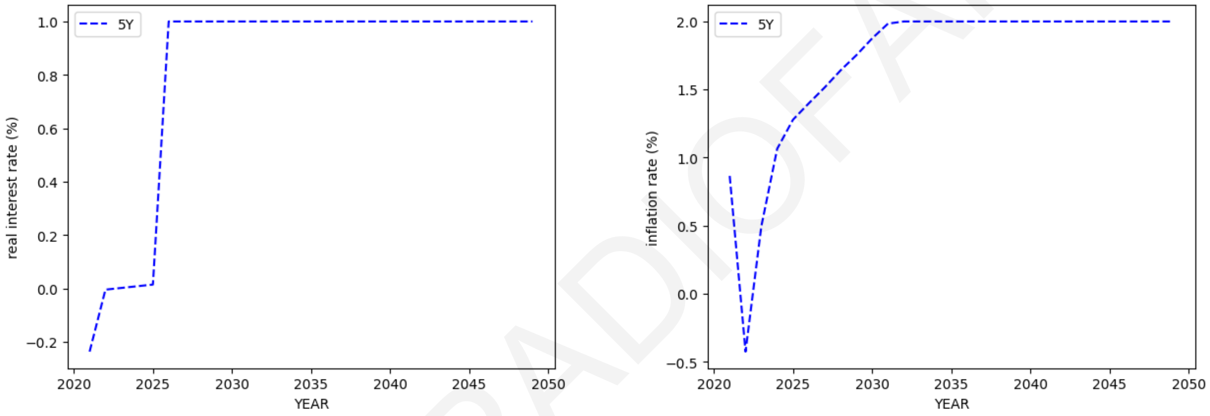
(d) Inflation Rate (%)

ITALY



(e) nominal GDP growth (%)

(f) Primary Balance (% GDP)



(g) Real interest rate (%)

(h) Inflation Rate (%)

B.7 Debt Analysis under Climate burdens

ITALY

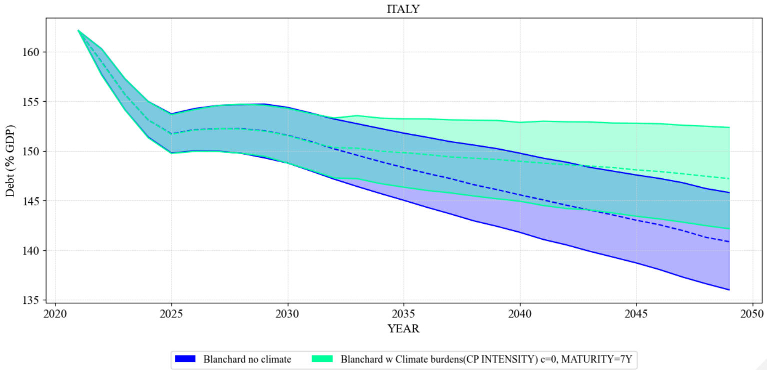


Figure 24: Debt/GDP (%) under CP Intensity.

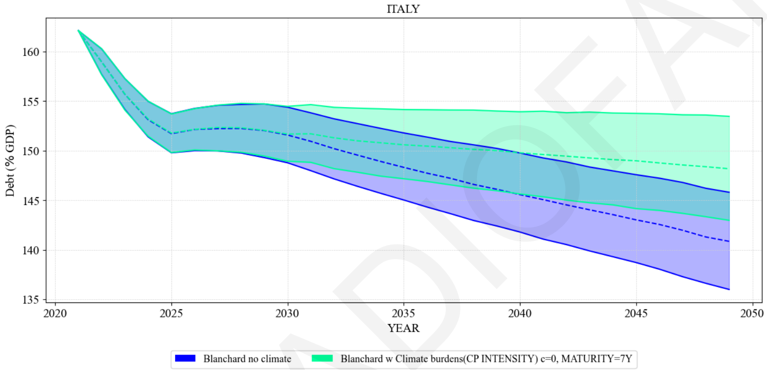
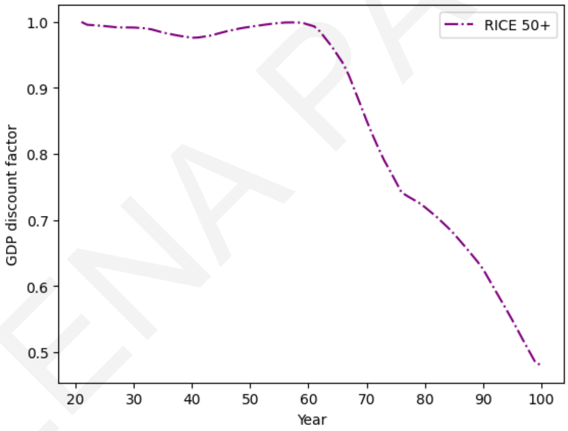
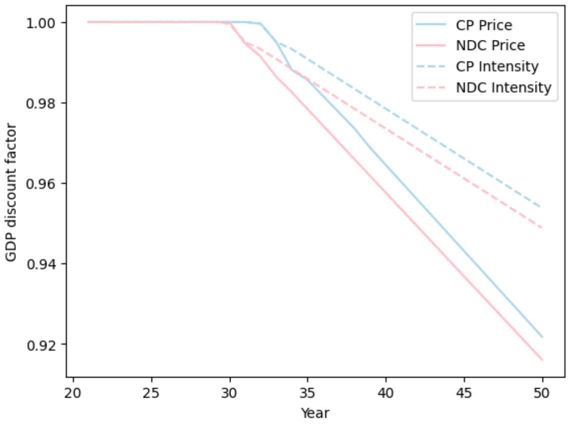


Figure 25: Debt/GDP (%) under NDC Intensity.



(a) GDP discount factor under scenario SSP2-RCP2.6 using Burke, Hsiang, and Miguel(2015) damage function.(Source: [S. Zenios 2022])



(b) GDP damage factor under CP and NDC Policies as obtained from the ICES-XPS 1.0 model. Source: AR6 Database.

NETHERLANDS

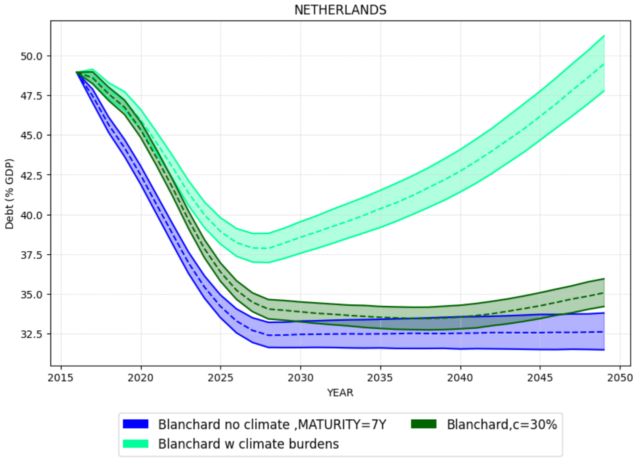


Figure 26: Debt/GDP ratio (%) without and with NDC Price Climate Policy, stabilized when $c = 35\%$

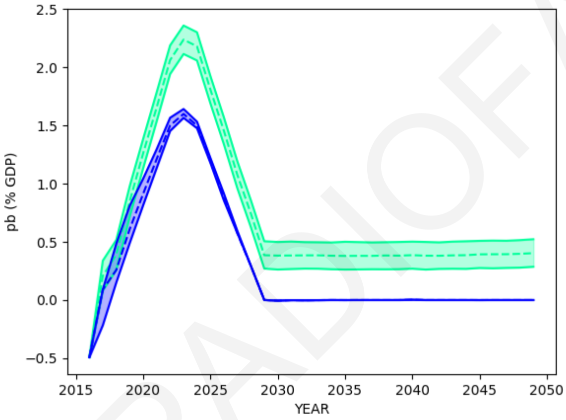


Figure 27: Primary balance without and under NDC Price Policy for 2016-2050.

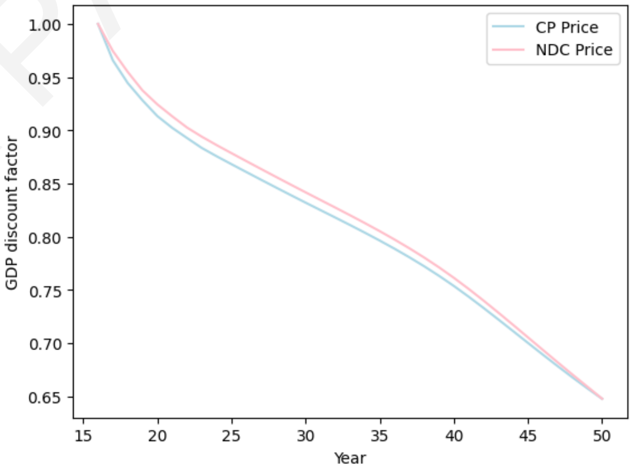


Figure 28: GDP discount factor as obtained from NEMESIS model under CP and NDC Price policies computed with NEMESIS model. Source :AR6 Database [*IPCC's sixth Assessment Report (AR6) Database* n.d.].

Bibliography

[1] David Anthoff and Richard SJ Tol. "The uncertainty about the social cost of carbon: A decomposition analysis using fund". *Climatic change* 117.3 (2013), pp. 515–530.

[2] Michael Barnett, William Brock, and Lars Peter Hansen. "Pricing uncertainty induced by climate change". *The Review of Financial Studies* 33.3 (2020), pp. 1024–1066.

[3] Stefano Battiston and Irene Monasterolo. "A Climate Risk Assessment of Sovereign Bonds' Portfolio". *SSRN Electronic Journal* (2019). DOI: `10.2139/ssrn.3376218`. URL: `https://doi.org/10.2139/ssrn.3376218`.

[4] Olivier J. Blanchard. *Fiscal Policy Under Low Interest Rates.* `https://fiscal-policy-under-low-interest-rates.pubpub.org/`. 2022.

[5] Valentina Bosetti, Emanuele Massetti, and Massimo Tavoni. "The WITCH model: structure, baseline, solutions" (2007).

[6] Othman Bouabdallah et al. "Debt sustainability analysis for euro area sovereigns: a methodological framework". *ECB Occasional Paper* 185 (2017).

[7] Marshall Burke, Solomon M Hsiang, and Edward Miguel. "Global non-linear effect of temperature on economic production". *Nature* 527.7577 (2015), pp. 235–239.

[8] Katherine Calvin et al. "GCAM v5. 1: representing the linkages between energy, water, land, climate, and economic systems". *Geoscientific Model Development* 12.2 (2019), pp. 677–698.

[9] Mr Serhan Cevik and João Tovar Jalles. *This changes everything: Climate shocks and sovereign bonds.* International Monetary Fund, 2020.

[10] Nigel Chalk and Richard Hemming. "Assessing fiscal sustainability in theory and practice". In: *Fiscal Sustainability Conference.* 2000, p. 61.

[11] climate-ADAPT. *climate-ADAPT.* `https://climate-adapt.eea.europa.eu/`. 2022.

[12] Melissa Dell, Benjamin F Jones, and Benjamin A Olken. "Temperature shocks and economic growth: Evidence from the last half century". *American Economic Journal: Macroeconomics* 4.3 (2012), pp. 66–95.

[13] Rob Dellink, Elisa Lanzi, and Jean Chateau. "The sectoral and regional economic consequences of climate change to 2060". *Environmental and resource economics* 72.2 (2019), pp. 309–363.

[14] EEA. *EEA database on greenhouse gas policies and measures in Europe.* `http://pam.apps.eea.europa.eu/`. 2022.

[15] Mark C Freeman, Gernot Wagner, and Richard J Zeckhauser. "Climate sensitivity uncertainty: when is good news bad?" *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences* 373.2055 (2015), p. 20150092.

[16] International Monetary Fund. "Building Resilience in Developing Countries vulnerable to large natural disasters". *IMF Policy Paper* (2019).

[17] Carmine Gabriele et al. "Debt stocks meet gross financing needs: A flow perspective into sustainability" (2017).

[18] Paolo Gazzotti. "RICE50+: DICE model at country and regional level". *Socio-Environmental Systems Modelling* 4 (2022), pp. 18038–18038.

[19] Kenneth Gillingham et al. *Modeling uncertainty in climate change: A multi-model comparison.* Tech. rep. National Bureau of Economic Research, 2015.

[20] John Hassler, Per Krusell, and Conny Olovsson. "The consequences of uncertainty: climate sensitivity and economic sensitivity to the climate". *Annual Review of Economics* 10 (2018), pp. 189–205.

[21] Chris Hope. "The marginal impact of CO2 from PAGE2002: an integrated assessment model incorporating the IPCC's five reasons for concern". *Integrated Assessment Journal* 6.1 (2006).

[22] *IPCC's sixth Assessment Report (AR6) Database.* `https://data.ece.iiasa.ac.at/ar6/`. Accessed: 2022-09-30.

[23] David Klein et al. "The value of bioenergy in low stabilization scenarios: an assessment using REMIND-MAgPIE". *Climatic change* 123.3 (2014), pp. 705–718.

[24] Volker Krey et al. "Message-globiom 1.0 documentation". *International Institute for Applied Systems Analysis: Laxenburg, Austria* (2016).

[25] Francesco Lamperti et al. "The public costs of climate-induced financial instability". *Nature Climate Change* 9.11 (2019), pp. 829–833.

[26] Ken'ichi Matsumoto. "Climate change impacts on socioeconomic activities through labor productivity changes considering interactions between socioeconomic and climate systems". *Journal of Cleaner Production* 216 (2019), pp. 528–541.

[27] Malte Meinshausen et al. "Greenhouse-gas emission targets for limiting global warming to 2 C". *Nature* 458.7242 (2009), pp. 1158–1162.

[28] William Nordhaus. *A question of balance: Weighing the options on global warming policies.* Yale University Press, 2014.

[29] William Nordhaus. "Climate change: The ultimate challenge for economics". *American Economic Review* 109.6 (2019), pp. 1991–2014.

[30] William D Nordhaus. "An optimal transition path for controlling greenhouse gases". *Science* 258.5086 (1992), pp. 1315–1319.

[31] William D Nordhaus. *Evolution of Assessments of the Economics of Global Warming: Changes in the DICE model, 1992–2017.* Tech. rep. National Bureau of Economic Research, 2017.

[32] William D Nordhaus. *Managing the global commons: the economics of climate change.* Vol. 31. MIT press Cambridge, MA, 1994.

[33] William D Nordhaus. "The 'DICE'model: background and structure of a dynamic integrated climate-economy model of the economics of global warming" (1992).

[34] William D Nordhaus and Andrew Moffat. "A survey of global impacts of climate change: replication, survey methods, and a statistical analysis" (2017).

[35] Brian C O'Neill et al. "The roads ahead: Narratives for shared socioeconomic pathways describing world futures in the 21st century." *Global environmental change* 42 (2017), pp. 169–180.

[36] Robert S Pindyck. "Climate change policy: what do the models tell us?" *Journal of Economic Literature* 51.3 (2013), pp. 860–72.

[37] Robert S Pindyck. "The use and misuse of models for climate policy". *Review of Environmental Economics and Policy* (2017).

[38] H-O Pörtner et al., eds. *Climate Change 2022: Impacts, Adaptation, and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change.* Vol. 2022. Cambridge University Press. In Press.

[39] Keywan Riahi, Shilpa Rao, et al. "RCP 8.5—A scenario of comparatively high greenhouse gas emissions". *Climatic change* 109.1 (2011), pp. 33–57.

[40] Keywan Riahi, Detlef P Van Vuuren, et al. "The shared socioeconomic pathways and their energy, land use, and greenhouse gas emissions implications: an overview". *Global environmental change* 42 (2017), pp. 153–168.

[41] Joeri Rogelj et al. "Scenarios towards limiting global mean temperature increase below 1.5 C". *Nature Climate Change* 8.4 (2018), pp. 325–332.

[42] Olivier Sassi et al. "IMACLIM-R: a modelling framework to simulate sustainable development pathways". *International Journal of Global Environmental Issues* 10.1-2 (2010), pp. 5–24.

[43] Paul Schmelzing. "Eight centuries of global real interest rates, RG, and the 'suprasecular'decline, 1311–2018". *RG, and the 'Suprasecular'Decline* (2019), pp. 1311–2018.

[44] Sujeetha Selvakkumaran and Bundit Limmeechokchai. "Low carbon society scenario analysis of transport sector of an emerging economy—The AIM/Enduse modelling approach". *Energy Policy* 81 (2015), pp. 199–214.

[45] Nicholas Stern and Nicholas Herbert Stern. *The economics of climate change: the Stern review.* cambridge University press, 2007.

[46] Lawrence H Summers. "US economic prospects: Secular stagnation, hysteresis, and the zero lower bound". *Business economics* 49.2 (2014), pp. 65–73.

[47] Allison M Thomson et al. "RCP4. 5: a pathway for stabilization of radiative forcing by 2100". *Climatic change* 109.1 (2011), pp. 77–94.

[48] Richard SJ Tol. "A social cost of carbon for (almost) every country". *Energy Economics* 83 (2019), pp. 555–566.

[49] Detlef P Van Vuuren, Jae Edmonds, et al. “The representative concentration pathways: an overview”. *Climatic change* 109.1 (2011), pp. 5–31.

[50] Detlef P Van Vuuren, Elmar Kriegler, et al. “A new scenario framework for climate change research: scenario matrix architecture”. *Climatic change* 122.3 (2014), pp. 373–386.

[51] Detlef P Van Vuuren, Elke Stehfest, et al. “RCP2.6: exploring the possibility to keep global mean temperature increase below 2 C”. *Climatic change* 109.1 (2011), pp. 95–116.

[52] Detlef P van Vuuren et al. “Pathways to achieve a set of ambitious global sustainability objectives by 2050: explorations using the IMAGE integrated assessment model”. *Technological Forecasting and Social Change* 98 (2015), pp. 303–323.

[53] Martin L Weitzman. “Fat-tailed uncertainty in the economics of catastrophic climate change”. *Review of Environmental Economics and Policy* (2011).

[54] John Weyant. “Some contributions of integrated assessment models of global climate change”. *Review of Environmental Economics and Policy* (2017).

[55] Stavros Zenios. *Practical financial optimization : decision making for financial engineers*. Malden, MA: Blackwell Pub., 2007.

[56] Stavros Zenios. “The risks from climate change to sovereign debt”. *Climatic Change* 172.3 (2022), pp. 1–19.

[57] Stavros A Zenios et al. “Risk management for sustainable sovereign debt financing”. *Operations Research* 69.3 (2021), pp. 755–773.

[58] Zi-Jian Zhao et al. “Global climate damage in 2° C and 1.5° C scenarios based on BCC_SESM model in IAM framework”. *Advances in Climate Change Research* 11.3 (2020), pp. 261–272.