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By Katherine Calvin, Marshall Wise, David Klein, David McCollum, Massimo Tavoni, Bob van der Zwaan and Detlef P. van Vuuren

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A multi-model analysis of the regional and sectoral roles of bioenergy in near- and long-term CO2 emissions reduction

Katherine Calvin [(1)*], Marshall Wise [(1)], David Klein [(2)], David McCollum [(3)], Massimo Tavoni [(4)], Bob van der Zwaan [(5)], Detlef P. van Vuuren [(6,7)]

Affiliation:
[(1)]: *Pacific Northwest National Laboratory (PNNL), College Park, MD, USA*
[(2)]: *Potsdam Institute for Climate Impact Research (PIK), PO Box 60 12 03, 14412 Potsdam, Germany*
[(3)]: *International Institute for Applied Systems Analysis (IIASA), Schlossplatz 1, A-2361 Laxenburg, Austria*
[(4)]: *Fondazione Eni Enrico Mattei (FEEM) and Centro Euro-Mediterraneo sui Cambiamenti Climatici (CMCC), Corso Magenta 63, Milan, Italy*
[(5)]: *Energy research Centre of the Netherlands (ECN), Westerduinweg 3, 1755 LE Petten, The Netherlands*
[(6)]: *Utrecht University (UU), Utrecht, The Netherlands*
[(7)]: *PBL Netherlands Environment Assessment Agency, PO Box 303, 3720 BA Bilthoven, The Netherlands*

* *Corresponding author: katherine.calvin@pnnl.gov*

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A multi-model analysis of the regional and sectoral roles of bioenergy in near- and long-term CO2 emissions reduction

Abstract:

This paper examines the near- and the long-term contribution of regional and sectoral bioenergy use in response to both regionally diverse near-term policies and longer-term global climate change mitigation policies. The use of several models provides a source of heterogeneity in terms of incorporating uncertain assumptions about future socioeconomics and technology, as well as different paradigms for how different regions and major economies of the world may respond to climate policies. The results highlight the heterogeneity and versatility of bioenergy itself, with different types of resources and applications in several energy sectors. In large part due to this versatility, the contribution of bioenergy to climate mitigation is a robust response across all models. Regional differences in bioenergy consumption, however, highlight the importance of assumptions about trade in bioenergy feedstocks and the influence of energy and climate policies. When global trade in bioenergy is possible, regional patterns of bioenergy use follow global patterns. When trade is assumed not to be feasible, regions with high bioenergy supply potential tend to consume more bioenergy than other regions. Energy and climate policies, such as renewable energy targets, can incentivize bioenergy use, but specifics of the policies will dictate the degree to which this is true. For example, renewable final energy targets, which include electric and non-electric renewable sources, increase bioenergy use in all models, while electric-only renewable targets have a mixed effect on bioenergy use across models.

1. Introduction

Biomass energy, or bioenergy, is a heterogeneous set of renewable resources with a wide array of potential uses in different energy sectors. Traditional forms of biomass such as fuel wood and animal wastes have been used worldwide for millennia. In more recent times, crops high in sugar and starches are readily converted to ethanol, and oil crops such as soy are sources of biodiesel. Moreover, lignocellulosic resources, which come from a variety of resources including agriculture and forest residues, and dedicated energy crops, have potential uses in several energy applications including electric power, gasification, liquid fuels, and direct use as biosolids (See Chum et al 2011 for a comprehensive overview). Together, these various forms of bioenergy have a large technical potential for producing energy, and potentially, on mitigating CO_2 emissions from the energy system. Also the combination of bioenergy with CO_2 capture and storage (CCS) has been shown to hold significant potential for achieving deep emissions reductions (Azar et al 2010, Luckow et al 2010, van Vuuren et al. 2013, and Azar et al 2013). However, there are sustainability and mitigation effectiveness questions associated with large-scale reliance on bioenergy. Among the most important of these is the issue of (in)direct land use CO_2 emissions from bioenergy, which has been identified and studied by several authors, including Fargione et al (2008), Searchinger et al (2008), Wise, et al. (2009), Melillo et al (2009), and Popp et al (2012).

The previous analyses on the potential for bio-energy and possible implications have focused on the several important aspects. These include the potential of bio-energy low climate stabilization targets (Van Vuuren et al., 2010a), the sectoral use of bioenergy under climate policies (Luckow et al., 2010, van der Zwaan et al. 2013), and the land use implications of bioenergy (Wise et al., 2009; Melillo et al., 2009; and Popp et al., 2012) in individual models. Multi-model comparison studies on bioenergy have focused on global production and consumption of bioenergy with and without mitigation (van Vuuren et al. 2010b, Rose et al. 2012, Rose et al., in review) and land-use implications of bioenergy in mitigation scenarios (Popp et al., in review). All of these studies have used emissions constraints and carbon prices as their policy instruments. This study builds upon the existing work by focusing on the regional results in a multi-model comparison study and examining the effect of concrete near-term policy measures (including renewable portfolio standards and technology targets already on the books) on bioenergy, both in the near- and long-term. The work has been conducted in the context of the LIMITS (Low climate IMpact scenarios and the Implications of required Tight emission control Strategies) model inter-comparison exercise. For a description of the LIMITS scenarios, see Kriegler et al (this volume).

In this paper, we begin by briefly summarizing the scenarios and the approaches used to model bioenergy in each of the participating models. We then present the results for bioenergy use from three vantage points. First, we explore the global and regional contribution of bioenergy to the efficient global climate mitigation policies. Second, we study the near-term impact of combining the LIMITS regional policies with the global climate policy. We exploit the regional heterogeneity of the LIMITS policies, as well as the heterogeneity of modeling approaches and assumptions, to generate a range of outcomes for bioenergy use in different energy sectors in different regions. Third, we explore the impact of the LIMITS policies on the use of bioenergy in the long term, when all regions are assumed to converge to a common mitigation outcome. We finish with a discussion of results, exploring common outcomes and key differences in regional and global bioenergy use across the different models

2. Models and Scenarios

This paper analyzes the use of bioenergy in the seven global integrated assessment models participating in the LIMITS project. The models vary in their representation of bioenergy (Table 1), as well as their representation of other aspects of the economy and energy-system. In the interest of brevity, we refer the reader to other papers for more complete descriptions of the models: GCAM (Calvin et al., 2011), IMAGE (MNP 2006, van Vuuren 2007), MESSAGE (Riahi et al. 2007), ReMIND (Luderer et al. 2012), TIAM-ECN (Keppo and van der Zwaan 2012), and WITCH (Bosetti et al. 2009).[1]

[1] A seventh model, AIM-Enduse, also participated in the LIMITS project. However, because AIM-Enduse's time horizon is only through 2050, we have excluded it from the analysis here.

We focus on four of the twelve LIMITS scenarios (Table 2) for this bioenergy analysis. We use the first three scenarios (Base, 450, and 500) to explore the effect of climate policy, in the form of a globally harmonized carbon price), on bioenergy production and consumption (Section 3). The final scenario (StrPol-500) includes regional emissions and renewable energy policies in the near-term (see Section 4 and Kriegler et al., this volume), and a transition to a globally harmonized carbon price in the long-term. In this scenario, the long-term climate target is the same as the 500 ppm scenario. Thus, we use this scenario to explore the effect of near-term policy on bioenergy consumption in the near- (Section 4) and long-term (Section 5).[2]

3. Regional and Global Bioenergy Use under Global Carbon Prices

In the Base Scenario in the absence of the climate and other policies specified here, bioenergy plays an important, but not transformational role in the energy sector. Total global consumption of bioenergy[3] ranges from 36 to 62 EJ per year in 2020 across the different models (i.e. 6-10% of total primary energy) and from 11 to 180 EJ per year in 2100 (i.e. 1-13% of total primary energy) (Figure 1). The imposition of a climate policy results in increased global bioenergy consumption in all models, particularly in the second half of the century. Some models, however, reach total constraints on bioenergy, and thus, have no increases in bioenergy use between the 500 and 450 scenario. Those models do show earlier deployment of bioenergy under the 450. Other models have increased bioenergy with target stringency. That bioenergy would increase under tighter mitigation targets in these models indicates that there is a net positive mitigation between bioenergy and land use change in the deployment of bioenergy as computed in these models (see also Rose et al., in review). Total global consumption of bioenergy in the policy scenarios ranges from 140 to 350 EJ/yr in 2100 (15-50% of total primary energy), with the highest value of 350 EJ/yr in the GCAM 450 scenario.[4]

The range of values is not simply due to different assumptions about the bioenergy production possibilities and transformation technologies. The bioenergy results are also driven by the heterogeneity of assumptions across the models about energy technologies, mitigation technologies, agricultural productivity, socioeconomic growth, and many other factors. For example, bioenergy use in TIAM-ECN is lower than many of the other models due to conservative assumptions about transportation requirements, biodiversity concerns, and food price concerns. All of the results are well below the estimated technical potential of 500 EJ/yr by 2050 as estimated by Dornburg et al (2010), where technical potential is the production possibility given assumptions about land priority for food, fiber, and timber. And, 2050 bioenergy values (103 to 301 EJ/yr) are quite consistent within the 2050 deployment level (300 EJ/yr) identified in Chum (2011).

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[2] In all models, near-term policy affects the long-term because of its influence on emissions and investment. In models with perfect foresight (e.g., MESSAGE, REMIND, WITCH), long-term policy will also influence the near-term.

[3] The bioenergy results described in this paper include all forms of bioenergy, including traditional biomass. However, 1st generation and traditional bioenergy play comprise only a small fraction of total bioenergy by the end of the century; thus, the results are dominated by modern lignocellulosic resources and crops.

[4] While GCAM uses the most bioenergy in absolute terms, bioenergy consumption comprises the largest share of total primary energy in WITCH.

To explore the variance in the use of bioenergy across models and scenarios, we look at the differences in consumption by region and sector, as shown in Figure 2 for 2100, when the relative magnitude of the differences is most pronounced. In all models and regions, bioenergy as a share of primary energy increases when climate policy is introduced. However, the degree of change varies by region and model. For example, GCAM and MESSAGE show very little change in bioenergy consumption in India+ and very significant increases in bioenergy in Latin America as a result of policy. IMAGE and WITCH in contrast show significant increases in bioenergy dependence in all regions. In REMIND, while climate policy increases bioenergy's share of primary energy in all regions, it has a mixed effect on bioenergy consumption in absolute terms in 2100 (Figure 3). The decline of bioenergy deployment from Base to 550/450 in some regions is a combination of two effects: (1) the relatively high bioenergy demand in 2100 in the Base, and (2) limits on the annual injection rate for captured carbon, that is binding in many regions. In regions where this limit is not binding, more bioenergy is consumed in the 450/500 scenarios than in the Base.

Bioelectricity plays an increasing role in most models and scenarios (Figure 2B). In most cases, bioelectricity deployment increases with the imposition of climate policy (exceptions include Latin America in MESSAGE and Europe in TIAM-ECN). However, bioenergy exceeds 20% of total electricity generation in only a limited number of instances: North America (GCAM 450 & 500, IMAGE 500), China+ (GCAM 450 & 500, IMAGE 500), and Latin America (GCAM 450 & 500, WITCH 450 & 500). Bioelectricity only exceeds 50% of electricity generation in Latin America in WITCH. WITCH assumes that bioenergy must be produced locally, and thus, we only observe significant deployment of bioelectricity in regions that have high bioenergy potential. For models that assume global trade in raw biomass feedstocks (e.g., GCAM, ReMIND, TIAM-ECN), bioenergy production potential does not limit the consumption of bioenergy on a regional basis. Differences in bioenergy use across regions in these models are due to differences in the cost and potential of other competing fuels and technologies, among other factors.

The scenario results show a higher dependence on bioenergy in liquids production, than they do in electricity generation (Figure 2B,C). That is, bioenergy has a higher share of liquid fuels production than it does of electricity production.[5] Under a climate policy, bioliquid use is substantial, exceeding 50% of liquid fuels in nearly all regions and models (Europe and India in GCAM, China+ and India+ in MESSAGE, and all regions in TIAM-ECN are exceptions). In fact, bioliquids are the only source of liquid fuels in WITCH in the 450 scenario. The difference in bioenergy deployment in liquids versus electricity is a result of different economics of mitigation alternatives in the liquids and electricity production sectors of the models, and they highlight different plausible pathways for mitigation using bioenergy.

[5] Note that this does not mean that more bioenergy is consumed by the liquids sector than the electricity sector. These two conversion processes have different efficiencies and thus there is not a one-to-one correspondence between production and consumption.

Direct bioenergy consumption varies more across models than across scenarios (Figure 2D). In most models, the bioenergy contributes a negligible amount to total final energy. However, IMAGE model results show high growth of biosolids use in all scenarios and regions, highlighting the feasibility of modern biosolids production as input for residential and industrial energy. In GCAM and TIAM-ECN, the imposition of the climate policy drives down biosolid consumption in the second half of the century as it becomes more valuable for mitigation in the electric and liquids sectors. IMAGE, however, shows an increase in dependence on biosolids under climate policy.

The use of bioenergy with CO_2 capture and storage (BECCS) also differs across models and scenarios (Figure 3), due to differences in sectoral use of bioenergy across regions (Figure 1) and differences in technology assumptions (Table 1). For example, WITCH only includes BECCS in the electricity sector, and in the climate policy scenarios bioelectricity is only widely deployed in Latin America. As a result, WITCH shows a significant dependence on BECCS in Latin America, and a smaller use of BECCS in all other regions. Other models show fewer differences across regions. For example, REMIND deploys nearly all of its bioenergy with CCS in all regions. This is because bioenergy is relatively expensive in REMIND, but negative emissions technologies like bioenergy with CCS have high value because they can compensate for emissions from other sources and times.

4. The Effect of the Near-Term LIMITS Policies on Regional Bioenergy Use in 2020

In this section, we present the results for the LIMITS StrPol-500 scenario, which adds region-specific near-term policies that can affect the production and use of bioenergy (Table 2). The regional policies considered include: (1) emissions constraints, which incentivize bioenergy and other low-carbon fuel sources, (2) emissions intensity targets, which behave similarly to emissions constraints, (3) renewable electricity standards, which incentivize bioelectricity and other renewable electricity technologies, (4) renewable energy standards, which incentivize bioelectricity, bioliquids, direct consumption of bioenergy, and other renewable energy technologies, and (5) technology-specific capacity targets, which require a specific amount of installed capacity for particular technologies. The first four policies will tend to increase the use of bioenergy.[6] However, the degree of increase and the sectors targeted depend on (1) the particular model and (2) the policy type and its stringency. For example, renewable electricity standards will not have a direct effect on bioliquids production. Because each region has a different combination of policies, we discuss the effects of these policies in the near-term for separate regions, focusing on Europe, North America, China+, India+, and Latin America.

To assist in explaining the results, Figure 4 compares the year 2020 global carbon price in the 500 scenario to the regional carbon prices for the other scenarios for each of the models. Although the presence of the additional, overlapping technology policies makes the carbon prices imperfect indicators, a comparison of the regional carbon prices to the global carbon prices in 2020 provides some insight. From the figure, there is variation by model and

[6] Theoretically, the fifth type of policy could also increase bioenergy production. However, the capacity targets included in the LIMITS scenarios are limited to wind, solar, and nuclear.

region as to whether the regional-specific 2020 targets are more or less stringent than the mitigation taken under the global carbon policy taken in the 500 scenario. The different carbon prices reflect differences in assumptions of key factors such as socioeconomic growth, technology development, and foresight, as well as the differences in the impact of the overlapping near-term policies.

4.1. Europe

In 2020, Europe has a GHG emissions constraint (20% below 1990), and a renewable energy policy (20% of final energy from renewables).[7] The European carbon price with near-term policies is higher than the global 500 scenario in most models (REMIND is an exception), indicating that the policies are relatively ambitious. As a result, also the bioenergy consumption is higher in 2020 in the near-term policies scenario than in the 500 scenario (Figure 5B) in all models. Both effects are influenced by the renewable energy policy. Since this policy is on final energy, renewables in both electric and non-electric sectors count toward the target. All models use bioenergy to meet the renewable targets, however, the degree to which this is true varies (Figure 5A). MESSAGE uses more non-biomass renewables than bioenergy. GCAM and REMIND rely heavily on biosolids. WITCH relies heavily on bioliquids. Bioelectricity increases with the near-term policies (Figure 5C) in most models (MESSAGE is an exception), but is a small contributor to the renewable target in all models, with the highest contribution in TIAM at ~2% of final energy. The increased use of bioliquids in response to the near-term policy is pronounced in GCAM, IMAGE, and WITCH (Figure 5D).

4.2. North America

In the near-term policy scenario it is assumed that North America has a 2020 GHG emissions constraint of (17% reduction from 2005), and a renewable energy policy (25% of electricity). The North American carbon price with near-term policies is lower than the 500 scenario in some but not all models (GCAM, TIAM, and IMAGE are exceptions). The change in bioenergy consumption is strongly correlated with the carbon price in North America (Figure 6B). Increases in bioenergy consumption (and significant declines in coal use) are seen in models where the carbon price is higher than in the 500 scenario (GCAM, TIAM-ECN, IMAGE). Declines in bioenergy (and increases in coal use) are seen in MESSAGE. Unlike in Europe, the renewable target is for electricity alone, and thus, bioliquids (Figure 6D) and biosolids cannot contribute to the target. All models rely on non-biomass renewable electricity to meet their targets, with bioelectricity contributing a relatively small amount (Figure 6A). Bioelectricity production is increased relative to the 500 scenario, but the magnitude of the change is small (Figure 6C).

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[7] The policies listed here are for EU27. Other portions of Europe may have slightly different policies (e.g., Turkey has a 20GW wind capacity target).

4.3. China+

In 2020, China+ has an emissions intensity target (45% reduction from 2005), a renewable energy policy (25% of electricity), and technology capacity targets (300 GW of wind, 80 GW of PV, and 80 GW of nuclear). The China+ carbon price with near-term policies is lower than in the 500 scenario in all models. The largest changes in energy consumption are not bioenergy related (Figure 7B). For instance, there is a large increase in coal use compared to the 500 scenario in many models due to the lower carbon price. And, there are increases in non-biomass renewable electricity generation due to technology targets and the renewable electricity standards (Figure 7C).

4.4. India+

In 2020, India+ has an emissions intensity target (25% reduction from 2005) and technology capacity targets (40 GW of wind, 20 GW of solar, and 20 GW of nuclear). Like China+, the India+ carbon price with near-term policies is lower than the 500 scenario in all models and scenarios. Thus, also in India, the largest changes in energy consumption are not bioenergy related (Figure 8B). Instead, we observe large increases in coal use compared to the 500 scenario due to the lower carbon price and increases in non-biomass renewable electricity generation and nuclear power in some models due to technology targets (Figure 8C).

4.5. Latin America

In the near-term policy scenario, Latin America has an 2020 emissions intensity target based on a 36% reduction from BAU in Brazil and 30% reduction from BAU in the rest of Latin America and a renewable energy policy (35% of electricity in all Latin American countries except Brazil). The Latin America carbon price with near-term policies is higher than the 500 scenario in some models (IMAGE, MESSAGE, REMIND) and lower in other models. Interestingly, Latin America exceeds its renewable energy target in the Base and 500 scenarios (Figure 9A). Thus, the inclusion of this policy has no effect on bioenergy use. Instead, the difference in bioenergy use between the near-term policy scenario and the 500 scenario is more related to the carbon price. For example, total bioenergy consumption increases with near-term policies in MESSAGE, which has higher carbon prices for Latin America than the 500 scenario, and decreases with near-term policies in GCAM, which has lower carbon prices for Latin America than the 500 scenario (Figure 9B). In all other models, bioenergy consumption is virtually identical in the two scenarios.

5. Long-Term Impacts of the Near-Term LIMITS Policies on Regional Bioenergy Use: a Look at 2050

In the near-term policy scenario it assumed that after 2020, the only remaining policy is a globally harmonized carbon price, just as in the 500 scenario. Bioenergy consumption varies across the scenarios in the long-term due to differences in carbon prices as well as to any differences in existing long-lived capital as a result of investments made to meet the 2020 policy targets.[8] In this section, we present results for 2050 – far enough into the future for the global climate policy to be established yet near enough that there may be effects from the 2020 policies.

The effect of near-term policy on long-term carbon prices varies across models (Figure 10), though most of the relative differences are not large. GCAM shows very little difference in 2050 carbon prices across the scenarios analyzed. For MESSAGE, REMIND, and WITCH, near-term policy increases long-term carbon prices. This increase implies that the imposition of these specific near-term policies may have an impact on long-term economic efficiency of the global climate mitigation policy, though there may be other important justifications for these near-term policies. In IMAGE and TIAM-ECN, near-term policy leads to a slight decline in 2050 carbon prices. In IMAGE scenarios, the regional carbon price in the near-term policies is much higher than the global 500 scenario for North America, Europe, and Latin America, as seen in Figure 4. This higher level of near-term carbon pricing offsets the carbon price and mitigation amounts required in the rest of the century to meet the target.

Looking at global bioenergy results across the scenarios in the year 2050 (Figure 10), we observe differences in 2050 bioenergy consumption in most models (WITCH is an exception). Most of the regional differences between the 500 and StrPol-500 scenarios are relatively small, with a couple of exceptions. Though IMAGE has slightly less bioenergy in North America, it has noticeably more bioenergy in China+ and India+, with most of the increase coming from use for bioelectricity. In REMIND, bioenergy deployment is slightly higher in all regions in the scenario with near-term policy, in line with the higher carbon price from that scenario.

Finally, bioenergy must be considered and understood not alone but in the context of the entire energy system. In 2050, bioenergy is an important but not dominant source of energy in each of the scenarios for each of the models. Furthermore, although bioenergy is a major component of the energy system in several of the models, it still accounts for less than 25% of global total primary energy in the IMAGE results, the model with the highest use of bioenergy in 2050. Additional emissions reductions are achieved by use of CCS on coal and gas, other renewables, and increased use of nuclear power in some models (see van der Zwaan, this volume).

[8] Constraints on bioenergy consumption in some models may prohibit responses to carbon prices.

6. Discussion and Conclusions

This paper builds on previous literature on bioenergy use in the future by focusing on regional and sectoral bioenergy consumption under a variety of near- and long-term climate and energy policies. This regional and sectoral focus provides insights into some of the implementation details, as well as a look into what drives differences in global results across models. Bioenergy consumption is just one aspect of each of the modeled scenarios. Models will vary in their assumptions about socioeconomic growth, energy efficiency, and the cost and availability of low-carbon energy sources, which in combination will manifest a range of carbon price paths across models to reach the same climate target. The imposition of the near-term LIMITS policies offers an exploration of regional bioenergy deployment under policies that are based on realistic policy design within each region. These policies themselves are a source of regional heterogeneity in bioenergy consumption.

All of the models showed increased bioenergy levels with higher carbon prices, until a constraint is reached in a couple of them. Differences in sectoral results show the importance of not just bioenergy technologies and bioenergy with CCS, but also the importance of assumptions about competing technologies such as wind, solar, and nuclear. Regional differences in bioenergy consumption in some of the models highlight the importance of assumptions about trade in bioenergy feedstocks. In the models that assumed global trade, regional patterns of bioenergy follow global patterns. However, when trade is assumed not to be feasible, regions with high bioenergy supply potential tend to consume more bioenergy, with the notable example being Latin America in the WITCH model.

We examine several different categories of near-term policies, including renewable energy targets, renewable electricity targets, emissions constraints, emissions intensity goals, and technology deployment targets. These policies influence bioenergy deployment in different manners. For example, renewable energy targets increase use of bioliquids, biosolids, and bioelectricity, while renewable electricity targets only incentivize bioelectricity. Emissions constraints and emissions intensity targets can increase bioenergy use in all sectors, but other technologies (e.g., fossil CCS, renewables, and nuclear) can also be used to meet these goals. The degree to which bioenergy is used to meet these policies varies by model, and depends on many factors.

The long-term impact of the 2020 LIMITS policies on the global climate policy is relatively small in most of the models. In the models such as REMIND, where the impact is more significant, the near-term policies resulted in an increased carbon price in 2050, indicating some inefficiencies of the near-term policies on the long-term climate target, and more bioenergy is consumed in 2050 as a result of the higher price. In other models, such as GCAM, the small impact indicates that these models assume a more responsive capital stock and infrastructure so that near-term policies lead to limited lock in. In either case, the results do highlight the importance of considering the trade-off between implementing practical near-term policies and long-term efficiency.

In summary, the LIMITS scenarios provide a vehicle for exploring a range of outcomes for bioenergy use in response to both regionally diverse near-term policies and the transition to a long-term global mitigation policy and target. As with any of the major non-fossil technologies and resources involved in climate mitigation, deployment of bioenergy on the scales presented here involves overcoming several technological, institutional, and societal challenges. Many of these challenges are not addressed by the modeling in this study. However, while not discussed in this paper, most of the models here do include land required for food and timber, as well as the impact of land use change on reaching the mitigation targets, when determining bioenergy availability. Thus, the deployment of bioenergy suggests that there is sufficient land to supply both food and bioenergy to a growing population. However, implications of the use of bioenergy on food prices are outside the scope of this study. Additionally, we do not consider the effects of a changing climate on bioenergy supply and the competition for food in this study. The use of several models provides a source of heterogeneity in terms of incorporating uncertain assumptions about future socioeconomics and technology, as well as different paradigms for how different sectors and regions of the world may use bioenergy in response to policies. One common result is that the contribution of bioenergy to climate mitigation is a robust response across all models, despite their differences in assumptions and results about its use. The heterogeneity of the results reflect the heterogeneity of bioenergy itself, with the potential for application in several energy sectors.

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8. Figures and Tables

Table 1: Representation of bioenergy in the models analyzed[9]

Model	Bioenergy Technologies								Land-Use Model	Maximum Bioenergy Supply	Trade		Emissions	
	Electricity		Liquid fuel		Hydrogen		Biogas	Biomass heat						
	w/o CCS	w/ CCS	w/o CCS	w/ CCS	w/o CCS	w/ CCS					Primary Energy (e.g., biosolids)	Secondary Energy (e.g., bioelectricity, bioliquids)	LUC CO_2	N_2O
GCAM	x	x	x	x	x	x	x		x	Unlimited	yes	no	x	x
IMAGE	x	x	x		x	x			x	Unlimited	no	yes	x	x
MESSAGE	x	x	x	x	x	x	x	x		225 EJ/yr	no	yes		x
ReMIND	x	x	x	x	x	x	x	x	x	300 EJ/yr	yes	no	x	x
TIAM-ECN	x	x	x	x	x	x	x	x		140 EJ/yr	yes	yes	x (exogenous)	x (endogenous and exogenous parts)
WITCH	x	x	x							250 EJ/yr	no	no	x	

Table 2: Scenarios

	Climate Policies Included		
	2020	2020-2100	2100 Climate Target
Base	None	None	N/A
450	Global Carbon Price	Global Carbon Price	450 ppm CO_2-e
500	Global Carbon Price	Global Carbon Price	500 ppm CO_2-e
StrPol-500	Emissions constraints, Emissions intensity targets, Renewable energy targets, Technology-specific capacity targets	Global Carbon Price	500 ppm CO_2-e

[9] The information contained in this table is relevant for the model versions used in the LIMITS study. Other versions of the models included may have different assumptions. For example, other versions of WITCH do allow trade in bioenergy.

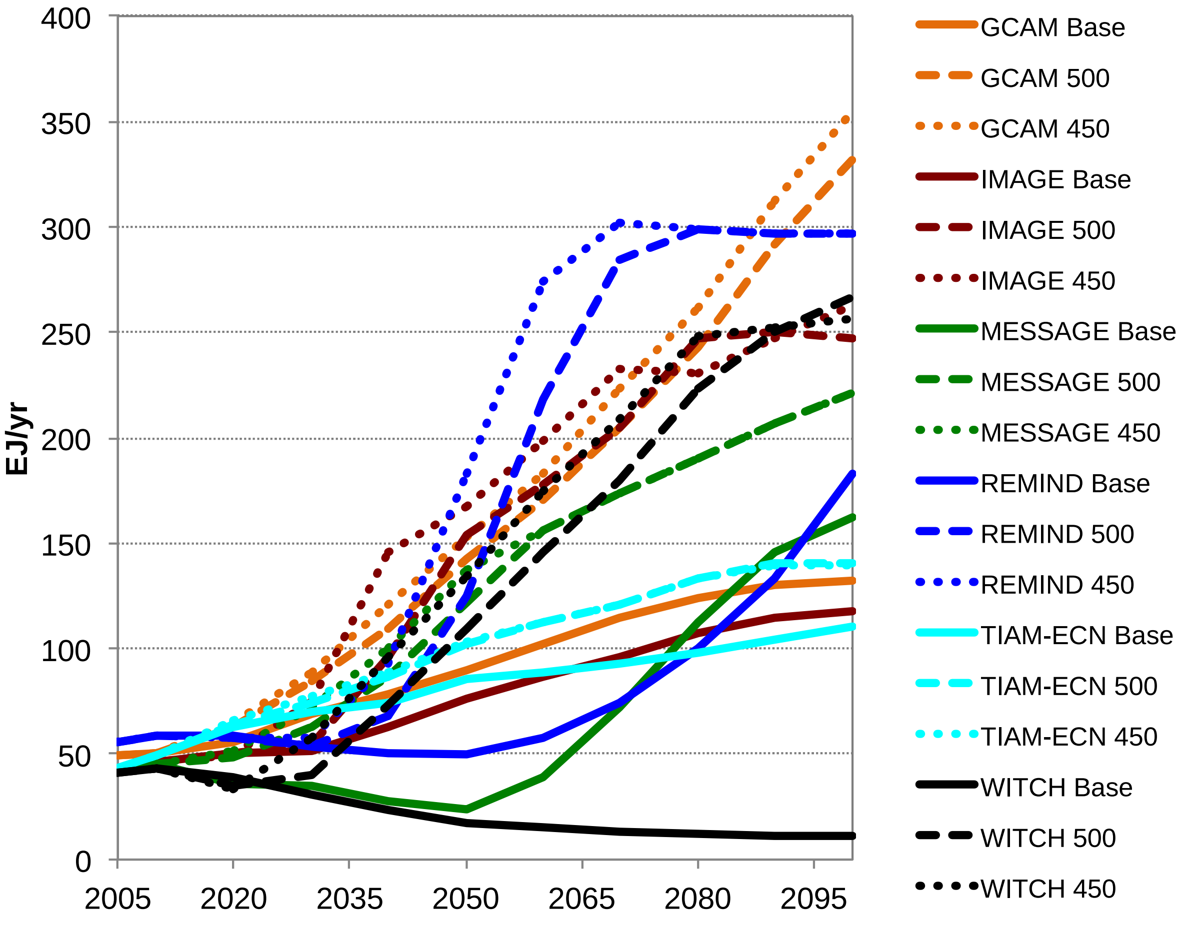

Figure 1: Global bioenergy production and consumption

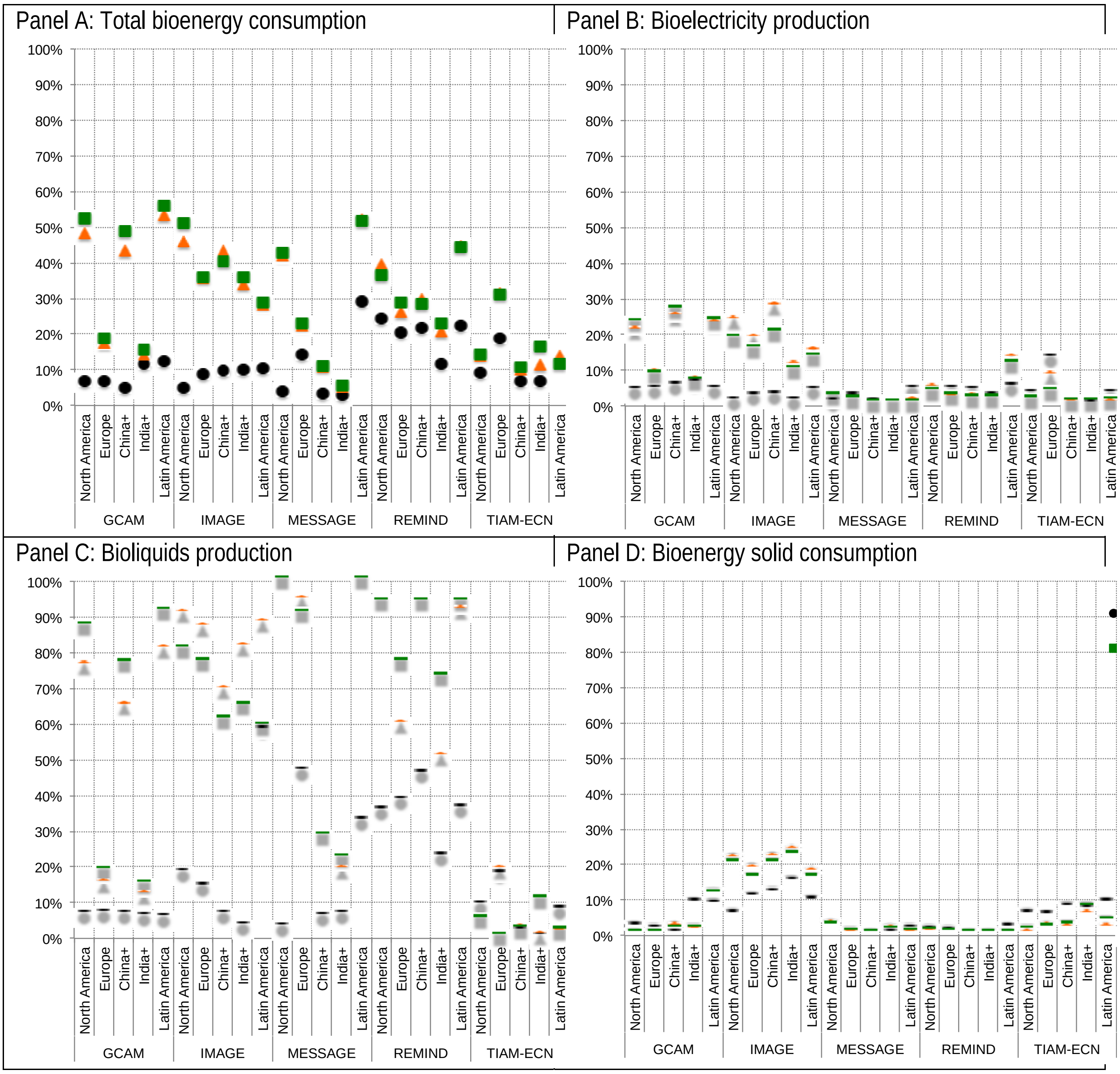

Figure 2: Regional bioenergy production and consumption, as a percentage of sectoral production/consumption, in 2100

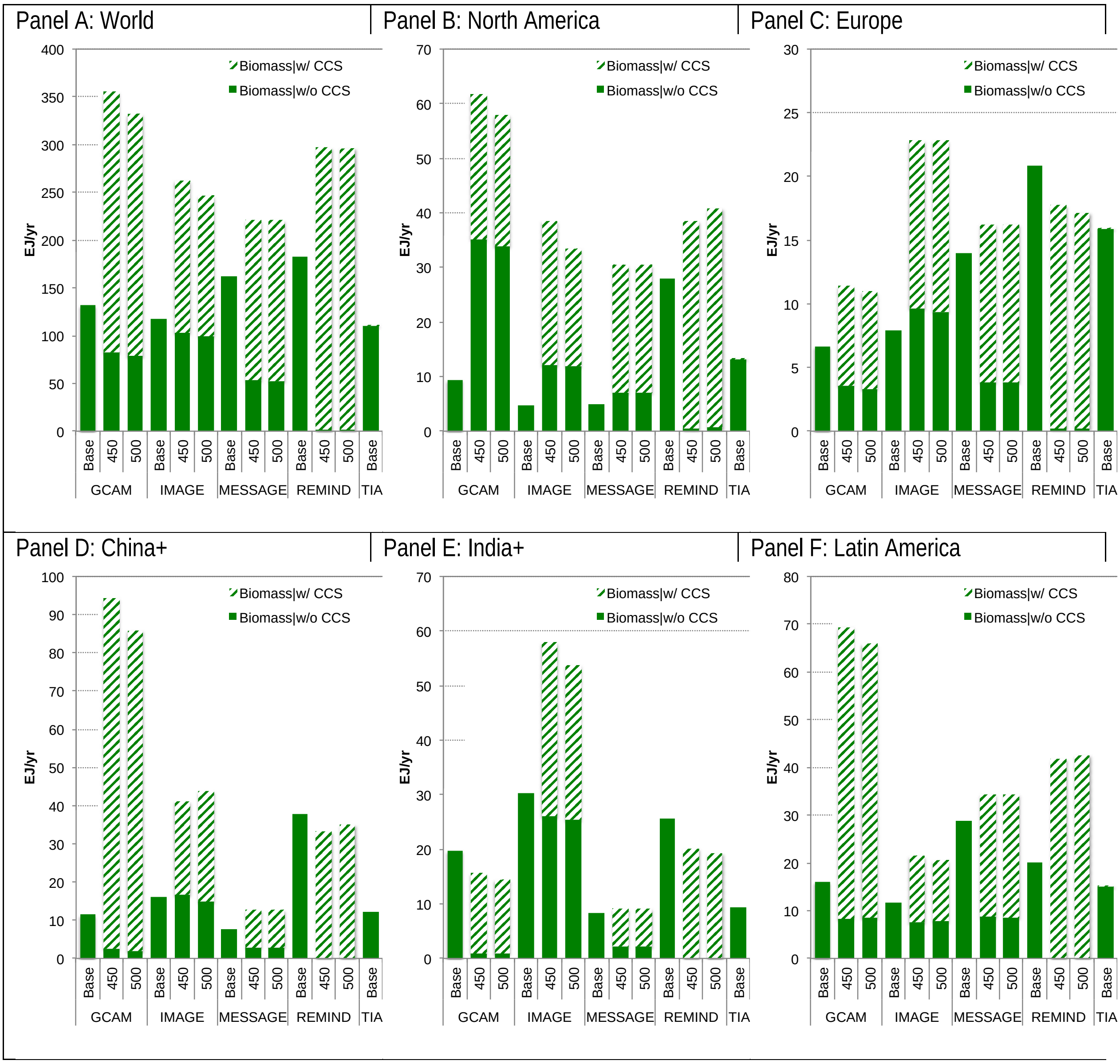

Figure 3: Global and Regional Bioenergy Consumption in 2100

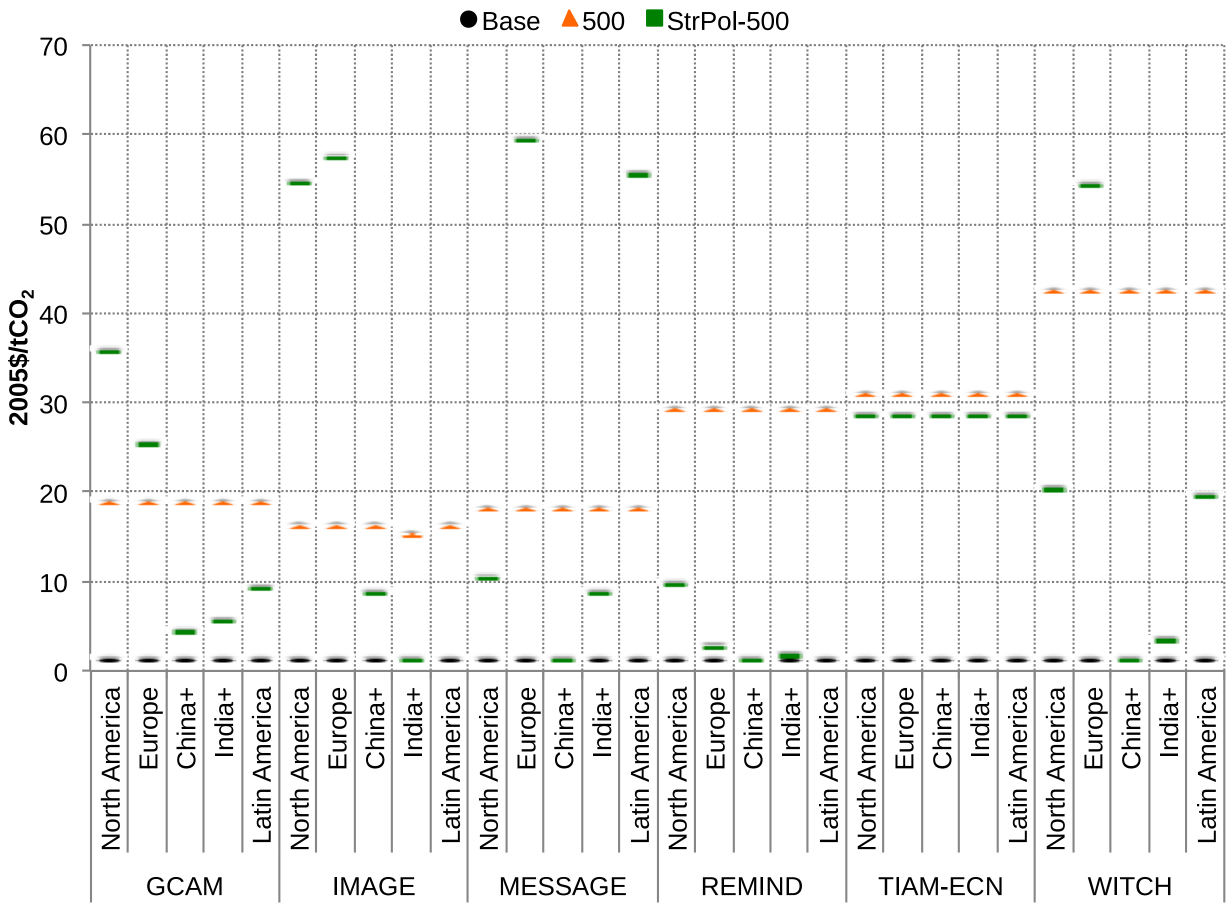

Figure 4: 2020 Regional CO_2 Prices by Scenario and Model in Context with Global 500 Scenario[10]

[10] Note, we have truncated the axis of this figure. IMAGE and REMIND have higher CO2 prices in Latin America in the StrPol-500 scenario ($509 and $335/tCO₂, respectively) and these prices are not shown in this figure.

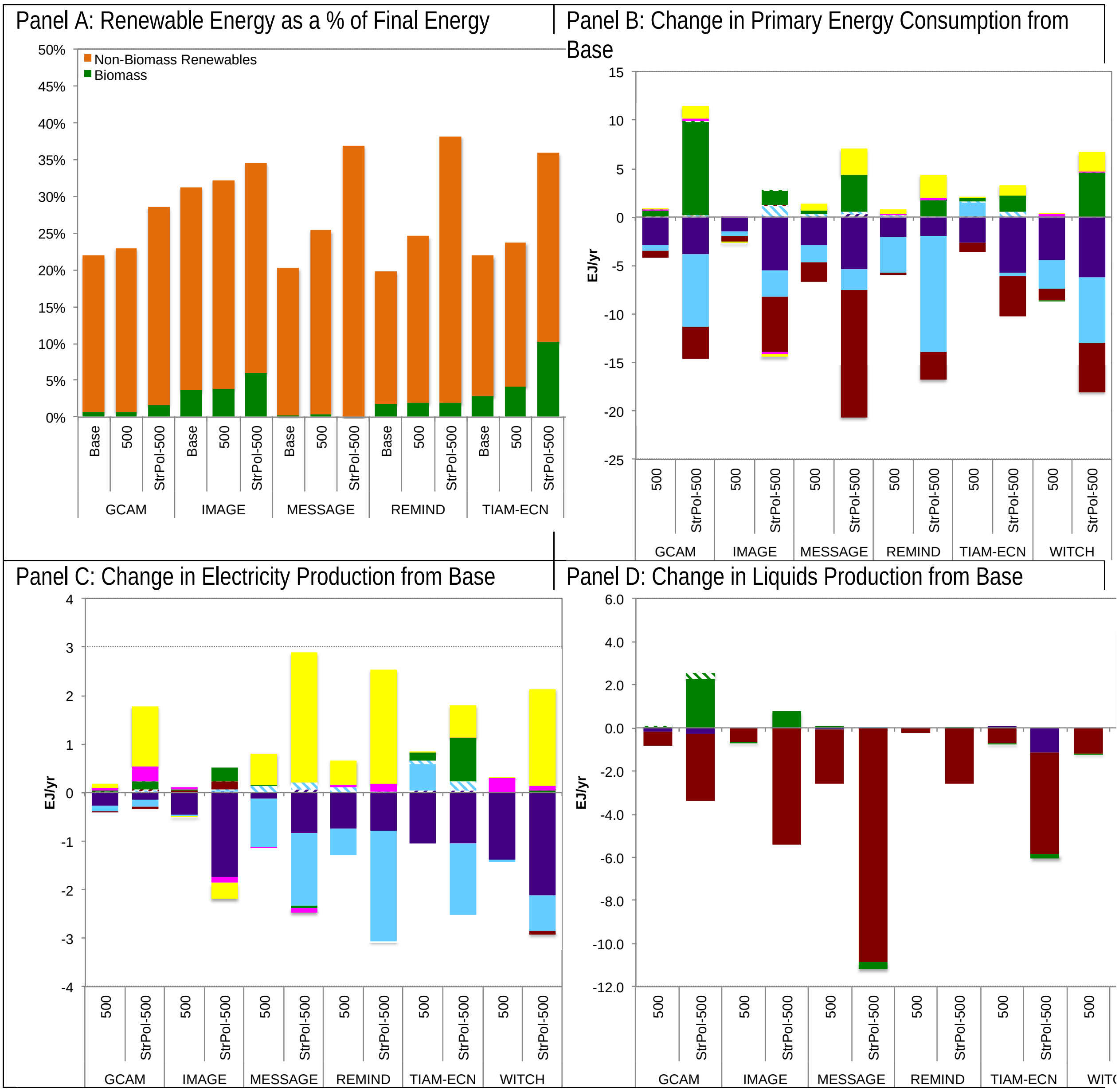

Figure 5: The effect of near-term policy on renewables, primary energy, electricity, and liquids in Europe in 2020

Figure 6: The effect of near-term policy on renewables, primary energy, electricity, and liquids in North America in 2020

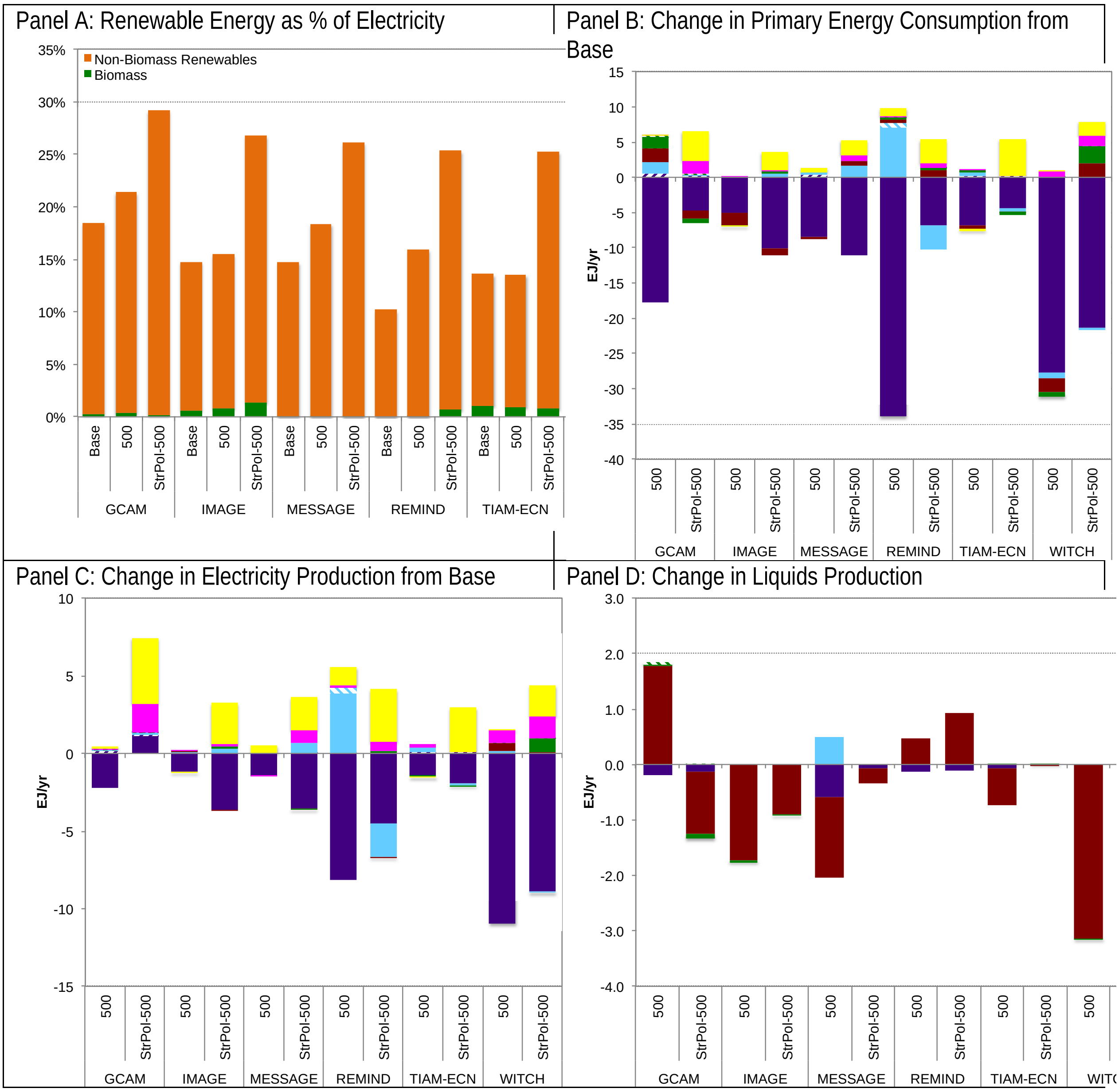

Figure 7: The effect of near-term policy on renewables, primary energy, electricity, and liquids in China+ in 2020

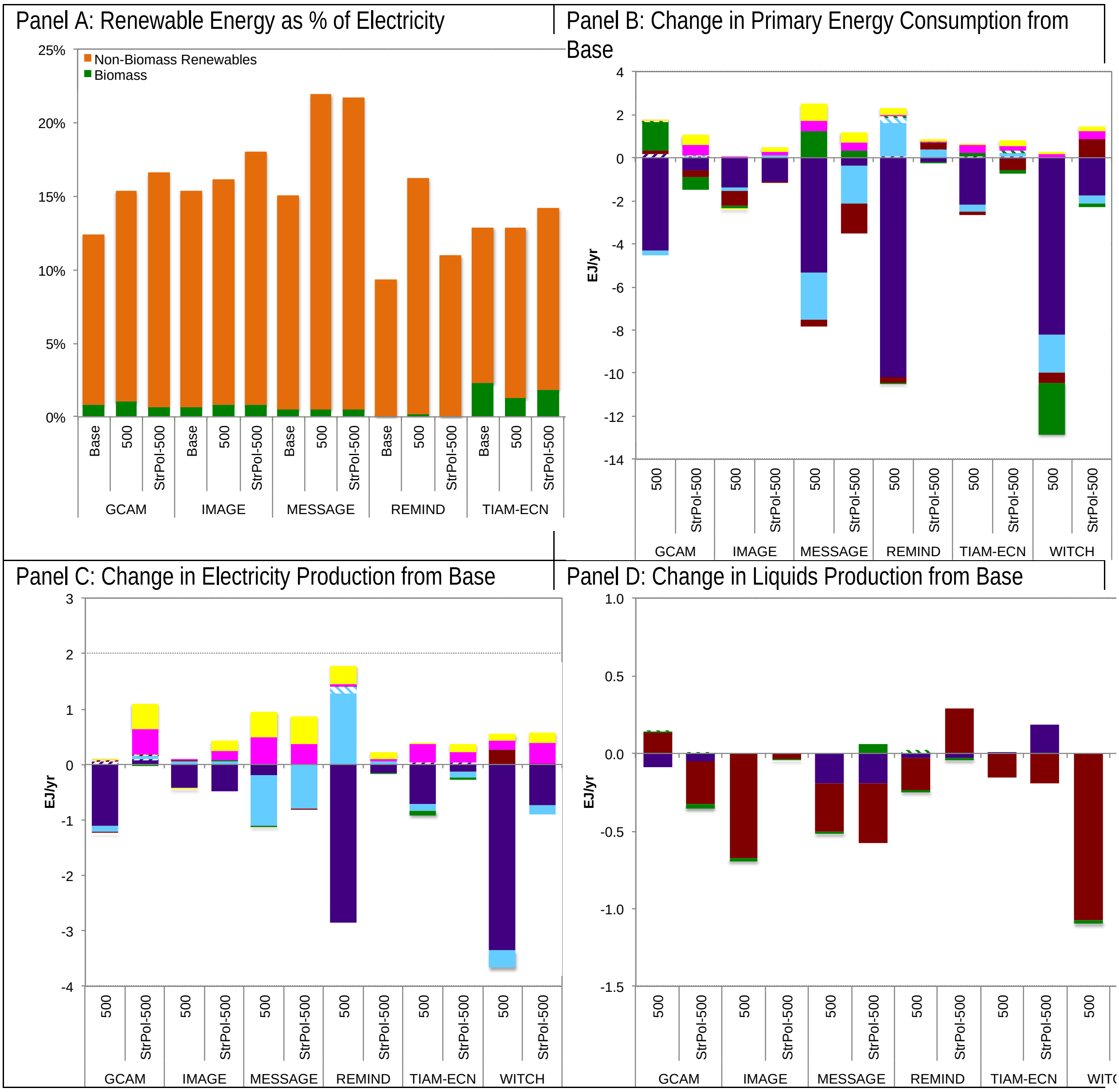

Figure 8: The effect of near-term policy on renewables, primary energy, electricity, and liquids in India+ in 2020

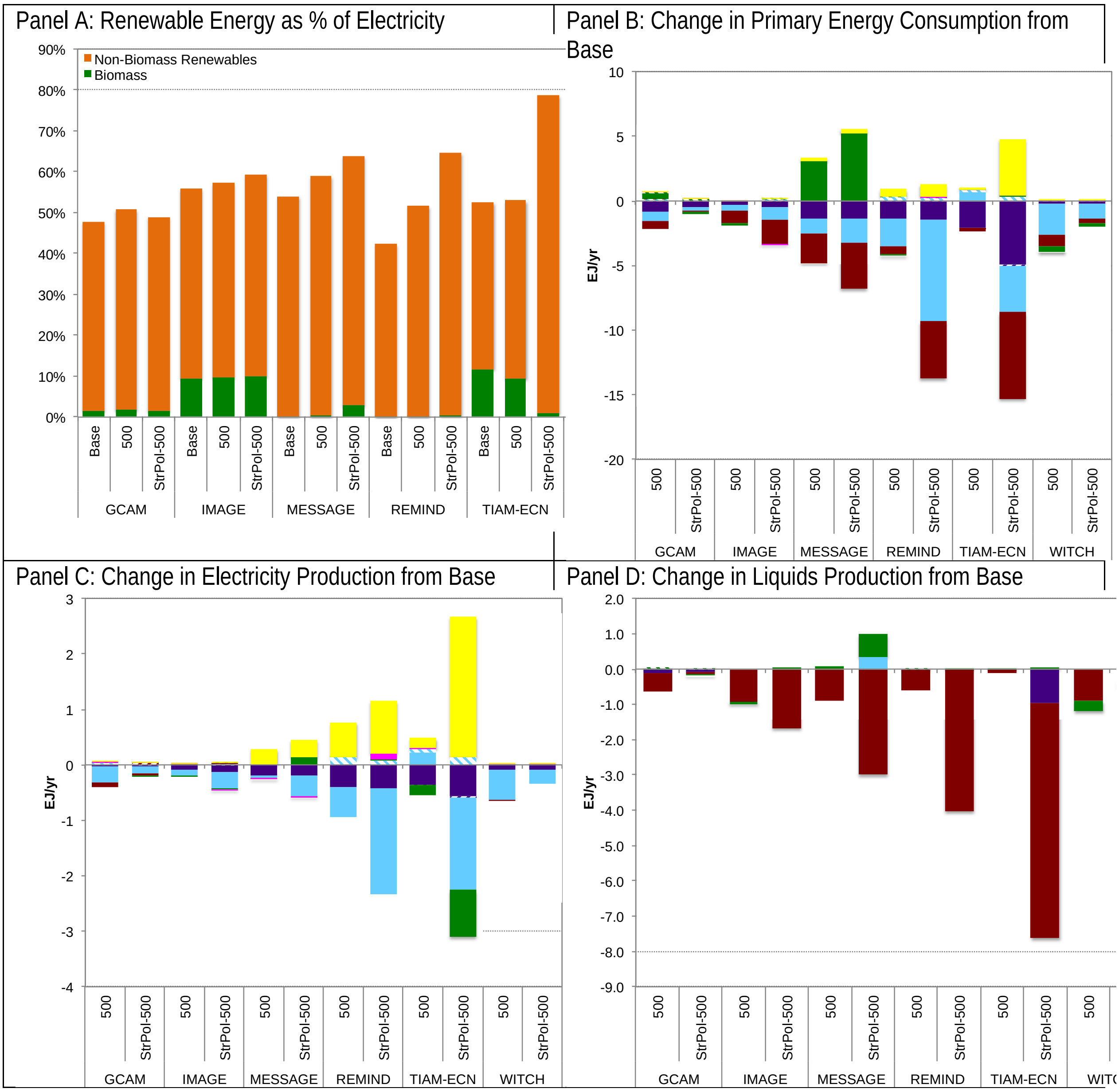

Figure 9: The effect of near-term policy on renewables, primary energy, electricity, and liquids in Latin America in 2020

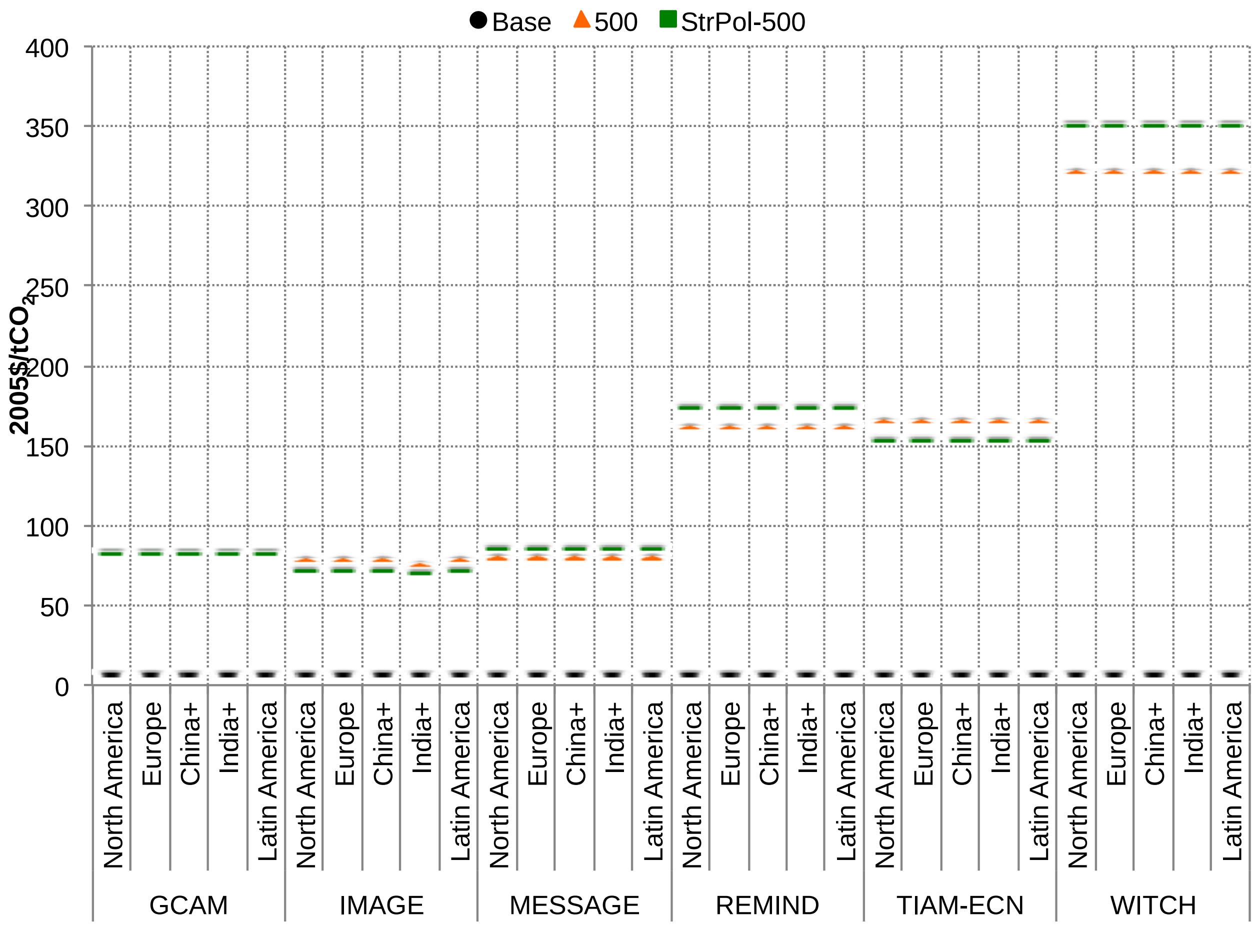

Figure 10: Carbon prices in 2050

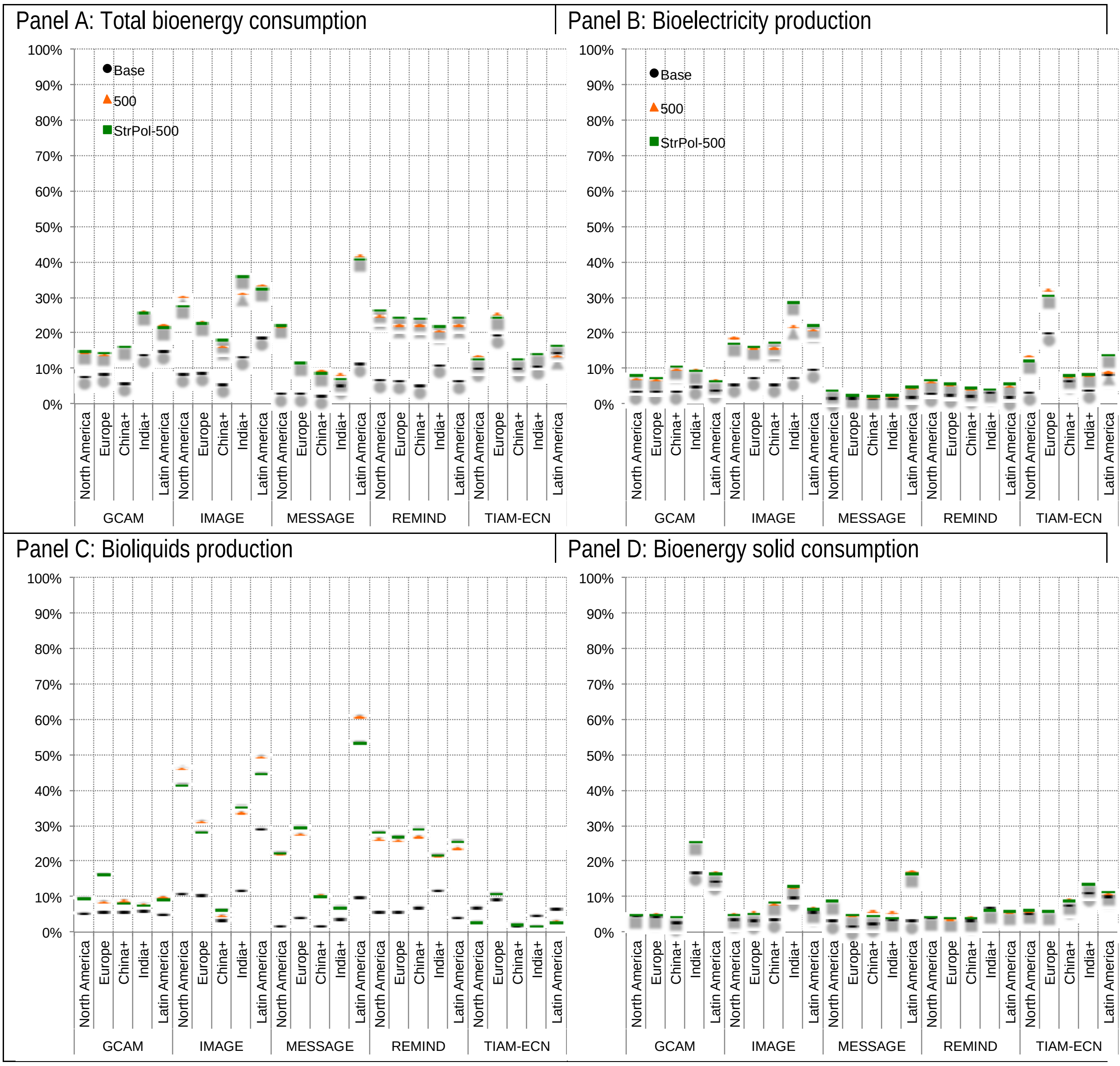

Figure 11: Regional bioenergy production and consumption, in 2050