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Analysing the Transformative Changes of Nationally Determined Contributions and Long-Term Targets

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Abstract: As the imperative to address climate change intensifies, understanding the effectiveness of policy interventions becomes paramount. In the context of addressing these urgent challenges and given the inadequacy of current policies to address this issue, this study examines the extent to which Nationally Determined Contributions (NDCs) and Long-Term Targets (LTTs) can contribute to achieving ambitious climate goals. Recognizing the critical need for effective climate action, we employ the advanced modelling tools PROMETHEUS and GCAM to assess the implications of different scenarios–Current Policies (CP), Nationally Determined Contributions (NDC), and combination of NDCs with Long-Term Targets (NDC_LTT)–on the future development of energy system and emission. This study, by employing these well-known models, seeks to provide an improved understanding of the impacts of NDCs on global emission trajectories and whether the integration of NDCs and LTTs can help close the gap towards Paris-compatible pathways. The study analyzes various sectors including buildings, transportation, electricity generation, and industry to provide insights into the limitations of existing policies and the potential of enhanced commitments to drive transformative changes in a global scale. The effectiveness of these policies varies across different sectors, highlighting the challenges that need to be addressed for achieving the required emission reduction targets in the medium- and long-term. Key findings indicate significant shifts in energy consumption, fuel mix, technology adoption, and emission trajectories, particularly under the synergistic action represented by the NDC_LTT scenario.

Keywords: Nationally Determined Contributions (NDCs); Long Term Targets (LTTs); modelling scenarios; Integrated Assessment Models; PROMETHEUS model; GCAM model

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1. Introduction

Climate change is one of the most pressing challenges of our time, with far-reaching implications for the environment, society, and global economies. Despite international efforts, current climate action policies and strategies, as outlined in the Nationally Determined Contributions (NDCs) under the Paris Agreement (PA), fall short of the ambitious targets necessary to limit global temperature rise to 1.5 °C [1]. The NDCs are national climate pledges including national climate plans and targets until 2030 and are one of the key mechanisms of PA as each Party is required to develop them reflecting their individual commitments and strategies to mitigate greenhouse gas emissions and adapt to the impact of climate change. Overall, NDCs include measures for both adaptation and mitigation actions and must be periodically updated (at least every five years) to increase their climate ambition. The fact that they must be updated gives space to provide more ambitious targets in order to collectively move towards the 1.5 °C goal set out in the PA. Parties to the PA have to periodically undertake a Global StockTake (GST) to assess collective progress toward the PA's long-term goals on mitigation, adaptation, and means of implementation; the 1st GST concluded at COP28 in Dubai in December 2023. After being informed by the

GST, each Party is expected to communicate a new NDC; this must include more ambitious targets and commitments that go beyond the previously declared NDC and must reflect the highest possible ambition. While NDCs serve as vital tools for translating the global goals of the Paris Agreement into actionable measures at the national level, their focus on short- to medium-term goals [2] often lacks the appropriate long-term vision and ambition required to achieve deep decarbonization and climate resilience.

Recognizing the need to analyze the long-term climate ambitions of countries beyond 2030 [3], there is a growing imperative to integrate Long-Term Targets (LTTs) into national climate policy frameworks [4]. LTTs provide a strategic, long-term, and forward-looking perspective, extending beyond the typical timeframe covered by NDCs to encompass multi-decadal planning for low-emission, climate-resilient development of countries. The alignment of short-term actions outlined in NDCs with long-term visions included in LTTs facilitates a more holistic approach to emissions reduction, adaptation, and sustainable development, taking into account technological advancements and socio-economic developments while also considering national policy priorities and specificities [5].

The combination of NDCs and LTTs offer a comprehensive framework for achieving ambitious climate goals while promoting sustainable development objectives in the medium and long-term. By strengthening and guiding NDCs, LTTs help to steer investments away from fossil-fuel intensive activities, signaling clear signals to investors and providing economic incentives for clean energy innovation and development of low-carbon technologies and climate-resilient infrastructure. Moreover, LTTs play a crucial role in facilitating a just transition towards a low-carbon economy and mobilizing climate finance to support vulnerable communities and sectors. Drawing on insights from international climate policy frameworks and empirical evidence from case studies such as Chile's long-term strategy [6], which leads to estimated economic savings of more than USD 267 billion by moving towards carbon neutrality by 2050, this study explores the potential synergies between NDCs and LTTs in driving ambitious climate action and advancing clean energy transition and sustainable development goals [7].

A growing body of literature evaluates the impacts of NDCs at both national and global levels, employing various analytical approaches. Numerous studies have employed energy system and Integrated Assessment Models (IAMs) to evaluate the impacts of NDCs on global and national level, providing valuable insights into the effectiveness of various climate policies and strategies. For example, the International Energy Agency's World Energy Outlook (WEO) series utilizes energy system modelling to assess the implications of different policy scenarios, including NDCs, and offers comprehensive insights into how NDCs influence global energy trends and emissions trajectories [8]. A study led by E3M lab addressed a key gap in existing literature by combining global and country-level models to comprehensively examine the energy, emissions, and economic impacts of NDCs [9]. The Intergovernmental Panel on Climate Change (IPCC), in its Special Report on Global Warming of 1.5 °C, evaluates the feasibility and implications of limiting global warming to 1.5 °C, considering the role of NDCs and their impact on energy transitions [10]. The International Renewable Energy Agency's REmap series also analyzes the potential and implications of scaling up renewable energy; this includes assessing how NDCs contribute to renewable energy adoption, energy efficiency improvements, and emission reductions across various countries [11].

Several studies employ IAMs to evaluate the impacts of climate policies, including NDCs, on emission trajectories, energy system development, and economic indicators. Their goal is to contribute to the understanding of the potential effectiveness of NDCs in achieving climate goals as well as the challenges to achieve the climate goals [12]. Several research institutes use various advanced large-scale IAMs to assess the impacts of NDCs on energy systems, focusing on how different mitigation pathways, aligned with NDCs, affect energy supply, demand, and greenhouse gas emissions [13–16]. More recent studies using IAMs examine the effects of NDCs in combination with longer-term policies and

LTTs [17–19] for the energy transition at national level, while also assessing their consistency with the global Paris Agreement climate goals.

Overall, energy system and Integrated Assessment Models (IAMs) have become instrumental in assessing the impacts of NDCs and long-term climate strategies on global and national levels. These studies contribute valuable insights into the feasibility, challenges, and opportunities associated with achieving climate targets, providing an analytical foundation for informed policymaking and strategic planning.

The current study employs two well-established global IAMs, the PROMETHEUS [20] and GCAM [21], to analyze the impacts and effectiveness of climate policies of different level of ambition, including current policies, NDCs, and LTTs targets for countries that have submitted an LTT. The paper contributes in a useful manner to the understanding of the energy, emissions, and economic implications of climate targets pursued in the major economies. To this end, we use these models to simulate, in detail, the complex interactions between energy demand and supply, technology uptake, land-use changes, and emissions to 2050 and beyond, providing an improved understanding on the sectoral transitions triggered by climate policies. Thus, the policy relevance and the realism of the global model-based scenario analysis is enhanced, especially combined with bottom-up NDC and LTT data at the country level. The study allows for a comprehensive quantitative assessment of the NDCs and LTTs embedded in the global policy context and international energy markets. Taking a sectoral approach, the analysis indicates the main transformation challenges and opportunities in major emitting sectors, namely transport, industries, buildings, and electricity generation. Our study aims to answer the following research questions: (i) what are the emission outcomes if countries follow their current policies, their NDCs, and their LTTs by 2050?, (ii) are the national pledges, including NDCs and LTTs, in line with the global climate goals?, (iii) what are the sectoral contributions towards reducing global emissions, and (iv) what sectoral transformations are required in major emitting sectors (transport, industry, energy supply, buildings) towards reducing emissions in line with climate goals?

The results of the study show that the combination of NDCs and LTTs achieves larger emission reductions and a more ambitious shift in the fuel mix towards renewable energy technologies and electrification. The model results provide evidence on the energy system restructuring required to achieve ambitious climate targets, on the sectoral allocation of the CO_2 reduction effort, and on the low-carbon transition costs.

The rest of the paper is organized as follows: Section 2 presents the methodological approach, including the scenarios examined and the models used; Section 3 presents the scenario results derived from the two IAMs including the impact on CO_2 emissions and energy system development, and Section 4 concludes.

2. Materials and Methods

2.1. Scenario Design Protocol

The scenarios are designed to reflect different levels of national climate policy ambitions after the COP26. In particular:

- Current policies (CP): reflect the short-term policy ambition materialized through actual, already implemented policies or concrete policy targets.
- NDCs (NDC): reflect the level of short-term ambition included in the countries' NDCs for 2030, but with implementation risks if dedication is not high enough and/or of changes in the political landscape.
- Long-term targets (LTT): reflect the longer-term ambition of national mitigation pledges, which in most cases is not backed with an actual policy agenda.

Three scenarios are implemented with the global IAMs PROMETHEUS and GCAM to assess the gap between the current national policies, NDC commitments, and ambitious Long-term mitigation targets, as shown in Table 1.

Table 1. Scenario assumptions used by the PROMETHEUS and GCAM models.

CP	The scenario is based on the current portfolio of actual emissions reduction policies as well as credible policy targets until 2030 in EU and non-EU countries. For the period post-2030 action, the CP scenario assumes that climate policy continues but is not strengthened. Following [22], the CP scenario assumes that the rate of change of emission intensity of GDP over 2020–2030 remains the same after 2030. The applied policy targets until 2030 (for example, renewable energy mix targets, vehicle fuel standards) are maintained as minimum levels beyond 2030 to avoid backtracking of achieved policies.
NDC	The scenario assumes the implementation of stated 2030 emission targets captured in NDCs submitted or announced by June 2022, capturing all mitigation ambition updates during and after COP26. These NDC targets are applied on top of current policies (CP) modelled in the previous scenario; in regions where current policies overachieve on the mitigation targets in NDCs, no additional emission constraints are applied. For the period after 2030, the same method based on constant carbon intensity of GDP reduction rates over 2020–2050 is applied as in the CP scenario.
NDC_LTT	The scenario is based on the NDC assumptions until 2030 but, for regions that formulated an LTT, such as net-zero commitments or other targets for 2050 or later (either in law, policy documents, or only announced), emission constraints are applied that linearly decline from 2030 NDC emission levels towards the LTT. For regions without LTTs, post-2030 emissions follow an identical path as in the NDC scenario.

The first two levels of climate action are aimed at 2030, which is the common year for NDC targets and for many current policy targets. To project the longer-term emission futures, the Emissions Intensity (EI) method is applied [22] after 2030, keeping the rate of change in emissions intensity of GDP in each region from 2020 to 2030 in the CP and NDC scenarios constant in the period after 2030. The NDC_LTT scenario includes specific emission reduction targets both for the medium and the longer term. A detailed list of NDC and LTT targets for major economies is provided in Appendix A below.

To increase the realism of how emissions reductions take place in our scenarios, current policies are represented explicitly in both the CP and NDC scenarios, both before and after 2030. After 2030, current policies are assumed to remain in place as “constant” or “minimum” bounds on effort (e.g., on renewable mix targets or fuel standards). The third level of climate action (LTTs) aims to incorporate long term pledges, predominantly net-zero emission pledges, to the modelled scenarios. These will come on top of pledged NDC targets for 2030, to create another increased level of proposed ambition. These pledges are included for each model region as a linear pathway from the 2030 NDC target to the LTT target in 2050 or later (NDC_LTT scenario).

In all policy scenarios, the models use harmonized assumptions about the future development of main socioeconomic drivers, namely population and GDP by region, based on widely used established databases such as Eurostat [23], UN Population projections [24], Shared Socioeconomic Pathways- SSP2 [25], and IMF [26]. In addition, the technoeconomic assumptions (e.g., costs and efficiencies of technologies) and fossil fuel prices used in the models are also harmonized based on the latest EC Reference scenario [27] and the IEA, World Energy Outlook projections [28].

2.2. Modelling Tools

GCAM [21] is a dynamic-recursive model with technology-rich representations of the economy, energy sector, land use, and water linked to a climate model that can be used to explore climate change mitigation policies including carbon taxes, carbon trading, regulations, and accelerated deployment of energy technology. Regional population and labor productivity growth assumptions drive the energy and land-use systems, employing numerous technology options to produce, transform, and provide energy services as well as to produce agriculture and forest products, and to determine land use and land cover. Providing results at 5-year intervals until 2100, GCAM has been used to explore the potential role of emerging energy supply technologies and the greenhouse gas consequences of specific policy measures or energy technology adoption, including CO_2 capture and storage, bioenergy, hydrogen systems, nuclear energy, renewable energy technology, and energy use technology in buildings, industry, and transportation sectors. GCAM can be used to simulate scenarios, policies, and emission targets from various sources, including the Intergovernmental Panel on Climate Change (IPCC). Output includes projections of future energy supply and demand and the resulting greenhouse gas emissions, radiative forcing, and climate effects of 16 greenhouse gases, contingent on assumptions about future population, economy, technology, and climate mitigation policy.

PROMETHEUS [20] 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. The main objectives of PROMETHEUS are to assess climate change mitigation pathways and low-emission development strategies for the medium and long-term, analyze the energy system, economic, and emission implications of a wide spectrum of energy and climate policy measures, differentiated by region and sector, and quantify the impacts of climate policies on the evolution of fossil fuel production and global energy prices. The PROMETHEUS model provides detailed projections of energy demand, supply, power generation mix, energy-related carbon emissions, energy prices, and investment in the future, covering the global energy system. The model simulates both demand and supply of energy, interacting with each other to form market equilibrium at different regional scales: detailed regional balances are aggregated in order to simulate world energy markets. Apart from international fuel prices, regional energy systems influence each other particularly through trade, technical progress, and network effects, including changing patterns of consumption and spillover effects with regard to technology diffusion. PROMETHEUS quantifies CO_2 emissions and incorporates environmentally oriented emission abatement technologies (like RES, electric vehicles, CCS, energy efficiency) and policy instruments. The latter includes both market-based instruments such as cap and trade systems with differential applications per region and sector specific policies and measures focusing on specific carbon emitting activities. PROMETHEUS is designed to provide medium- and long-term energy system projections and system restructuring, both in the demand and the supply sides. The model produces analytical quantitative results in the form of detailed energy balances in the period up to 2050. The model can support impact assessment of specific energy and environment policies and measures, applied at both the regional and global levels, including price signals, such as taxation, subsidies, technology, and energy efficiency promoting policies, RES supporting policies, environmental policies, and technology standards.

3. Results

3.1. Impact on CO_2 Emissions in a Global Scale

Both models, GCAM and PROMETHEUS, consistently show a decline in global CO_2 emissions across all scenarios explored (Figure 1) in 2050. In the Current Policies (CP) scenario, PROMETHEUS projects a 7% emissions reduction by 2050 compared to 2020 levels, while the GCAM model exhibits a 12% decrease as a result of the implementation of current climate policies globally combined with the cost reductions of low-carbon technologies (especially solar PV, wind, batteries, electric vehicles). Moving to NDC-constrained scenarios, global emissions are projected to decline by 8–11% by 2030 compared to 2020 levels due to the implementation of Nationally Determined Contributions, which, in most countries, lead to an acceleration of climate action compared to CP scenario; by 2050, emissions are further reduced by 34–39% compared to 2020 levels (assuming that the NDC policy effort continues at similar levels until 2050). The difference between current policies and NDC constrained scenarios arises as most regions are not on track to meet their NDC targets with already implemented policies and thus a strengthening of climate effort is required. The NDC_LTT scenario is characterized by its heightened climate ambition as it considers countries' long-term commitments (and, in particular, the net-zero targets and pledges adopted by several countries globally). This leads to a remarkable 67–74% reduction in global CO_2 energy-related emissions by 2050 from 2020 levels in the PROMETHEUS and GCAM models, respectively. The progressively more ambitious climate scenarios drive substantial reductions in global CO_2 emissions over time, emphasizing the importance of combining realistic medium-term climate plans and NDC strategies with long-term, ambitious, and comprehensive climate targets to ensure low-carbon and climate resilient development for both developed and developing countries (Figure 1).

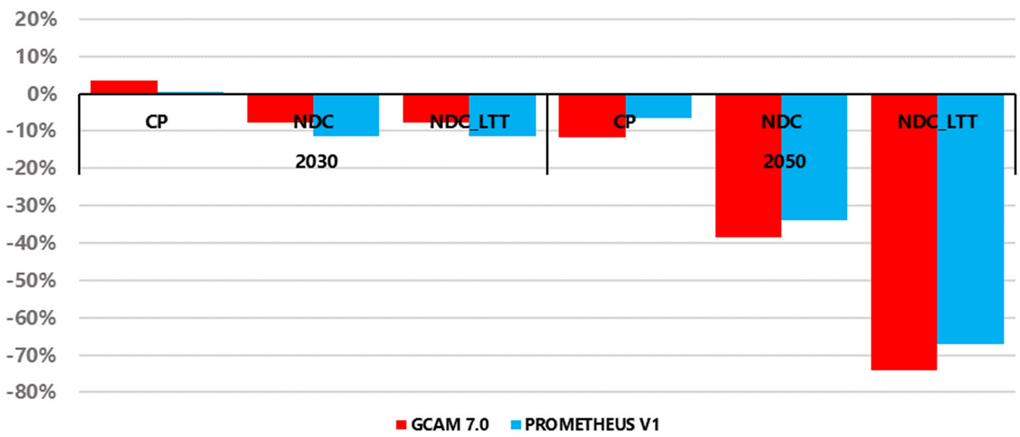

Figure 1. Changes in global CO_2 emissions in 2030 and 2050 compared to 2020 levels under different scenarios, PROMETHEUS and GCAM results.

3.1.1. Impact on CO_2 Emissions in Major Emitting Sectors

The results of the NDC-constrained scenarios (NDC and NDC_LTT) are identical until 2030, but their differences increase substantially in the following period (2030–2050) in both energy supply and demand sectors (including transport, industry, and buildings). Focusing on the industry sector, the NDC-constrained scenarios would lead to a 3–7% reduction in industry-related emissions compared to CP scenario in 2030, with even larger emission reductions achieved in the NDC_LTT scenario by 2050 (reductions larger than 25% from CP levels in both models) due to the increased adoption of cleaner technologies and fuels (e.g., renewable electricity, green hydrogen), the imposition of carbon pricing that penalizes fossil fuel use (so as to meet the NDC and LTT targets), and the accelerated energy efficiency improvements in all industrial sub-sectors.

The model results show some variation for the buildings and transportation sectors. Specifically, global CO_2 emissions from buildings sector will experience a 12% reduction in the GCAM model in 2030 (in the NDC constrained scenarios relative to CP) and a more substantial 17% in PROMETHEUS due to the more holistic representation of several energy efficiency options such as building retrofits to improve thermal insulation and uptake of electric heat pumps. The projected emission reductions accelerate in the period after 2030, especially in the NDC_LTT scenario, with models showing a 31–39% reduction compared to CP levels in 2050. This indicates a growing emphasis on energy efficiency to reduce energy requirements, especially for space and water heating purposes, and an accelerated transition toward electrification of end-uses and cleaner energy solutions for residential and commercial buildings.

In the transportation sector, the models show that the NDC constrained scenarios will lead to CO_2 emissions reduction in 2030 (relative to CP levels), but the magnitude ranges from 2% in the GCAM model to 10% in PROMETHEUS (Figure 2). This is due to the higher potential both for efficiency improvements (e.g., uptake of more efficient cars, trucks, and planes) and for an accelerated uptake of electric vehicles. The variance in these results arises from the different assumptions about the pace of technological advancements, policy support for electric vehicles, and consumer preferences in the two models. This variance increases even more in the long-term, as the NDC_LTT scenario is projected to lead to a mere 8% reduction in global transport CO_2 emissions in GCAM (compared to CP levels), while the reduction is substantially higher in the PROMETHEUS model (67% below CP levels), largely driven by the restructuring of the transport sector through the uptake of electric vehicles as well as other clean energy options in specific transport segments (e.g., advanced biofuels, hydrogen, e-fuels). In contrast, GCAM, due to its structure, follows a more conservative estimate of emission reduction in the transport sector, including the representation of technological advancements, fuel transitions, and policy effectiveness, and assumes that most of the mitigation effort will be driven by the energy supply sector. The increased renewable energy uptake in 2030 (in the NDC and NTC_LTT scenarios compared to CP) combined with the phase out of carbon-intensive technologies (in particular coal and gas-fired power plants) would lead to a 13% and 20% reduction in CO_2 emissions from electricity generation according to GCAM and PROMETHEUS, respectively. The adoption of high carbon pricing that penalizes the use of fossil fuels is the major driver for emissions reductions achieved in energy supply. These scenarios involve a strategic approach to technology deployment, where the benefits of new clean technologies are maximized and potential disruptions are minimized, to ensure a stable energy supply during this transitioning period. Looking ahead to 2050, the widespread adoption of low- and zero-carbon technologies—driven by a fast ramp-up of solar PV and wind power with smaller contributions by biomass, hydro, and nuclear—combined with the closure of high emission power plants would lead to reduction in CO_2 electricity-related emissions that range from 37–51% in the NDC scenario. The combination of NDCs and LTTs, though, would further accelerate decarbonization efforts and lead to a transformative shift in electricity generation, with electricity-related CO_2 emissions reaching reductions of 90–94% by 2050 due to widespread uptake of renewable energy technologies, the deployment of advanced carbon capture and storage (CCS) technologies—including Biomass combined with CCS (BECCS) leading to net negative emissions–and comprehensive policy frameworks that create a conductive environment for sustainable energy practices, especially in the form of high carbon pricing.

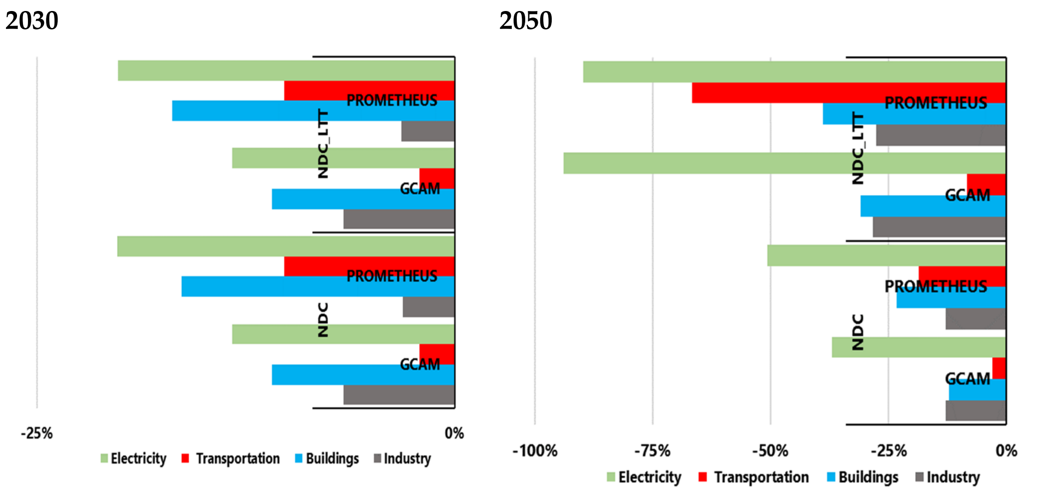

Figure 2. Percentage changes in global CO_2 emissions in 2030 and 2050 compared to CP scenario in major emitting sectors, PROMETHEUS and GCAM results.

3.1.2. Carbon Price and Its Impacts on Global CO_2 Emissions

The carbon pricing mechanism plays a pivotal role in achieving large emission reductions by 2050 as it provides economic incentives to reduce emissions. At the time, several carbon pricing instruments exist that cover about 40 countries around the world. In all policy scenarios, PROMETHEUS and GCAM show increased carbon prices that drive reductions in global CO_2 emissions, underscoring the crucial role of this mechanism in influencing emission reductions and accelerating investments to greener and more sustainable technology alternatives. In the CP scenario, the global average carbon price is projected to rise gradually in both models (from around USD 10 2015/tn CO_2 in 2020 to USD 31 in 2050 in PROMETHEUS and further to USD 50 in GCAM), leading to a reduction in global CO_2 emissions of 7% in PROMETHEUS and 12% in GCAM, indicating a limited impact on driving substantial changes in the global energy system. On the other hand, the implementation of NDC targets would lead to higher increases in the global average carbon price increasing to USD 55–80'2015/tn CO_2 in 2050 in PROMETHEUS and GCAM achieving a notable 34–39% reduction in emissions by 2050, showcasing the efficiency of climate policies and plans embedded in NDCs (Figure 3). The most pronounced results, though, are seen in the NDC_LTT scenario where the average carbon price increases to USD 125 in PROMETHEUS and USD 143 in GCAM by 2050 to achieve the national Long-Term Targets, resulting in an extensive reduction of 67–74% in global CO_2 emissions in the period 2020 to 2050 and illustrating the effectiveness of the carbon pricing strategy. This economic incentive aligns with the broader goal of mitigating climate change by discouraging the use of carbon-intensive fuels and technologies, but it would be challenging to achieve net zero by 2050. The effectiveness of carbon pricing relies on being part of broader climate policies, with enhanced policy portfolios including a combination of market-based, regulatory, innovation, and informational policies, as analyzed in [29]. This includes regulations, standards, subsidies, incentives, and supportive measures. This has also been highlighted in the International Energy Agency's scenario "Net Zero by 2050" [5], where regulatory policies are combined with carbon pricing to achieve deep decarbonization.

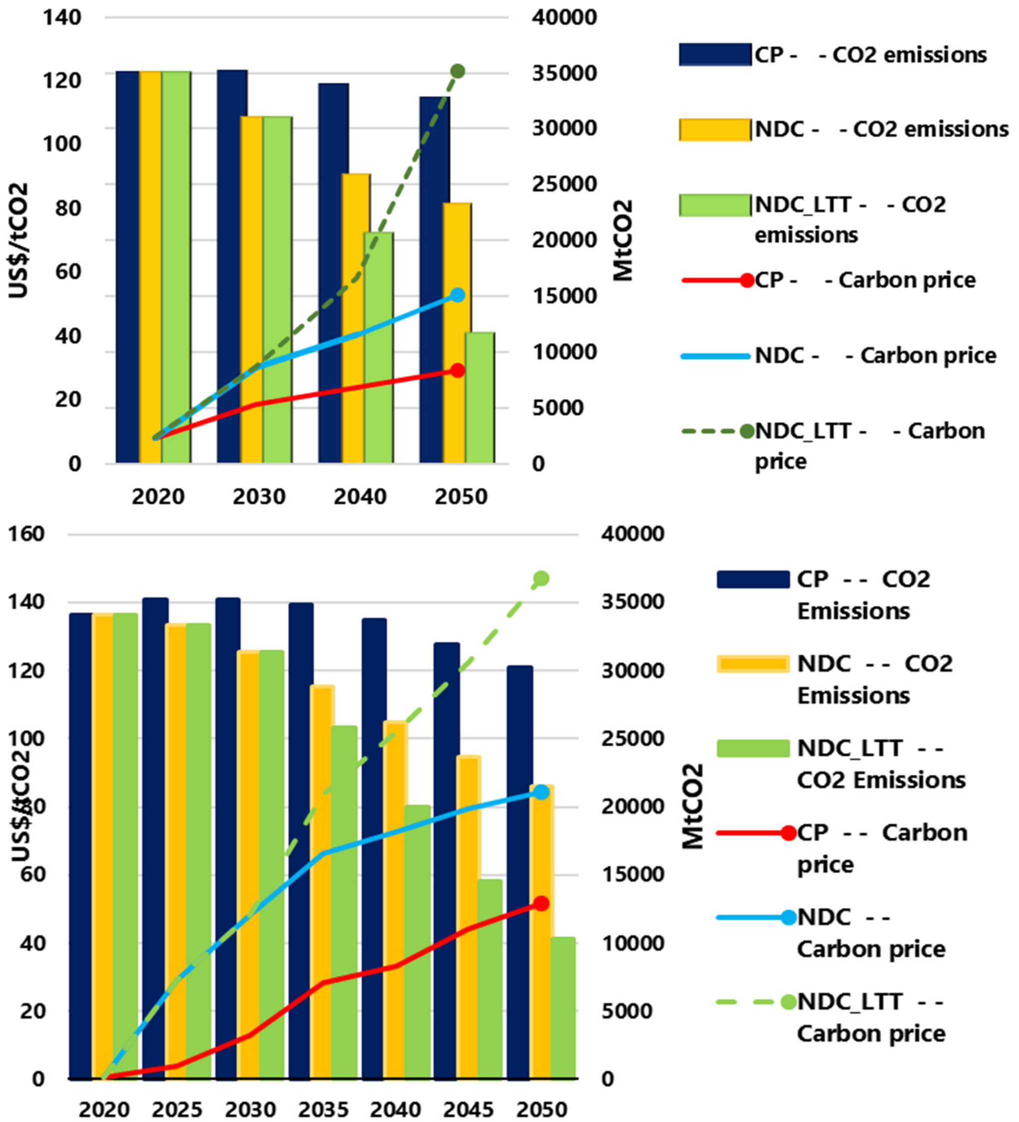

Figure 3. Evolution of Carbon price (**left** axis) and global CO_2 emissions (**right** axis) over 2020–2050, PROMETHEUS results (**upper** chart) and GCAM results (**lower** chart).

3.2. Energy System Development

The different levels of climate policy ambition across scenarios would drive significant changes both in energy demand and energy supply. In the Current Policy scenario, both GCAM and PROMETHEUS show a continued increase in global energy consumption ranging from 10–12% in the period 2020–2030, driven by the increasing GDP, urbanization, and rising living standards, especially in developing countries, combined with limited efforts to reduce emissions and increase energy efficiency (Figure 4). However, the implementation of the NDC targets in all regions drives a reduction in global energy consumption compared to the CP levels, by about 2% and 4% in 2030 in GCAM and PROMETHEUS, respectively. This is driven by the imposition of climate policies–and in particular carbon pricing–to meet the NDC targets, which increase the costs of using fossil fuels thus leading to reduced energy demand, both through energy efficiency improvement and the uptake of more efficient carriers and technologies (e.g., electric heat pumps replacing gas boilers for space heating, electric cars replacing conventional oil-fueled ICE cars). Therefore, the imposition of NDC targets can curb the growth of global energy consumption by 2030, a key ingredient to achieve climate goals.

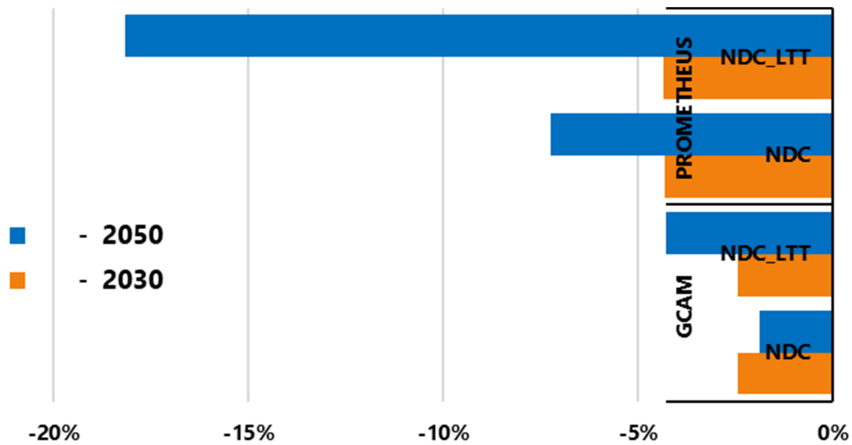

Figure 4. Percentage changes in global final energy consumption under different scenarios compared to CP in 2050 and 2030, results from PROMETHEUS and GCAM.

The climate policy effects are stronger in the longer-term as, in 2050, the NDC scenario shows a reduction in global energy consumption ranging from 2% in GCAM to 7% in PROMETHEUS compared to CP levels. This trend accelerates substantially with the imposition of long-term targets in the NDC_LTT scenario, with global final energy consumption projected to decline by 4% (GCAM) and 18% (PROMETHEUS) from the CP scenario levels in 2050. The PROMETHEUS projections indicate that the ambitious long-term targets (with accelerated energy efficiency and renewable energy deployment) can significantly reduce global final energy consumption through significant progress in technologies that contribute to energy conservation and efficiency as well as the emergence of energy efficient technologies and fuels (e.g., heat pumps, electric vehicles). On the other hand, GCAM's more conservative estimate is influenced by its modelling structure, which assumes a slower pace of technology adoption that reflect a more cautious approach to the transformative effects of long-term targets on energy consumption and prioritizes transformations in the energy supply side.

3.2.1. Buildings Sector

Globally, electricity and natural gas are the main energy sources used in residential and commercial buildings in 2020 [30]. In 2050, the GCAM and PROMETHEUS models project that the imposition of ambitious climate policies in the NDC_LTT scenario would result in large changes in the energy consumption and fuel mix in the sector compared to the CP scenario (Figure 5). First, both models show stronger energy efficiency improvements in the NDC_LTT driven by dedicated investment to reduce energy consumption (e.g., thermal renovation to improve shell's insulation), reduced demand due to higher energy costs, and uptake of energy efficient appliances and equipment, in particular heat pumps. The projected energy demand reduction is larger in PROMETHEUS than in GCAM, as the former incorporates more details in the representation of energy efficiency actions and options and higher technological granularity in the buildings sector. Both models show an increasing contribution of electricity to cover the sector's demand by 2030 and 2050, with the share of electricity increasing to more than 60% in the NDC_LTT scenario in 2050. Similar trends are evident in the other policy scenarios, but efficiency and electrification trends are of smaller magnitude compared to NDC_LTT. In contrast, the shares of gas, oil, and solids (including biomass) are projected to rapidly decline due to the imposition of ambitious climate policies promoting cleaner alternatives and energy efficiency, with fossil fuels increasingly replaced by low-emission fuels. Finally, the remaining quantities of solids refer to (traditional and modern) biomass, the use of which is projected to continue, albeit declining, by 2050, especially in low-income countries.

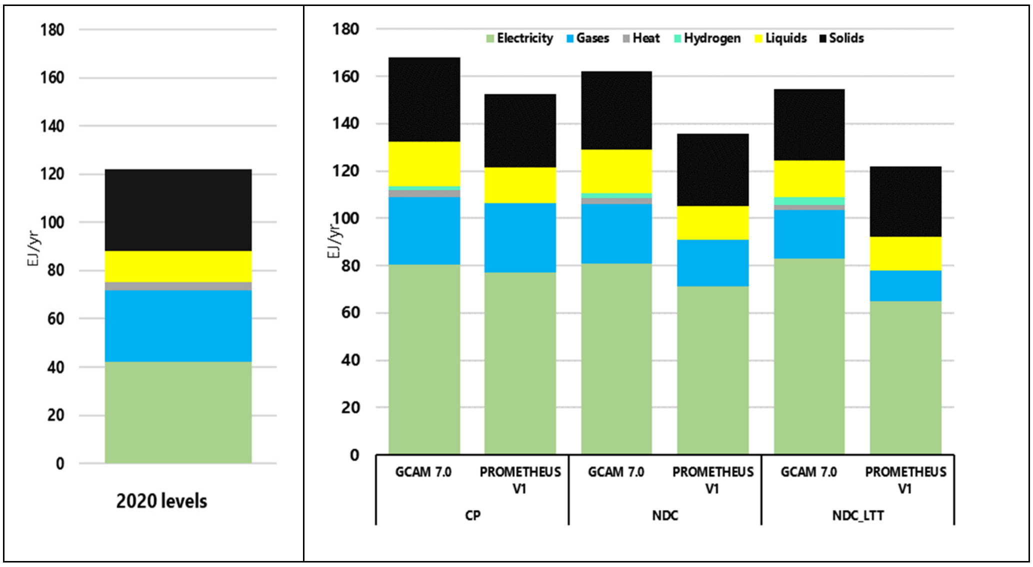

Figure 5. Residential final energy consumption in 2050 under different scenarios, PROMETHEUS and GCAM results.

3.2.2. Industry Sector

In the industry sector, both GCAM and PROMETHEUS models project significant changes in the final energy consumption and energy mix, especially under the long-term targets included in the NDC_LTT scenario (Figure 6). In the CP scenario, both models show an increasing trend in global energy consumption in industries driven by the increasing production of goods and products (e.g., steel, cement, chemicals, equipment), driven by higher global economic activity. In this scenario, there are limited changes in the fuel mix, mainly towards a higher use of electricity and gases that replace the carbon-intensive coal and oil products. The imposition of NDC and LTT targets would reduce industrial energy consumption compared to CP levels due to some efficiency improvements in industrial processes (e.g., enhanced heat recovery and improved energy management practices), the uptake of efficient technologies, fuels, and equipment, and the transition to cleaner processes and feedstocks. However, efficiency gains in industry are much smaller compared to other demand sectors (i.e., residential buildings), highlighting the predominant need for substantial efforts in decarbonizing the energy mix used in industry and incorporating cleaner processes and feedstocks in industrial activities. This is shown in the modelling results of the NDC_LTT scenario (Figure 6), with a large increase in the contribution of electricity (which is fully decarbonized by 2050) and a replacement of the more carbon intensive fossil fuels (coal, oil) with gaseous fuels and biofuels. PROMETHEUS projects a more transformative shift in industrial processes and activities than GCAM under the NDC_LTT scenario, with larger energy savings, increased electrification, emergence of green hydrogen (in heavy industrial applications like steelmaking), and a large reduction of coal use. These trends are also evident in GCAM but at limited rates, as GCAM is more conservative in its modelling assumptions about demand-side transitions and opts for accelerated supply-side mitigation. In addition, both models project the emergence of CC(U)S to capture industrial process emissions.

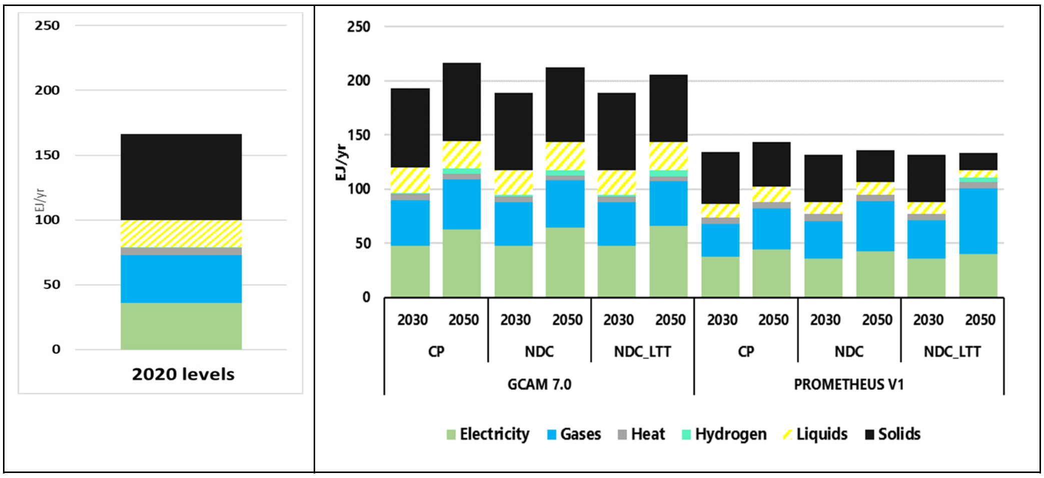

Figure 6. Fuel mix in industrial energy consumption in 2030 and 2050 under different scenarios, GCAM and PROMETHEUS results.

3.2.3. Transport Sector

In the evolving landscape of motorized transport, the dependency on oil products and internal combustion engines persists (especially under the current policies CP scenario), highlighting the need of transitioning to sustainable, low-emission alternatives. Biofuels, supported by decades of policy initiatives (at least in some countries/regions), have increased their share in transport energy consumption from under half a percent in 1990 to approximately 3.5% in 2022 [30]. However, the further uptake of conventional biofuels is limited due to their varied impact on greenhouse gas emissions due to land-use changes, raising sustainability concerns when they compete for land resources with food supply. In the NDC_LTT scenario, the transport sector is projected to be transformed away from the oil-based paradigm with the massive uptake of cleaner technologies (especially electric vehicles) and fuels (advanced biofuels). This is more evident in PROMETHEUS, which projects a 55% reduction in transport oil consumption by 2050 compared to CP, with only a 10% reduction in GCAM (driven by its conservative assumptions of costs and uptake potential of electric vehicles). This large reduction in the consumption of oil products in PROMETHEUS is a result of two trends: on the one hand, the massive uptake of electric vehicles that replace fossil-fired ICEs and the emergence of advanced biofuels (especially in segments not easily electrified, like aviation, navigation) and, on the other, the continuous efficiency improvements in all transport-related technologies and engines/vessels.

The electrification of road vehicles emerges as a crucial pathway to decarbonize the transport sectors, offering increased conversion efficiencies (for direct electrification) and emissions reductions, particularly as power generation is dominated by renewable energy after 2030. In the NDC_LTT scenario, the lion's share of electrification measures target road transport, and are mostly related to passenger transport, while electrification of rail will be completed globally by 2030/2040 at the latest. The electrification of ships or airplanes is not mentioned in NDCs, and only 1% of LTTs include references to these sectors [31]; to reduce emissions from these sectors, other clean fuels should be deployed [32], including advanced biofuels and hydrogen or hydrogen-based synthetic fuels, as analyzed in [33].

PROMETHEUS results underscore its optimism regarding the transformative potential of long-term commitments and policies while GCAM results reflect a more conservative estimate to mitigate transport emissions (Figure 7). Electricity could power 23% of global transport in 2050, up from 1% at today's levels [34], while modelling results in the most ambitious scenario (NDC_LTT) suggest that electricity's share in transport fuel mix can reach 37% in 2050 (14% in the NDC scenario and 10% in the CP scenario). Road transportation appears to lead the way in this transformation, reducing fossil fuel use by 14% in 2030 and 57% in 2050 in the NDC_LTT scenario compared to CP, according to PROMETHEUS results. GCAM results show a lower contribution of electricity in the transport fuel mix compared to PROMETHEUS, but an enhanced role for biofuels and hydrogen-based fuels to decarbonize the transportation sector.

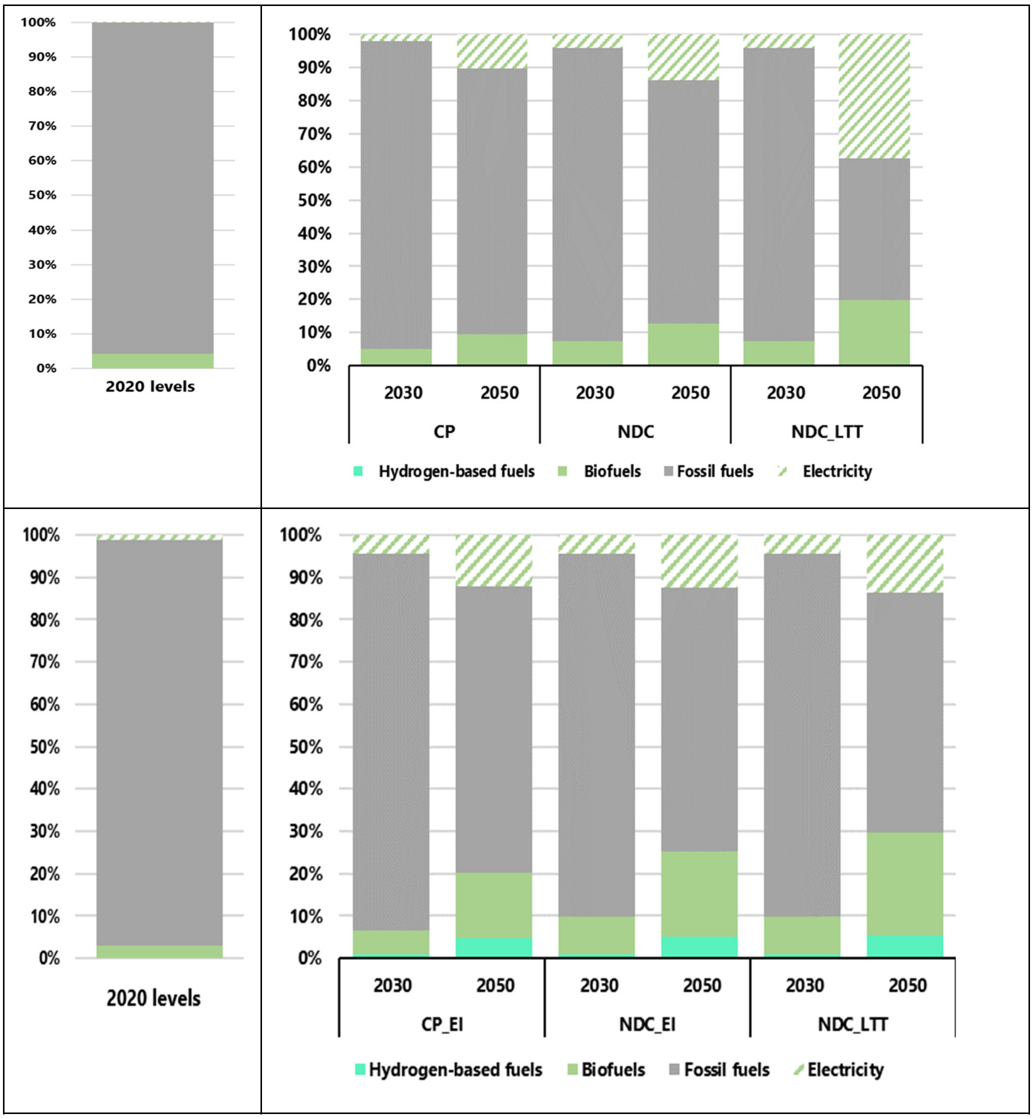

Figure 7. Fuel mix in transport sector under different scenarios from 2020–2050, PROMETHEUS results (**upper** figure) and GCAM results (**lower** figure).

3.2.4. Electricity Generation

The imposition of Nationally Determined Contributions and Long-Term Targets would drive major changes in the global power generation mix, with a fast and massive uptake of renewable energy and Carbon Capture and Storage (CCS) combined with a large-scale reduction in fossil fuel use and a rapid phase-out of coal and lignite power plants both in developed and developing economies. In this scenario, the CCS route involves the application of post-combustion capture technologies while the CCU technologies are assumed to be deployed only in the long-term and only if mentioned in a national LTT. This entails the utilization of captured carbon dioxide for various purposes, such as the production of synthetic fuels, chemicals, and other valuable materials that contribute to the broader goals of sustainable resource use and emissions reduction. However, the transition pathway in the power sector differs in the two models, depending on specific model assumptions (e.g., about the costs and potentials of technologies and fuels by region). For example, in the NDC_LTT scenario, both GCAM and PROMETHEUS show that solar and wind power will become the major sources of electricity, increasing their share to about 45–55% in global electricity production, with PROMETHEUS being more optimistic about renewable energy uptake compared to GCAM. The latter model, however, projects a substantial contribution of nuclear power in the global power mix by 2050, with massive expansion of the nuclear plant fleet, especially in developing economies to cover part of their rapidly expanding electricity requirements (Figure 8).

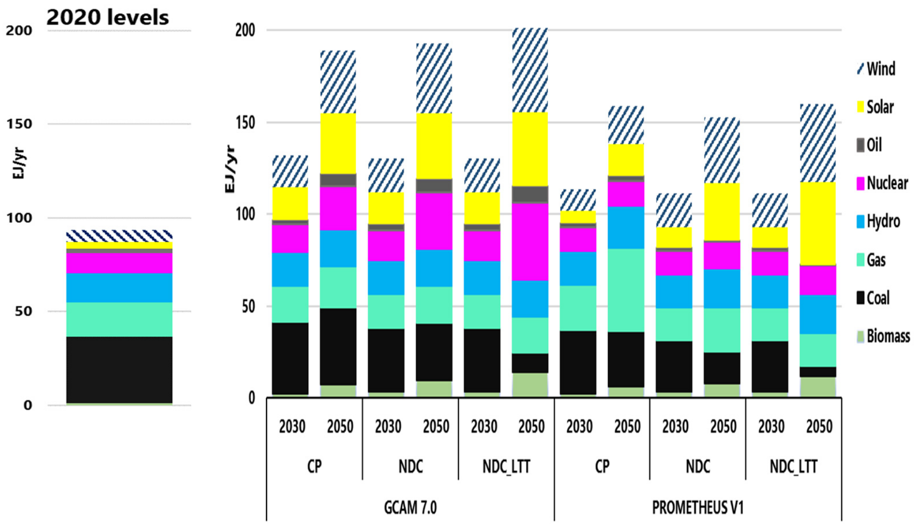

Figure 8. Electricity generation mix in 2030–2050 under different scenarios, PROMETHEUS and GCAM results.

Global efforts to reduce reliance on coal due to its high carbon intensity and detrimental environmental impacts is evident in both NDC-constrained scenarios, showing a reduction in coal share by 2030. In the NDC_LTT scenario, the enhanced ambitious climate targets for 2050 would lead to an almost complete phase-out of coal from the global power mix in PROMETHEUS (and a very large reduction in GCAM). Similar to coal, the influence of decarbonization targets, strong carbon pricing, and efforts to minimize the reliance on fossil fuels would lead to a large drop in gas use to produce electricity in the NDC scenario and even more in NDC_LTT by 2050. In both models, there is a relatively limited uptake of CCS technologies, combined either with fossil fuels or with biomass (in this case, net-negative emissions are generated), especially in the period after 2035.

The significant changes in the power generation mix indicate extensive transformations in power capacity and electricity investment dynamics under different scenarios. The adoption of climate policies and NDCs combined with the strong innovation dynamics and related cost improvements would drive a large-scale expansion of wind power and solar PV in the global mix, with these two technologies taking the lion's share in terms in electricity supply investment. This trend further accelerates in the NDC_LTT scenario where solar and wind dominate new capacity investment, with a smaller contribution by other low-carbon technologies having relatively smaller contributions (e.g., hydro, biomass, geothermal, concentrated solar power). The main difference lies in the large deployment of nuclear power in GCAM (with PROMETHEUS showing a limited nuclear uptake) especially in the NDC_LTT scenario as shown in Figure 8. To reach ambitious LTTs by 2050 requires the phase out of unabated coal-fired power plants, especially in advanced economies by 2030 and around the globe in the decade 2040–2050.

Both models show that Carbon Capture and Storage (CCS) technologies can play a role in the future energy landscape under the NDC_LTT context, especially in regions with a relatively new stock of fossil-based power plants that may continue to operate by 2050 if refurbished with carbon capture. The capacities of unabated fossil fuel power plants are projected to gradually decline in the CP and NDC scenarios over the 2025–2050 period, while the higher climate ambition incorporated in the NDC_LTT scenario would lead to massive capacity reductions of around 60–70% for oil and gas-fired plants and more than 90% for coal-fired plants (without the use of CCS technologies). Reductions in coal-fired power capacity are evident in all policy scenarios but phasing out unabated coal raises challenges in terms of energy affordability, energy access, and energy security. We must highlight that the time to phase out coal power plants is different for each country and depends on the share of coal in each country's electricity mix and the availability of other available sources to replace it, considering the continuous increases in energy and electricity demand, especially in developing economies.

The utilization of CCS technology that emerges after 2035 in both models as a mature technological option will somewhat reduce the need for additional investment in renewable energy and nuclear power. In the NDC_LTT scenario, GCAM projections depend more on the uptake of CCS technologies compared to PROMETHEUS (Figure 9); in particular, GCAM projects that hundreds of GWs of coal-, gas-, and biomass-fired capacities will come online by 2050 to replace unabated fossil fuel use for power generation. The conversion of coal-, gas-, and oil-fired power plants to an alternative that can provide cheap and low-emission electricity using the existing transmission grid lines and provide inertia to keep the system frequency in acceptable range so as more variable renewables can join the grid seems an efficient approach to achieve deep decarbonization, especially in emerging economies. Furthermore, the risk of these infrastructures becoming stranded assets is very low, as they provide carbon-free electricity (or even net-negative emissions in the case of BECCS). Overall, fossil-based power plants with the utilization of CCS are expected to produce 9% of global electricity in 2050, while fossil-fueled plants without CCS account for only 5% globally in 2050 according to GCAM. In contrast, PROMETHEUS suggests that 12% of fossil-fueled plants without CCS (6% with the use of CCS) will cover global electricity generation due to regional disparities in CCS deployment. Certain regions, such as the Middle East (which is rich in low-cost oil and gas reserves) and Africa (which has limited access to financing and regulatory frameworks to support CCS deployment), rely more heavily on fossil-powered plants without CCS even in 2050.

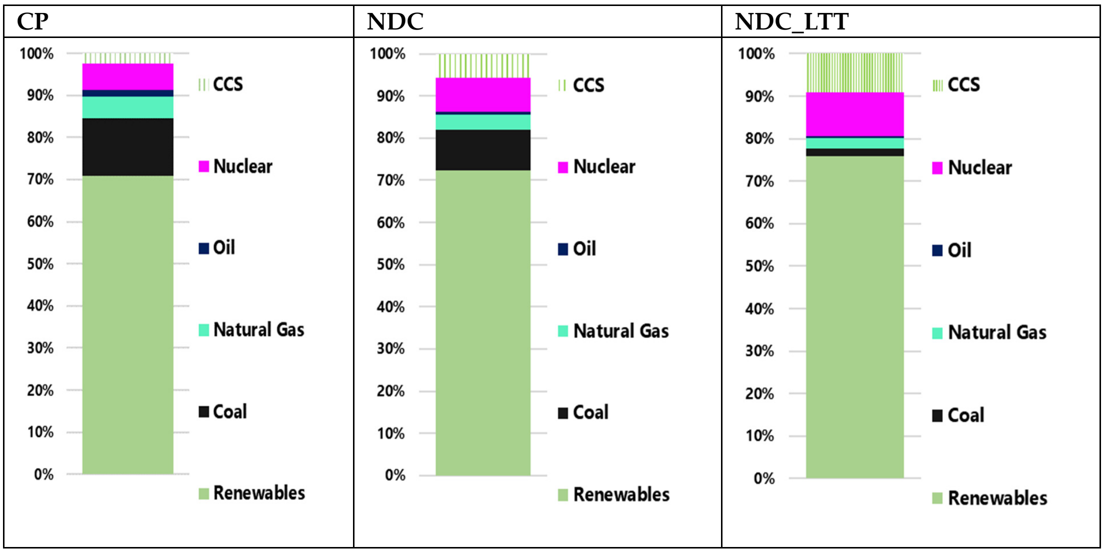

Figure 9. *Cont.*

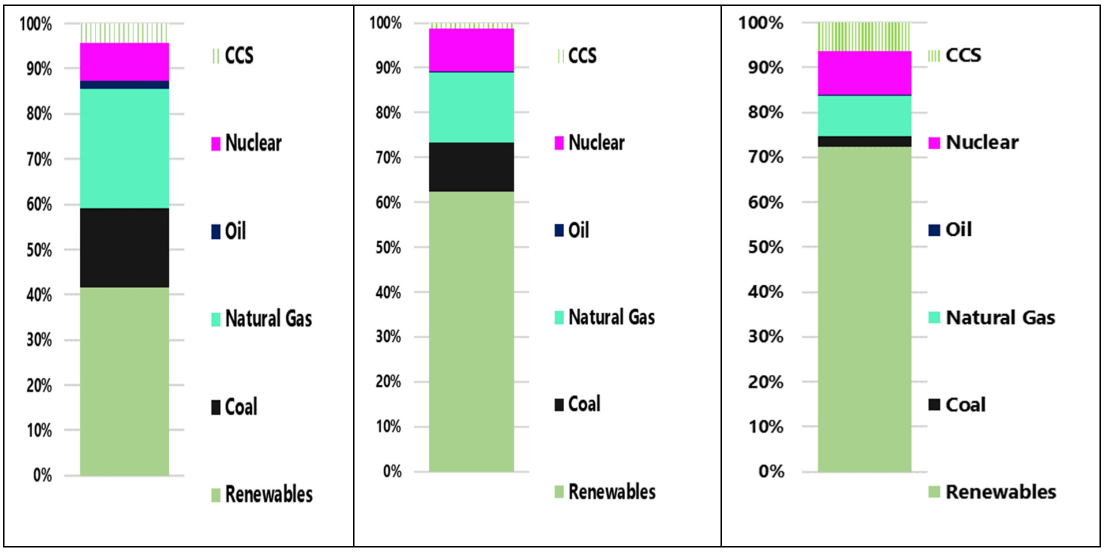

Figure 9. Power generation mix in 2050, under different policy scenarios, GCAM (**upper** figure) and PROMETHEUS (**lower** figure) results.

4. Discussion and Conclusions

This study examined the environmental, energy system, and technology impacts of current policies, NDCs, and LTTs. The central research question revolves around the effectiveness of these policy frameworks, individually and in combination (as in the combination of NDCs with LTTs), in steering the world towards a trajectory that is consistent with the Paris Agreement while considering national specificities and policy priorities. We used two well-established and extensively used IAMs (GCAM and PROMETHEUS) that capture the complex interactions in the energy-climate-technology-environment nexus to provide an improved understanding of the energy, emissions, and economic impacts of climate policies and targets pursued in countries globally, while focusing on their sectoral impacts and transformational challenges and opportunities. Therefore, the policy relevance of the global model-based scenario analysis is enhanced, especially combined with bottom-up NDC and LTT data at the country level, but embedded in the global development, technology, and climate policy context.

The global level analysis showed that current climate policies can lead to limited CO_2 emissions reductions in 2050 (of about 8–12% compared to 2020 levels), and they fall considerably short of aligning with the national long-term targets (LTTs) and the Paris Agreement climate goals. The implementation of NDCs by 2030 and assuming constant policy ambition by 2050 deepens this reduction, reaching approximately 34–39% in 2050 from 2020 levels. The incorporation of NDCs and LTTs emerges as a powerful strategy driving global emissions reductions of about 67–74% by 2050 compared to 2020 levels while paving the way towards the net zero transition after 2050. This result aligns with the overarching goal of the Paris Agreement to limit global warming to well below 2 °C above pre-industrial levels but falls short of the goal to limit the temperature increase to 1.5 °C, in line with the findings of similar model-based studies that also estimated the temperature outcome of NDCs and LTTs [17–19]. The comprehensive model-based analysis underscores the challenge of achieving substantial emissions reductions already by 2030, especially in sectors with multiple low-cost and easily scalable options like electricity generation, emphasizing the need for accelerated and transformative actions in the next decade to keep the world on track to meet the Paris Agreement objectives.

Final energy consumption is on the rise globally in all major emitting sectors due to increasing economic activity, rising incomes, and improved standards of living, especially in developing economies, in the absence of strong climate and energy efficiency policies. While this upward trend is expected to continue under Current Policies, the implementation of NDCs presents an opportunity to curtail the growth in energy demand, as the implementation of NDCs could result in a modest reduction of 2–4% in global final energy consumption by 2030. However, the combination of NDCs with Long-Term Targets (LLTs) has a much higher impact, achieving 18% reduction in final energy consumption by 2050, underscoring the significance of aligning short-term goals (NDCs) with longer-term, more ambitious targets (LTTs) to address the challenges of rising energy consumption, security of energy supply, energy affordability, and climate change mitigation.

Sectors like industry and transportation face high transformational challenges that require targeted policies and accelerated climate efforts. Modelling results for the industry sector suggest that while the NDCs contribute to reducing energy consumption and integrating low-carbon fuels and technologies, they are not sufficient to pave the way towards the net-zero emissions transition. The transformative shift projected under the NDC_LTT scenario indicates the potential of this policy combination to reduce industrial emissions with a large increase in the contribution of electricity (which is fully decarbonized by 2050) and a replacement of coal and oil (that have the highest carbon intensity) with gaseous fuels and biofuels. Transformational challenges of the sector remain, especially to decarbonize industrial processes requiring high-temperature heat and cannot easily be electrified but require the emergence of novel technologies, i.e., hydrogen-based DRI for steelmaking, synthetic e-fuels, Carbon Capture and Use, which require ambitious policy action to be on track to achieving the long-term targets. Challenges are more evident in 2030 compared to 2050. The cost of technology adoption and the availability of alternative solutions constitute high barriers in achieving significant CO_2 emissions reduction by 2030. Industry is a sector heavily reliant on fossil fuels and the transition requires extensive low-carbon innovation and accelerated deployment of new technologies that are not readily available yet for commercial uptake.

The high carbon price combined with strong national regulatory policies imposed in the NDC_LTT scenario could not achieve emission reductions higher than 75% by 2050. The analysis points out that even with a high carbon price, emission reductions cannot reach net zero mainly because of the availability and scalability challenges facing some low- and zero-carbon technologies, including CCS, hydrogen, and synthetic fuels. As the electricity sector can be fully decarbonized by 2050, clean electricity will become the most important option to reduce emissions from energy demand sectors (transport, industry, buildings). However, several end-uses in industry sector (e.g., steel, cement, chemicals) and in transport (e.g., shipping, aviation, freight transport) cannot be directly electrified so other low-carbon alternatives need to be massively deployed, including hydrogen, advanced biofuels, and synthetic fuels, to decarbonize these sectors, in line with other modelling studies [33,35]. Many of the options needed to decarbonize the demand sectors, and mainly the industry sector, involve technologies that are not yet deployed on a commercial scale, such as fuel cell technology and synthetic fuels. This indicates large challenges in accessing and adopting low-carbon technologies and innovation due to limited research and development capabilities; as such, carbon pricing alone cannot incentivize the necessary investments in clean technologies to pave the way towards net-zero and must to be combined with strong regulatory policies, e.g., technology or emission standards, fuel blending mandates, and subsidies, as shown in [29].

In this direction, the next round of NDCs, informed by the first Global Stocktake that just concluded at COP28, will help some regions to enter the upcoming climate negotiations with more ambitious climate targets while ensuring successful policy implementation. While electrification dominates road transport by 2050 in the combination of NDCs and LTTs, the electrification of ships and airplanes is not explicitly addressed in NDCs. Given the specificities of different transport modes, strong reductions in transport-related emissions can be achieved through multiple diverse options and technologies in a holistic approach (mix of electrification, sustainable biofuels, deployment of hydrogen, and technological advancements tailored to different transport segments). Overall, each sector faces unique challenges in achieving deep emission reductions and making a paradigm shift towards a low-emission future while ensuring cost efficiency, energy security, and overall sustainability.

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. First, the low-emission strategies would have important socioeconomic repercussions (e.g., on GDP, employment, trade etc.) that are not assessed in the current study and could be the focus of future works. The role of different climate policy instruments (e.g., market-based or regulatory policies) can be further explored in major emitters, 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 to derive more robust policy recommendations on the development of low-emission strategies by major emitters that ensure compatibility with the Paris goals. We should also note that various external factors can impact the modeling results, including diseases, climate extremes, technology disruptions, societal changes, and energy crises, as demonstrated recently with the impacts of COVID-19 and subsequent lockdowns and the Russian war on Ukraine. As these factors are external to our modelling tools and cannot be predicted as they are inherently uncertain, we can analyze their impacts by simulating extreme, out-of-the-ordinary scenarios with the models and try to analyze their medium-term effects, as the IAMs cannot capture the short-term effects of scenarios.

The model-based results crucially depend on the assumptions made, especially on the values of specific elasticities or technology costs. A comprehensive sensitivity analysis on the technology cost assumptions and the elasticity values is required to consistently evaluate the impacts of ambitious climate policies.

In conclusion, this study provides valuable insights into the impacts and challenges for achieving LTTs, including net-zero emissions, emphasizing the role of ambitious long-term commitments to pave the way towards a clean future. The modelling results show that the NDCs alone fall considerably short of meeting the ambitious climate goals at national and global levels. The combination of NDCs with LTTs increases the policy effectiveness towards reducing emissions in all demand and supply-side sectors, and mitigating climate change through transformative changes across sectors. The effectiveness of these policies relies on sector-specific dynamics, technological advancements, and policy interplays. Future analyses should delve into sectoral specificities, aiming to address economic and other barriers and refine policies for deeper and larger emission reductions at the sectoral level pointing to the emergence of transformative technologies. Our analysis suggests the need for comprehensive climate policies and strategies, considering both short- and long-term targets to navigate the complexities of achieving ambitious climate goals while ensuring sustainable development, energy security, and climate resilience.

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Appendix A

Table A1. NDC targets for 2030 for major economies as included in the NDC scenario.

Country Name	Target Type	NDC Target Unconditional (%)	NDC_Target Conditional (%)	Base Year
South Africa	Absolute emissions target			
Brazil	Emissions reduction target	50		2005
European Union	Emissions reduction target	55	NA	1990
Indonesia	Emissions reduction target	31.89	43.2	2030
China	Emission intensity reduction target	65		2030
India	Emission intensity reduction target		45	2030
United States of America	Emissions reduction target	50	52	2005

Table A2. LTT targets for major economies as included in the NDC_LTT scenario.

Country Name	LTT Year	Target Type	Reduction Values (%)	Target Value
South Africa	2050	Absolute emissions target		0
India	2070	Absolute emissions target		0
Indonesia	2050	Absolute emissions target		540
European Union	2050	Absolute emissions target		0
United States of America	2050	Absolute emissions target		0
China	2060	Absolute emissions target		0

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