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

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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-19 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 that it should be significantly upscaled and prolonged to ensure compatibility with the Paris Agreement goals.

Keywords: COVID-19; economic recovery; stimulus packages; climate scenarios; integrated assessment modelling

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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 [1]. 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 [2]. 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 return to full capacity [3,4]. IEA [5] 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 [6], which could propel or undermine the energy transition, depending on future investment profiles [7].

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 [1]. 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 [8]. Climate action is embedded in most of these packages, but with sharp differences at regional level.

The European Union has launched a EUR 750 billion recovery package, from which at least 30% of expenditure is committed to mainstreaming climate action [9]. The United States Biden administration, similarly, has launched a "Build Back Better plan" which aims at canalising USD two trillion into low-carbon investment, including USD 400 billion directly to clean energy over the next ten years [10]. In contrast, an economic recovery based on low oil prices, such as the stimulus announced by Indonesia, Turkey and Russia [11], 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. It assesses 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 allows the research community to produce integrated and comparable analyses of climate change impacts, adaptation and mitigation [12,13]. Providing shared scenarios is crucial to promoting interactions among disciplines and research interests, in order to make conclusions compatible and consistent across the literature, thus allowing easier communication of modelling results, as well as reducing scattered individual efforts towards elaborating consistent assumptions for their own scenarios [13].

While the scenario framework used by the Intergovernmental Panel on Climate Change (IPCC) and other authors [12,14–18] 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 [14,15] 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-19 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 [19].

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.

2.1. Modelling Frameworks

This study uses two different modelling frameworks to assess the impacts of green recovery packages. The COFFEE-TEA IAM suite of models [20] comprehends a bottom-up, partial equilibrium, global model for the energy and land systems (COFFEEComputable Framework for Energy and the Environment) soft-linked to a global Computable General Equilibrium (CGE) model; the Total Economy Assessment (TEA) 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 minimising the total cost of the system from pre-established policy restrictions (Rochedo, 2016). 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 [21]. TEA follows the standard microeconomic optimisation 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 [22,23]. 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, in both 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 [22,24]. 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 A.

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" [25] 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 [26] and the OECD Economic Outlook of December 2020 [27]. 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 [28]. 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 [29], the Energy Policy Tracker [11], the Climate Action Tracker [30] and the Greenness Stimulus Index [31]. When regional trend data are needed, the IEA Country Statistics [30] 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, consistent with the European Green Deal, commits at least 30% of its EUR 750 billion budget to climate action, while the remaining 70% should follow the principle to "do no harm" to the environment (European Council Conclusions, 17–21 July 2020—Consilium, n.d.). At the same time, countries such as France and Germany, as well as the UK, outperform in the greenness of their stimulus packages, with a net positive impact towards climate action [31]. Additionally, the Energy Policy Tracker traced no commitment to direct fossil fuel support from the European Commission, in contrast with a USD 385.36 commitment to clean energy investment [11].

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 USD 22 billion to clean energy investment when compared to fossil fuel energy [11], it still plans to install as many new GW of coal power plants as its previous trajectory [31].

The US has notably the largest economic stimulus package in the world. In the early stages of the pandemic, the US administration pledged USD 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 USD 72.35 billion to oil, oil products and coal, and USD 27.27 billion to support clean energy, mostly directed to biofuels and wind power [11]. A clear shift took place when, in 2021, the Biden administration committed to "Make a historic investment in clean energy and innovation", pledging an additional USD 400 billion to renewable energy investment [10]

Economies that heavily rely on fossil fuel exploitation such as Russia and Middle Eastern countries unsurprisingly indicate a fully brown recovery [11,31]. The remaining world regions seem to show rather dubious stimulus profiles, with investment directed both ways, but mostly showing brown net impacts [32,33].

Having screened national and regional policy packages for the post-COVID-19 pandemic economic responses, we translate them into assumptions for each of the scenarios and their main policy instruments (Table 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 [8]. The scenario conceptualises a situation of prolonged needs for recovery packages, given that most countries face challenges to fight new COVID-19 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 [34]. 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.

Table 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 GtCO2 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).

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 a 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.

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 particular 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) [7]. 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 details—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. 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.

3.1. Policy Scenarios (National Pledges)

Figure 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 a larger reduction in 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.

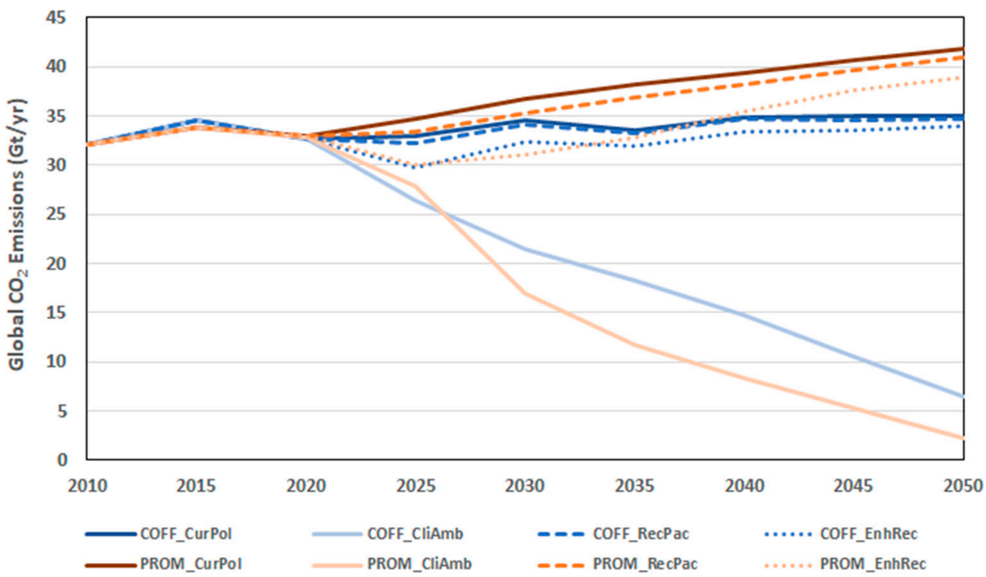

Figure 1. Global CO_2 emissions pathway over 2010–2050.

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

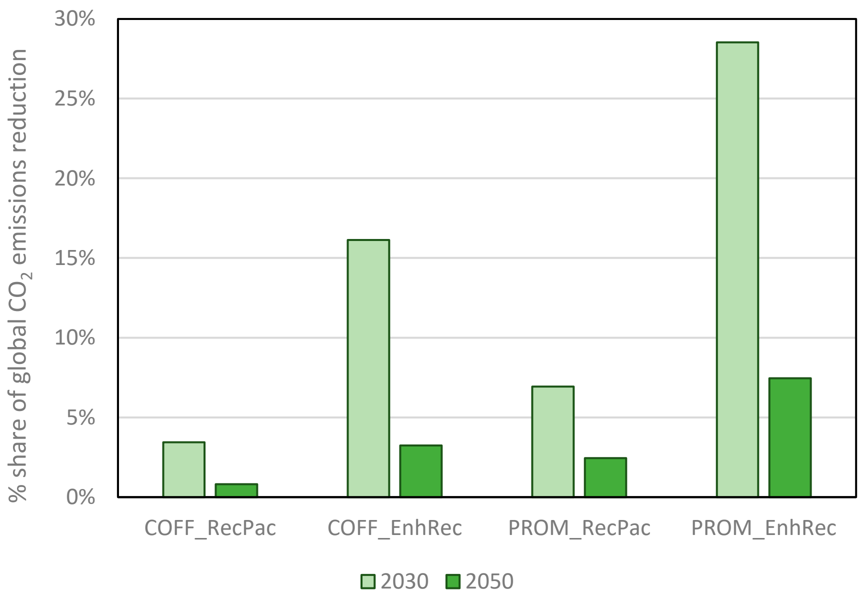

Figure 2. Closing the ambition gap—Share of global CO_2 emissions reduction from CurPol levels achieved in RecPac and EnhRec scenarios compared to reductions required to achieve the 1.5 degree target in a cost-optimal way in 2030 and 2050.

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.

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 [22]. Figure 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 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.

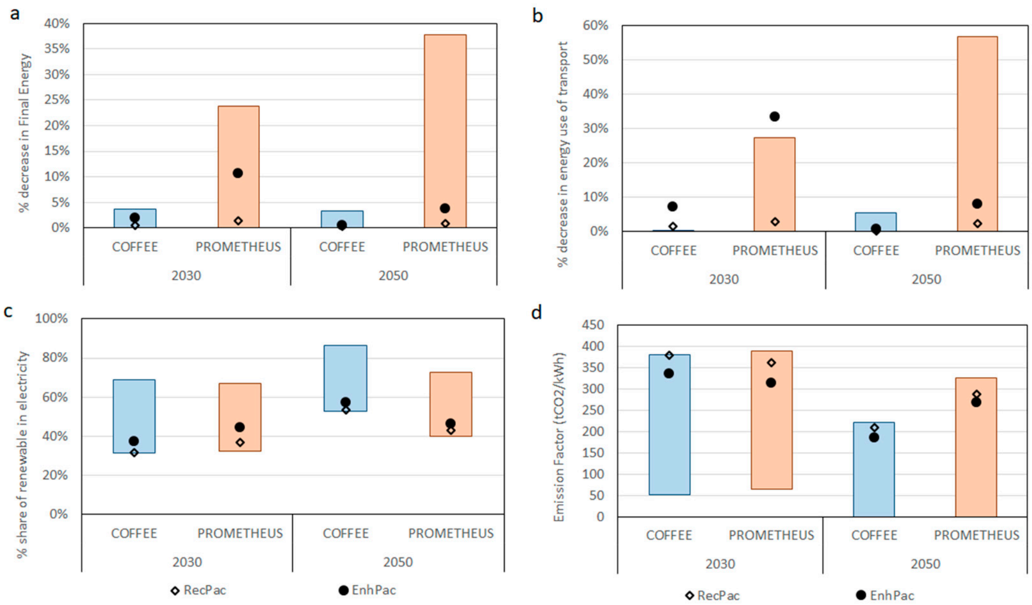

Figure 3. Energy system transformation—decrease in final energy consumption (**a**); decrease in energy use of transport (**b**); share of renewables in electricity generation (**c**); and global emission factor of electricity generation (**d**) in 2030 and 2050.

Figure 3a 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 in 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 3b, PROMETHEUS shows a reduction in 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 in 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 3d). 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 (485–576 $MtCO_2$/MWh). However, although they are 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 4 presents the results for the green energy investment required to close the gap in 2030 and 2050. In the horizontal axis, the investment gap is the level of cumulative investment (present value (PV) in 2020 of the level of investment over 2020–2030, discounted at a 5% p.y. rate) 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 4, numbers for

RecPac and EnhRec scenarios are summarised as COFFEE and PROMETHEUS Standard, while results for the GloGov scenario appear as COFFEE Global Optimal.

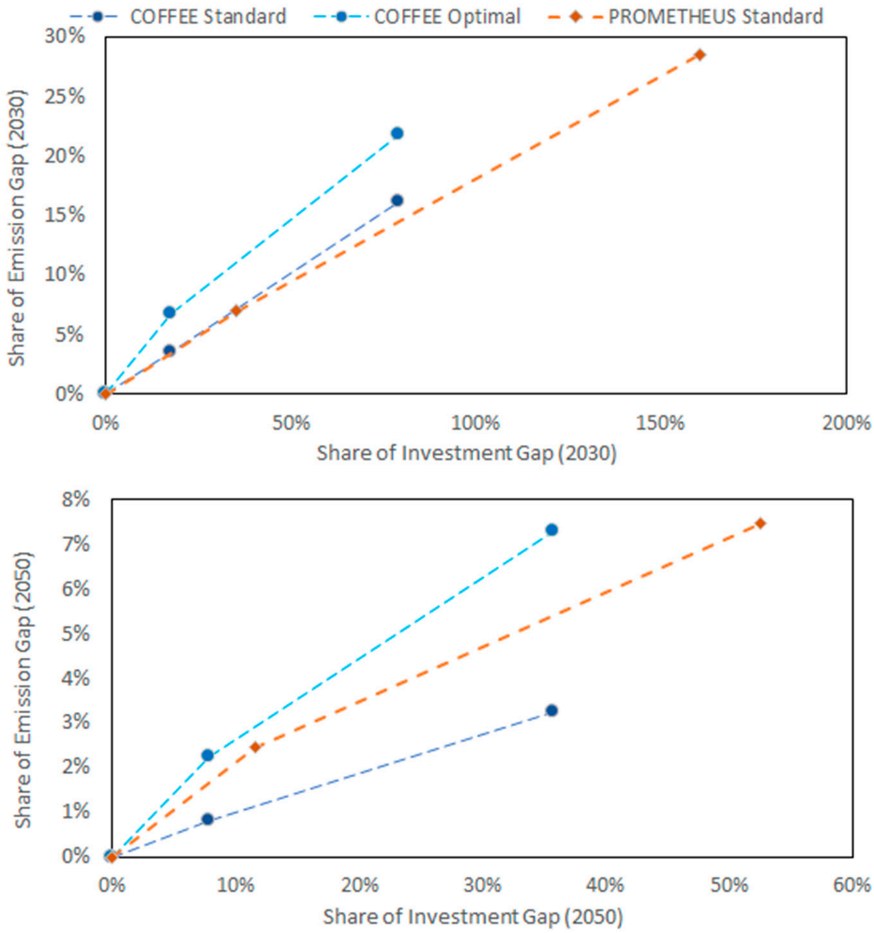

Figure 4. Ambition gap and investment gap in 2030 and 2050.

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).

We also note that, in the 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 1082 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 internalising the cost of the pollutants in the prices of goods and services, therefore reducing the costs of the climate policy. As illustrated in Figure 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.

3.2. Global Governance

Differences across the RecPac/EncRec and GloGov results also reveal that going global achieves a greater reduction in 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 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.

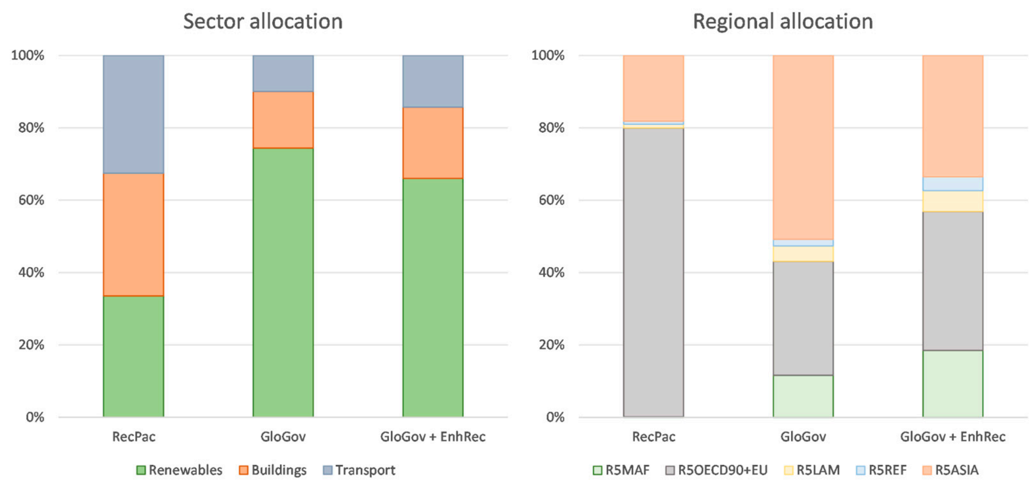

Figure 5. Investment allocation by regions and sectors in Global Governance scenario. Note: R5MAF (Middle East and Africa), R5OECD90 + EU (OECD countries), R5LAM (Latin America), R5REF (Rest of the World), R5ASIA (Asia).

Results indicate that a greater share of green investments would flow to renewables (60–70%) in GloGov and GloGov + EnhRec scenarios (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), decreasing the amount directed to buildings and transport sectors. The optimal solution of the modelling framework is chosen due to having 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 (IEA, 2021) [7].

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.

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. A 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 [5] 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 [33] with long-term repercussions on land use, fossil fuel use and GHG emissions. A fossil-based post-COVID-19 recovery would create a carbon lock-in, which would delay climate compatible development in those economies.

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 [35] (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) they 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 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. However, 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. Therefore, 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.

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-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 substantial geographical heterogeneity. In this paper, we provide novel evidence on the energy system and emission implications of post-COVID-19 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 the 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 [36]. 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. Additionally, 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 [37], 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 [38–42]. 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, such as in [37], 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).

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Appendix A

Appendix A.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-CO_2 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 [43], 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 [44].

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 A1).

Table A1. Sectoral coverage in COFFEE-TEA IAM suite.

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 A1). In addition, COFFEE has a global region represented as the 19th region of the model for the assessment of global climate policies.

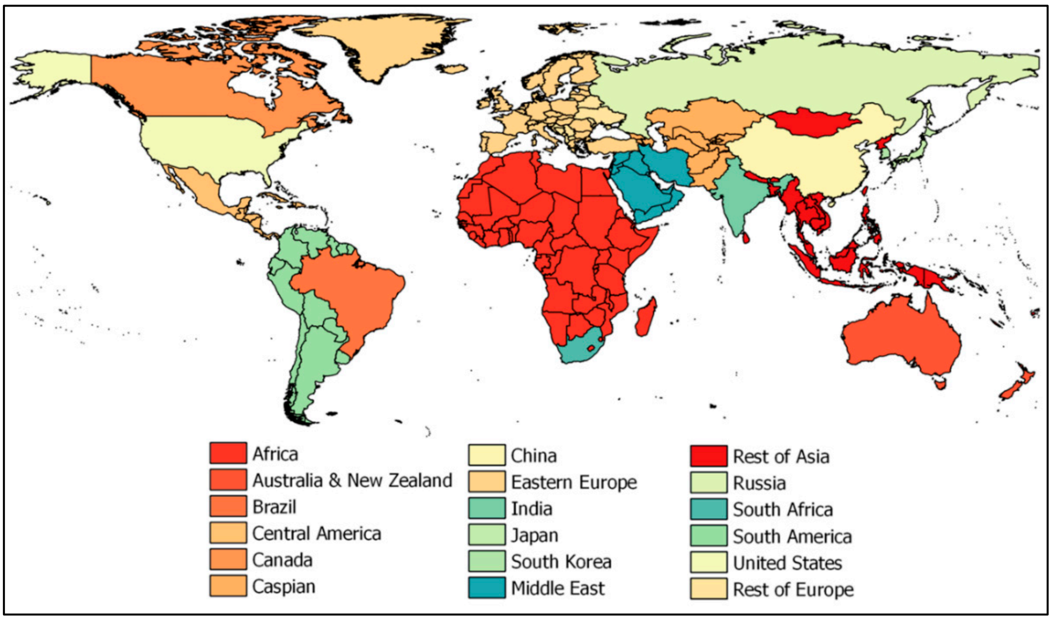

Figure A1. Regional breakdown of the COFFEE-TEA IAM suite.

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.

Appendix A.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.

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