Instituto Alberto Luiz Coimbra de Pós-Graduação e Pesquisa de Engenharia

COPPE UFRJ

BRIDGING THE EMISSIONS GAP: POLICY PATHWAYS AND TECHNOLOGICAL STRATEGIES FOR ACHIEVING THE PARIS AGREEMENT GOALS USING INTEGRATED ASSESSMENT MODELS

Luiz Bernardo Carneiro da Silva Baptista

Tese de Doutorado apresentada ao Programa de Pós-graduação em Planejamento Energético, COPPE, da Universidade Federal do Rio de Janeiro, como parte dos requisitos necessários à obtenção do título de Doutor em Planejamento Energético.

Orientadores: Pedro Rua Rodriguez Rochedo
Roberto Schaeffer

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Aos que valorizam a ciência, a pesquisa,
o conhecimento científico e a sua divulgação.
Que consigamos seguir os passos dos que passaram antes de nós,
nos apoiando nos ombros de gigantes para desenvolvermos um mundo melhor.

"*Journey before destination.*"
- Brandon Sanderson, Oathbringer

"*It's a long story.*"
- The Witcher, Baptism of Fire

"*I can rest when I'm dead.*"
- Rand al'Thor, The Fires of Heaven

"*Make haste slowly.*"
- Rand al'Thor, Lord of Chaos

"*How young I was. How foolish. How wise.*"
- Patrick Rothfuss, The Name of the Wind

"*Soon the sun would be edging above the horizon. Morning. A time for new hopes; a time to be up and doing. New hopes. He almost laughed. How long had he been awake? An hour or more, surely...*"
- Robert Jordan, The Shadow Rising

"*The flesh surrenders itself. Eternity takes back its own. Our bodies stirred these waters briefly, danced with a certain intoxication before the love of life and self, dealt with a few strange ideas, then submitted to the instruments of Time. What can we say of this? I occurred. I am not...yet, I occurred.*"
- Frank Herbert, Dune Messiah

"*You will be required to do wrong no matter where you go. It is the basic condition of life, to be required to violate your own identity. At some time, every creature which lives must do so. It is the ultimate shadow, the defeat of creation; this is the curse at work, the curse that feeds on all life. Everywhere in the universe.*"
- Philip K. Dick, Do Androids Dream of Electric Sheep?

"*These things cannot be stopped: Inherited will.*
People's dreams. The ebb and flow of the ages.
As long as people seek the answer to freedom, these will never cease to be!"
- Gol D. Roger, One Piece

"*Use statistics as a drunk man uses lamp posts -*
for support rather than for illumination."
- Andrew Lang

"*Declare this an emergency*
Come on and spread a sense of urgency
And pull us through
And pull us through
And this is the end
This is the end
Of the world"
- Apocalypse Please, Muse

"*Whew. This is turning into an epic acknowledgments.*"
- Brandon Sanderson, The Way of Kings

"*No matter what happens, I have faith in humanity's capacity for wisdom!*
I have faith in science!!"
- Dr. Vegapunk, One Piece

"*We're all small and stupid.*"
- Evelyn Wang, Everything Everywhere All at Once

"*A guerra destrói. O que constrói é o desenvolvimento,*
é o conhecimento científico, é o conhecimento tecnológico."
- Lula

"*Shit time to be a scientist.*"
- 3 Body Problem

"*The changeability of the world is, as it happens,*
the only thesis in this treatise you can agree with."
- Dandilion, That Last Wish

"*When you want to know how things really work,*
study them when they're coming apart."
- William Gibson

"*We all want to change the world*"
- The Beatles, Revolution

"*Whatever comes, face it on your feet.*"
- Robert Jordan, The Great Hunt

"*A wise man views a moonless night with fear.*"
- Patrick Rothfuss, The Wise Man's Fear

"*Because goodbyes are inherently sad. They mean that something's ending.*
And this one is especially sad because what we had was so great."
- Jake Peralta, Brooklyn 99

"*Va'esse deireádh aep eigean, va'esse eigh faidh'ar.*"
(Something ends, something begins.)
- The Witcher, Andrzej Sapkowski

"*This is my peak, this is...*"
- Monkey D. Luffy, One Piece

Resumo da Tese apresentada à COPPE/UFRJ como parte dos requisitos necessários para a obtenção do grau de Doutor em Ciências (D.Sc.)

TÍTULO DA TESE

Luiz Bernardo Carneiro da Silva Baptista

Abril/2025

Orientadores: Pedro Rua Rodriguez Rochedo
Roberto Schaeffer

Programa: Planejamento Energético

Esta tese analisa trajetórias de políticas e estratégias tecnológicas para reduzir a lacuna de emissões e alcançar as metas do Acordo de Paris por meio da aplicação de modelos de avaliação integrada. A pesquisa está estruturada em três estudos complementares. O primeiro avalia o potencial das políticas de boas práticas em diferentes países, demonstrando que, embora essas políticas contribuam significativamente para a redução das emissões, elas são insuficientes para cumprir integralmente as metas de Paris sem medidas adicionais e específicas a cada contexto. O segundo estudo examina os pacotes de recuperação econômica pós-COVID-19 e mostra que os esforços atuais são inadequados para alinhar-se às trajetórias de emissões necessárias, enfatizando a necessidade de investimentos mais ambiciosos e sustentados. O terceiro estudo foca no papel das tecnologias de remoção de dióxido de carbono, destacando a importância crítica da sua implementação precoce e da cooperação internacional para otimizar os esforços de mitigação globais e regionais. Coletivamente, os resultados evidenciam a necessidade de integrar instrumentos de política e opções tecnológicas diversificadas, adaptadas às circunstâncias nacionais, para reduzir efetivamente a lacuna de emissões e alcançar as metas do Acordo de Paris.

Abstract of Thesis presented to COPPE/UFRJ as a partial fulfillment of the requirements for the degree of Doctor of Science (D.Sc.)

BRIDGING THE EMISSIONS GAP: POLICY PATHWAYS AND TECHNOLOGICAL STRATEGIES FOR ACHIEVING THE PARIS AGREEMENT GOALS USING INTEGRATED ASSESSMENT MODELS

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April/2025

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This thesis investigates policy pathways and technological strategies to bridge the emissions gap and achieve the Paris Agreement goals through the application of integrated assessment models. The research is structured into three complementary studies. The first evaluates the potential of good practice policies in major emitting countries, demonstrating that while these policies significantly contribute to emissions reductions, they are insufficient to fully meet the Paris targets without additional, context-specific measures. The second study examines post-COVID-19 economic recovery packages, and shows that current efforts are inadequate to align with the necessary emissions trajectories, emphasizing the need for more ambitious and sustained investments. The third study focuses on the role of carbon dioxide removal technologies, highlighting the critical importance of early deployment and international cooperation to optimize global and regional mitigation efforts. Collectively, the findings present the necessity of integrating diverse policy instruments and technological options, tailored to national circumstances, to effectively close the emissions gap and achieve the Paris Agreement goals.

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Chapter 1

Introduction

1.1 Climate change and Integrated Assessment Modeling

Climate change is upon us. Anthropogenic greenhouse gas (GHG) emissions have steadily increased, driving a recently unprecedented global warming, with severe consequences including intensified droughts, floods, cyclones, and other extreme weather events [1, 2]. The latest assessments by the Intergovernmental Panel on Climate Change (IPCC) indicate that the emissions of the past decade alone have approximately the same size as the remaining carbon budget to limit global warming below 1.5 °C and between one-third and one-half of the 2 °C carbon emission budget [3]. To mitigate this warming trajectory, it is urgent that we reach the peak of global emissions and transition to climate neutrality, thus reducing the level of impacts caused by climate change [4, 5].

Responding to this urgency, nations around the world adopted the Paris Agreement (PA), committing to limit warming to 'well below' 2 °C, with efforts to cap it at 1.5 °C above pre-industrial levels [6]. The PA called on countries to propose their nationally determined contributions (NDCs) as a response to climate change, where each country sets a target for GHG emissions in 2025 and 2030. These NDCs include unconditional pledges that countries commit to implement independently, as well as conditional pledges that depend on international support[1]. In addition, all participating parties are to communicate their targets and to periodically review their value in a global stocktake [6, 7].

However, significant gaps remain to limit warming below 2 °C. NDCs, which can

[1]Which can be financial, technological and capacity-building support from developed countries.

be considered the core pledges of the PA, currently fall short of these ambitious goals, indicating a clear ambition gap [8–10]. The UNEP Emissions Gap Report 2024 [11] estimates an emission gap of 14 $GtCO_2e$ between projected 2030 emissions under current unconditional NDCs in a below 2 °C limit, and a 22$GtCO_2e$ emission gap for 1.5 °C scenarios. Even the implementation of current 2030 NDCs would yield only a 4 to 10% reduction in emissions from 2019 levels, considering unconditional and conditional NDCs, respectively, far from the 28% cuts required to align with the PA's goals [11].

Even where ambition exists, implementation frequently lags behind due to insufficient policies and concrete actions [12, 13]. This discrepancy is exemplified by the fact that while 142 countries and 193 regions have announced net zero emission targets, only 75 parties have formalized their commitments through submitted Long-Term Strategies (LTS) [14, 15].

The ambition and emissions gap needs action as a means of dealing with it. To reduce GHG emissions to below the proposed NDC targets, political traction is needed to push forward even more ambitious policies, otherwise it will be impossible to achieve PA goals [11]. In addition to that, national incentives for R&D and international cooperation agreements can also promote the development and expansion of cleaner technologies in many countries and are also taken into account, as a means of implementation, in some countries conditional NDCs [16].

Closing the gaps between climate ambition and implementation requires an analytical framework to guide policymakers. Integrated Assessment Models (IAMs) can fulfill this function by assessing the interactions between energy, environmental, socioeconomic, and terrestrial systems, which can provide insights for policy decisions [7, 17–19]. The IPCC consistently uses IAMs to assess potential climate impacts and mitigation pathways, focusing on global and regional assessments of scenario-based analyzes [1, 3]. The IPCC has been using IAM research in its analysis since its First Assessment Report and has been increasing its importance since then, with even greater influence on the IPCC Fifth Assessment Report and its influence on the formulation of the Paris Agreement [19–21]. In its Sixth Assessment Report (AR6), the IPCC synthesized key mitigation strategies using a set of five Illustrative Mitigation Pathways (IMPs), which represent different socioeconomic and technological transformations consistent with limiting warming aligned with PA goals. These pathways, derived from IAM scenarios, highlight different emphases such as the deployment of renewable energy, reduced energy demand, extensive use of carbon dioxide removal in the energy and industrial sectors, and supply-side measures, and are used across the report [3]. The COFFEE model [22–26], which will be presented in the following sections, had one of its scenarios selected as the IMP-Neg scenario in AR6.

Moreover, IAMs can offer policymakers some guidance on optimal decarbonization strategies, highlighting cost-effective or highest-benefit approaches to allow detailed analyses under various climate constraints [18, 27, 28]. Although IAMs are traditionally used to test techno-economic assumptions and inform new policy proposals [29, 30], there is room to apply this modeling approach to directly assess existing or proposed policies and their medium to long-term impacts [7, 31]. By quantifying emissions reductions and clarifying transition pathways, IAM analyses have become foundational tools for climate policy formulation at global, national, and regional levels [3, 7, 31, 32].

Therefore, despite the growing reliance on IAMs and policy instruments individually, a key gap remains in understanding how insights from IAMs and climate policy instruments can synergistically inform each other, thereby effectively bridging global and regional emissions and implementation gaps. Addressing this literature gap is the core of this thesis, with its supporting research questions being presented in the following subsection.

1.1.1 Objectives of the thesis

Given the aforementioned literature gaps, the main research question (RQ) of this thesis is: How can climate policy instruments and IAMs synergistically inform each other to effectively bridge the global emissions gap and achieve the PA temperature goals? Using this question as the underlying scope of this thesis, we also propose three sub-questions, which are answered throughout the chapters:

1. *RQ1*: How can a set of 'good practice policies' help bridge the emissions gap among major emitting countries through the use of IAMs?

2. *RQ2*: To what extent the application of post-Covid recovery packages can bridge the investment gap and align with short- and medium-term emissions trajectories compliant with Paris goals, according to a set of IAMs?

3. *RQ3*: What are the regional global implications of deploying CDR, as informed by IAM analyses, and what policy recommendations can be derived from its deployment pathways?

To answer the aforementioned questions, different sets of IAMs are used, but the focus of this thesis is on two models: The Brazilian Land-Use and Energy Systems (BLUES) model [29, 33–36], and the COmputable Framework For Energy and the Environment

(COFFEE) model [22–24, 30, 37]. In addition, for each research question addressed below, we indicate the methodological challenges or modifications that were required — either by adapting the model structure or introducing new parameters to accommodate the necessary changes in assumptions.

First, focusing on *RQ1*, we evaluate the implementation of a set of good practice policies that are effective in some countries [12, 32] in a group of national IAMs. We then compare the scenario results of the good pratice policies implemented with a NDC scenario[2], as well as the implementation of a current policies scenario and a 2 °C scenario. In this context, to assess the effectiveness of the GPP in closing the emissions gap, a Bridge scenario combining both the GPP and the 2 °C scenario is considered. This is the first implementation of such a GPP/Bridge scenario at the national level, enabling analysis of these climate policies and offering a comparison with the NDCs. Then, we compare the effectiveness of the implementation of these policies in each region, taking into account regional capabilities and difficulties. Answering this question required implementing this set of good practice policies in the BLUES model, representing the first effort to incorporate multiple climate policies into this Brazilian IAM, which involved methodological adjustments to correctly interpret these policies and enable their application within a national process-based IAM.

For *RQ2*, we analyze the short- and medium-term impacts of policy responses related with post-COVID green recovery packages. We test the hypothesis that the planned recovery from COVID-19 would undermine the response to climate urgency by modeling 'post-COVID-19' scenarios until 2050. We apply short-term regional shocks to GDP growth due to COVID-19 on an SSP2 pathway. We then use policy packages[3] consisting mostly of policies for investments, focusing on three main technology groups related to a low-carbon transition: Power generation, energy efficiency and the transport sector. As an example, the US government administration pledged almost US$3 trillion of public expenditure, focusing on environmental measures for the power, industry, manufacturing and transport sectors, while China announced a support of US$ 22 billion to clean energy investments, and the European Union commited as least 30% of its €750 billion budget to climate action [38–40]. This analysis represents one of the first efforts to explicitly incorporate investment policy packages into the COFFEE-TEA modeling suite, uniquely exploiting the model's constraint structure to capture policy-specific investment dynamics.

[2] Consisting on the Nationally Determined Contributions from each country or region that were made public as of November 15th 2020.

[3] That were made public as of May 2021.

Lastly, for *RQ3*, we assess the role and regional deployment of carbon dioxide removal (CDR) technologies required to meet different long-term climate targets. Using the COFFEE global IAM, we run carbon budget scenarios ranging from 300 to 2,400 $GtCO_2$, from 2020 to 2100, and analyze the deployment of four main CDR categories: energy-based, land-based, materials-based, and others. These scenarios reflect end-of-century temperature outcomes between 1.5 °C and over 2 °C, with increasing reliance on CDR as ambition increases. We evaluate the global and regional timing of net zero CO_2 emissions, cumulative CDR needs, and the mix of technologies deployed. This represents one of the first efforts to quantify the differentiated roles of CDR technologies across regions in a consistent modeling framework, while comparing increasing ambition level. The results highlight that BECCS and afforestation and reforestation dominate in more stringent scenarios, while DAC and materials-based removals contribute marginally but grow in importance as carbon prices evolve and ambition increases. We then analyze how different policy packages align with our results and emphasize the need for targeted policy instruments to support the development, deployment, and scaling of CDR technologies.

Hence, each chapter addresses one of the three research questions using specific modeling strategies. For *RQ1*, we invert the conventional role of IAMs: rather than using model outputs to design policies, we test how existing policy packages — proven effective in some countries — can be applied within IAMs to assess their potential for bridging regional ambition and implementation gaps. For *RQ2*, we evaluate how green recovery packages introduced in response to COVID-19 could contribute to short- and medium-term emissions reductions. These policy packages are incorporated into IAMs to explore their alignment with low-carbon pathways and Paris-aligned trajectories. For *RQ3*, we adopt a more traditional IAM approach to explore long-term climate targets. We use a global model to simulate a wide range of carbon budget scenarios and evaluate the deployment and regional contribution of different CDR methods, then we analyze specific policies designed for mitigation strategies aligned with CDR.

1.1.2 Thesis outline

To answer the questions proposed above, this thesis is divided into five chapters, with three of them consisting of research articles. In two of the three articles, the author of this thesis[4] is the first author, and in one of them was responsible for the model runs and analysis of the COFFEE model. Chapter 2 is the article entitled Good practice policies

[4]The author selected these three articles among fourteen already published, and in addition to one already accepted.

to bridge the emissions gap in key countries, published in *Global Environmental Change* [31]; Chapter 3 consists of the paper entitled Is Green Recovery Enough? Analysing the Impacts of Post-COVID-19 Economic Packages, published in *Energies* [23]; Chapter 4 presents the manuscript of the paper entitled Global and Regional Dynamics of Negative Emissions: Pathways to 'Paris', ready to be submitted. Finally, chapter 5 consists of the final remarks of this thesis, also taking into account how the proposed research questions are answered throughout the document, and limitations from each chapter.

Chapter 2

Good practice policies to bridge the emissions gap in key countries

Baptista, L.B., Schaeffer, R., Van Soest, H.L., Fragkos, P., Rochedo, P.R.R., Van Vuuren, D., Dewi, R.G., Iyer, G., Jiang, K., Kannavou, M., Macaluso, N., Oshiro, K., Park, C., Reedman, L.J., Safonov, G., Shekhar, S., Siagian, U., Surana, K., Qimin, C., 2022. Good practice policies to bridge the emissions gap in key countries. Global Environmental Change 73, 102472. https://doi.org/10.1016/j.gloenvcha.2022.102472

Abstract

One key aspect of the Paris Agreement is the goal to limit the global average temperature increase to well below 2 °C by the end of the century. To achieve the Paris Agreement goals, countries need to submit, and periodically update, their Nationally Determined Contributions (NDCs). Recent studies show that NDCs and currently implemented national policies are not sufficient to cover the ambition level of the temperature limit agreed upon in the Paris Agreement, meaning that we need to collectively increase climate action to stabilize global warming at levels considered safe. This paper explores the generalization of previously adopted good practice policies (GPPs) to bridge the emissions gap between current policies, NDCs ambitions and a well below 2 °C world, facilitating the creation of a bridge trajectory in key major-emitting countries. These GPPs are implemented in eleven well-established national Integrated Assessment Models (IAMs) for Australia, Brazil, Canada, China, European Union (EU), India, Indonesia, Japan, Russia, South Korea, and the United States, that provide least-cost, low-carbon scenarios up to 2050. Results show that GPPs can play an important role in each region, with energy supply policies appearing as one of the biggest contributors to the reduction of carbon emissions. However, GPPs by themselves are not enough to close the emission gap, and as such more will be needed in these economies to collectively increase climate

action to stabilize global warming at levels considered safe.

2.1 Introduction

A key aspect of the Paris Agreement is the goal to limit the global average temperature increase to well below 2 °C [6]. To achieve the Paris Agreement goals, each party of the United Nations Framework Convention on Climate Change (UNFCCC) needs to play its part, by presenting, and periodically updating, its Nationally Determined Contribution (NDC) towards more ambitious emission reduction targets. NDCs are a set of policies and targets aiming to reduce country-level emissions and are determined by each country, with no legal obligation towards its implementation, and should be updated every five years [18]. Recent studies show that NDCs and national policies are not sufficient to cover the ambition level of the temperature limit agreed by the Paris Agreement, meaning that, perhaps, all countries need to collectively increase climate action to stabilize global warming at levels considered safe [8, 12, 41]. To that end, we may need unprecedented and far-reaching national and global responses in terms of practices and policies [7]. Several options are on the table, including energy efficiency improvements, electrification of final energy uses, uptake of renewable energy in power generation, advanced biofuels, carbon capture and storage (CCS), bioenergy with carbon capture and storage (BECCS), afforestation, reforestation, reducing deforestation, etc., depending on national priorities and local conditions [18, 42].

To assess the contribution of greenhouse gas (GHG) emissions reductions from practices and climate policies, Integrated Assessment Models (IAMs) provide a thorough analysis of potential trade-offs, opportunities, and challenges for their implementation. IAMs are widely used by the climate research community, with studies ranging from policy implementation to climate scenarios and inter-model comparison analyses, both at the global and national levels [7, 12, 18, 42].

To this end, climate change mitigation is typically facilitated in IAMs by a global carbon price to identify cost-effective mitigation strategies [43, 44]. However, while price-driven or least-cost trajectories are indicative, they may sometimes not be particularly realistic, as probably in most countries a carbon price is going to be the single most important driver of an efficient low-carbon transition, but with other energy, transport and climate policy measures also playing a role. As such, a carbon price is normally an artifact that IAMs use to indicate mitigation actions: it equals the marginal abatement cost across regions and sectors of a theoretical world with a limited representation of heterogeneous behavior and institutions. Nonetheless, it is worthwhile to explore those mitigation actions in more detail.

Most of these studies indicate the need to close the emissions gap between current policies, the NDCs, and the more ambitious climate targets set by the Paris Agreement. Many studies focus on how to achieve climate goals, either through the use of global models [7], or from national models that make use of results from global models [12, 18, 42, 45]. However, few studies focus on regionalized policy packages and their effects. This may be an indication that a broader selection of new, eventually already proved, policies and practices at the national level is needed as an alternative to least-cost solutions coming out of IAMs, at least in the short and medium-term [46, 47].

This article aims to evaluate scenarios with a new set of standardized practices and policies and their application in national IAMs, identifying how these practices and policies can contribute towards a below 2 °C world, and supporting the revised NDCs and global stocktake in 2023. These scenarios are analyzed in ten different countries and one region - Australia, Brazil, Canada, China, European Union (EU), India, Indonesia, Japan, Russia, South Korea, and the United States, thus covering almost three-fourth of global CO2 emissions in 2018 [18, 42].

The innovation of this article is in the implementation of good practice policies (GPP) in eleven national/regional IAMs that capture national specificities and policy priorities. Furthermore, this study compares the results of the new scenarios with those associated with the implementation of the NDCs, as well as the implementation of current policies scenario and a 2 °C scenario. In this context, to assess the effectiveness of the GPP in closing the emission gap, a Bridge scenario is also considered, which account simultaneously the GPP and 2 °C scenario. It is the first time that such GPP/Bridge scenarios are implemented at the national scale, allowing an analysis of the implementation of these climate policies and a counterpoint to the NDCs. Besides, these scenarios were created jointly by national and global model teams, with the latter also running the same scenario protocol (for more detail on global model runs see [7]). Common indicators are calculated and shown to present whether the implementation of these practices and policies is sufficient to bridge the emission gap and contribute to the strengthening of the NDCs over time, along with a sector-level assessment.

2.2 Methods

To evaluate a new set of practices and policy scenarios, named here as Good Practice Policies (GPP) and Bridging scenarios (Bridge), and their application in national IAMs, we identify how these practices and policies can contribute towards a 2 °C world, and how they can support the ratcheting up in 2023. As described in more detail below, the Bridge scenario is based on the GPP scenario until 2030, and then it transitions to a 2 °C pathway afterwards.

Then, these scenarios are compared to a Current Policies (CurPol) scenario, a Nationally Determined Contributions (NDCplus) scenario, which maintains its effort after 2030, and an emission scenario consistent with an average global 2°C temperature change above pre-industrial levels (2Deg2030).

These scenarios are analyzed in eleven major-emitting economies - Australia, Brazil, Canada, China, European Union, India, Indonesia, Japan, Russia, South Korea, and the United States. Eleven national/regional and nine global models were part of the COMMIT project (for more detail about the COMMIT project, see https://themasites.pbl.nl/commit/, [7, 42]), with this study focusing on national models results.

For a more detailed discussion on global model results from the COMMIT project, see [7]. For consistency between national and global analyses, the scenarios analyzed in this study were developed simultaneously at both global and national levels. To that end, the same conditions are incorporated at the global and local levels, providing a consistency between national pathways and global carbon emission budgets, as done in [18]. Thus, both national and global model teams involved in this effort followed the same scenario protocol for comparability.

2.2.1 Models

Figure 2.1 shows the national models participating in this analysis, representing more than 75% of global GDP and carbon dioxide emissions, as well as 57% of the global population. They represent 13 of the largest economies in the world, except Mexico and Turkey.

The national/regional models included here are: AIM/Enduse [Japan], AIM/CGE [Korea], BLUES (Brazil), DDPP Energy (Indonesia), GCAM-Canada, GCAM-USA, India MARKAL, IPAC-AIM/technology (China), PRIMES (EU), RU-TIMES (Russia) and TIMES-AUS (Australia). As said before, this paper focuses on national models and

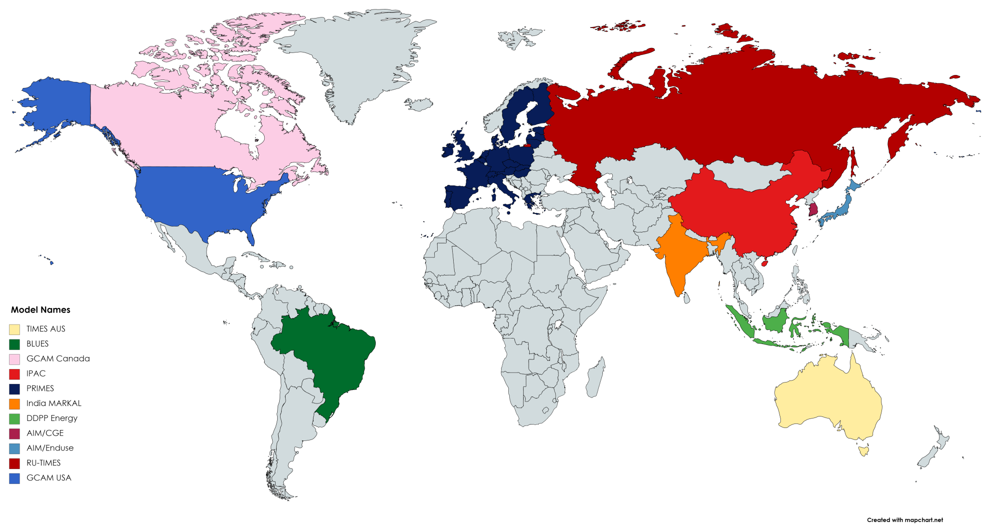

Figure 2.1: Economies covered by the national/regional models included in this work

results, comprising some comparisons to some global models results, while global results are deeply explored in [7]. A brief description of each national model can be found in the supplementary material.

2.2.2 Scenarios

Five scenarios are explored in this paper in order of stringency, namely a current policy scenario (CurPol), a scenario that represents the nationally determined contributions and the continuation of its efforts (NDCplus), a scenario of applying good practice policies (GPP), and two "mitigation" scenarios corresponding to an increase of global warming up to 2 °C from pre-industrial levels to 2100, one building on NDCs (2Deg2030) and the other referring to a scenario is based on the GPP scenario until 2030, and then it transitions to a 2 °C pathway afterwards (Bridge).

The CurPol scenario is a middle of the road socio-economic conditions scenario throughout the century, based on the socio-economic development assumptions of the second marker baseline scenario from the Shared Socioeconomic Pathways (SSP2). It also assumes the implementation of energy, climate, and land-use policies that are currently endorsed and legislated, with a cut-off date of 1st of July 2019. It follows the same protocol as shown in [12] and [18] and presented in the Climate policy database (`http://www.climatepolicydatabase.org/`). The continuation of these policies is also considered, as shown in the NDC-plus scenario that follows.

The NDCplus scenario relies upon the CurPol scenario and assumes that both unconditional and conditional NDC pledges and targets are implemented by 2030[1] in major emitting economies and considering the continuation of the effort beyond 2030, by the extrapolation of an equivalent carbon price in 2030 using the GDP growth rate as a proxy up to 2050. The equivalent carbon price represents the value of carbon that would produce the same emission reduction as the NDC policies in a region. If a region has a carbon price of zero during the implementation of the NDC in 2030, a minimum carbon price of 1 \$/tCO2 in 2030 has been assumed. If a region has a negative carbon price in 2030, the resulting trajectory of 1 \$/tCO2 has been offset to the model's starting point in 2030. For land use, a \$200/tCO2 price cap has been applied.

Our representation of the US NDCplus pathway is consistent with the official U.S. Midcentury report submitted by the U.S. government to the UNFCCC (The White House, 2016). In this representation, the NDCplus scenario for the U.S. coincides with the 2Deg2030 scenario. This is because the US NDC lies on a straight-line path toward 80% reduction in 2050 [48, 49], which is in turn consistent with a 2-degree pathway and budget [50]. This is not the case with other countries explored in this study. Thus, it is important to note that that our modeling of the NDCplus scenario for the U.S. assumes that the U.S. will achieve their NDC as stated and will continue to follow through with stringent policies to achieve 80% reduction in economy-wide GHG emissions by 2050. This representation is understandably more ambitious compared to the other countries and regions studied in this paper and care must be taken in interpreting cross-country comparisons.

The 2 °C (2Deg2030) scenario assumes a carbon budget until the year 2100 consistent with a warming of 2 °C above pre-industrial levels by 2100. Each national modeling team used a national carbon budget derived from the global budget of 1,000 Gt of CO2 in the period from 2011 to 2100, as done in CD-LINKS (`https://www.cd-links.org`) and presented in [18]. This carbon budget represents a high probability (66%) to keep global warming levels below 2 °C by 2100. This carbon budget derives from global models and may be subject to the least-cost optimization to reflect the smallest impact on the global economy. Other methods can be applied to allocate such emissions to individual countries as well, as seen in [51].

The good practice policies (GPP) scenario relies upon the CurPol scenario and assumes the implementation of good practice policies that are effective in some countries[2].

[1] The NDCs here used are those that were already made public as of 15 November 2020.

[2] The protocol for the GPP implementation assumed a national level policy implementation. However, each model has its own regional disaggregation (e.g.: the BLUES model represents 5 Brazilian macro regions, the GCAM model represents 50 states of the US), and this may affect the results of other policy scenarios, such as the Current Policies and NDCplus scenarios

These policies are considered to be implemented by 2050, taking into account distinctions between low/medium income and high-income countries in terms of timing and stringency of climate policy targets. The description of each of the selected good practice policies is presented in Table 2.1.

Table 2.1: The good practice policies assumed in the national models

Sector	Measure	High-income countries	Low-/medium-income countries	Other (differs per measure)
AFOLU (Agriculture and LULUCF)	Treat manure from livestock with anaerobic digesters – Reduction of CH4 emissions from manure, relative to 2015	33% by 2030	15% by 2030	-
	Increase nitrogen use efficiency – Reduction of N2O emissions from fertilizer, relative to 2015	10% by 2030	5% by 2030	-
	Selective breeding to reduce CH4 emissions from enteric fermentation – emission factor or emissions reduction, relative to 2015	10% by 2030	0% by 2030	-
	Increase natural forest afforestation and reforestation (annual increase 2015-2030)	Tier 1 (China, Latin America): 2%/yr	Tier 2 (South & SE Asia, Sub-Saharan Africa, Australia): 1%/yr	Tier 3 (Europe, Turkey, 23% of Russia, USA): 0.5%/yr
Energy supply	Halt natural forest deforestation	0 ha/year by 2030	0 ha/year by 2030	-
	No new installations of unabated coal power plants	By 2025	By 2030	-
	Increase renewables share in electricity generation (2020-2050)	1.4%-point/yr	1.4%-point/yr	-
	Coal mine CH4 emissions recovery	30% by 2030	30% by 2030	-
	Reduce venting and flaring of CH4 and CO2 emissions relative to 2015	36% by 2030	36% by 2030	-
Buildings	Improve final energy efficiency of appliances relative to 2015	17% by 2030	7% by 2025/2030	-
	Improve energy intensity of new buildings	22 & 30 kWh/(m².yr) by 2025	22 & 30 kWh/(m².yr) by 2035	EU: 35 & 40 kWh/(m².yr) by 2025
	No new oil boiler capacity in buildings	By 2030	By 2040	EU: by 2020
	Improve efficiency of existing buildings (share renovated)	11% by 2030	6% by 2030	-
Industry	Apply CCS – Carbon captured and stored (% of total emissions)	1.5% by 2030	1.5% by 2040	-
	Improve final energy efficiency relative to 2015	11% by 2030	6% by 2030	-
	Reduce N2O emissions from adipic/acid production	99% by 2030	99% by 2030	-
Transport	Improve aviation energy efficiency (annual, from 2018)	0.78%/yr by 2030	0.78%/yr by 2030	-
	Improve fuel efficiency of new passenger cars	38 km/l by 2030	27 km/l by 2030	-
	Increase share of non-fossil vehicle sales	50% by 2030	25% by 2030	China: 25% by 2025
Waste	Reduce CH4 emissions relative to 2015	55% by 2030	28% by 2030	-
Economy-wide	Carbon pricing pathways	Tier 1 (OECD, EU): $40/tCO_2$ by 2030	Tier 2 (Russia, East Europe, China, Korea, Latin America): $25/tCO_2$ by 2030	Tier 3 (others): $10/tCO_2$ by 2030
	Reduce F-gas emissions relative to 2015	60% by 2030	38% by 2030	-

There are good practice policies for six different economic sectors, as well as a policy that affects the entire economy. The range of good practice policies includes policies in the energy, transport, agricultural, industrial, building sectors, among others. These policies, based on the literature [32, 52, 53], present differentiated targets for high-income and low/medium-income countries. Some of these measures include targets for reducing F-gas emissions, increased uptake of renewable energy sources, greater efficiency in the final energy in the buildings and industrial sectors, greater fuel efficiency in new passenger cars, the impediment to deforestation of natural forests, carbon pricing with tiers differentiating countries, and others. Thus, these scenarios serve as a background to analyze how these good practice policies can contribute, at the national level, to minimize the emission gap between the NDCs and more carbon-constrained scenarios.

Finally, the bridging (Bridge) scenario builds upon the GPP scenario, transitioning it towards a 2 °C scenario after 2030. The GPP and Bridge scenarios were developed in a multi-round approach, consisting of an initial round with responses to literature-based good practice policies by national modeling teams, regarding the feasibility of implementing these policies in their countries or which target level or years would be possible.

2.3 Results

The GHG emissions trajectories up to 2050 from the countries/regions represented by the national/regional models and for each of the presented scenarios is available in Figure 2.2. Results from the global models are also shown for comparison. Some variations regarding historical emissions are mostly due to the use of different databases, especially historical land-use emissions [54], by the global and national model teams. From the national/regional models' perspective, almost all the presented scenarios show a reduction in the emissions level when compared to 2010 levels. This is not seen in the CurPol scenario for Brazil, Canada, and South Korea, in the Brazilian NDCplus scenario, and in all scenarios for India. Most of the national/regional trajectories are consistent with global models results, with India and the United States being the regions with the largest number of non-converging scenarios, the latter being a consequence of the implementation of certain policies at the subnational (states, cities, and firms) level as well.

By 2030, the good practice policies[3] are effective in reducing GHG emissions (even

[3]In order to avoid confusion with the GPP scenario, the set of good practice policies (also named

more effective than NDCs) in a manner consistent with the 2 °C scenario for most of the analyzed countries. In the case of Australia, these policies are shown to be effective as an early action measure. However, until the year 2050, it is clear that there is still an unabated amount of carbon emissions to close the emissions gap towards the expected levels of emissions for the ambition of the Paris Agreement.

In the Australian case, the good practice policies appear to be relevant for reducing carbon emissions until 2030, but these policies alone are insufficient to meet the 2 °C carbon budget for the country. For Brazil, the GPP scenario is slightly more efficient in reducing GHG emissions by 2030 when compared to NDCplus, with the latter not being overly ambitious beyond the AFOLU sector [55]. For Canada and the EU, the GPP scenario lead to significant emission reductions from CurPol and NDC levels and they converge towards the 2 °C scenario with little effort, when compared to the NDC scenario. In the Indian scenarios, the good practice policies lead to a 15% decline in the emissions in 2030 (with respect to CurPol), making it more ambitious than its NDCplus scenario. By 2050, the GPP scenario shows a decline of 51% in emissions with respect to CurPol scenario and 45% with respect to NDCplus scenario. However, the GPP scenario is not in line with the cost-optimal budget allocation for India for a 2 °C world and additional effort is needed to bridge this gap. For Japan and Russia, the GPP scenario can reduce carbon emissions by 2030 but are still not enough for closing the emission gap to the 2 °C trajectory. The USA has a greater emission reduction in its NDC scenario than in its GPP scenario, with the former being consistent with an 80% GHG emission reduction in 2050 when compared to 2005 levels [49]. Lastly, for Korea the NDC scenario is more effective than the GPP scenario in reducing carbon emissions by 2040. Nonetheless, neither are enough for achieving the national 2 °C carbon budget.

The waterfall charts in Figure 2.3 illustrate which are the largest contributors to emissions reduction between NDCplus and GPP scenarios by 2050. This analysis aims to help indicate which sectors has the largest potential contribution to enhance NDCs' ambitions. Additionally, it presents the differences in regional perspectives related to the sectors with the greatest potential for emissions reduction. Regarding AFOLU emissions, some models lack their representation[4], which explains their null contribution in Figure 2.3. It is worth noting that the USA's NDC scenario is more stringent than the GPP scenario, resulting in lower carbon emissions, which are shown in the waterfall chart as negative values in all sectors.

GPP) embodied in the GPP, and Bridge scenarios will be referenced as "good practice policies" from this point forward.

[4]GCAM-Canada, Primes, IND-MARKAL, AIM/Enduse/RU-Times.

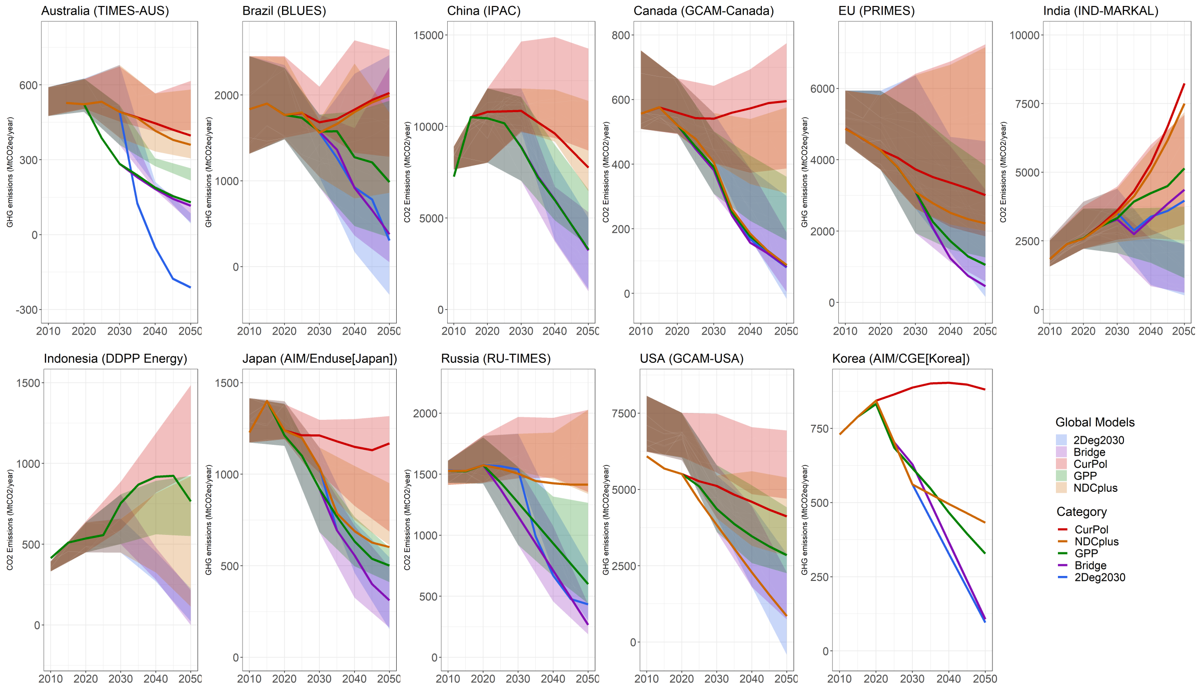

Figure 2.2: Greenhouse gas emissions trajectories from national/regional models (lines) and global models (wedges) up to 2050. For Canada, China, India, and Russia only CO2 emissions are presented. Different scales are applied to facilitate reading the results for each region

Overall, the residential and commercial (buildings) sector presents itself as the smallest contributor toward GHG reduction in the compared scenarios, while the largest contributions come from the electricity supply and transport sectors, mostly driven by the expansion of renewable energy and electric vehicles, respectively. These results are in line with the global models results presented by [7].

By 2050, emissions from energy supply are significantly reduced in Brazil, India, Japan, and Russia with the implementation of the good practice policies, with only a small reduction in South Korea when comparing the NDC and GPP scenarios. Japan, Russia, and South Korea could also take advantage of the good practice policies in the transport sector, such as aviation efficiency improvement and a higher share of non-fossil vehicle sales, for improving their NDC targets.

Regarding carbon emissions from industrial processes, the good practice policies can be interpreted as a counterproductive for Japan, causing a small increase in its industrial processes emissions when compared to its NDC scenario. On the other hand, the opposite happened for Brazil and South Korea.

In the case of the impacts of the good practice policies on AFOLU emissions, Brazil stood out amongst the other regions. Whilst the good practice policies are somewhat aligned with the Brazilian NDC concerning natural forest deforestation, GPP scenario also consider the improved rates of natural reforestation, which accounts for almost 17% of GHG emission reduction compared to the NDCplus scenario.

When comparing the 2030 results for the NDC and GPP scenarios, as seen in Figure S.1 in the Supplementary Material, it can be noticed that the good practice policies are more effective than the NDCs for reducing carbon emissions, with the exception of EU, South Korea, and the USA. Once more, the selected good practice policies for energy supply and transportation are more effective in reducing GHG emissions, when compared to NDCs.

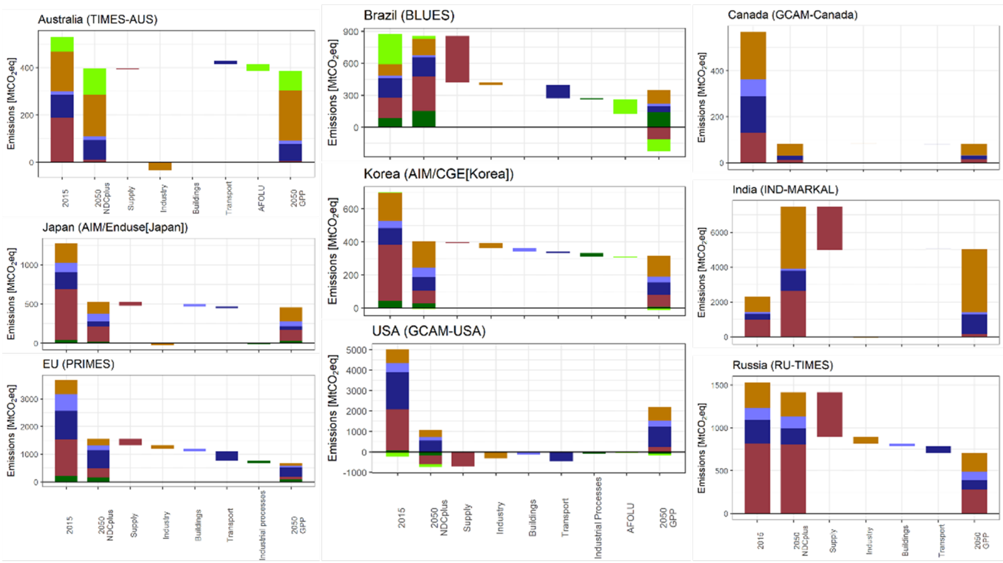

Figure 2.3: Contribution of each sector to the reduction of carbon emissions between the NDCplus and GPP scenario in 2050. Emissions in 2015 are shown for comparison (Negative values represent an increase in emissions between the compared scenarios). Different scales are applied to facilitate the reading of the results for each region. The sectoral representation varies according to the model, which may explain some zero values

The electricity share in final energy consumption from national/regional and global models is available in Figure 2.4. Figures S.2, S.3 and S.4 in the Supplementary Material present the share of electricity in industry, transportation, and residential and commercial (buildings) sectors, respectively. In the case of Australia, Brazil, India, and Japan, global models estimate a higher share of electricity consumption in final energy than national/regional models, which can be represented by a greater degree of optimism regarding electrification in these models. Overall, the good practice policies contribute to a greater share of electrification in final energy consumption when compared to CurPol and NDCplus scenarios, with higher trends in electrification shown in Canada and the EU.

In the Industrial sector, a higher share of electrification is seen in GPP and Bridge scenarios in most of the analyzed countries, with significant changes in China, EU, Russia, and South Korea. The same occurs in the residential and commercial (buildings) sectors, with electrification occurring earlier in Canada, Japan, the EU, and South Korea. Excluding India and the USA, the GPP scenario presents higher electrification rates in the transportation sector, following the good practice policies of higher fuel efficiency in vehicles and increased share of electric and hydrogen cars in new vehicles sales. Additionally, some models may consider hybrid electric or biofuel-powered fuel cell vehicles as an alternative towards vehicle electrification (in particular to achieve the fuel efficiency targets), which is only indirectly shown in the share of electricity in the transport sector figure available in the Supplementary Material.

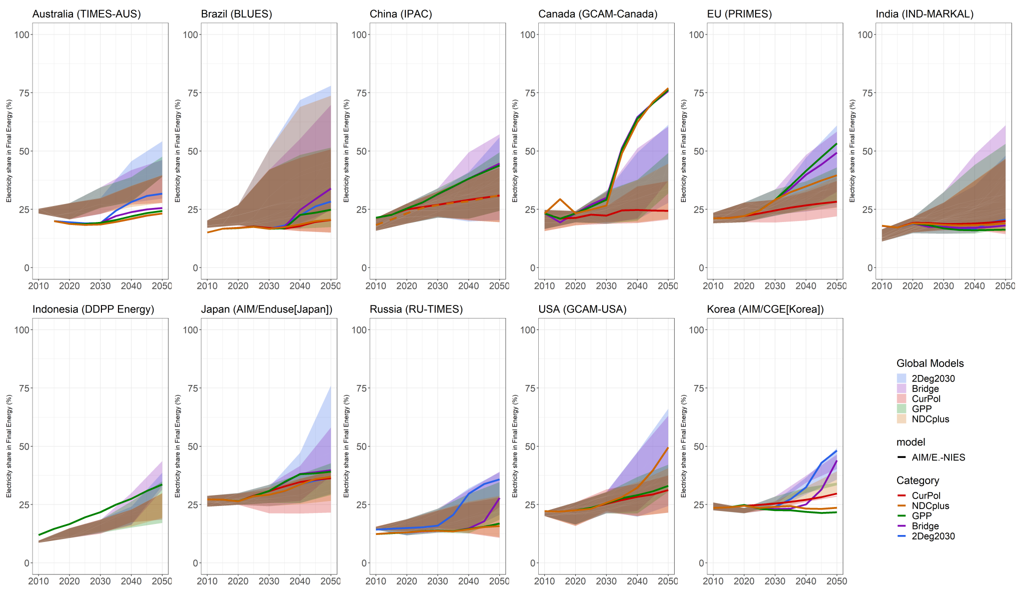

Figure 2.4: Share of electricity in final energy consumption from national/regional models (lines) and global models (wedges)

2.4 Country-level discussions

Based on the results mentioned above, this session focus on specific and individual analyses for each country/region.

In the case of Australia, the intensification of electrification occurs in more restrictive GHG emission reduction scenarios, with electricity production achieving almost zero emissions due to the vast Australian renewable energy resources, as seen in [56]. Compared to the current policy scenario, the share of electricity in the final energy use in the GPP scenario and the Bridge scenario is slightly higher, with the latter scenarios having a reduction in total final energy consumption. Land-use changes play an important role in reducing Australian carbon emissions, which are 26% lower by 2050 when comparing the NDCplus with the Bridge scenario.

For Brazil, the good practice policies for the land-use change sector are not as effective in the short term for reducing emissions when compared to the Brazilian NDC, which is not the case by 2050. In the GPP's transport sector, there is an increase in the share of ethanol use in the short term. However, the Bridge scenario presents shift towards electrification, reducing ethanol consumption, which is in line with what was found by [57] and [33]. Moreover, the good practice policies help to reduce the need for carbon capture by up to 12% by 2050 to mitigate carbon emissions in carbon restricted scenarios, reducing the need of technologies with a lower level of technological readiness, confirming results of previous studies [58].

Carbon dioxide emissions in China are reduced by almost 20% with the implementation of the good practice policies by 2030, when compared to the CurPol scenario. The largest reductions occurring in the industrial, residential, and commercial sectors. By 2050, these policies lead to a reduction of more than 50% in carbon emissions, greatly driven by the reduction of emissions in electricity generation, with the share of coal-fired power plants being reduced below the levels presented by [59]. This reduction in the emission factor of the Chinese electricity grid allows for a greater reduction in Chinese carbon emissions further facilitated by the increased share of electricity of final energy, which achieves more than 42% of the final energy consumption by 2050. Compared to the baseline scenario, the good practice policies increase the share of renewable sources in the Chinese electricity matrix by 70% by 2050.

In the EU, the good practice policies present an opportunity to reduce carbon emissions from the power and industrial sectors, reducing them by almost 60% below their NDC scenario levels by 2050. The increased uptake of renewable energy significantly reduces the carbon content of electricity and leads to a large emission reduction across the EU economy, especially when combined with the increased electrification of energy services, through the uptake of electric vehicles and heat pumps. This shows an alignment with the 'no regret' policy decisions presented by [60] and [61], in which measures such as electrification, which is 34% higher in the GPP scenario than in the NDC scenario by 2050, can be considered for a sustainable and cost-effective EU transition to climate neutrality.

The application of good practice policies in India allows a 20% reduction in carbon emissions from energy supply by 2030, and a reduction of more than 90% in emissions in 2050, when compared to the NDC scenario. In the short term, the most effective policy instrument for India appears to be a carbon tax which would help to phase out fossil fuels from the system. Moreover, the GPP scenario can also contribute towards reducing the burden of mitigation in the later years by preventing problems such as technological lock-in of carbon-intensive technologies (especially coal-fired power plants). However, as presented by [62], such early actions may be more expensive in the short term. It is worth mentioning that this study focuses on climate/energy related policy impacts only, and as such it does not cover implementation costs (for studies analyzing costs in a cost optimal policies scenario, see [63] and [64]). For a detailed analysis on the cost and economic impacts of GPP scenarios at the global level, please see [7].

As in the European case, electrification in Japan occurs more significantly in the GPP and Bridge scenarios, and the good practice policies are presented as an opportunity to reduce Japanese emissions in the short term, as seen in [65] and [66]. The good practice policies are consistent with the emissions from the high budget scenarios presented in [66], which is compatible with the upper limit of emissions under the Paris Agreement. However, the good practice policies are more efficient in the buildings sector, while the increase in effort in the transport sector is marginal when comparing them with the results of [66].

In the case of Russia, good practice policies are capable of reducing emissions from the energy sector by more than half by 2050, while improving energy efficiency measures that reduce primary energy consumption, when compared to the NDC scenario. Similar to that presented in [67], the adoption of climate policies may weaken some barriers to new technologies in the energy sector, thus showing the importance of policies of good practices to bridge the gap for the Russian energy sector.

For the United States, good practice policies fail to prove to be more effective than the USA NDC, which is largely due to the Mid-Century Strategy for Deep Decarbonization, as presented in [50]. Therefore, the good practice policies are not sufficient to reduce USA carbon emissions, as its NDC is much more stringent in reducing carbon emissions.

2.5 Final remarks and conclusions

Most of the good practice policies play an important role in each region, with energy supply policies appearing as one of the biggest contributors to the reduction of carbon emissions over time. Namely, the alignment of the policy of renewable electricity share increase with the intensification of carbon pricing in the analyzed economies have shown to be a great contributor for closing the gap. Nonetheless, these policies are still not enough to completely close the emission gap. In fact, initial good practice policies have to be complemented, after 2030, by additional policies and measures, so as to emulate, as much as possible, the Bridge scenarios explored in this study.

Finally, there are two additional main issues that still need to be addressed, such as the homogeneity of these policies in such disparate countries/regions, and the political feasibility of the policy packages across regions and sectors. The first presents itself as the problem related to the development of a standardized set of good practice policies, given that each country/region has its own specificities, therefore requiring different approaches for implementation and further analysis to allow individual adaptation without compromising the endgame. Therefore, these policies must be reevaluated by policymakers in order to align them with each country specifically.

The second, is related to the political feasibility of policy packages and other social issues across regions and sectors, which in turn can be greatly facilitated by the way they are designed and implemented. Experience has shown that policy packages need to balance different objectives and administer their interactions to succeed and last long, so as to also reach additional objectives successfully from other policy domains [68]. It is also worth mentioning that alternative approaches to the NDCplus scenarios could also be used, such as the approach presented by [69], as the authors have considered a minimum decarbonization rate regarding CO2 emissions per unit of GDP. Complementing this, the NDC scenario is mainly used as a counterfactual to the good practice policies scenario.

This study has shown that the assessment of the implementation of good practice policies at the country/regional level can be used by policymakers to understand how these policies can add to each country's/region's NDC. Furthermore, these good practice policies can contribute to more ambitious NDCs aiming at a higher consistency with the objectives of the Paris Agreement, adding to the first global stocktake, which is due to take place in 2023. As a matter of fact, good practice policies should serve as a guide for the next global stocktake towards more ambitions NDCs, which later on will need to follow a pathway similar to that given by the Bridge scenarios, towards a below 2 °C world. In fact, complementary to this study, [7] present the results of global models, in which it is shown that rapidly implemented climate policies are more effective than delayed climate action. As long as there is no immediate climate policy, the good practice policies can put the world on a path more compatible with a 2 °C world, later on to be complemented by a Bridge scenario.

Data availability

Model results can be found in the COMMIT scenario explorer: `https://data.ece.iiasa.ac.at/commit/#/login?redirect=%2Fworkspaces`. Policy relevant data is available in the Global Stocktake tool: `https://themasites.pbl.nl/o/global-stocktake-indicators/#home`. The scenario data generated in this study have been deposited in the Zenodo database under accession code `https://doi.org/10.5281/zenodo.5163588`.

2.6 Good practice policies to bridge the emissions gap in key countries Supplementary material

This supplementary material aims to detail some of the methodological procedures followed in the manuscript, as well as to provide additional data developed in this research. Thus, the description of the models used in this study is presented in subsection 2.7.1, while section 2.8, presents other results complementary to those presented in the Results section of the manuscript.

2.7 Supplementary methods

2.7.1 Model description

PRIMES model description:

The PRIMES model is a structural partial equilibrium energy system model that quantifies the energy system developments for the EU and each of its Member States by 2050 and 2070, simulating the responses of energy consumers and suppliers to different economic, policy and technology developments. The model treats the decision-making of various stylized actors as a fully-fledged microeconomic problem, including its structural details, often embedding both engineering and economic features. PRIMES represents in an explicit and detailed way the energy demand for transport, buildings and industrial sectors, energy and electricity supply and various emission abatement technologies. It projects the future development of energy demand, fuel mix, technology uptake, capacity additions, investment requirements, energy costs and prices as well as energy-related CO_2 emissions under alternative policy scenarios in the 2015-2050 period [61]. Technology vintages are included in the modelling, while PRIMES is calibrated to Eurostat data for detailed energy balances. Detailed description of the model and most prominent applications can be found in literature [60, 70].

AIM/Enduse [Japan] model description:

AIM/Enduse [Japan] is a partial equilibrium, recursive dynamic model for Japan which is characterized by the detailed energy technology treatment in the energy demand sectors, as well as the energy supply sectors [65, 71]. The energy technologies are selected by linear programing minimizing total energy system costs, given exogenous parameters such as technology cost and efficiency, energy service demands, emissions constraints. The energy demand sectors are composed of industry, buildings, and transportation sectors, and they are disaggregated into several subsectors with respect to types of products, buildings, and transportation mode. In the industry, building and transportation sectors, wide mitigation options are included, such as energy-efficient devices and fuel switching. It covers 10 sub-regions in Japan which is broadly coinciding with the areas of 10 public power supply firms, to consider characteristics of energy supply and demand across the various regions.

BLUES model description:

BLUES is a partial equilibrium, perfect foresight, least-cost optimization model for Brazil, covering the energy, industrial, transport and AFOLU sectors representing 5 geographic sub-regions of Brazil, which are interconnected with the rest of the world through trade. The BLUES model includes all GHG emission gases and sources by sector. The model incorporates a detailed representation of the energy and land uses systems, with over 28,000 technologies included [33, 55] and `https://www.iamconsortium.org/resources/model-resources/brazilian-land-use-and-energy-system-blues/`.

AIM/CGE [Korea] model description:

AIM/CGE [Korea] is a general equilibrium, recursive dynamic model for Korea, covering building, industrial, transportation, energy supply and AFOLU sectors. This model contains 42 industrial classifications. Supply, demand, investment, and trade are described under individual behavioral functions that respond to changes in the price of production factors and commodities, as well as changes in technology and preference parameters on the basis of assumed population, GDP, and consumer preferences. This model simulates national scenario by treating exogenous parameters such as technology share, efficiency, energy service demand management, emissions constraints [72].

GCAM-USA Description:

The Global Change Analysis Model (GCAM) is an open-source global integrated assessment model (IAM) with representations of energy, economic, agriculture, land, and water systems and their interactions in 32 geopolitical regions in the world [73, 74]. The version of the model used in this study, namely, GCAM-USA, disaggregates the economic and energy systems of the United States into the 50 states and the District of Columbia [48, 75]. The version of GCAM-USA used in this study is calibrated to 2010. The model operates in five-year time steps through 2100 but the focus of the present study is 2050. GCAM-USA is a partial equilibrium model that solves for equilibrium prices and quantities of several hundred energy, agricultural, and GHG markets in each time period and region. GCAM-USA is embedded within the global GCAM model. Hence, prices, supplies, and demands, within the states are consistent with international conditions. Key inputs into GCAM-USA include population, labor participation, and labor productivity, and representations of resources, technologies, and policies for the 32 geo-political regions and the 50 states and D.C. Activity in the energy, agriculture, and land-use systems produce emissions of 16 GHGs which are tracked endogenously. More details about the model, its assumptions, and structure can be obtained from the documentation website (`http://jgcri.github.io/gcam-doc/gcam-usa.html`).

India MARKAL model description:

India MARKAL model is a single region, national level energy system model based on the MARKAL (MARket ALlocation) modeling framework. The framework is a bottom-up, dynamic, least-cost optimization model following perfect foresight and rational expectation hypothesis. The model is set-up over a period of 2001 to 2051 at five-yearly intervals with a detailed representation of the energy sector in India. It primarily covers CO_2 emissions emanating from energy production (i.e., electricity generation) and use (in agriculture, residential, commercial, industrial and transport sectors). The end-use demands are exogenously estimated based on GDP, population, and past trends. The model incorporates around 100 energy conversion technologies, around 300 end-use technologies and both conventional (fossil fuels) and modern (solar, wind, nuclear, biofuel, etc.) forms of energy [62, 76, 77].

TIMES-AUS model description:

TIMES-AUS is an Australian implementation of the TIMES (The Integrated MARKAL-EFOM System) energy system modelling framework developed and maintained by the Energy Technology Systems Analysis Programme (ETSAP) of the International Energy Agency (IEA). TIMES-AUS divides Australia into 8 regions (6 states and 2 territories) with a detailed representation of demand sectors including agriculture (8 sub-sectors), mining (6 sub-sectors), manufacturing (19 sub-sectors), other industry (5 sub-sectors), commercial and services (11 building types), residential (3 building types), road transport (10 vehicle segments) and non-road transport (aviation, rail, shipping). The electricity sector in TIMES-AUS has generators mapped to 19 transmission zones with sub-transmission zone spatial resolution of renewable resource availability. The model has been used to inform near- and long-term abatement trajectories [78] including net-zero emissions [79].

GCAM-Canada model description:

GCAM-Canada is a variant of the Global Climate Assessment Model (GCAM) that is maintained and used Environment and Climate Change Canada (ECCC). GCAM-Canada is a global recursive-dynamic integrated assessment model with 32 world geo-political regions (including Canada as a region) with technology-rich representations of the economy, energy sector, land use and water linked to a climate model. GCAM-Canada is uniquely parameterized to capture the Canadian energy supply and demand market dynamics. It covers detail energy system flow from resource extraction to final energy consumptions with energy integration to agriculture and land use activities. The model further integrates human activities to the climate model to assess the anthropogenic emissions impact into global climate change.

RU-Times model description:

The RU-TIMES model is based on the Integrated MARKAL-FOM System aimed at modeling and long-term planning of energy systems and technological processes. The model covers major sectors and industries of Russian economy, including energy industries (power and heat, oil, gas, coal, nuclear, renewables, etc.), ferrous and non-ferrous metallurgy, transport, chemical and petrochemical industry, residential and commercial buildings, foreign trade with energy resources [80]).

IPAC-AIM/technology model description:

See `http://ipacâĂŘmodel.org.cn/About%20IPAC%20Model.html`

DDPP Energy model description:

The model is developed using GAMs based (v.2.5) - AIM EndUse and AIM ExSS. The AIM Enduse covers technology selection based on least cost to marginal abatement cost). The AIM ExSS for the projection of energy demand.

2.7.2 Scenario Implementation

Table 2.2: Implemented scenario by national model

Model/Scenario	CurPol	NDCplus	GPP	Bridge	2Deg2030
TIMES-AUS	x	x	x	x	x
BLUES	x	x	x	x	x
IPAC	x		x	x	
GCAM Canada	x	x	x	x	x
PRIMES	x	x	x	x	
India MARKAL	x	x	x	x	x
DDPP Energy			x		
AIM/Enduse	x	x	x	x	x
AIM/CGE	x	x	x	x	x
RU-TIMES		x	x	x	x
GCAM USA	x	x	x		

2.8 Supplementary results

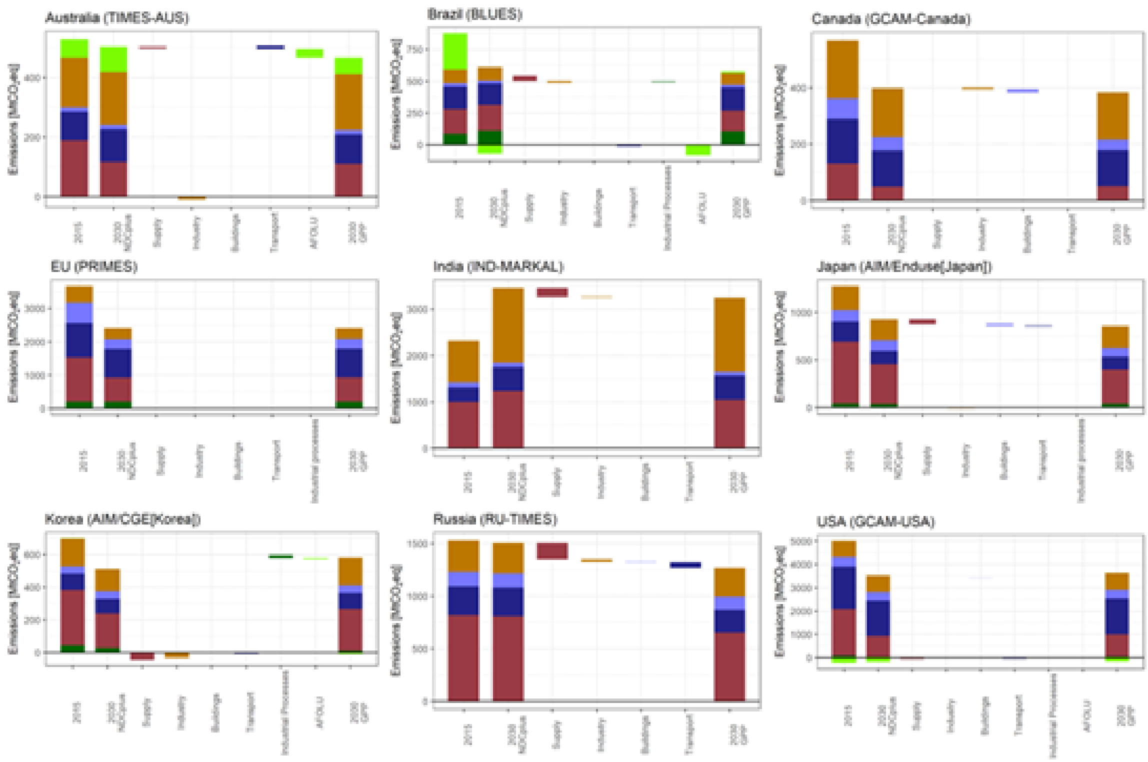

Figure 2.5: Contribution of each sector to the reduction of carbon emissions between the NDCplus and GPP scenario in 2030. 2015 emissions are shown for comparison (Negative values represent an increase in emissions between the compared scenarios). Different scales are applied to better read the results of each region

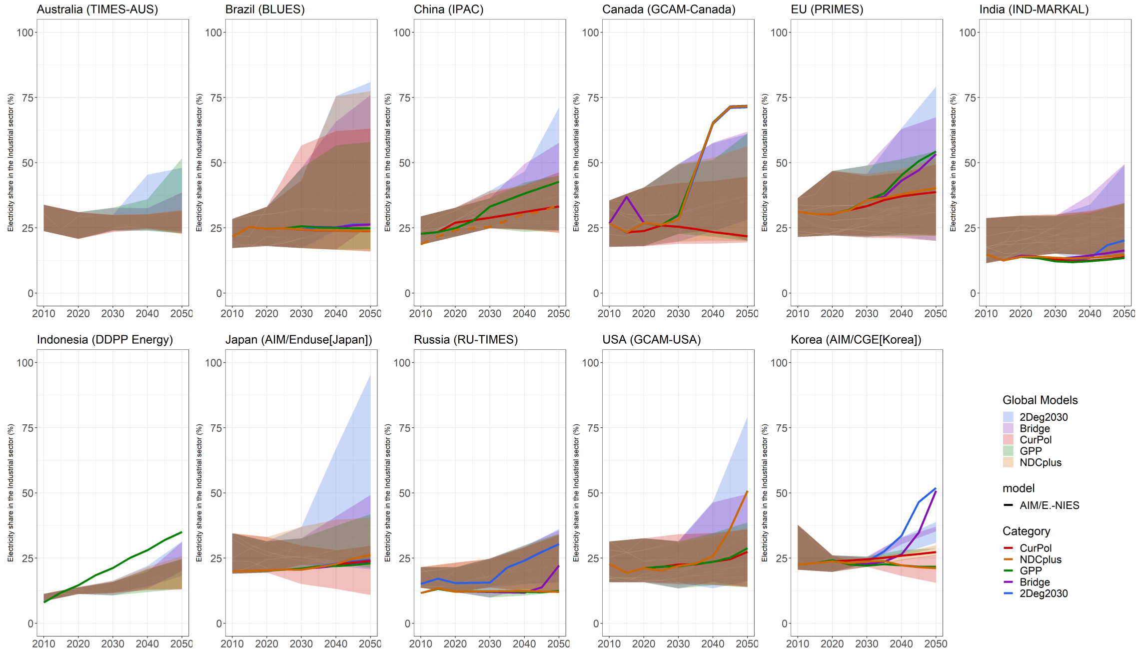

Figure 2.6: Share of electricity in the industrial sector from national/regional models (lines) and global models (wedges)

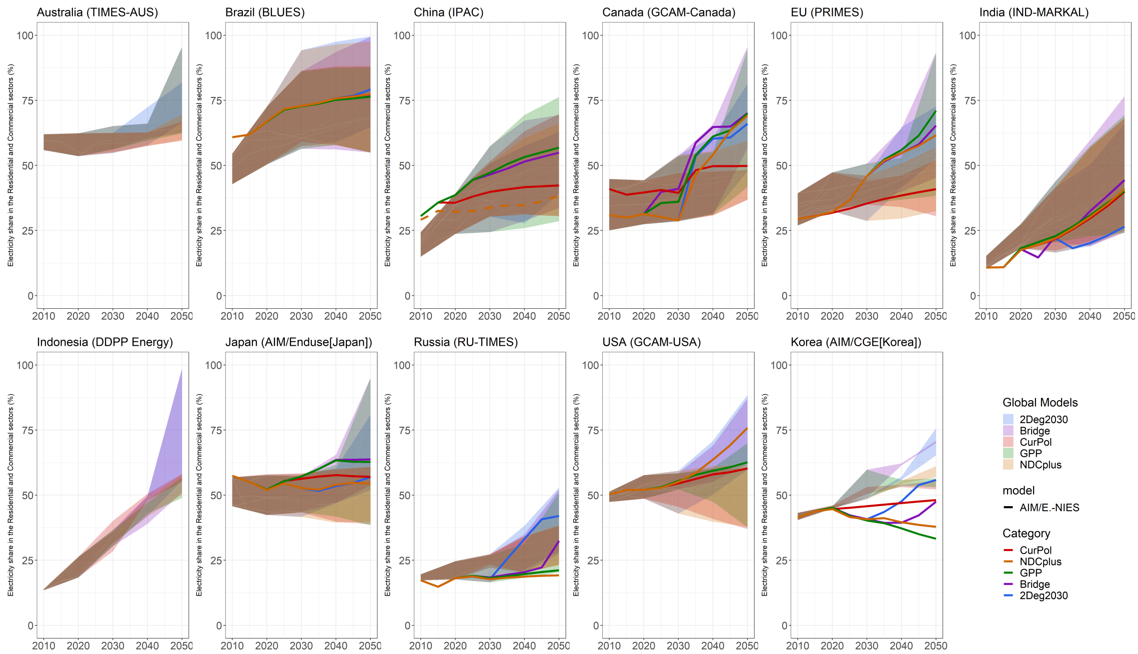

Figure 2.7: Share of electricity in the residential and commercial (buildings) sectors from national/regional models (lines) and global models (wedges)

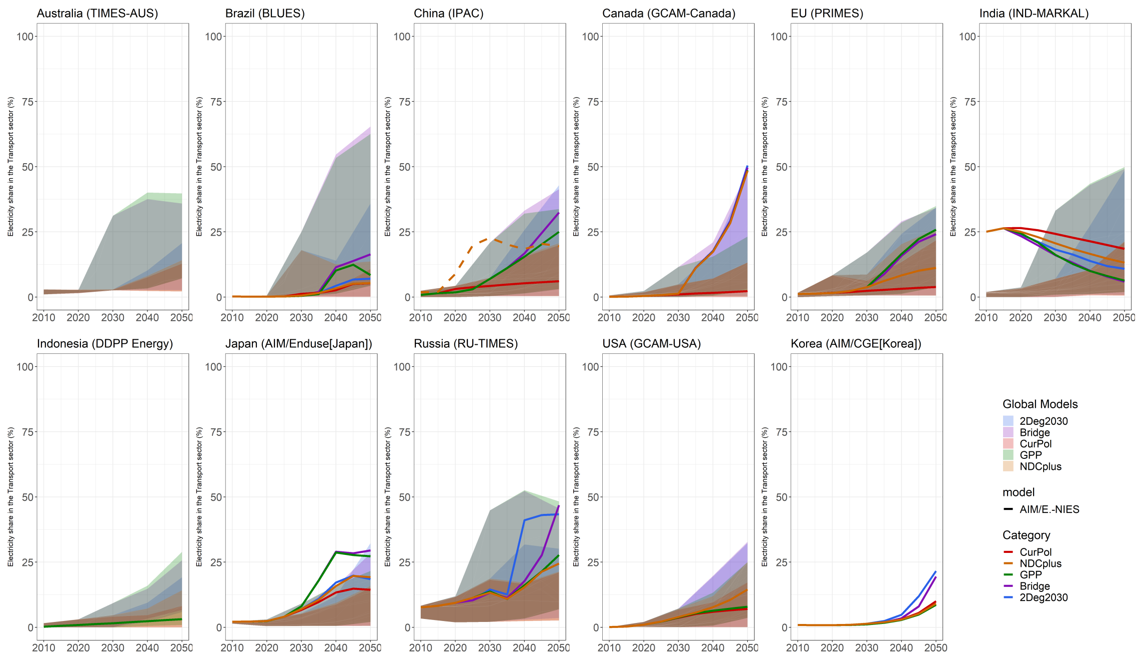

Figure 2.8: Share of electricity in the transportation sector from national models (lines) and global models (wedges)

Chapter 3

Is green recovery enough? Analysing the impacts of post-Covid economic packages

Rochedo, P. R. R., Fragkos, P., Garaffa, R., Couto, L. C., Baptista, L. B., Cunha, B. S. L., Schaeffer, R., & Szklo, A. (2021). Is Green Recovery Enough? Analysing the Impacts of Post-COVID-19 Economic Packages. Energies, 14(17), 5567. https://doi.org/10.3390/en14175567

Abstract

Emissions pathways after COVID-19 will be shaped by how governments' economic responses translate into infrastructure expansion, energy use, investment planning and societal changes. As a response to the COVID-19 crisis, most governments worldwide launched recovery packages aiming to boost their economies, support employment and enhance their competitiveness. Climate action is pledged to be embedded in most of these packages, but with sharp differences across countries. This paper provides novel evidence on the energy system and greenhouse gas (GHG) emissions implications of post-COVID recovery packages by assessing the gap between pledged recovery packages and the actual investment needs of the energy transition to reach the Paris Agreement goals. Using two well-established Integrated Assessment Models (IAMs) and analysing various scenarios combining recovery packages and climate policies we conclude that currently planned recovery from COVID-19 is not enough to enhance societal responses to climate urgency and should be significantly upscaled and prolonged to ensure compatibility with the Paris Agreement goals.

3.1 Introduction

The impact of the COVID-19 pandemic on climate change mitigation will ultimately depend on long-term trajectory shifts caused by economic recovery [81]. The emission reduction rate observed during the restrictive confinement period in the first half of 2020 is broadly comparable to the annual emission reduction rate needed to achieve the 1.5 °C target [82]. However, the sharp 7%drop in emissions experienced during 2020 is likely to reflect only the very short term, not causing any lasting effect since the previous fossil-fuel based infrastructure is still in place and could rapidly get back to full-capacity [83, 84]. IEA [85] has predicted a major surge in CO_2 emissions from the energy sector in 2021, as the world rebounds from the pandemic via accelerating rollouts of Covid-19 vaccinations in several countries and extensive fiscal responses to the economic crisis. Emissions pathways after COVID-19 will be shaped by how economic responses translate into infrastructure expansion, energy use, investment planning and societal changes.

The urgency to curb greenhouse-gas (GHG) emissions and attain the Paris Agreement temperature goals is now at risk of being overlooked by the need for an economic response to the COVID-19 pandemic crisis. The economy-wide recession has led to a steep decrease in oil and gas prices and a widely agreed need for governments to intervene with substantial economic stimulus [86], which could propel or undermine the energy transition, depending on future investment profiles [87].

Arguably, both the climate crisis and the pandemic-related crisis should be tackled at once through a low-carbon economic response, by ensuring that large funding is directed to clean energy [81]. As a response to the COVID-19 crisis, most governments worldwide have launched recovery packages aiming to boost their economies, support employment and enhance their competitiveness [88]. Climate action is embedded in most of these packages, but with sharp differences at regional level.

The European Union has launched a € 750 billion recovery package from which at least 30%of expenditure is committed to mainstreaming climate action [38]. The United States Biden administration, similarly, has launched a “Build Back Better plan” which aims at canalising US$2 trillion low-carbon investment, including US$400 billion directly to clean energy over the next ten years [39]. In contrast, an economic recovery based on low oil prices, such as the stimulus announced by Indonesia, Turkey and Russia [89], and investment in traditional infrastructure would hinder progress towards limiting global temperature rise and would increase the risk of locking our economies into a high-emission trajectory.

Climate change research addresses long-term impacts of current and mid-term decision-making through modelling to respond to 'what if' questions. They assess the long-term impacts of policies and societal changes over emissions and consequent temperature changes. Scenarios play a key role as long-term research tools for the transition to a low-carbon world. The analysis of common scenarios using multiple modelling frameworks allow the research community to produce integrated and comparable analyses of climate change impacts, adaptation and mitigation [90, 91]. The effort of providing shared scenarios is crucial to promote interactions among disciplines and research interests, to make conclusions compatible and consistent across the literature, to allow easier communication of modelling results, as well to reduce scattered individual efforts towards elaborating consistent assumptions for their own scenarios [91].

While the scenario framework used by the Intergovernmental Panel on Climate Change (IPCC) and other authors [1, 61, 90, 92–94] still serves as the basis for future narratives and mitigation pathways, COVID-19 raises a substantial policy shift, which impacts mitigation in the long-run, as it changes the core socio-economic assumptions underpinning these scenarios, the investment planning in various countries and (potentially) consumer behaviour (e.g. through reduced air transport and increased home working). The climate research community will therefore have to update scenarios reflecting such trade-offs in order to analyse future pathways from the COVID-19 pandemic onwards and inform policy debate on appropriate ways of allocating recovery funds.

This paper draws on the existing IPCC scenario framework [1, 92] to advance the field by including potential long-term impacts of policy responses to what is plausibly believed to be the harshest societal crisis of the century: the COVID-19 pandemic. We provide novel evidence on the energy system and emission implications of post-COVID recovery packages by revealing the wide gap between pledged recovery packages and the actual investment needs of the energy transition. We test the hypothesis that currently planned recovery from COVID-19 will undermine the response to climate urgency by modelling post-COVID-19 scenarios until 2050 through two different modelling frameworks: the COFFEE-TEA and the PROMETHEUS IAMs [95].

3.2 Materials and Methods

The following sections describe the modelling frameworks and the scenarios designed for this study, together with our analyses on current recovery packages.

3.2.1 Modelling framework

This study uses two different modelling frameworks to assess the impacts of green recovery packages. The COFFEE-TEA IAM suite of models [96] comprehends a bottom-up, partial equilibrium, global model for the energy and land systems (COFFEE - COmputable Framework For Energy and the Environment) soft-linked to a global Computable General Equilibrium (CGE) model, the TEA - Total Economy Assessment model. COFFEE represents the optimal pathway for the interaction and uptake of technologies and energy sources to meet a given demand for energy services, by minimizing the total cost of the system from pre-established policy restrictions. The model captures the evolution of sectors such as energy, industrial processes, AFOLU, waste and others and their respective GHG emissions until 2100, including a detailed representation of energy resources, extraction and conversion technologies for each region, both in terms of volume and costs. TEA is a multi-regional and multi-sectoral model that represents the production and trade of goods, capturing industry-to-industry linkages, in the global economy [97]. TEA follows the standard microeconomic optimization framework, assuming total market clearance and perfect competition. The TEA model provides consistent macroeconomic pathways, projecting future economic activities' demands to COFFEE, while COFFEE improves the representation of energy markets in TEA, given their compatibility in terms of base year data, sectoral and regional disaggregation.

PROMETHEUS is a comprehensive energy system model focusing on technology uptake analysis,energy price projections, and assessment of climate policies [98, 99]. It captures the interactions between energy demand and supply at regional and global level and provides detailed projections of fuel mix in energy consumption, electricity production mix by technology, carbon emissions, energy prices and investment to the future.PROMETHEUS can provide medium and long term energy system projections up to 2050, both in the demand and the supply sides, under different policy and technology scenarios.

Most importantly, the modelling frameworks can be used for the impact assessment of energy and environment policies at regional and global levels, including price signals, such as carbon or energy taxation, subsidies, technology and energy efficiency promoting policies, Renewable Energy Systems (RES) supporting policies, and technology standards [33, 98]. The modelling frameworks are therefore designed to address the questions about the short-, medium- and long-term effects of post-COVID-19 economic recovery based on long-term scenarios for global GHG emissions, capturing the extent to which pledged recovery packages manage to avoid carbon lock-in given key assumptions that drive investment in the energy system (e.g., oil prices, cost of technologies, efficiency, lifespan). For detailed information about the modelling frameworks, see Appendix.

3.2.2 Scenario design: COVID-19 economic recovery packages screening and modelling

We depart from a baseline (CurPol) scenario framed within the Shared Socioeconomic Pathway - SSP2 "middle of the road" [100] rationale, but applying short-term regional GDP growth shocks due to COVID-19. We use short-term projections of the COVID-19 pandemic impact from the International Monetary Fund World Economic Outlook updated in October 2020 [101] and the OECD Economic Outlook of December 2020 [102]. The CurPol scenario does not comprise any additional economic recovery policy or climate policy apart from the policy framework currently in place, which is described in detail in [12]. From 2025 onwards the SSP2 GDP growth rates are applied.

In order to design scenarios reflecting policies launched as a response to the COVID-19 economic crisis, we screened policy packages announced up to May 2021 for investment in three main technology groups related to low-carbon transition: Power generation, Energy Efficiency and Transport. For this purpose, we assessed government plans and tools created specifically to analyse the greenness and brownness of post-COVID-19 stimulus, namely: the Green Recovery Plan Tracker [103], the Energy Policy Tracker [89], the Climate Action Tracker [104] and the Greenness Stimulus Index [40]. When regional trend data are needed, the IEA Country Statistics [105] are used.

Markedly, the European Union and the United Kingdom led in terms of launching green recovery plans still in 2020. The Next Generation EU Recovery Plan, consistently with European Green Deal, commits at least 30%of its €750 billion budget to climate action, while the remaining 70%should follow the principle to "do no harm" to the environment [38]. At the same time, countries like France and Germany, as well as the UK, outperform in the greenness of their stimulus packages, with a net positive impact towards climate action [40]. Besides, the Energy Policy Tracker traced no commitment to direct fossil fuel support from the European Commission, in contrast with a US$385.36 commitment to clean energy investment [89].

China still faces major uncertainties regarding the emission profile of its economic recovery plans. While China has announced a target for net zero carbon emissions by 2060, and committed additional US$22 billion to clean energy investment when compared to fossil fuel energy [89], it still plans to install as many new GW of coal power plants as its previous trajectory [40]. The US has notably the largest economic stimulus package in the world. In the early stages of the pandemic, the US administration pledged US$2.98 trillion of public expenditure, which included environmental measures for the power, industry, manufacturing and transport sectors, involving, for example, penalty exemptions. The US overall energy investment commitment originally included US$72.35 billion to oil, oil products and coal, and US$27.27 billion to support clean energy, mostly directed to biofuels and wind power [89]. A clear shift took place when, in 2021, the Biden administration committed to "Make a historic investment in clean energy and innovation" pledging additional US$400 billion to renewable energy investment [39].

Economies that heavily rely on fossil fuel exploitation like Russia and Middle Eastern countries unsurprisingly indicate a fully brown recovery [40, 89]. The remaining world regions seem to show rather dubious stimulus profiles, with investment directed both ways, however, mostly showing brown net impacts.

Having screened national and regional policy packages for the post-COVID19 pandemic economic responses, we translate them into assumptions for each of the scenarios and their main policy instruments (Table 3.1). The Recovery Packages scenario (RecPac) assumes the implementation of plans for investments on a portfolio of green energy options in different countries, amounting USD 1 trillion over the 2020-2025 period. In both IAMs green recovery packages are implemented as investment subsidies to low-carbon technologies, including solar PV, wind, electric vehicles, biofuels, heat pumps and efficiency measures. The implementation of subsidies incentivises the uptake of clean energy technologies in power production, transport and buildings sectors.

Given that economic recovery packages comprise broader sectoral coverage than solely green energy and that investment in infrastructure requires longer maturity, we further assess the implications of a 5-fold increase in green energy investments as compared to the RecPac scenario. We call it the Enhanced Recovery scenario (EnhRec), where the total amount invested in green energy reaches approximately USD 5 trillion over the 2020-2025 period, which is in line with the 3-year extension of the recovery packages found in [87]. The scenario conceptualises a situation of prolonged needs for recovery packages, given that most countries face challenges to fight new COVID variants, upscale vaccination rates and boost their economies. It gives an indication of how much investment in green energy is required in order to support the energy transition.

To assess the ambition gap of the recovery packages in previous scenarios we simulate a Climate Ambition scenario (CliAmb) that is based on a remaining carbon budget of 600 $GtCO_2$ over 2018-2100, considered compatible with a 1.5 °C average global warming by 2100 without temperature overshoot [106]. In this scenario, we simulate an economy-wide, global carbon market, in the form of an emission trading system in TEA, with the resulting carbon prices taken as input to COFFEE.

Finally, we also account for inter-regional disparities by simulating a Global Governance scenario (GloGov) in which the total amount of green recovery funds is allocated globally (i.e., investments are not restricted to each region). We acknowledge the fact that a mechanism of global governance is extremely difficult to be implemented in the context of the COVID-19 pandemic. Therefore, the results of the GloGov scenario should be interpreted as an hypothetical exercise, reflecting the global least-cost optimal solution of the modelling framework, given the green energy technological portfolio included in the two IAMs. The models therefore allocate the total sum of each pledged recovery package to choose the optimal set of technologies and their locations.

Table 3.1: Summary of policy scenarios

Scenario	Tag	Policy Instruments	Description
Baseline	CurPol	Current policies	Current energy and climate policies. Short-term COVID-19 socio-economic impacts are included, but recovery packages are not.
Recovery Packages	RecPac	CurPol + Direct investment, subsidies	Recovery packages implemented as investment in green energy technologies reflecting national policies announced up to May 2021.
Enhanced Recovery	EnhRec	CurPol + Direct investment, subsidies	Green energy investments are increased by 5 times as compared to the RecPac scenario to cover the 2021-2025 period.
Climate Ambition	CliAmb	Carbon pricing	Long-term pathways consistent with a well below 2 °C average global warming by 2100 based on a carbon budget of 600 $GtCO_2$ over 2018-2100 without temperature overshoot.
Global Governance	GloGov	CurPol + Direct investment, subsidies	Total amount of recovery packages announced up to May 2021 implemented as investment in green energy technologies globally (modelling framework optimal choice).

We translate the green recovery packages into variables and parameters to be simulated in the modelling framework. The recovery packages were inserted in the modelling tools by changing specific parameters depending on model formulation, in partiular by imposing additional investment in low-carbon technologies exogenously or by inserting subsidy rates in the capital costs to reduce the purchase price and accelerate the deployment of mitigation options. We start by allocating the amount of packages to sectors following the allocation proposed by the IEA (2020) [88]. In particular:

- 33% of the total amount goes to power generation, mostly in renewable energy technologies (wind and solar) but also to grid enhancements to support the increased uptake of variable renewable sources;
- 30% of the total amount is directed to low-emission transport modes, mostly in the purchase of electric cars;
- 30% of the total amount goes to increase energy efficiency and electrification of buildings; and
- The remaining 7% is directed to increase energy efficiency in industrial sectors.

After setting the sectoral allocation, we define what instruments are used in each sector. Here our choice is somehow limited by the modelling framework – typically, bottom-up models with rich technological detail –, so we mainly explore supply-side instruments, not including demand-side instruments that could play a role in a green recovery context (e.g., consumer behaviour, digital services, lifestyle changes).

On the supply-side instruments, we therefore rely on direct investments for the expansion of renewable energy, mostly to wind and solar PV, as well as to grid enhancements to support the increased penetration of variable RES; subsidies on the purchase of electric vehicles and other zero-emission alternatives in the transport sector; and direct incentives through reduced prices of efficient equipment purchases and subsidise costs to increase renovation rates and accelerate the deployment of heat pumps and other low-emission options in buildings.

3.3 Results

In this section, we present the results of the different policy scenarios. The IAMs depart from similar/comparable but different baselines (CurPol), and so the modelling results should be interpreted in relative terms when comparing them across the modelling frameworks.

3.3.1 Policy scenarios (national pledges)

Figure 3.1 describes the global CO_2 emissions pathway of each modelling framework by scenario from 2020 to 2050. In the RecPac scenario, COFFEE shows a small decrease in global emissions between 2020 and 2025, mostly reflecting short-term effects of the investment in green energy. In the absence of additional stimulus to green energy, this trend is however reversed from 2025 onwards, with emissions returning to the original pathway of the CurPol scenario and achieving 34.7 $MtCO_2$ in 2050. The emissions trajectory in PROMETHEUS presents similar behaviour as COFFEE in RecPac, particularly after 2025, with the model reaching 40.9 $MtCO_2$ in 2050, showing a decline of 1-2 Gt annually from CurPol over 2020-2050. PROMETHEUS shows larger reduction of global emissions from CurPol levels in the short-term (by 2025), induced by the implementation of green recovery measures as investment subsidies stimulating the increased uptake of renewable energy, electric vehicles, and energy efficiency.

In the EnhPac scenario, the additional investment in green energy leads to larger mid-term effects in terms of emissions mitigation in both models - with global emissions declining by [9.6%-13.2%] in 2025 and [6.2%-15.3%] in 2030 from Cur Pol levels. This shows that the prolongation of green recovery packages can support further emission reductions and partly close the emissions gap with the cost-optimal pathway to 1.5 °C in 2030. However, if not combined with ambitious climate policy, alone they are not sufficient to trigger structural changes towards net zero by mid-century, with global emissions amounting to [34.0-38.9] $GtCO_2$ across models in 2050, which is clearly not compatible with the goal of carbon neutrality by 2050.

Figure 3.2 presents the ambition gap for different scenarios in 2030. The ambition gap accounts for the difference in global CO_2 emissions between the policy scenarios (RecPac and EnhPac) and the more ambitious mitigation scenario compatible with the Paris Agreement goal of 1.5 °C (CliAmb). The implementation of recovery packages results in limited emission reductions, thus closing only a small part of the emission gap from the 1.5 °C cost-optimal pathway in 2030 (3%-7% across models in the RecPac

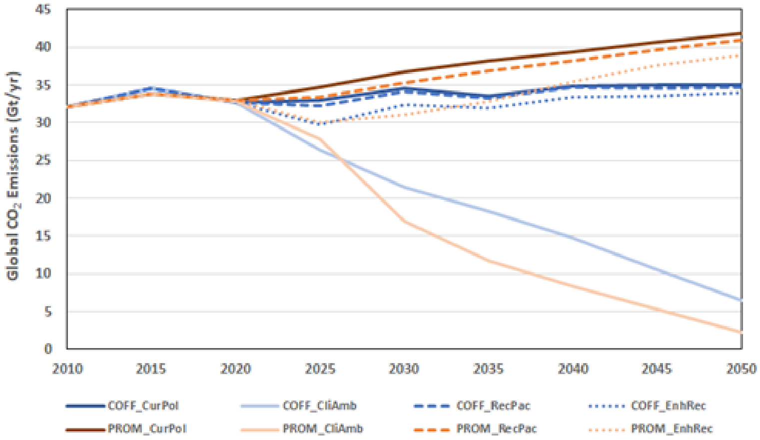

Figure 3.1: Global CO_2 emissions pathway over 2010-2050

scenario). The Enhanced Recovery scenario leads to larger mitigation, closing (16%-29% across models) of the ambition gap in 2030.

The impacts by 2050 are even smaller, with recovery packages representing about [1%-7%] of the overall effort towards the Paris Agreement goal of 1.5 °C. The impacts of green recovery packages vanish in the longer term, as in the absence of strong climate policy signals for investment in green energy and reducing fossil fuel use beyond 2025, emission pathways return to their CurPol trends with limited reductions until 2050.

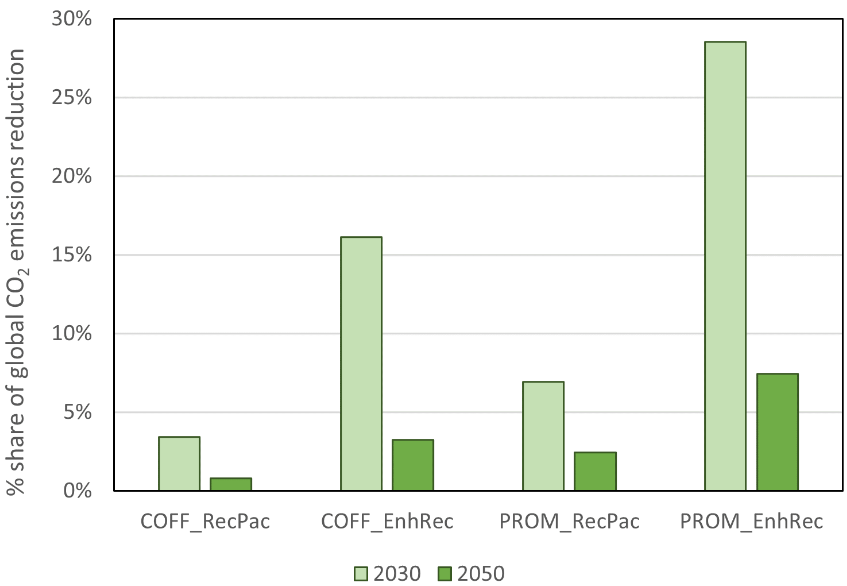

Figure 3.2: Closing the ambition gap - share of global CO_2 emissions reduction from CurPol levels achieved in RecPac and EnhRec scenarios compared to reductions required to achieve the 1.5 degree target in a cost-optimal way in 2030 and 2050

Mitigation in policy scenarios comes as a consequence of changes in the energy system, triggered by the increased deployment of renewable energy, energy efficiency, low-carbon fuels and electrification of energy services [98]. Figure 3.3 presents the results of both modelling frameworks under alternative policy scenarios in 2030 and 2050 for: (a) final energy consumption; (b) changes in total energy use of the transport sector; (c) the share of renewables in electricity generation; and (d) the global emission factor of electricity generation (CO_2 emissions per MWh produced). The bars in Figure 3.3 describe the results for the ambition gap – i.e., the difference between CliAmb and CurPol scenarios –, while the empty dot and the filled dot represent the levels achieved in RecPac and EncRec scenarios, respectively.

Figure 3.3 shows low to moderate changes in final energy consumption in RecPac and EnhPac scenarios [-0.2% to 10.6%]. Final energy use in COFFEE shows a more similar trajectory in these scenarios than in CliAmb, while PROMETHEUS presents a more substantial reduction of final energy consumption in the long-term, particularly due to energy efficiency measures and to a more rapid electrification of the transport sector.

As illustrated in Figure 3.3, PROMETHEUS shows a reduction of transport-related energy consumption of nearly -33% in 2030, while the penetration of electric vehicles in COFFEE is more moderate, which combined with a greater use of biofuels, leads to a reduction of around -7% in 2030. Given the lack of long-term climate policies to increase the uptake of low and zero-emission vehicles, the projected reduction of energy consumption in transport declines over time, ranging from -0.1% to -8.1% in 2050.

Nonetheless, results suggest that the green recovery packages promote a greater transformation in the power sector, in particular due to a fast increase in wind and solar PV electricity generation. In both RecPac and EnhRec scenarios, the share of renewable energy in electricity production reaches substantial levels in 2030 [32%-37% in RecPac and 38%-44% in EnhPac], lying within the projected range of the CliAmb scenario. Although pushed by the green recovery packages, results confirm that the penetration of renewables in electricity generation is not solely driven by the packages and a greater share than in 2030 is reached by mid-century driven by technology cost reduction and increased adoption of renewable energy technologies [43%-54% in RecPac and 47%-57% in EnhRec].

The transformation of the energy system can also be illustrated by the global emission factors of electricity generation (Figure 3.4). Over 2030-2050, emission factors decrease from a range of [313-380 $MtCO_2/MWh$] to [185-287 $MtCO_2/MWh$] as a result of the decarbonisation of the power system, showing substantial decrease as compared to 2015

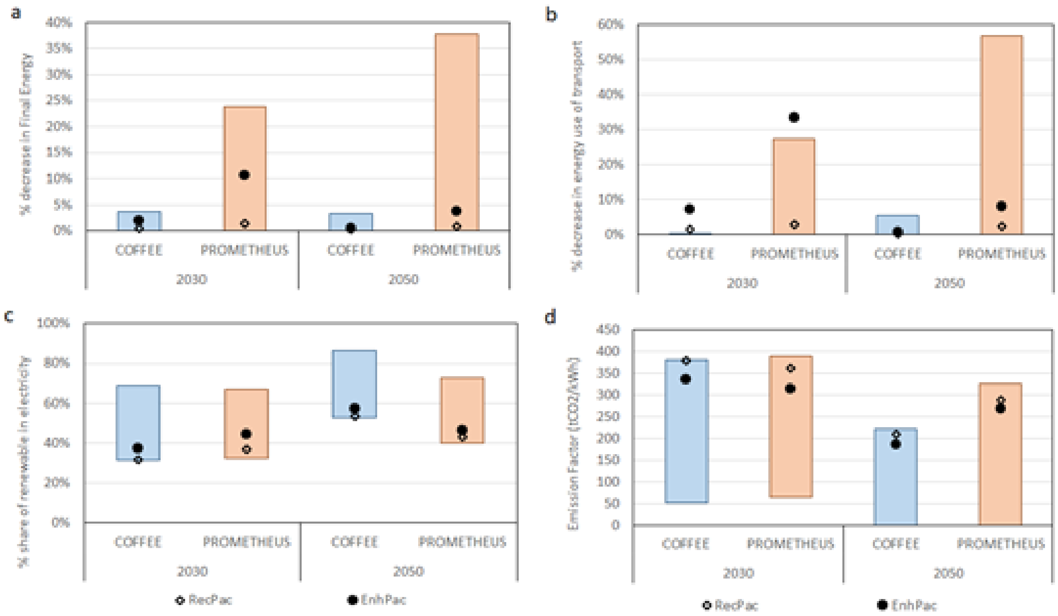

Figure 3.3: Energy system transformation - decrease in final energy consumption (a); decrease in energy use of transport (b); share of renewables in electricity generation (c); and global emission factor of electricity generation (d) in 2030 and 2050.

[485-576 $MtCO_2$/MWh]. However, although in the upper ranges of the CliAmb scenario, these levels are far from meeting the lower bounds in 2030 [52-64 $MtCO_2$/MWh] or even zeroing emissions in 2050 as required to meet the Paris Agreement goals of 1.5 °C.

Closing the ambition gap comes at different costs across the modelling frameworks. Figure 3.4 presents the results for the green energy investment required to close the gap in 2030 and 2050. In the horizontal axis, investment gap is the level of cumulative investment[1] in policy scenarios compared to the level of the more ambitious mitigation scenario (CliAct). In the vertical axis, the emission gap is shown. In Figure 3.4, numbers for RecPac and EnhRec scenarios are summarized as COFFEE and PROMETHEUS Standard, while results for the GloGov scenario appear as COFFEE Global Optimal.

Green recovery packages close a high fraction of the investment gap in 2030 [17%-35% in RecPac and 79%-116% in EnhRec], but a relatively smaller part of the emission gap [3%-7% in RecPac and 16%-29% in EnhRec]. This result suggests that other policy instruments that incentivise changes not only in the investment patterns, but also in the use patterns of energy infrastructure, vehicles, appliances and equipment are required to achieve greater levels of mitigation (e.g. carbon pricing that penalises the use of fossil fuels).

[1]Present value (PV) in 2020 of the level of investment over 2020-2030, discounted at a 5% p.y. rate.

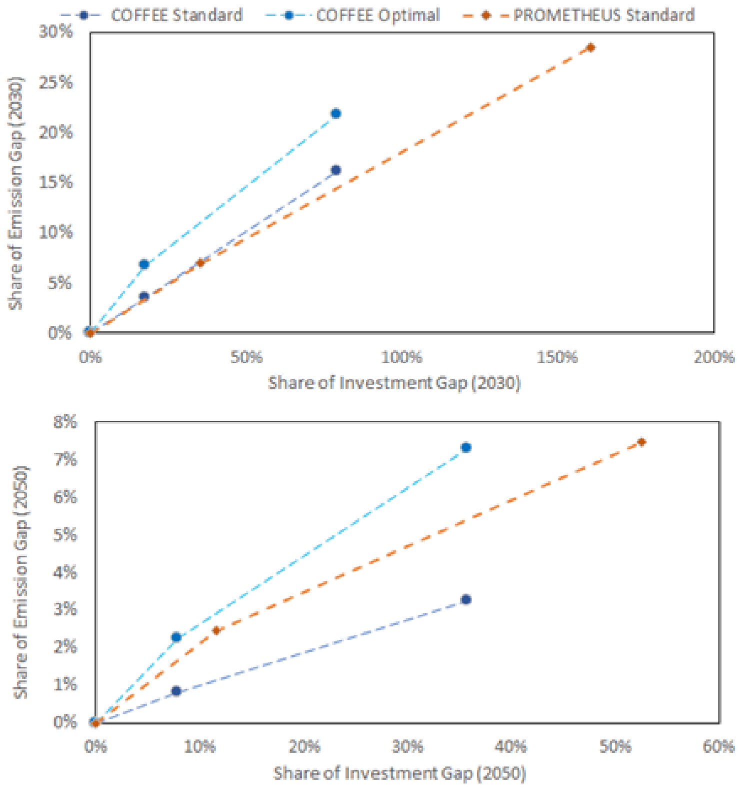

Figure 3.4: Ambition gap and investment gap in 2030 and 2050.

We also note that, in CliAmb scenario, carbon prices in the global emission trading system rise from USD 29/tCO_2 to USD 55/tCO_2 over the 2025-2050 period, corresponding to a total revenue of USD 643 billion in 2025 and USD 1,082 billion in 2050. The simulation of a comprehensive carbon pricing instrument adds to our analysis of a green economic recovery by providing a few insights. First, the total revenue of the carbon market serves as a proxy of what the figures at play are and how they compare to the amount of the green recovery packages announced – for instance, green recovery amounts to USD 1 trillion, while our simulations suggest a global carbon market of USD 2.3 trillion over the 2020-2025 period. Second, carbon pricing is widely regarded as a cost-effective instrument by internalizing the cost of the pollutants in the prices of goods and services, therefore reducing the costs of the climate policy. As illustrated in Figure 3.4, despite the substantial effort in closing the investment gap, policy instruments included in the green recovery packages are less efficient in terms of closing the ambition gap. Third, in CliAmb, a global carbon pricing is in place over the full period, highlighting the relevance of long-term signals to abate emissions, in contrast to the instruments included in the green recovery packages that do not provide long-term signals and are discontinued after 2025.

3.3.2 Global Governance

Differences across the RecPac/EncRec and GloGov results also reveal that going global achieves greater reduction of worldwide emissions than implementing national green recovery strategies independently. By simulating a hypothetical mechanism of global governance (GloGov scenarios), results suggest a further reduction of 4-6 percentage points in global emissions relative to the scenarios where recovery packages are simulated following national pledges, meaning that a greater share of the emission gap is achieved with the same amount of money invested, thus increasing the overall cost-efficiency of recovery packages. However, recovery packages announced up to May 2021 are highly concentrated in developed regions, particularly in Europe and North America. Investment allocation by regions and sectors in the Global Governance scenario in 2030 is presented in Figure 3.5. The modelling framework optimal choice leads to a different allocation of recovery funds as compared to the RecPac scenarios, both in terms of sectors and regions of where investment is directed to.

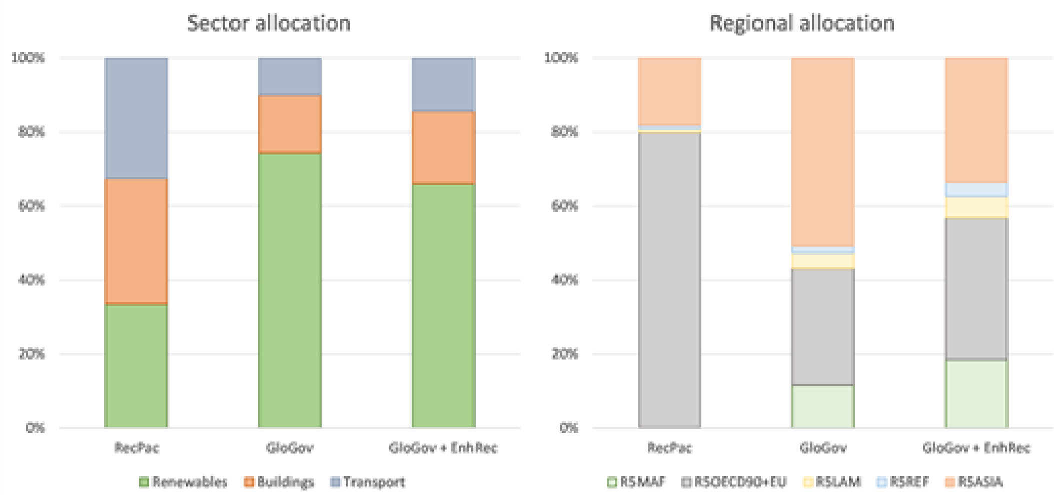

Figure 3.5: Investment allocation by regions and sectors in Global Governance scenario. Note: R5MAF (Middle East and Africa), R5OECD90+EU (OECD countries), R5LAM (Latin America), R5REF (Rest of the World), R5ASIA (Asia)

Results indicate that a greater share of green investments would flow to renewables [60%-70%] in GloGov and GloGov+EnhRec scenarios[2] , decreasing the amount directed to buildings and transport sectors. The optimal solution of the modelling framework chooses for the least-cost abatement opportunities which are found in the renewable energy sector especially as solar PV and wind technologies are already cost competitive to fossil fuels in many parts of the world [85].

Most interestingly, the choice is not restricted to sectors, but also includes the regional dimension. The results suggest that the optimal allocation of investments would differ substantially from the initial one where Europe and North America are protagonists; the joint share of OECD economies declines from 80% in the RecPack scenario to 31% in the GloGov case. In both scenarios (GloGov and GloGov+EnhRec), Asia stands as the strongest candidate to where investments should be directed to, given that the least-cost abatement opportunities are placed within this region, resulting in a [35%-55%] share of total investment. Africa takes a greater share of investments as compared to RecPac scenario, reaching up to 20% of the total investment, while other regions also emerge in the scenarios' results (Latin America and Rest of the World) with lower shares.

3.4 Discussion

Scenario results show that even an enhanced green recovery strategy would not be enough to close the emission or investment gap in order to shift the global emission pathway consistently with the Paris Agreement temperature goals. As larger and fully green stimulus should be implemented, it is clear that a fossil-based recovery would cause an unaffordable delay to climate action. The IEA [85] projects a sharp rebound in electricity demand of nearly 5% in 2021 and 4% in 2022, with an inevitable rebound in fossil-fuel generation since renewable investments have been postponed by the pandemic. Despite low investment attractiveness and the stranded-asset threat, countries may seek to accelerate fossil fuel production in the context of moderate crude oil prices. The critical post-COVID-19 situation in emerging countries may generate relatively predatory strategies based on mineral extraction and agricultural production [103] with long-term repercussions on land use, fossil fuel use and GHG emissions. A fossil-based post-COVID recovery would create a carbon lock-in, which would delay climate compatible development in those economies.

[2]GloGov+EnhRec scenario simulates the Global Governance scenario with the green energy investments being increased by 5 times as compared to the amount of RecPac scenario to cover the 2021-2025 period.

Our model-based analysis shows that recovery packages stimulating investment in clean energy and energy efficiency can reduce global emissions by [10%-13%] in 2025 and [6%-15%] in 2030 relative to the CurPol scenario. So, they can close less than 7% of the emission gap to Paris-compatible pathways in 2030 [107] (and up to 30% if they are enhanced and prolonged for 5 years), but cannot induce the structural changes required to reach global net-zero energy systems by 2050. Current green recovery packages are not enough to deal with climate urgency, but (if upscaled and combined with ambitious climate policies) can potentially catalyse the transition to net-zero energy emissions by mid-century. A green recovery should therefore include considerably more ambitious climate policies.

Interestingly, results have shown that green recovery packages provide more of an investment gap closure than an emission gap closure (Figure 3.4). In the enhanced recovery case (EnhRec), in 2030, the resulting level of investment can meet or even exceed projected requirements (in the case of the PROMETHEUS model), while the emission gap closure could reach a maximum of 29%. This could mean that chosen technologies need a large upfront investment to reach a minimum scale, or that infrastructure should be put in place beforehand. It can also mean that combined policies are necessary as demand drivers. As proposed in the CliAmb scenario, a global carbon pricing mechanism, namely an ETS, should be effective as an incentive for such shifts.

Combining green recovery packages (in the form of investment subsidies to low-carbon technologies) with carbon pricing schemes may drive the required medium and long-term system transformations towards net zero by mid-century. Currently pledged recovery packages, if fully green, can propel the post-pandemic economic recovery "doing no harm" to climate ambition. Enhanced packages could probably accelerate economic recovery, and be more successful in closing the emission gap. But ultimately, combining strengths of recovery packages with carbon pricing could accelerate the technological transition while ensuring post-pandemic economic stimulus. Green recovery packages would avoid redundancies through the creation of green jobs, while carbon pricing sustains mitigation in the longer, necessary, time frame. And so, this combination could be a successful way of closing the gap between RecPac/EnhPac and CliAmb scenarios, not only until 2030, but also in the long run. On the one hand, mitigation achieved through green recovery packages can increase the social acceptance of climate policy by reducing the need for high carbon pricing . On the other hand, the introduction of (mild) carbon pricing schemes can increase the effectiveness of green recovery packages in terms of emissions reduction by penalising also the use of fossil fuels and not only investment decisions taken by energy consumers and producers.

Overall, our model-based analysis shows that green recovery packages can accelerate energy system transformation with higher uptake of renewable energy, electric vehicles and energy efficiency until 2030, but cannot deliver the systemic long-term restructuring to pave the way towards carbon neutrality by 2050. Additionally, our analysis makes the case for a hypothetical mechanism of global governance for green stimulus packages. Institutionally challenging as it may be, global optimal allocation of recovery packages yields a larger level of mitigation through larger shares of wind and PV power generation. It could also potentially lead to reducing inequalities, since resources would migrate from Europe and North America to less developed regions, mostly Africa, Latin America and parts of Asia.

3.5 Conclusions

Investment choices for the post-pandemic recovery will strongly affect the climate trajectory in this century. While most policy packages launched can potentially undermine the response to climate urgency, pursuing a green recovery is the minimum to set the world on track for keeping the Paris Agreement temperature goals within sight.

Emission pathways after COVID-19 will be shaped by how governments' economic response translates into infrastructure expansion, energy use, investment planning and societal changes. As a response to the COVID crisis, most governments worldwide launched recovery packages aiming to boost their economies, support employment and enhance their competitiveness. Climate action is pledged to be embedded in most of these packages, but with substantial geographical heterogeneity. In this paper, we provide novel evidence on the energy system and emission implications of post-COVID recovery packages by assessing the gap between pledged recovery packages and the actual investment needs of the energy transition to reach Paris goals. Using two well-established IAMs and analysing various scenarios combining recovery packages and climate policies we conclude that currently planned recovery from COVID-19 is not enough to enhance societal responses to climate urgency and should be significantly upscaled and prolonged to ensure compatibility with the Paris Agreement goals.

We point out that our impact assessment does not account for economy-wide impacts of economic stimulus, sectoral feedbacks, or the effects of money creation through discretionary fiscal policy [108]. Shifts in energy demand caused by societal changes resulting from the pandemic are not considered either, or those related to furlough schemes, which are noticeably concentrated in the very short term. Besides, many of the policy instruments assessed in our simulations imply structural changes across supply chains (e.g. electrification of road transport). Although these changes are explicitly or implicitly represented in our modelling frameworks, we acknowledge that they are often represented in an aggregated way, which can lead to optimistic assumptions about the penetration rates of technologies. Finally. despite having explored five different scenarios, we have not analysed the combination of recovery packages with a global carbon pricing mechanism to sustain emission reductions in the longer run [98], which would probably represent the next step to expand this study.

The analysis can be significantly expanded in various dimensions that were not fully captured in this paper and could be the source of future works. As observed, recovery packages cover a wider range of measures other than climate policies, such jobs and firms direct support, which are of high relevance for political decision making [109–113]. Assessing the overall socio-economic impacts of recovery packages and possible policy measures to boost the economy and create jobs (e.g. VAT reduction, investment tax reduction, lower social security contributions etc.), is one dimension to be explored. Other ways to use green recovery packages related to energy transition (e.g. subsidies, grants/loans, low-carbon R&D, procurement, fuel mandates, regulation) could be explored, also considering a broader set of technological options, particularly in sectors where emissions are harder to abate, due to high costs or other barriers. Finally, further improvements can be driven by including additional modelling tools towards a multi-model scenario comparison study like in [98] to derive more robust policy recommendations and by including real-world data and estimations on technology allocation of green recovery packages (which differ by country).

3.6 Is Green Recovery Enough? Analysing the Impacts of Post-COVID-19 Economic Packages Appendix

3.6.1 COFFEE-TEA Integrated Assessment Modelling Suite

The COFFEE-TEA is an integrated assessment modelling suite. The COmputable Framework For Energy and Environment (COFFEE) model is a global perfect-foresight, least-cost optimisation, and partial equilibrium model that is based on the Model for Energy Supply Strategy Alternatives and their General Environmental impacts (MESSAGE) platform, a linear programming optimisation platform for energy systems and physical balances (mass, energy, exergy and land) developed by the International Institute for Applied System Analysis (IIASA).

COFFEE was developed to assess long-term energy supply strategies, based on technological deployment and resource availability, given constraints on GHG emissions and other air pollutants from the energy and land-use systems. Each of the model's regions has a detailed representation of energy extraction and conversion technologies, and individualised estimates of energy resources (both in terms of volume and costs), which are mostly reported as cost supply curves. The model accounts for all primary energy produced by the energy systems and its later transformation into secondary and, further, into final energy. The international trade of the energy commodities is also captured by the model. Final energy is consumed by end users to fulfil the energy service demands.

Regarding sectoral coverage, COFFEE is divided into five main sectors: Energy, Industry, Transportation, Services/Residential (Buildings) and Agriculture (Table A1). Industry is divided into four subsectors: cement, iron and steel, chemical and other industries. The model includes explicit demand for clinker, steel, and non-energy products such as plastics and ammonia. Furthermore, there is demand for industry energy services, such as: direct heat; steam; HVAC; lighting; drive; and other uses.

The transport sector is divided into freight and passenger transport, measured in ton/kilometer (tkm) and passengers/kilometer (pkm), respectively. In COFFEE, the transport service is represented by different technologies of private transport (light duty vehicles, motorcycles, three-wheelers) and public transport (buses, trains, ships, airplanes). Each of these has a set of technologies varying from energy vector and efficiency levels, including variations of conventional vehicles, flex vehicles, hybrid vehicles, battery electric vehicles and fuel cell vehicles. Freight transport includes transport technologies such as trucks (Light, Middle and Heavy Duty), trains and ships, with all technologies previously listed for passenger vehicles also applying for trucks. Additionally, COFFEE relies on the production of drop-in synthetic fuels (such as diesel, jet fuel and marine bunker) as mitigation options for the freight transport sector.

The buildings sector includes both the residential and the commercial/public sectors. Each subsector has regional energy services demand for: space heating, water heating, cooking, lighting, appliances (electrical) and space cooling. To meet demand, the model has a range of technology options, ranging from low-efficiency lamps and cookers (non-commercial wood and kerosene), mid-range commercial options of appliances and heaters/air conditioning, up to more advanced options, such as LED lamps and highly efficient appliances. This sector also presents Distributed Generation (DG) options, either through photovoltaic (PV) or solar water heating.

Residues and agriculture sectors have a lesser impact on the energy consumption, despite being significant socioeconomic and environmental sectors. As for residues, they include the water management and municipal solid wastes. This sector has a low energy (mostly electric) consumption, but its mitigation options have a great impact on non-CO2 emissions, including options for renewable energy, such as landfill gas and incineration. Regarding agriculture, the energy consumption for agricultural practices and crop processing is accounted in COFFEE.

The land-use system also presents several mitigation options through the adoption of sustainable practices and production of bioenergy, all of which are fundamental in long-term climate stabilisation scenarios. COFFEE derives from most global integrated assessment models in two manners: spatial resolution and integration with other sectors. Firstly, COFFEE does not have a spatial explicit representation of the land system. The model includes cost categories of each land cover to represent a cost supply curve of available land for use and land use change. As such, the cost supply curve for bioenergy, for instance, is completely endogenous and subject to competition for other land uses, such as crop and livestock production. Nonetheless, COFFEE also differs from most IAMs in the sense that the integration between the energy and the land-use systems is hard linked, meaning that its optimal solution accounts for the constraints and costs of both sectors simultaneously, including any potential trade-offs and synergies.

The Total-Economy Assessment (TEA) is a global top-down, recursive dynamic, Computable General Equilibrium (CGE) model. TEA uses the general equilibrium microeconomic theory as an operational tool in empirical analyses. The model simulates the evolution of the global economy, capturing industry-to-industry linkages, to assess policies on issues related to climate change, energy transitions, resource allocation, trade flows, technological change, income distribution, among others.

TEA is built as a mixed (non-linear) complementary problem on Mathematical Programming System for General Equilibrium (MPSGE), a tool written in the General Algebraic Modelling System (GAMS) software. To reach the general equilibrium of the economy, the TEA model assumes total market clearance (supply equals demand through commodity price equilibrium), zero profit condition for producers and perfect competition. The equilibrium is obtained when prices and quantities (endogenous variables) are balanced so that agents cannot improve their situation (welfare) by changing their behaviour, nor making other agents worse-off (Pareto optimal condition).

Production in each sector is represented by multi-level nested Constant Elasticity of Substitution (CES) functions, which use intermediate goods, labour, capital, land and energy as their input. The CES functions describe the substitution possibilities between factors of production and intermediate inputs in the production process, based on a least-cost approach. International trade follows Armington's aggregation [114], in which a composite CES function differentiates consumer's preferences between imported and domestic goods. Consumer preferences (household sector) are expressed by a CES utility function. Firms maximise their profits and the household sector maximises its welfare (utility) under budget constraints. Such choices are determined by the parameters of substitution and transformation elasticities in the utility and production functions.

In the TEA model, the macroeconomic closure assumes full employment of the factors of production (capital and labour). Savings equal investment in the general equilibrium, but regionally the imbalances are closed by a surplus (or deficit) in the current account. An endogenous real exchange rate clears the current accounts and the capital account decreases exogenously in the long-run. Capital stock evolves at each period with the formation of new capital that depends on the investment level in that period and the capital depreciation rate [96].

COFFEE and TEA models are long-term global models suitable for policies and climate aspects evaluation. They are integrated and have perfect compatibility in terms of base year data, sectoral and regional disaggregation. The COFFEE model provides data inputs for electricity generation and production shares to the TEA model, which accounts for the transformation of primary energy (coal, natural gas and crude oil) to secondary energy (oil products and electricity) to be consumed by end-use sectors, such as transport sectors (land, air and waterway) and energy-intensive industries (iron and steel, chemical, non-metallic minerals and other manufactures). The food production and land-use systems, which include the agricultural and livestock sectors, are also represented in the TEA model. The sectoral coverage comprehends 21 sectors that can be grouped into the five main sectors represented in the COFFEE model (Table 3.2).

Table 3.2: COFFEE x TEA sectoral alignment.

COFFEE	**TEA**	**Description**
Agriculture	AGR	Agriculture
	CTL	Cattle
	OAP	Other animal products
	FSH	Fishing
Energy	COL	Coal
	CRU	Crude oil
	ELE	Electricity
	GAS	Natural gas
	OIL	Oil products
Industry	I_S	Iron and steel
	CRP	Chemical rubber and plastic
	NMM	Manufacture of non-metallic mineral products
	MAN	Other manufacture
	OFD	Other food (except meat)
	OMT	Other meat products
Transportation	OTP	Land transport
	WTP	Water transport
	ATP	Air transport
Services	SER	Services
Residential	DWE	Dwellings

TEA and COFFEE are divided into the same 18 regions, including large representative economic regions/countries, such as Europe, China, USA and Japan, while putting emphasis on developing countries in which energy and environmental issues are relevant globally, such as India and Brazil (Figure 3.6). In addition, COFFEE has a global region represented as the 19th region of the model for the assessment of global climate policies.

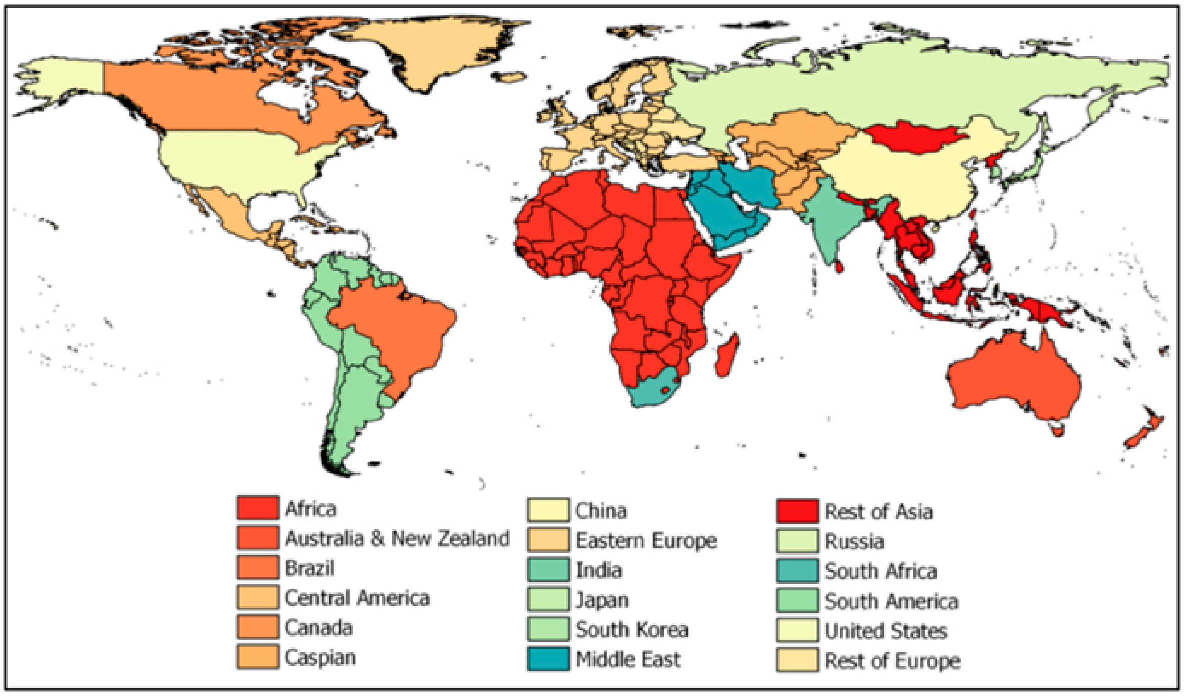

Figure 3.6: Regional breakdown of the COFFEE-TEA IAM suite.

The COFFEE-TEA suite is included in the category of IAMs that combines techno-economic and environmental variables to generate a cost-optimal solution in a hybrid approach; bottom-up technological solution with top-down macroeconomic consistency. COFFEE fully represents energy markets, while TEA projects future economic activities' demands based on macroeconomic drivers, such as population and GDP growth. The COFFEE-TEA IAM suite accounts for the three main GHG gases: CO_2, CH_4 and N_2O. These emissions are associated with the main sectors of land-use, agriculture and livestock, fugitive emissions, fuel combustion, industrial processes, and waste treatment. The model runs with a 5-year time step, from 2010 to 2100, with historical data (2010–2020) being used for calibration.

3.6.2 PROMETHEUS Model

PROMETHEUS is a global energy system model covering in detail the complex interactions between energy demand, supply and energy prices at the regional and global level. Its main objectives are: (1) to assess climate change mitigation pathways and low-emission development strategies for the medium and long-term; (2) to analyse the energy system, economic and emission implications of a wide spectrum of energy and climate policy measures, differentiated by region and sector); and (3) to explore the economics of fossil fuel production and quantify the impacts of climate policies on the evolution of global energy prices.

PROMETHEUS quantifies CO_2 emissions and incorporates environmentally oriented emission abatement technologies (such as RES, electric vehicles, CCS, energy efficiency) and policy instruments, such as carbon pricing schemes that may differentiate by region and economic activity. The model can be used to assess energy and climate policies, as it endogenously determines the international prices of fossil fuels through detailed world and regional supply/demand dynamics and technology dynamics mechanisms focusing on low-carbon technologies (e.g., wind, PV, electric cars, CCS, advanced biofuels, hydrogen).

PROMETHEUS is a recursive dynamic energy system simulation model. The economic decisions regarding the investment and operation of the energy system are based on the current state of knowledge of parameters (costs and performance of technologies, etc.) or with a myopic anticipation of future costs and constraints. Some foresight can be forced in the electricity production sector. The PROMETHEUS model assumes market equilibrium, where each representative agent (e.g., energy producer or consumer) uses information on prices and makes decisions about the allocation of resources. The interactions of representative agents are governed by market dynamics with market-derived prices to balance energy demand and supply in each sector (e.g., electricity production, transport and energy industries). The regional fuel markets are also integrated to form an international (global or regional) market equilibrium for crude oil, natural gas and coal. The model produces projections of global and regional fossil fuel prices, which depend on demand, supply, technology and resources. The model runs with a 1 year time step, usually from 2018 to 2050, the 2015–2018 period being entirely set by data and used for calibration.

Chapter 4

Global and Regional Dynamics of Negative Emissions: Pathways to 'Paris'

Baptista, L. B., Rochedo, P. R. R., Schaeffer, R. Global and Regional Dynamics of Negative Emissions: Pathways to 'Paris'. *To be submitted.*

Abstract

Achieving the Paris Agreement's objectives of limiting global warming to well below 2 °C, preferably 1.5 °C, necessitates substantial reliance on Carbon Dioxide Removal (CDR) technologies. This paper analyzes the global and regional dynamics of CDR deployment through the lens of integrated assessment modeling using the COFFEE model. We evaluate four Marker scenarios aligned with different global temperature targets and their respective carbon budgets, exploring the timing, regional perspectives, and scale of required negative emissions. The results show that scenarios consistent with ambitious climate goals, particularly the 1.5 °C target, requires significant deployment of CDR technologies such as bioenergy with carbon capture and storage (BECCS), afforestation/reforestation (A/R), direct air capture (DAC), and materials-based sequestration. Regional analyzes indicate that countries such as Brazil, the European Union, and the United States are key players, each leveraging distinct strategies, land-based solutions or technologically driven approaches. Furthermore, we discuss policy implications, emphasizing the importance of international cooperation, market-based mechanisms, and policies addressing infrastructure development and public acceptance to facilitate CDR deployment.

4.1 Introduction

In the frame of the Paris Agreement's (PA) goal of limiting global warming to "well below" 2 °C above pre-industrial levels, with efforts to cap it at 1.5 °C, the Intergovernmental Panel on Climate Change (IPCC) 6th Assessment Report from Working Group III assessed a range of pathways aligned with the PA and found that most of the scenarios with limited or no temperature overshoot need to rely on carbon dioxide removal (CDR) technologies [3]. The State of Carbon Dioxide Removal report indicates that CDR will be necessary to limit the effects of climate change [115]. Its authors suggests that CDR can fulfil three major roles for emissions reduction: (a) in the short term, it can help mitigate emissions; (b) in the medium term, it can counterbalance residual emissions of hard-to-decarbonize sectors; and (c) in the long term, it can help achieve net negative emissions [115], which may be necessary to reduce emissions after a temperature, and emissions, overshoot [28, 116].

The IPCC defines CDR as the process of removing CO_2 from the atmosphere and storing it in reservoirs - be them geological, terrestrial or oceanic - or products, excluding natural uptake not from human activities [3]. CDR methods can be considered either conventional or novel[1] [115, 117], and both categories are necessary to achieving the net zero targets proposed by 142 countries, 193 regions and 281 cities[2] in the world [14]. The CO_2 removal process can either be biological or geochemical, encompassing methods such as afforestation and reforestation (A/R), and soil carbon sequestration for biological processes, and enhanced rock weathering and direct air capture and storage (DAC) for geochemical processes. These methods exhibit varying readiness levels, mitigation potential, and storage timescales [115]. For instance, A/R are well-established processes with significant mitigation potential, largely due to the availability of land. However, their CO_2 storage timescale spans only a few decades and remains vulnerable to disturbances such as forest fires [118–120]. Conversely, geochemical methods like DAC in geological formations offer longer-term CO_2 sequestration, often extending beyond centuries [115]. Most of these CDR methods are, to some extent, modelled by Integrated Assessment Models (IAMs), being considered as options to reduce and remove CO_2 emissions in climate constrained scenarios.

[1] Conventional methods, such as afforestation/reforestation, agroforestry, forest management, soil carbon sequestration, and durable wood products, are established, scalable, and reported under LULUCF activities. Novel methods, including BECCS, DAC, enhanced rock weathering, biochar, and ocean alkalinity enhancement, are less ready for large-scale deployment. These novel methods typically capture CO_2 for storage in geological formations, oceans, or products.

[2] Cities with populations greater than 500,000 people.

In general, IAMs historically relied upon selected CDR options, notably bioenergy and carbon capture and storage (BECCS) and A/R [28, 92, 121], that can be more easily modeled within their energy and land-use systems frameworks. Particularly, BECCS has been considered a major CDR option in IAM runs [28, 122–124], although even this technological option has been criticized by various studies [125–129], because of its potential land-use change impacts (and consequent food supply impacts), water resources impacts, and fertilizer demand increase, which could lead to environmental and climate side-effects. However, many studies show that, even in scenarios without BECCS, biomass use can be equally or more intense compared to the inclusion of BECCS [130, 131], given its capability to replace fossil fuels in different sectors. Other studies focused on the potential of A/R as a source of negative emissions [124, 132, 133]. Recent studies further assess the role of A/R in IAMs by addressing key biophysical constraints that affect its feasibility [133], highlighting how careful forest types selection can enhance carbon sequestration potential while mitigating land-use trade-offs [132], and exploring the implications of land-based mitigation strategies under scenarios that limit reliance on net-negative emissions [128].

IAMs have recently introduced DAC, biochar, enhanced weathering, bioplastics, biomaterials, and other new CDR strategies into their technological portfolio [34, 134–138]. DAC can complement other CDR approaches by reducing mitigation costs in the near term when available [135, 136]. However, its large-scale deployment remains contingent on the availability of geological storage. Biochar can create an annual sink of up to 2.8 $GtCO_2$ while enhancing crop yields, particularly at lower carbon prices [134]. Enhanced weathering presents a potential annual sequestration capacity of up to 4 $GtCO_2$, though its actual effectiveness depends on geochemical and biological factors that introduce significant uncertainties [137]. Bioplastics and biomaterials offer a dual benefit of reducing fossil-based feedstock reliance and enabling carbon sequestration [34, 139], with IAM studies demonstrating their potential to replace up to 62% of chemical sector feedstocks and turn plastics into a net carbon sink [30].

Hence, in this article, we identify CDR requirements to reach global net zero-carbon emissions, detailing the distinct types of technologies that may be needed around the world that will be essential to comply with stringent climate goals. For that, we use a global IAM, the COFFEE (Computable Framework For Energy and the Environment) model [22, 23], for evaluating a set of scenarios that varies the remaining carbon budget, thus implying in different global average temperature increases and regional net zero years. We focus on four marker scenarios, three of which that comply with the Paris Agreement goals, and one that does not comply with it. Then we indicate the policy implications that can be derived from our results.

4.2 Methods

The COFFEE model is a perfect foresight, least-cost optimization model representing the global energy and land-use systems in 18 regions. To evaluate CDR requirements under different climate targets, we run the COFFEE model using end-of-the-century global carbon budget scenarios, following the protocol for the National Policies implemented scenarios as presented in [28].

Although many countries, states, cities and companies have recently announced their intentions to achieve CO_2 or greenhouse gas (GHG) emissions neutrality [140], we do not consider any national mid-century strategy explicit in these scenarios; instead, we simply consider a range of global full-century budgets applied over the 2020-2100 period. Our analysis is based on the least-cost pathways provided by the COFFEE model for full-century budget scenarios ranging from 300 to 2,400 $GtCO_2$. In the following discussions, we focus the analysis on selected (Marker) scenarios presented in Table 1 , focusing on four different climate scenarios and their respective temperature profiles. Nonetheless, the results from all scenarios are available in the SM.

Table 4.1: Carbon emission budgets (2020–2100, in Gt CO_2) for the analyzed Marker scenarios and their likely global temperature outcomes (67% likelihood).

Scenario	Budget 2020-2100 (Gt CO_2)	End-of-the-century temperature (67% likelihood)
1.5 °C	400	1.5 oc
1.7 °C	700	1.7 oc
2 °C	1,100	2.0 oc
>2 °C	1,400	2.3 oc

The use of a global IAM allows us to identify, for each scenario, the year in which the world and selected regions reach zero CO_2 emissions. Also, the scenario design allows us to evaluate the remaining carbon budgets until the net zero years and detail the profile of CDR options deployed regionally. To this end, based on different definitions and arrangements of CDR technologies available in the literature [126, 131, 141–143], we split them into four categories, to distinctly assess their role in low-carbon emissions scenarios: (i) energy-based, such as BECCS; (ii) land-based, such as A/R, soil carbon sequestration and biochar; (iii) materials-based, such as bioplastics and biomaterials; and (iv) others, including DAC, enhanced weathering and ocean fertilization.

4.3 Model results for the analyzed scenarios

This section presents the key findings of our analysis, focusing on the deployment and requirements of distinct CDR technologies under various global carbon budget scenarios. Results are discussed from both global and regional perspectives, and we highlight differences in the timing of net zero and the technology mix required to achieve the carbon budget range.

4.3.1 Global trajectories and CDR deployment

Global CO_2 emissions trajectories are presented in Figure 4.1, highlighting the selected temperature marker scenarios, as shown in Table 1. All scenarios show a faster decline in emissions after 2030, converging on the need to peak CO_2 emissions in the coming years. However, the rate and timing of emissions reductions differ significantly depending on the temperature target.

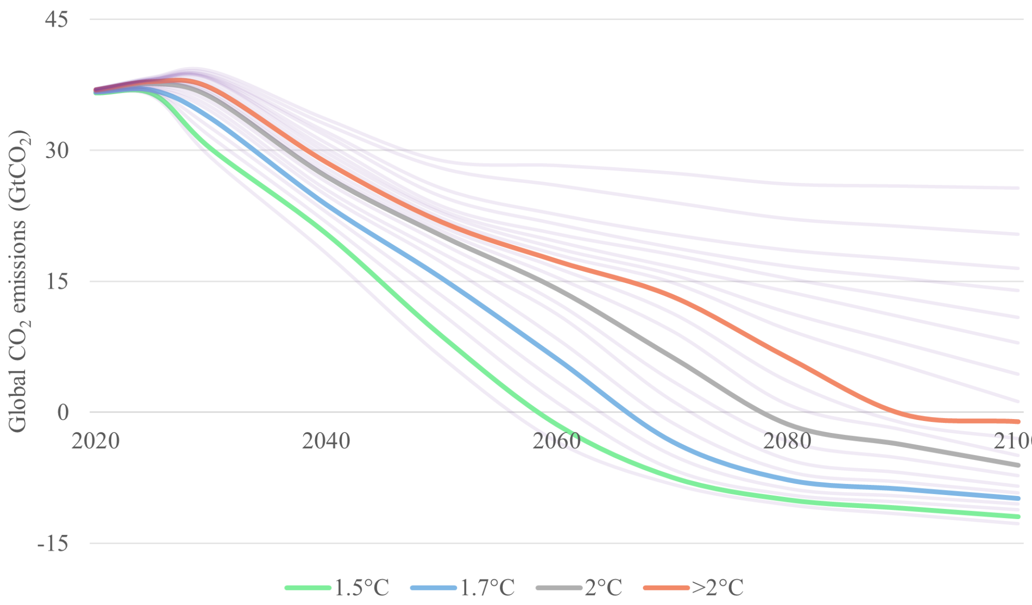

Figure 4.1: Annual global CO_2 emissions ($GtCO_2$ per year) for the analyzed scenarios. Note: Thicker, colored lines show the Marker scenarios; transparent lines show additional scenarios.

The 1.5 °C scenario (green line) demonstrates the highest level of ambition among all Marker scenarios, with a sharp and rapid decline in emissions, reaching net zero around 2060. Notably, this scenario requires significant deployment of CDR options to compensate for emissions until the net zero year and to offset residual emissions after that. The 1.7 °C scenario (blue line) also shows considerable ambition and effort, but with a slower decline rate, requiring fewer negative emissions compared to the 1.5 °C pathway. Both trajectories stabilize by 2080, maintaining emissions at around -10 $GtCO_2$ for the 1.5 °C scenario and -8 $GtCO_2$ for the 1.7 °C scenario.

In contrast, the 2 °C (gray line) scenario, reflecting a more moderate ambition, declines at a slower pace and reaches marginally negative emissions by the end of the century. The >2 °C scenario (orange line), representing the lowest level of ambition of the four Marker scenarios, maintains remaining positive CO_2 emissions through most of the century, peaking after 2030 and achieving global net zero CO_2 emissions only by 2090. Our results highlight the marginal effort required to achieve more stringent temperature targets, especially after following a delayed pathway. Thus, steeper reductions and greater deployment of CDR become necessary to compensate for earlier inaction.

Figure 4.2 presents the projected carbon price trajectories across different temperature targets. All scenarios show a sharp increase after 2050, reflecting the growing effort required to mitigate CO_2 emissions. For scenarios aligned with a 1.5 °C world, carbon prices exceed 200 USD/tCO_2 by mid-century, while those targeting 1.7 °C range between 170 and 110 USD/tCO_2. In contrast, the 2 °C scenario maintains prices below 100 USD/tCO_2 in 2050, highlighting a lower short-term cost burden.

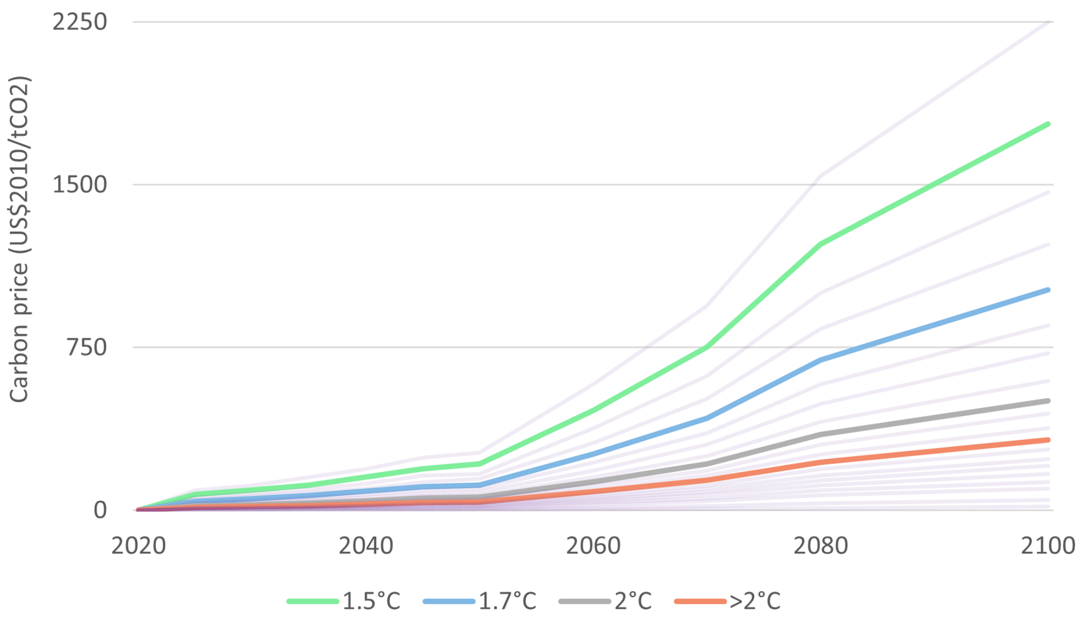

Figure 4.2: Annual global carbon price (US$$_{2010}$/t$CO_2$) for the analyzed scenarios.
Note: Thicker, colored lines show the Marker scenarios; transparent lines show additional scenarios.

By the end of the century, price disparities widen significantly, with the 1.5 °C scenario surpassing 2,000 USD/tCO_2, while the 1.7 °C pathway ranges from 1,800 to 1,000 USD/tCO_2. Even the more moderate 2 °C scenario sees prices increase to 800–500 USD/tCO_2. These results emphasize the substantial economic burden of aligning with the PA goals, as more ambitious pathways imply significantly higher mitigation costs to remain in line with these goals.

One key challenge to achieving net zero CO_2 emissions is addressing residual emissions from hard-to-decarbonize sectors. Figure 4.3 illustrates the cumulative global negative emissions implied by the different carbon budgets. The results show that COFFEE requires increasing negative emissions to meet lower global carbon budgets, highlighting the need for large-scale CDR deployment to balance emissions under stringent carbon budgets. In fact, for high-ambition targets (low carbon budgets), such as those below 500 GtCO_2, the cumulative amount of CO_2 captured through CDR is higher than the original carbon budget. This clearly shows that meeting these targets will require significant deployment of CDR, mostly compensating for a slow reduction rate in emissions from the global economy. Figure 4.3 also shows that BECCS emerges as the dominant technology, with significant contributions also observed from A/R. Despite their relatively low significance, the need for DAC and materials marginally increases with the increase in ambition.

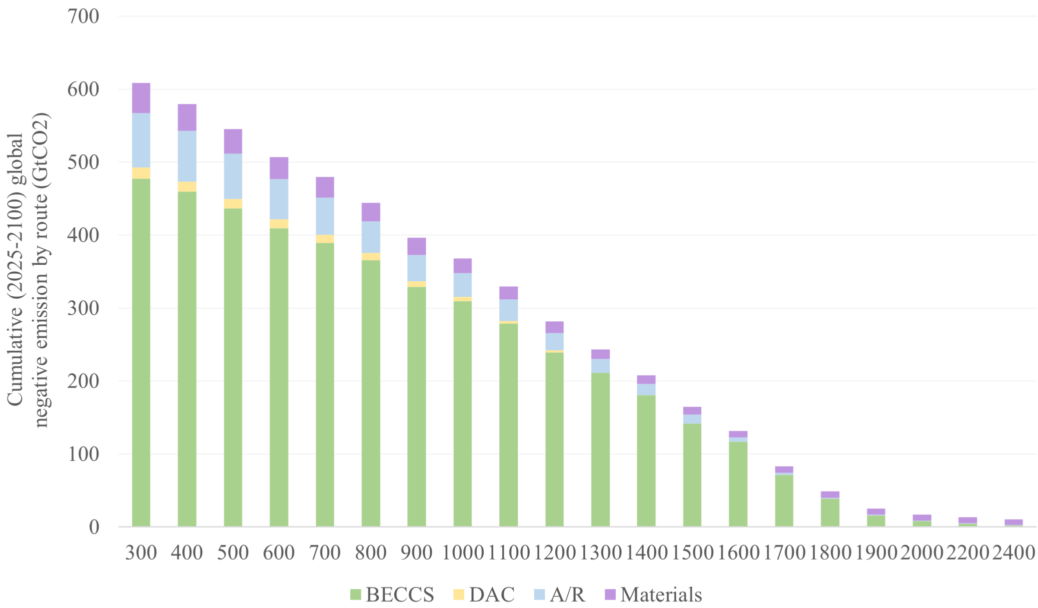

Figure 4.3: Global cumulative negative CO_2 emissions from CDR between 2025 and 2100.

Note: BECCS: Bioenergy and CCS; DAC: Direct air capture; A/R: Afforestation and reforestation.

BECCS, A/R, and materials' negative emissions play a significant roles in scenarios with mid-range budgets, while DAC has negligible relevance in budgets higher than 1,200 $GtCO_2$. However, for budgets exceeding 1,900 $GtCO_2$, any CDR deployment is almost insignificant.

For the 1.5 °C scenario, CDR deployment is most significant, reflecting the overall high ambition of this scenario. Once again, BECCS dominates the CO_2 removal across all years, representing more than 70% of the overall captured CO_2 in all scenarios after 2050. DAC and materials make smaller contributions, as seen in Figure 4.4, with both representing almost 12% of all captured CO_2 in 2100 for the 1.5 °C and 1.7 °C Marker scenarios.

In the 1.7 °C scenario, while BECCS remains the dominant technology, the total CO_2 captured is slightly lower than that in the 1.5 °C pathway (17.9% in cumulative terms). DAC plays a minor role before 2070 but expands by the end of the century in most scenarios, reaching 674, 633 and 312 $MtCO_2$/yr for the 1.5 °C, 1.7 °C and 2 °C scenarios respectively. The 2 °C scenario requires less reliance on CDR overall, with BECCS still

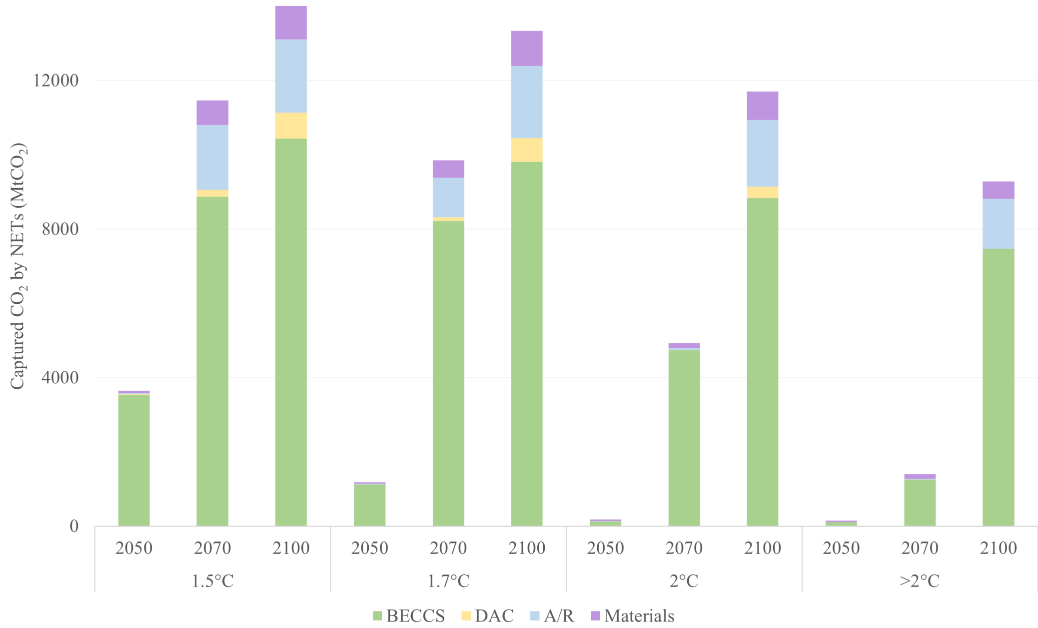

Figure 4.4: Captured CO_2 ($MtCO_2$) by CDR for the Marker scenarios in selected years. Note: BECCS: Bioenergy and CCS; DAC: Direct air capture; A/R: Afforestation and reforestation.

leading but at reduced levels compared to the more ambitious pathways (39.3% lower than in the 1.5 °C scenario, in cumulative terms). Finally, in the >2 °C scenario, CDR deployment is minimal, reaching only 1.4 $GtCO_2$/yr by 2070, with a cumulative use 64.2% lower than that in the 1.5 °C scenario.

The distribution of CDR in the net zero year for each temperature increase is presented in Figure 4.5. It is important to note that the lower the temperature outcome, the earlier the net zero year occurs. Despite differences in timelines, the ambition for deploying CDR to achieve net zero emissions remains consistent. BECCS continues the leading CDR technology, followed by A/R, both of which facilitate the transition to net zero. DAC and materials play supplementary roles, contributing smaller but essential shares to compensate for residual emissions.

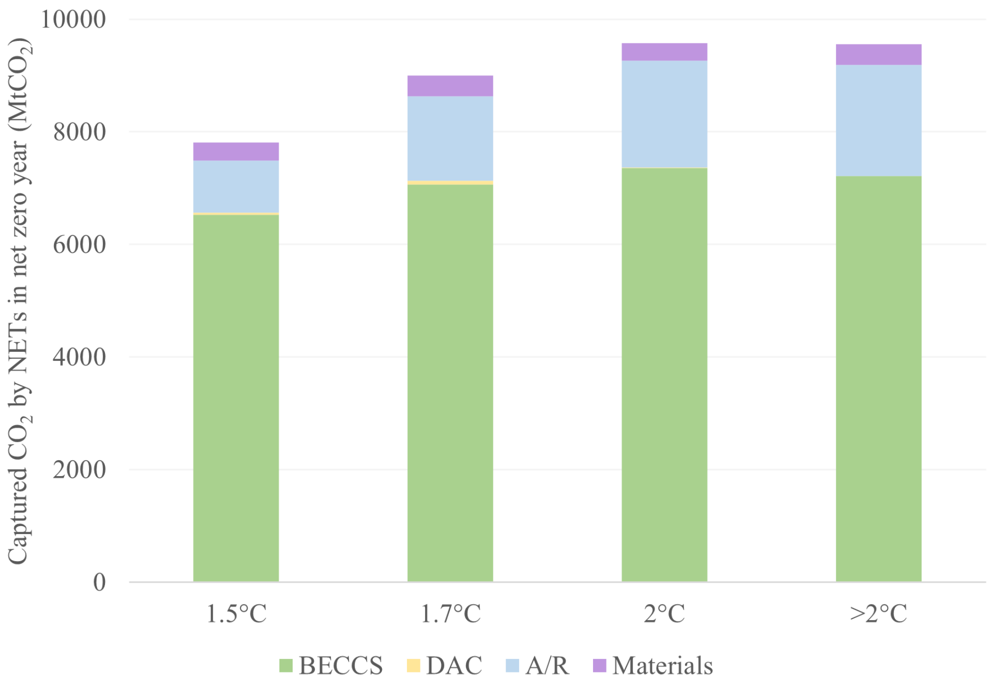

Figure 4.5: Captured CO_2 by CDR in net zero year ($MtCO_2$).
Note: BECCS: Bioenergy and CCS; DAC: Direct air capture; A/R: Afforestation and reforestation; Net zero year varies across scenarios: 1.5 °C: 2059, 1.7 °C: 2066, 2 °C: 2078 and >2 °C: 2089.

4.3.2 Regional dynamics on pathways to net zero

The following results highlight the regional role in enabling the achievement of the different global climate targets explored in this work. As such, Figure 4.6 presents an overview of the year in which the world and selected regions reached net zero CO_2 emissions for all scenarios, according to the cost-optimal pathway. The global net zero year gradually shifts from approximately 2055 to as far as 2090, highlighting the direct relationship between remaining carbon budgets, climate ambitions and mitigation efforts, and the timeline for achieving global carbon neutrality.

Regional trajectories exhibit significant variations, but certain patterns can be identified. For instance, Brazil achieves net zero earlier under all carbon budgets, followed by South Africa and Russia. For budgets more aligned with limiting warming to 1.5 °C, Brazil's net zero CO_2 year occurs before 2050. On another note, the European Union and India show intermediate patterns, aligning more closely with the global trend. In contrast, regions such as China, Japan and the US tend to delay the timing of their net zero beyond the global value, meaning that while the world has reached net zero CO_2

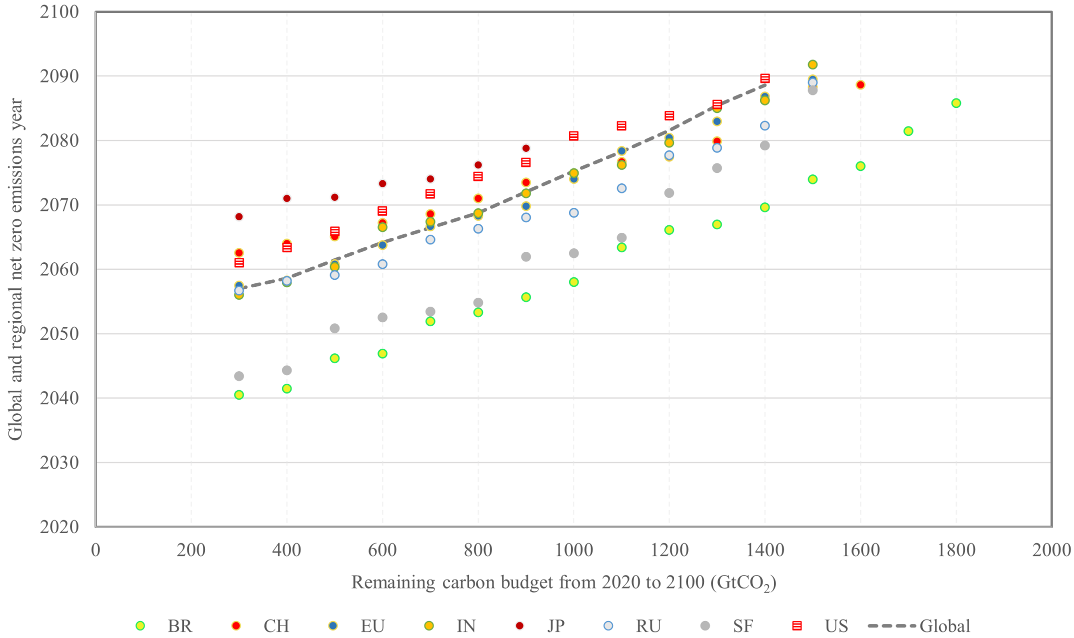

Figure 4.6: Global and regional net zero CO_2 emissions year for each of the analyzed carbon budget scenarios.

Note: After the 1,800 $GtCO_2$ budget scenario, no region reaches net zero CO_2.BR: Brazil; CH: China; EU: European Union; IN: India; JP: Japan; RU: Russia; SF: South Africa; US: United States.

emissions, these regions remained with positive emissions being compensated by other regions. In less ambitious targets (higher budgets), the US gets closer to the global net zero CO_2 year, whilst China shows a more ambitious profile than the global value.

Regional trajectories also reveal distinct dynamics for other regions. South Korea does not achieve net zero CO_2 emissions in any of the analyzed scenarios. Meanwhile, the Middle East region only reaches net zero under very low carbon budgets, such as limiting warming to approximately 1.5 °C. In contrast, the Africa region aligns more closely with the global trend. It is important to note that these results are based on cost-optimal model runs, which do not incorporate considerations of climate justice or equity. For instance, if a region achieves net zero in a cost-optimal path earlier than its expected (fair) timeline, this could potentially be leveraged as a source of carbon credits to compensate for other regions, reflecting the influence of market mechanisms on global decarbonization pathways. Therefore, despite criticism of the use of least-cost analyses [144, 145], significant contributions to climate policies can still be derived from such analyses.

This study also evaluated the cumulative negative emissions achieved through each main CDR option, with regional segregation and for all scenarios (Figure 4.7). As mentioned before, BECCS dominates as the most relevant technology in terms of scale, being used for fuel and electricity production. Brazil, the European Union and the US emerge as the main regions for BECCS, with Brazil consistently holding a leading position in the most stringent scenarios. Brazil also plays a key role in A/F, with some smaller contributions from other regions.

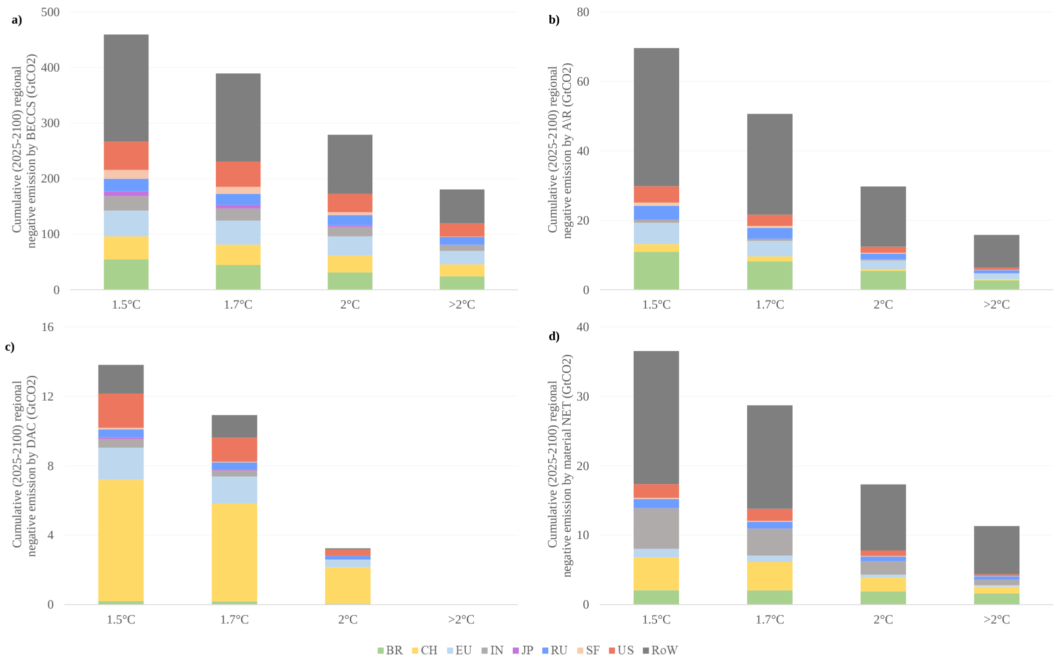

Figure 4.7: Cumulative (2025-2100) regional negative emission from different CDR options for selected climate scenarios (in $GtCO_2$). a) BECCS; b) A/R; c) DAC; and d) Materials.

Note: Figures at different scales. BECCS: Bioenergy and CCS; DAC: Direct air capture; A/R: Afforestation and reforestation; MNET: materials negative emissions); BR: Brazil; CH: China; EU: European Union; IN: India; JP: Japan; RU: Russia; SF: South Africa; US: United States; RoW: Rest of the World.

The overall negative emissions are significantly smaller for DAC and materials compared to BECCS and A/R, with DAC being the clear marginal option for negative emissions across all scenarios. China shows the most notable contributions to DAC, particularly under the 1.5 °C and 1.7 °C scenarios. Regarding using materials for negative emissions, China and India maintain a consistent leading role across the stricter temperature scenarios, and the remaining contributions are distributed across multiple regions.

Across all CDR alternatives, Brazil stands out for its significant contributions to

BECCS and A/R, highlighting its considerable land-based carbon removal potential. Meanwhile, regions like China, the European Union, India, and the US contribute significantly with more technology-driven CDR options, reflecting a diversification in their carbon removal strategies.

Figure 4.8 illustrates the regional breakdown of CO_2 emissions at net zero year for the Marker scenarios. The net zero year significantly influences the contributions of different regions to global CO_2 emissions and their ability to achieve net zero emissions. Regions such as Brazil and South Africa play a significant role in the global context by compensating for emissions, primarily driven by BECCS and A/R.

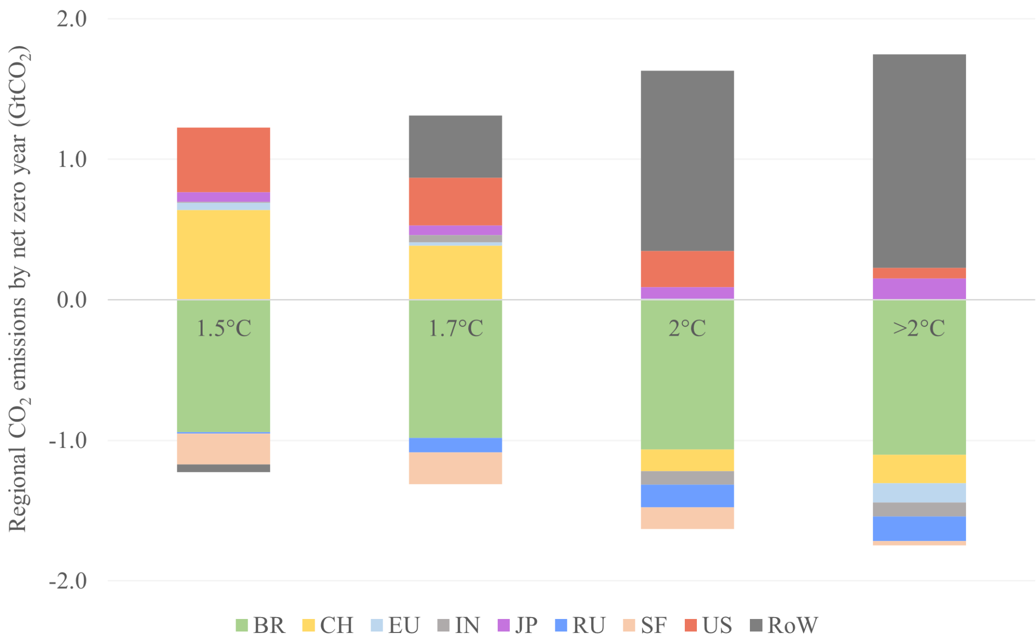

Figure 4.8: Regional CO_2 emissions by net zero year ($GtCO_2$).
Note: Net zero years varies across scenarios: 1.5 °C: 2059, 1.7 °C: 2066, 2 °C: 2078 and >2 °C: 2089. BR: Brazil; CH: China; EU: European Union; IN: India; JP: Japan; RU: Russia; SF: South Africa; US: United States; RoW: Rest of the World.

The contributions from other regions, such as China, the European Union, and the US, remain predominantly positive across scenarios, though their proportions change as the temperature target increases. Notably, China emerges as a major contributor to global CO_2 emissions in the 1.5 °C and 1.7 °C scenarios, reflecting its continued reliance on fossil fuels and the challenge of decarbonizing its large economy under tighter timelines. However, in the 2 °C and >2 °C scenarios, China's contribution decreases, even becoming a net negative emission region, as more time is available to decarbonize its economy.

4.4 Discussion

The findings presented in this study align with some data provided by the AR6 [146]. The IPCC highlights relevant milestones for achieving net zero emissions globally, including the year different models achieve net zero CO_2 by emission categories. The AR6 presents that limiting warming to approximately 1.5 °C would require net zero CO_2 emissions to be achieved by at least 2060[3], which is comparable to the scenarios presented in this study (budgets from 300 to 500 $GtCO_2$). For scenarios aligned with a less than 2 °C world[4], the IPCC has found 2070 to 2075 as the median years for net zero CO_2 emissions, which, using budgets of 500 to 1,100 $GtCO_2$ as a proxy, aligns with what is found in this study, as seen in Figure 4.6.

For 1.5 °C, the cumulative net-negative CO_2 emissions after net zero year found in this study ranges from approximately 320 to 400 $GtCO_2$, which has the same order of magnitude of AR6, where the median of C2 scenarios is 360 $GtCO_2$. When considering the C3 category as a proxy for the 2 °C scenario, the IPCC reports a median cumulative net-negative CO_2 emission of 40 $GtCO_2$. In comparison, the results for the 1,100 $GtCO_2$ budget scenario, our 2 °C Marker scenario, yield approximately 80 $GtCO_2$, with other less than 2 °C scenarios ranging from 280 $GtCO_2$ to 80 $GtCO_2$. These findings suggest that the scenarios in this study compensate for a slightly greater number of emissions up to the net zero year than those reported in the AR6, which reflects a potentially stronger reliance on CDR to offset these emissions.

The carbon prices projected in this study exhibit a distinct trajectory compared to those reported in AR6. For 2050, the median values found in AR6 are lower than those estimated here, with 401 and 213 USD/tCO_2 for the 1.5 °C and 2 °C scenarios, respectively. However, this trend reverses by 2100, when the AR6 estimates (1,186 and 551 USD/tCO_2) fall below the values found in this study. Moreover, while this study does not account for damage from climate impacts or the additional costs of delayed adaptation, it is crucial to consider the potential revenues from negative CO_2 markets. Using the 1.5 °C marker scenario as a reference, CDR alternatives could generate up to $25 trillion by the year 2100, highlighting their economic relevance.

The deployment of negative emissions technologies reveals substantial regional disparities in capacity and resources, underscoring the need for equitable approaches to climate action. Regions such as Brazil, the European Union and the US are well-positioned

[3]Using median values found in IPCC WGIII AR6 Technical Summary, table TS.3, considering C1 and C2 categories.

[4]Considering C3 category scenarios.

to lead in deploying CDR due to their abundant resources and existing infrastructure. Brazil, for instance, stands out in its potential for land-based CDR like A/R and BECCS, as seen in [36]) and [29]. In contrast, regions with less arable land availability or other technological barriers, such as the Middle East or South Korea, face significant challenges in achieving net zero emissions, particularly in less stringent carbon budget scenarios. These regions could benefit from the development of technologies such as DAC, which are not directly linked to any regional condition.

Carbon markets could help bridge these disparities by enabling regions with earlier net zero achievements to generate credits for those with more challenging pathways [147]. Brazil's capacity to implement BECCS and achieve early net zero targets could provide offsets to regions like China or the US. However, reliance on such mechanisms must be carefully managed to avoid inequitable outcomes, where wealthier regions offset emissions without substantive reductions domestically. Policies must be carefully designed to ensure that these mechanisms incentivize real emissions reductions and support sustainable development in less advantaged regions.

Furthermore, equity and burden-sharing schemes often consider accounting for historical emissions, current capabilities, and socioeconomic contexts [51]. Wealthier regions with historically high emissions, such as the European Union and the US, can theoretically bear a greater responsibility to invest in and support CDR deployment globally [148]. At the same time, regions in the Global South face opportunities associated with land-intensive CDR alternatives, highlighting the need for fair compensation or support through international funding and technology transfer initiatives. Other concerns, such as social inequalities, biodiversity impact, land concentration and land-grabbing, corruption and other illegal activities might also need to be dealt with to fully allow these countries to benefit from these opportunities.

From the market perspective, it is worth noting that the technological readiness level of CDR technologies and their scalability remains a key source of uncertainty in their large-scale deployment [115], as some scenarios get to an annual 12 Gt CO_2 captured by these technologies. While BECCS is often considered an almost mature option, its widespread implementation has not yet been proven. It also involves significant factors, such as land-use change, water resource demand, and infrastructural need for CO_2 transportation and storage. On the other hand, DAC is still in its early stages of development, with high costs and resource restrictions which can limit its scalability [115]. These uncertainties highlight the need for further research and policies to better understand the practical and environmental implications of deploying these technologies at the scale required to meet PA goals.

Related to the technological uncertainties, there is also a key limitation for implementing these options within an IAM. Key variables, such as future cost trajectories, regional availability, and efficiency gains have very high uncertainties and can significantly influence the findings [149]. Sensitivity or stochastic analyses could be particularly valuable in addressing these uncertainties, by exploring how changes in critical parameters such as carbon prices, technology costs or availability impact model outputs [17, 150]. Such analyses would provide a more robust understanding of the range of outcomes and help policymakers navigate uncertainties in planning the deployment of NETs.

Lastly, social acceptance should also be taken into account in the discussion of future CDR deployment, as it plays a pivotal role in the success of negative emissions technologies, particularly in A/R and BECCS . Public concerns about the safety and long-term effectiveness of CCS, including risks of CO_2 leakage and its association with fossil fuel industries, can hinder its adoption despite its technical potential [151]. Additionally, the "not in my backyard" phenomenon often poses significant challenges, as communities may oppose the siting of CCS infrastructure near their homes due to perceived risks and disruptions [152]. Similarly, A/R initiatives often face resistance due to land-use conflicts, displacement risks, and the perception of prioritizing carbon removal over food production and biodiversity issues [119, 153]. Addressing these challenges requires transparent communication, stakeholder engagement, and policies that align carbon removal efforts with community needs and environmental conservation goals, fostering trust and broader societal support.

4.5 Policy Implications

As previously mentioned, IAMs are an important tool for policy testing, checking and indication [7, 12, 154]. The scenario results indicate that CDR methods may be essential in a carbon constrained world. Consequently, it is essential to develop and implement effective policies to incentivize these methods. Various policy mechanisms can support the entry and economic viability of CDR, such as: grant support, operational subsidies, carbon pricing, land-use regulations, demand-side measures, regulatory standards and obligations, risk mitigation measures, infrastructure development, and innovation and R&D [55, 143, 155–157]. With the main challenge being in designing and applying policy instruments for various CDR methods to make them economically viable. This discussion looks at how some of these tools can help the dissemination of these carbon removal methods.

Some of our results have shown the importance of carbon emission markets for the implementation of CDR methods in a PA-compliant world. Country-specific or regional emissions markets are necessary to curb GHG emissions, because as of today, most countries around the world consider CO_2 (and its equivalents) as a waste product. To incentivize carbon removal and GHG reduction, these gases should be treated and priced as pollutants, hence the necessity of carbon emission markets [143, 158]. Currently, only country-specific and regional carbon emissions markets exist with different scopes [159, 160]. However, regional particularities such as local potential for CO_2 capture through A/R or geological CO_2 storage capacity should be considered. Proper evaluation of these regional potentials would only be possible in a unified global carbon market spanning multiple regions or countries. Therefore, this can also improve innovation and R&D of novel CDR technologies, and the development of its infrastructure.

In addition to general market-based regulations, technological, forestry, biofuels, and storage regulations also directly impact CDR methods. For A/F, the techniques needed for seed collection, seedling production and the development of these trees are well known [161]. But policies must ensure certificates account for carbon stored both above and below ground, guaranteeing that it remains stored rather than converted to short-lived timber products [162], and improving land management, forestry and monitoring systems to properly account for LUC and related emissions [163]. In relation to bioenergy with negative emissions, fuel mandates, subsidies, and emissions taxes can be explored as potential methods for developing these pathways. Mandates for BECCS production for biofuels or bioelectricity could be an option to reduce the overall emissions of a country or region; however, this approach should consider potential technological lock-in issues arising from predefined pathway selections, rather than allowing market-driven choices. Subsidies can boost voluntary demand, if considered as a demand-side subsidy, and support innovation and improve access to finance, reducing risks for companies [157, 164]. Regarding transportation and geologic storage of CO_2, the transportation side suffers from a classic 'chicken and egg' problem, as it is not worthwhile to build a pipeline system without enough capture plants to supply CO_2 to the pipelines. Conversely, emitters are hesitant to invest in expensive capture equipment without assurance that a CO_2 pipeline is going to be built. Aside from that, there is the uncertainty regarding the regulatory regimes governing CO_2 pipelines [165]. Furthermore, these pipelines may extend across state and national boundaries; therefore, the regulatory framework must account for this aspect [166]. Finally, for CO_2 storage, policies should account for geochemical interactions between injected gas and geological storage. It is important to model these interactions to anticipate reactions that might hinder CO_2 injection or cause potential gas leakages [143].

4.6 Conclusion

Limiting global warming to meet the goals of the PA will require unprecedented transformations across sectors to reduce global CO_2 emissions [28, 106]. However, the slow pace of decarbonization to date has likely committed the world to the inevitable use of carbon removal options. CDR alternatives are therefore an essential component for meeting the ambitious targets of the PA. Alongside other decarbonization measures, CDR can shift companies', sectors', and countries' strategies toward carbon neutrality or even net-negative pathways, reinforcing their importance in achieving stringent climate targets.

This study presents two major uses for CDR, as they can compensate for residual emissions in hard-to-decarbonize sectors and enable net-negative emissions to reverse overshoots in global temperature targets. Using the COFFEE model, we show that achieving ambitious temperature goals, such as limiting warming to 1.5 °C, requires significant deployment of CDR, which are still incipient. Therefore, the use of A/R, BECCS, DAC, materials and others not considered in this study will be indispensable. These findings highlight the necessity of developing and scaling these technologies to address the need to meet PA goals.

The analysis also reveals significant regional variations in the capacity and timing of CDR deployment. Regions like Brazil, the US, and South Africa are considered leading regions in implementing A/R and BECCS, while China and India exhibit potential for a more diverse use of carbon removal strategies. Adjusting deployment strategies to regional specificities, coupled with strengthened international collaboration, will be crucial for enhancing the effectiveness and ensuring the equitable implementation of CDR. Regional and global emissions markets could help attenuate regional disparities, while also reducing the possibility of carbon leakage in other countries.

Early and sustained action is important to minimize reliance on CDR in the latter half of the century. Delays in mitigation can heighten the technical, economic, and ecological challenges associated with CDR deployment and may lead to surpassing temperature thresholds, which could potentially lead to impacts that might not occur in a trajectory without overshoot, thus amplifying the associated risks and uncertainties of a delayed mitigation [4, 167]. Policymakers should focus on decarbonizing more easily to decarbonize sectors as soon as possible, thereby limiting the scale of negative emissions required. And CDR could be added to countries NDCs, but without weakening other mitigation efforts [168]. Mandates or quotas of renewable fuels or materials linked to CDRs can also foster the development of novel CDRs in the short term.

Achieving these goals will require a robust policy framework that supports the development and deployment of CDR. Investments in R&D are essential to advance the readiness of less mature options like DAC and materials-based CDR. International collaboration and equitable funding mechanisms are also necessary to address disparities in regional capacities and foster a just transition, with technology-transfer helping to strengthen global capacity for CDR. Carbon trading systems and global financing initiatives are essential for distributing responsibilities and benefits fairly.

Chapter 5

Conclusion

This thesis explored different strategies to bridge the emissions gap and achieving the Paris Agreement targets using IAMs. The research, carried out through three studies, provided information into effective climate policies, the role of economic recovery packages after COVID-19, and how climate ambition affect global and regional dynamics of CDR technologies. The overarching research question addressed how climate policy instruments and IAMs can synergistically inform each other to effectively bridge the global emissions gap and achieve the PA temperature goals. These issues were systematically explored in three interconnected studies, each addressing specific aspects as presented in the Research Questions proposed in subsection 1.1.1.

The first paper (chapter 2) responded to the first research question by analyzing how a set of 'good practice policies' could help bridge the emissions gap between major emitting countries using IAMs. The chapter demonstrated that while these good practice policies contribute significantly to emission reductions, they alone are insufficient to achieve PA targets. The analysis showed that examining standard and sector-specific policies could help assess cross-country learning and clarify the mitigation potential and limitations of each sector. Future efforts must therefore focus on tailored country-specific policies that consider political feasibility, economic contexts, and natural capabilities for each region.

The second paper (chapter 3) addressed the second research question by evaluating to extent to which post-COVID-19 economic recovery packages could bridge the investment gap and align with short- and medium-term emissions trajectories compliant with Paris goals. These findings highlighted that the recovery packages considered do not adequately address the needs of a climate-constrained scenario, indicating the need for more ambitious, continuous, and targeted investments and policies. Although this study considered specific sectors and the role of targeted investments in them, other sectors could also have been included to further understand their potential contributions. Additionally, sensitivity analyses with investment fully focused on different sectors could provide insights into the potential of directed investments and their effectiveness in bridging the emissions and investments gap.

The third paper (chapter 4) examined the role of CDR technologies across global and regional scales, by analyzing different levels of climate ambition. The results emphasized the importance of early and extensive deployment of technologies such as BECCS and A/R to meet more stringent temperature targets. The study identified regional particularities in CDR capacities, suggesting a targeted policy and international cooperation carbon market to optimize effectiveness. It also highlighted the potential to incorporate new CDR technologies and assess how their inclusion impacts regional structures and results. Additionally, exploring the effectiveness of policies such as demand-side measures or restricted regional carbon markets could further illuminate their impacts on global CDR allocation and the resulting reliance on these methods.

Some key limitations identified in these studies involve several aspects that require a deeper exploration in IAMs. First, moving beyond cost-optimal runs in modeling is necessary; this indirectly occurred in the Good Practice Policies chapter by considering CO_2 budgets in the national models derived from global cost optimal scenarios. Similarly, the CDR chapter calculates budgets without explicitly incorporating justice or equity criteria, which is potentially disadvantageous to developing countries [51, 169, 170]. The cost-optimal approach remains valuable, as it provides important insights of the least-cost pathways, and can serve as a benchmark scenario. Such benchmark scenarios are essential for comparison against alternative scenarios that incorporate different considerations, such as equity criteria. Furthermore, comparing cost-optimal scenarios with equity-based scenarios can highlight opportunities for developing countries to update their conditional NDCs. These comparisons can also clarify the levels and types of financial or technological support required from developed to developing countries.

Second, uncertainty and sensitivity analyses could be explored. This includes testing variations in policy target years, implementation levels, and technological assumptions, particularly for CDR options [150, 171]. Such analyses are needed because uncertainty regarding cost projections of technologies can be significantly affected by the application of investment packages, or even the costs of low-carbon technologies and CDR. Furthermore, policies may fail to perform or meet the initial proposed targets, directly influencing the model results and the possibility of achieving the PA goals. In addition, methods such as the application of the Monte Carlo method can add new depths for the analysis, allowing comprehensive evaluations through numerous scenario runs and quantification of the effects of these uncertainties [150].

Third, some additional criteria that have not yet been taken into account for these models should be considered, such as biodiversity indicators, which could significantly influence the estimated levels of CDR required and therefore alter the presented outcomes [172]. Adding to that, justice and equity criteria can introduce a new dimension by incorporating principles such as sovereignty, equality, capability, responsibility, and others. Such considerations are important to reshape national emission budgets and pathways by recognizing historical responsibilities and disparities in development capacities [51], and taking these dimensions into account could change the regional allocation of CDR and some policy implications.

More broadly, future research and policy recommendations drawn from this thesis stress the importance of greater stakeholder involvement in IAM scenarios to develop scenarios that are more aligned with the perspective of policymakers. Addressing technological uncertainties, implementing heterogeneity in modeling lifestyle changes, ensuring a just transition, and improving transparency are crucial steps. In addition, the expansion of national IAM participation, with diverse research groups contributing varying perspectives, will strengthen the credibility and applicability of modeled insights, and also regional policy applications. Ultimately, IAMs must continuously evolve to effectively address emerging climate policy questions and societal challenges, enhancing their role in global climate change research.

Future research can focus on different aspects of what was explored in this thesis. Most of the analyzed policies focused on supply-side measures, as well as the economic packages, but demand-side policies and investments could also be considered for its application in IAM scenarios. This also relates to an over reliance on CDR in more ambitious scenarios, as demand-side measures can reduce the necessity of CDR compensating positive emissions [26]. The exploration of different SSPs and how sets of policies might be more aligned with different levels of mitigation and adaptation challenges can be considered. This could show how distant or close each SSP world is relative to the pathways aligned with the Paris Agreement, providing insights into their alignment or misalignment in terms of climate ambition.

Moreover, future analyses could explicitly incorporate equity and justice considerations, both in policy implementation and investment allocation. For example, assessing how investment packages can be distributed fairly based on national sovereignty or intergenerational aspects could provide an interesting perspective on the climate finance aspect of the PA. Similarly, integrating justice considerations into different ambition levels can present regional responsibilities and requirements regarding CDR use. Furthermore, investigating carbon credit trading schemes, where regions with greater mitigation potential can provide credits to those with fewer mitigation opportunities, could enhance global mitigation efficiency, although practical implementation challenges within some IAMs would need careful attention.

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