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1 The contribution of bioenergy to the 2 decarbonization of transport: a multi- 3 model assessment

4 Florian Leblanc¹, Ruben Bibas¹, Silvana Mima², Matteo Muratori³, Shogo Sakamoto⁴, Fuminori
5 Sano⁵, Nico Bauer⁶, Vassilis Daioglou^{7,8}, Shinichiro Fujimori^{9,10}, Matthew J. Gidden^{11,12},
6 Etsushi Kato¹³, Steven K Rose¹⁴, Junichi Tsutsui⁵, Detlef P van Vuuren^{7,8}, John Weyant¹⁵,
7 Marshall Wise¹⁶

8
9 ¹ International Research Center on the Environment and Development (CIRED), Nogent-sur-Marne,
10 France

11 ² GAEL, CNRS, Grenoble INP, INRA, Univ. Grenoble Alpes, 38400 Saint Martin d'Hères, France

12 ³ National Renewable Energy Laboratory (NREL), Golden, Colorado, United States of America

13 ⁴ Central Research Institute of Electric Power Industry, Japan

14 ⁵ Research Institute of Innovative Technology for the Earth 9-2, Kizugawadai, Kizugawa-shi, Kyoto, 619-
15 0292 Japan

16 ⁶ Potsdam Institute for Climate Impact Research (PIK), Potsdam, Germany

17 ⁷ Copernicus Institute of Sustainable Development, Utrecht University, Princetonlaan 8a, 3584 CB Utrecht

18 ⁸ PBL Netherlands Environmental Assessment Agency, P.O. box 30314, 2500 GH The Hague, The
19 Netherlands

20 ⁹ Department of Environmental Engineering, Kyoto University, C1-3 361, Kyotodaigaku Katsura,
21 Nishikyoku, Kyoto city, Japan

22 ¹⁰ National Institute for Environmental Studies, Center for Social and Environmental Systems Research,
23 Tsukuba, Ibaraki 305-8506, Japan

24 ¹¹ Climate Analytics, Berlin, Germany

25 ¹² International Institute for Applied Systems Analysis, Laxenburg, Austria

26 ¹³ Institute of Applied Energy (IAE), Minato, Tokyo 105-0003, Japan

27 ¹⁴ Energy Systems and Climate Analysis Research Group, Electric Power Research Institute (EPRI),
28 Washington, DC, USA

29 ¹⁵ Stanford University, Stanford, CA, USA

30 ¹⁶ Joint Global Change Research Institute, Pacific Northwest National Laboratory and the University of
31 Maryland, College Park, USA

32

33 **Corresponding Author:**

34 Florian Leblanc

35 Email: florian.leblanc@centre-cired.fr

36 Tel: +33 143947396

37 ORCID: 0000-0001-9154-5847

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41 **Abstract**

42 The expected growth in the demand for mobility and freight services exacerbates the challenges of
43 reducing transport GHG emissions, especially as low-carbon alternatives to petroleum fuels are limited
44 for shipping, air and long-distance road travel. Biofuels can offer a pathway to significantly reduce
45 emissions from these sectors, as they can easily substitute for conventional liquid fuels in internal
46 combustion engines. In this paper we assess the potential of bioenergy to reduce transport GHG
47 emissions through an integrated analysis leveraging various assessment models and scenarios, as part of
48 the 33rd Energy Modeling Forum study (EMF-33). We find that bioenergy can contribute a significant,
49 albeit not dominant, proportion of energy supply to the transport sector: in scenarios aiming to keep the
50 temperature increase below 2°C by the end of the 21st century, models project that bioenergy can
51 provide in average 42 EJ/yr (ranging from 5 to 85 EJ/yr) in 2100 for transport (compared to 3.7 EJ in
52 2018), mainly through lignocellulosic fuels. This is 9-62% of final transport energy use. Only a small
53 amount of bioenergy is projected to be used in transport through the electricity and hydrogen pathways,
54 with a larger role for biofuels in road passenger transport than in freight. The association of carbon
55 capture and storage (CCS) with bioenergy technologies (BECCS) is a key determinant in the role of
56 biofuels in transport, because of the competition for biomass feedstock to provide other final energy
57 carriers along with carbon removal. Among models that consider CCS in the biofuel conversion process
58 the average market share of biofuels is 21% in 2100, compared to 10% for models that do not.
59 Cumulative direct emissions from the transport sector account for half of the emission budget (from 300
60 to 670 out of 1,000 GtCO₂). However, the carbon intensity of transport decreases as much as other
61 energy sectors in 2100 when accounting for process emissions, including carbon removal from BECCS.
62 Lignocellulosic fuels become more attractive for transport decarbonization if BECCS is not feasible for any
63 energy sectors. Since global transport service demand increases and biomass supply is limited, its
64 allocation to and within the transport sector is uncertain and sensitive to assumptions about political as
65 well as technological and socioeconomic factors.
66

67 **Keywords**

68 Bioenergy, Transport sector, Lignocellulosic fuels, Climate mitigation, Integrated Assessment Models
69
70

71 1 Introduction

72

73 Mitigation of climate change requires the reduction of greenhouse gas emissions (GHG) in every
74 economic sector, including transport, which today relies heavily on petroleum fuels and accounts for 23%
75 of global energy sector emissions (IEA, 2020a; Victor et al., 2014). Decarbonization of transport is
76 challenging (Rogelj et al., 2018; Sims et al., 2014) due to the rapid growth in global passenger and freight
77 service demand and limited alternatives to liquid petroleum fuels. Switching to low-carbon fuels is one
78 option for GHG emission reduction in transport, among which biomass constitutes a versatile energy
79 carrier that can provide various low-carbon transport fuels: liquids, gases, electricity or hydrogen.
80 Moreover, further emission reduction can be achieved when bioenergy is combined with carbon capture
81 and storage (BECCS) for all these energy carriers (Muratori et al., 2020a; Azar et al., 2010). Liquid biofuels
82 are a convenient solution for transport decarbonization: biofuels can be integrated with the existing
83 infrastructure and end-use technologies, offering a solution to incrementally lower the emission intensity
84 of the current vehicle fleet¹ or in sub-sectors that currently do not have any cost-effective alternative to
85 liquid fuels such as freight (Muratori et al., 2017b), maritime, and air transport². However, compared with
86 the current demand for transport services as well as other final energy demands and the prospect of
87 substantial future growth, the total potential of biomass supply is limited. This makes the allocation of
88 bioenergy to and within the transportation sector a crucial question in the context of climate change
89 mitigation.

90 Significant progress has been made in developing effective and cost-competitive biofuel production. First-
91 generation biofuels, involving the conversion of sugar, starch or vegetable oil from food crops,
92 represented 4% (79 Mtoe) of the road transport energy mix in 2016 (IEA, 2017). Second-generation
93 biofuels (including lignocellulosic fuels) involve advanced bioenergy technologies (ABTs) to produce liquid
94 fuels. First and second-generation biofuels can be coupled with carbon capture and storage (CCS) to
95 provide negative emissions (Cheah et al., 2016; Johnson et al., 2014; Muratori et al., 2017a). Because
96 existing facilities are currently at an experimental stage, future costs of biomass production and
97 bioenergy feedstock are difficult to evaluate (Li et al., 2018; Fuss et al., 2018). However, lignocellulosic
98 fuels are likely to provide the largest market share of future biofuels (IEA, 2017). Compared to first-
99 generation biofuels, second-generation biofuels provide greater GHG emission reductions (Daioglou et
100 al., 2017; Macedo et al., 2014). Also, their indirect impact on land-use GHG emissions and food prices can
101 be limited if energy crops are grown on marginal and abandoned land, or if the biomass feedstock comes
102 from managed forests, residues and waste (Havlík et al., 2011).

103 Biofuels played a prominent role in previous transport decarbonization mitigation scenarios, depending
104 on the one hand on competition with other low-carbon fuels and on the other on the value of biomass
105 feedstock for carbon removal through BECCS in any energy sector. The EMF-27 study (Rose et al., 2014)

1 Note that high blended rates of biofuels can increase metal corrosion in engines compared to gasoline, thus requiring the use of specific materials for dedicated engines or selling flexible fuels vehicles (Kavitha and Vijayasarithi, 2015; Sorate and Purnanand, 2015; Du et al., 2013; Singh et al., 2012).

2 See Hileman and Stratton (2014) for a review of alternative jet fuels, Why et al. (2019) and Wei et al. (2019) for a specific review of alternative jet fuels including biojet fuels. See Wise et al. (2017) for an integrated assessment of the role of biojet fuels in mitigation pathways. The role of biomass in low-carbon marine transport compared to other technological alternatives is described in Tanzer et al. (2019), Taljegard et al. (2014) and TFI (2018).

106 shows a regional biofuel market share in transport of up to 70%, with the higher levels occurring in OECD
107 countries and Asia, within a set of harmonized mitigation scenarios comparing several integrated
108 assessment models (IAMs). Ahlgren et al. (2017) conduct a literature review of global energy-economy
109 scenarios and report the biofuel market share in transport to be as high as 40%. In IEA (2017), a scenario
110 aiming at stabilizing temperature increase at well below 2°C shows that biofuels contribute 36% of
111 emissions reduction in transport, compared to 15% for electricity. Increasing the climate policy stringency
112 from 2°C to 1.5°C in IAMs scenarios results in increased use of biofuels and a roughly constant share of
113 electricity use in transportation (Rogelj et al., 2015). This saturation of transport electrification for the
114 well-below 2°C target can be explained by model assumptions, for example, the lack of electric
115 transportation end-use alternatives (e.g. electric trucks) in IAMs (Muratori et al., 2020b). A Recent IAM
116 study with a linkage to a bottom-up transport model shows increasing electrification of passenger
117 transport when comparing the 2° and 1.5°C scenarios (Zhang et al., 2018). Higher electrification rates in
118 scenarios are generally associated with a reduced share of biofuels in transport, except in freight (Zhang
119 et al., 2020; McCollum 2014). However, without actions to support widespread EV adoption biofuels
120 might remain a relevant low carbon alternative for on-road transport (McCollum et al. 2017), and biofuel
121 blending rate standards could come as a complement to EV adoption policies (Mercure et al. 2018).

122 The main objective of this paper is to assess the potential contribution of biomass to the deep
123 decarbonization of the transport sector, leveraging different models in a consistent scenario framework
124 focusing on climate change mitigation and the role of Advanced Bioenergy Technologies (ABTs). In
125 particular, we answer the following questions: what is the role of bioenergy in the future transport
126 energy mix, through which final energy carrier, and how does it help to reduce transport emissions
127 compared to other energy sectors? We evaluate scenarios aiming to limit the temperature increase to
128 well below 2°C in 2100 with 10 global IAMs that use dedicated land-use models. The cost-effectiveness
129 analysis provided by IAMs is equivalent to assuming coordination of strategies between the different
130 energy sectors in order to minimize mitigation costs to achieve a climate stabilization target. These IAM
131 scenarios inform the tradeoffs in the distribution of mitigation efforts across sectors. In particular, we
132 evaluate bioenergy's role in transport decarbonization from two perspectives: inter-sectorial competition
133 for biomass feedstock, including the role of BECCS, and the competition between different fuels to
134 decarbonize transportation. We account for direct as well as indirect emissions from fuel production in
135 order to emphasize the role of transport in triggering carbon removal. This paper is part of, and leverages
136 results from, the EMF-33 project (Rose et al., 2020), which assesses the emission reduction potential of
137 bioenergy from the supply and demand sides. This paper therefore also contributes to increasing
138 transparency by providing insight into how the different modelling assumptions can be linked to the
139 results in the transportation sector.

140 The paper is structured as follows. Section 2 presents the methodology, the scenario design and model
141 assumptions. Section 3.1 describes the different pathways through which bioenergy enters the transport
142 energy mix under a stringent climate objective, as well as the role of CCS. Section 3.2 discusses the
143 competition of lignocellulosic fuels with hydrogen and electricity for the case of road transport. Section
144 3.3 analyzes the role of bioenergy in reducing transport emissions when considering process emissions
145 from fuel production, including negative emissions from BECCS. Section 4 discusses our results with
146 respect to the recent trend in transport electrification. Section 5 concludes.

147 2 Methods

148 2.1 EMF-33 transportation modeling

149
150 This paper presents simulation results from the demand phase of the EMF-33 modelling exercise, which
151 focuses on the role of ABTs for climate mitigation scenarios (Rose et al. 2020; Bauer et al., 2018). Ten IAMs
152 produced results to evaluate three climate policy scenarios described below. All models are multi-regional
153 with global coverage, designed to evaluate long-term mitigation pathways; most of them have already
154 participated in several model comparison exercises (Marangoni et al., 2017, Riahi et al. 2017; Kriegler et al.
155 2014; Rose et al. 2014; Clarke et al., 2014). This section describes the modelling of transport, while several
156 companion papers provide additional information: Bauer et al. (2018) describe EMF-33 bioenergy demand
157 scenarios regarding stringent climate targets and the availability of the different ABTs; Daioglou et al.
158 (2020) highlight the role of technological cost assumptions in driving scenario results; Muratori et al.
159 (2020a) highlight the role of BECCS with respect to the various bioenergy carriers; Rose et al. (this issue)
160 evaluate the supply of biomass feedstock with respect to the modelling of land-use in the different IAMs.

161 The differences in model assumptions are summarized in Table 1. Half of the models are recursive-dynamic,
162 the other half being solved with an inter-temporal optimization procedure. Almost all the models provide
163 an endogenous representation of the demand for passenger travel (8/10) with half including modal shift
164 (5/10). Fewer models include an endogenous representation of freight (6/10) and fewer still include modal
165 shift (3/10). Besides modal shift, emission reductions in IAMs are mainly achieved through fuel switching
166 and energy efficiency measures in contrast to more flexible demand measures as depicted by scenarios
167 evaluated with bottom-up transport models (Gota et al., 2018; Edelenbosch et al., 2017; Yeh et al. 2017).
168 Our analysis does not focus on the role of additional policies aiming to accelerate technology diffusion,
169 which are for example an important driver of transport electrification (McCollum et al., 2017; Mercure et
170 al., 2018), beyond those included implicitly or explicitly in the models. For example, the REMIND model
171 considers optimal subsidies for low-carbon technologies which allow for an acceleration of the learning
172 phase (Schultes et al., 2018).

173 The variety of assumptions across models regarding the availability of ABTs allows us to obtain insight into
174 the role of the different bioenergy pathways and CCS in driving transport emission reduction. Some models
175 include synthetic gases from biomass³, and all models except one (BET) include first generation biofuels,
176 however with limited growth potential (see section A.3 of the SOM). All models consider CCS with the
177 production of electricity (E) from bioenergy, while only eight models consider the production of hydrogen
178 (H) from biomass (six with CCS). Finally, all models incorporate lignocellulosic fuel⁴ (LC) production and six
179 have the upgrade that includes CCS. The penetration of low-carbon technologies into IAMs depends on the
180 way end-use technologies or fuels compete with each other within each energy sector (Bauer et al., 2018).
181 The competition of lignocellulosic fuel with other energy carriers in transport is modelled by multinomial

³ Through gaseification or anaerobic digestion of biomass feedstocks.

⁴ The lignocellulosic fuel conversion process may concerns biochemical or thermochemical conversion or both, depending on the assumptions of each models. See Table A.7 in the SOM.

182 logits for half of the models (AIM/CGE, GCAM, IMACLIM-NLU, IMAGE, POLES) and with more flexible
183 systems for the other half (BET, DNE21+, REMIND-MAGPIE, GRAPE-15, MESSAGE-GLOBIOM). Finally, some
184 models endogenously represent vehicle costs (4/10) and vehicle efficiency (2/10).

185

186 2.2 The scenario protocol

187 All scenarios assume costs and the availability of non-ABTs as considered in the Baseline, which includes
188 conventional technologies as well as renewable energies as commonly assumed in IAMs⁵. The Baseline
189 scenario is calibrated so as to reflect the SSP2 narrative in terms of GDP and population (Riahi, 2017). A
190 diagnosis of the EMF-33 harmonization procedure with respect to several indicators (population, GDP,
191 final energy) can be found in the overview paper (Bauer et al., 2018) and the corresponding supplementary
192 materials⁶.

193 Apart from the Baseline we evaluate three climate sensitivity scenarios using an intertemporal carbon
194 budget constraint of 1,000 GtCO₂ over the period 2011-2100 which account for CO₂ emissions from fossil
195 fuels and industries (FFI) net of carbon dioxide removal from BECCS. This emissions budget is indicative for
196 a 67% chance of limiting global surface temperature increase to below 2°C (Rogelj et al., 2016; IPCC, 2013).
197 Some models (AIM/CGE, DNE21+, GCAM, GRAPE-15, IMAGE, MESSAGE-GLOBIOM) assume that
198 afforestation is capturing CO₂ from the atmosphere in response to the carbon price, but this does not affect
199 the carbon budget considered from FFI. Apart from BECCS and afforestation, no other negative emissions
200 technologies are considered by models. A set of sensitivity scenarios with a higher emission budget (1,600
201 GtCO₂) is also discussed in the SOM. Baseline and climate policy scenarios are calibrated so as to reflect
202 near-term climate policies, including the Cancun pledges or National Determined Contributions (NDCs) for
203 2020. The set of climate sensitivity scenarios concerns three technological variants which emphasize the
204 role of lignocellulosic fuel on the one hand, and the role of CCS technology in decarbonizing transport on
205 the other:

- 206 • a scenario in which the full set of ABTs is available⁷ ('full')
- 207 • a scenario in which the lignocellulosic conversion route is not available ('nofuel')
- 208 • a scenario which serves to assess the role of lignocellulosic fuels when CCS (BECCS) is not available
209 for any bioenergy transformation pathway ('nobeccs').

210 The carbon budget is implemented after 2020 in each model (Table 1). Beside emission or budget
211 constraints, five models out of ten use a carbon tax on FFI emissions, which determines the cost-effective
212 choice of the transport energy mix regarding emission intensities and system flexibility in switching
213 between technologies. Policy implementation also drives the allocation of biomass feedstock across the
214 different energy sectors so as to minimize total policy cost, at each time-step for recursive dynamic models
215 or for the whole period in inter-temporal optimization models. The carbon price resulting from the policy

⁵ https://www.iamcdocumentation.eu/index.php/IAMC_wiki

⁶ https://static-content.springer.com/esm/art%3A10.1007%2Fs10584-018-2226-y/MediaObjects/10584_2018_2226_MOESM1_ESM.docx

⁷ The full set of ABTs includes the production of hydrogen and electricity from biomass, as well as lignocellulosic fuels.

216 constraint in each model is applied to emissions from agriculture, forestry, and other land uses⁸, thus
217 avoiding emission leakages towards the land-use sector. The competitiveness of bioenergy with other low-
218 carbon fuels then also depends on the value of GHG emissions which is reflected in the biomass feedstock
219 supply costs, as accounted for by each respective land-use model (Rose et al., this issue). The inclusion of
220 land-use based mitigation measures in response to carbon pricing in some models, such as avoided
221 deforestation and afforestation/reforestation, isare likely to influence the availability of biomass feedstock
222 and its emission intensity. Section A.7 in the SOM further discusses the indirect role of land use in transport
223 mitigation and checks that cumulative induced emissions from the land-use sector do not outweigh
224 emissions savings in FFI thanks to bioenergy.

225 3 Results

226 3.1 Bioenergy in the transport energy mix and the role of CCS

227 Without climate policy, bioenergy can still reduce GHG emissions in transport if it substitutes for
228 petroleum-based fuels to a sufficient degree. The Baseline scenarios show the average transport sector
229 final energy to be 219 EJ/yr in 2100 (ranging from 193 to 263 EJ/yr, Fig. 1), an increase of 80% over today's
230 figure compared to an overall increase in energy of 92%. The transport sector remains dependent on
231 carbon-intensive fuels: the energy mix is projected to continue to rely heavily on petroleum-based fuels
232 until 2050 and beyond (between 27 and 88% of total final energy in 2100), with substitution over time
233 mainly by fossil-fuel-based alternatives (gas-to-liquids for POLES; coal-to-liquids for IMACLIM-NLU and
234 REMIND-MAGPIE; gases for GCAM), driven by the relative increase in the oil price compared to coal and
235 natural gas (see Figs. A1 and A2 in SOM). The role of hydrogen and electricity is limited (9% on average for
236 electricity, 23% at most for MESSAGE-GLOBIOM), and the production of those two energy carriers remains
237 carbon-intensive in the baseline scenario. Bioenergy enters the energy mix for transport services *via* liquid
238 fuels, but only three models show significant shares (23%, 25% and 26% for POLES, GRAPPE-15 and
239 AIM/CGE respectively), giving lignocellulosic fuel a limited role in reducing transport emissions in the
240 Baseline scenario without additional policies such as biofuel mandates or carbon pricing.

241 The phase-in of biofuels in Baseline scenarios is mostly driven by increasing oil prices and competitiveness
242 of alternatives to the internal combustion engine. However, the use of bioenergy to decarbonize transport
243 under the climate constraint not only depends on cost competitiveness with other transport low-carbon
244 technologies but also on the competition for biomass feedstock with other energy sectors (Daioglou et al.,
245 2020). IAM assessments show that negative emissions associated with bioenergy production significantly
246 lower mitigation costs, so that from a cost-effectiveness perspective, biomass is more valuable in energy
247 conversion processes that can be up-graded with CCS (Muratori et al., 2020a, Bauer et al., 2018, Rose et al.
248 2014). All models in EMF-33 assume CCS to be available with electricity production from biomass.
249 Consequently, in our climate sensitivity scenario with the full set of technologies available ('full'),
250 lignocellulosic fuels are the predominant low-carbon alternative to petroleum fuels in only five models out
251 of ten in 2100, among which four assume CCS to be available in the conversion process.

8 With the exception of the BET model, which only considers CO₂ emissions from land-use change.

252 Our results suggest that the role of bioenergy for transport mitigation is strongly dependent on the
253 feasibility of CCS in the lignocellulosic conversion process if BECCS exists for other energy sectors. Biomass
254 feedstock is preferentially directed towards electricity generation to provide negative emissions in models
255 that do not assume the CCS upgrade for lignocellulosic production (see the BET and DNE21+ models)⁹, with
256 an exception for IMACLIM-NLU. Moreover, the use of biomass in transport increases in comparison to
257 Baseline only in models with the CCS upgrade in lignocellulosic production, with an average market share of
258 21% (2.3-40%) compared to 10% (0-30%) for models that do not include CCS. Looking at EMF-33 scenarios,
259 Daioglou et al. (2020) show the importance of revenues from carbon sequestration in lowering the LCOEs
260 of bioenergy technologies. Most models exhibit technical costs reduction through learning, which is in
261 some cases compensated by the increase of the cost of biomass feedstocks function of the the demand for
262 bioenergy. However, models with the lowest LCOEs are the one with the highest capture rates due to the
263 role of revenues from carbon sequestration.

264 Besides the availability of CCS, the absolute level of biofuels depends on the various technical assumptions
265 taken by models. Optimistic assumptions regarding the future development of non-biomass renewable
266 technologies in the power sector strongly influence the availability of biomass for liquid fuels production,
267 part of which is consumed by transports. From a supply-side perspective regarding EMF-33 scenarios, Bauer
268 et al. (2018) found a more balanced allocation of biomass between liquids and electricity production in
269 models with stricter constraints on the deployment of non-biomass renewables. On the demand side, the
270 absolute level of biofuels consumed by transport depends on end-use technology adoption and costs as
271 well as assumed by models, as well as the relative evolution of fossil fuel prices. The absolute level of
272 biofuel use reflects the end-use competition from low-carbon alternatives of the Baseline¹⁰: models with a
273 high share electricity, hydrogen or gases in Baseline (GCAM, MESSAGE-GLOBIOM, IMAGE) have a lower
274 share of lignocellulosic liquid fuels in the policy scenario; models with a high share of biofuels in the
275 Baseline scenario or relying on fossil-based alternatives include a higher share of biofuels in the mitigation
276 scenario (from 26 to 57%)¹¹. In comparison, Ahlgren et al. (2017) and Rose et al. (2014) found respectively
277 the largest market share to be 40% and 70% for liquid biofuels.

278 The recourse to negative emissions in mitigation strategies raises concerns about the uncertain feasibility
279 of BECCS, both regarding the technology itself and numerous externalities (Low and Schäfer, 2020; Stoy et
280 al., 2018). Yet if BECCS is not feasible or if CCS were to be deployed at a slower rate than expected, the
281 value of biomass will depend more heavily on its ability to lower GHG emissions in each respective energy
282 sector than on the requirement to provide carbon removal in any particular energy sector. In our sensitivity
283 scenarios without BECCS ('nobeccs') biomass become more valuable in providing lignocellulosic fuels to
284 decarbonize transport with an increased market share for seven models compared to the 'full' scenario (for
285 the 1,600 GtCO₂ budget scenario¹², see Fig. A5 and Table A.3 in SOM). Without BECCS, less biomass is
286 directed towards non-liquid energy carriers (electricity, hydrogen, gases) in favor of lignocellulosic fuel

9 Two other models do not consider CCS with lignocellulosic fuel production, leading to different behaviors: the GRAPE-15 model achieve transport decarbonization by using first-generation biofuels, whose feedstocks are not in competition for electricity generation (See section A.3 in SOM for the distinction between first-and second-generation biofuel in transport across models); the IMACLIM-NLU model is the only exception in using lignocellulosic fuels in transport even without CCS. In this model, the cross-sectoral allocation of biomass is not performed using a cost-effectiveness approach, but independently, in response to the biomass feedstock market price (Leblanc et al., this issue).

10 Biofuels for transport are also in competition with other uses, as in the IMAGE model, in which they are produced with CCS but destined for industrial energy use and to some extent for electricity production.

11 The GCAM model also has a high share of biofuels (38%) in the 'hi' policy scenario, whereas it relies on petroleum fuels and gases in its Baseline scenario.

12 Only few models found the 'nobeccs' scenario to be feasible for the 1,000 GtCO₂ target, so in the SOM we present a scenario with a 1,600 GtCO₂ emission budget to discuss sensitivity with respect to BECCS availability.

287 production, which is also illustrated by models which do not consider the CCS upgrade for lignocellulosic
288 production: in DNE21+ for example, large quantities of lignocellulosic fuel are allocated to the transport
289 sector at the expense of the decarbonization of the power sector when BECCS are not available.
290 Furthermore, the scenario without lignocellulosic fuels ('nofuel') shows that in some models (POLES,
291 REMIND-MAGPIE, IMACLIM-NLU) the release of biomass supplies for power generation with carbon
292 removal compensates for emissions from increased used of oil in transport. In this scenario, one model
293 (GRAPE-15) exhibits the same level of biofuels demand in transport compare to the 'full' scenario since in
294 both cases it involves the production of first generation biofuels.

295 3.2 Competition between lignocellulosic fuel and electricity & hydrogen

296 Considering all pathways, bioenergy accounts on average for 42 EJ/yr (between 5 and 85 EJ/yr) in the
297 transport energy mix. Although biomass is mostly used in transport *via* liquid fuels, bioenergy can also
298 enter the transport energy mix indirectly through electricity, hydrogen and gases (aggregated in light green
299 in Fig. 1). The amount of bioenergy used in transport *via* those pathways is rather small for all models (from
300 0.9 to 10.3 EJ/yr in the 'full' scenario, Table A.2) due to competition with other low-carbon technologies in
301 each energy market. The use of biomass in transport through these three energy carriers increases in the
302 'nofuel' scenario when the lignocellulosic liquid fuel conversion route is not available relatively to the 'full'
303 scenario (from 2.6 to 32.5 EJ/yr in the 'nofuel' scenario) and decreases if BECCS is not feasible ('nobeccs')
304 except for the GCAM model (19.3 EJ/yr).

305 Competition between biofuel and hydrogen & electricity varies across transport sub-sectors. Fig. 2 presents
306 the energy mix of road transport broken down between freight and passenger, for five selected models.
307 Road transport accounts for 74% of transport GHG emissions today (IEA, 2019). For most models, biofuels
308 compete with conventional liquid fuels (mostly petroleum) in freight, and with hydrogen or electricity for
309 on-road passenger transport. The contribution of bioenergy to transport emission reduction is greater in
310 freight than in passenger transport due to more limited alternatives to liquid fuels: the potential for
311 electrification is greater for road passenger than freight services, because of shorter distances driven and
312 the assumed difficulty of electrifying trucks (Nadel, 2019). The unavailability of lignocellulosic fuels
313 ('nofuel') then results in a decrease in freight services for three models (IMACLIM-NLU, GCAM and to a
314 lesser extent POLES, which shows higher potential for hydrogen, likely due to technological progress
315 regarding vehicle costs and efficiency). This result agrees with previous studies highlighting the difficulty of
316 mitigating GHG emissions outside on-road passenger transport (Muratori et al., 2017b), in which electricity
317 and hydrogen are easier to use, thus allowing biofuel to be used in the freight transport sector instead. For
318 example, the IMAGE model shows the greatest potential as being in on-road passenger transport
319 electrification, resulting in a smaller role for biofuels in this subsector. In the DNE21+ and BET models, on-
320 road transport services decrease more significantly because the limited supply of biomass feedstock is
321 directed towards the power sector. If CCS were not to be adopted in the lignocellulosic conversion process,
322 because of technological barriers in the upcoming decades or because of its lower capture rate compare to
323 other BECCS technologies, our results suggest that the more the mitigation strategy relies on BECCS, the
324 stronger the policy incentive to target the development of end-use technologies based on electricity and
325 hydrogen in transport subsectors would need to be.

327 Fig. 2.a shows the share of transport emissions in the 1,000 GtCO₂ emission budget, for the ‘full’ scenario.
328 Direct CO₂ emissions from combustion for transport (solid lines) range from 300 to 670 GtCO₂ across
329 models, which is about half of the CO₂ emissions budget. On average, the transport sector accounts for 23%
330 of total final energy in 2100, but the contribution in total emission reductions (compared to the Baseline in
331 2100) is rather small (15% on average, Table A.6). This result agrees with previous IAM studies highlighting
332 the difficulty of decarbonizing transport compared to other energy sectors (Rogelj et al., 2018; Muratori et
333 al. 2017b; Rogelj et al., 2015; Clarke et al., 2014). The first reason is the limited availability of low-carbon
334 alternatives to liquid fuels in non-terrestrial transport and on-road freight. Also the cost-effectiveness
335 approach used in scenarios tends to prioritize the decarbonization of sectors with lower mitigation costs. A
336 third reason is that some IAMs lack the dedicated transport policies which could lead to further emission
337 reductions (Creutzig et al., 2015).

338 We now look at whether lignocellulosic fuels help to intensify the decrease in the emission content of
339 transport final energy, compared to other energy sectors. Fig. 3.b shows the variation of the emissions
340 intensity compared to Baseline in the transport sector versus the rest of the energy sector in 2100 for two
341 scenarios (‘full’: end of line with symbol; ‘nofuel’: end of line without symbol¹³). All scenarios are above the
342 black line, meaning the reduction in transport emission intensity is lower than for other energy sectors in
343 2100. However, for most models the availability of lignocellulosic fuels results in an increase in transport
344 decarbonization. For two models (IMACLIM-NLU, REMIND-MAGPIE), this allows emissions to be shifted to
345 other energy sectors due to limits in the supply of biomass, mainly towards the power sector with less
346 carbon removal. On the contrary when BECCS technologies are not available (Fig. 3.c; ‘full’: with symbol;
347 ‘nobccs’: without symbol), the reduction in transport emission intensity is similar to that of other energy
348 sectors in four models out of five (DNE21+, POLES, REMIND-MAGPIE, IMAGE): without BECCS, biomass
349 becomes highly valuable in the form of liquid fuels for transport.

350 In the above analysis only direct combustion (tailpipe or tank-to-wheels) emissions are attributed to
351 transport as commonly assumed in IAMs (Rogelj et al. 2018; Luderer et al., 2018; Rogelj et al. 2015).
352 Accounting for fuel-production emissions (well-to-tank) is more relevant for dedicated sectoral studies
353 (Elgowainy et al., 2018; Muratori et al., 2017b; Yeh et al., 2017) especially with scenarios including BECCS.
354 Zhang et al. (2020) show that a significant amount of indirect carbon removal from liquid fuels and
355 electricity production can be attributed to the transport sector. Considering indirect emissions of energy
356 conversion processes (Fig 3.d; ‘full’: with symbol; ‘nofuel’: without symbol), transport emission intensity
357 decreases by the same percentage as other energy sectors for four (IMAGE, POLES, REMIND-MAGPIE,
358 IMAGE) of the six models that assume CCS with lignocellulosic fuel production¹⁴. The strongest decrease is
359 to be found for REMIND-MAGPIE, in which the production of lignocellulosic fuel accounts for 58% of the
360 transport energy mix in 2100. Regardless of land-use emissions, carbon neutrality could be achieved in
361 transport if liquid fuel BECCS were to account for more than 42% of the mix (assuming that transport uses
362 only petroleum liquids with 27kgC/GJ oil and -19kgC/GJ of carbon removal for lignocellulosic fuels). Among

¹³ Symbols with no line attached indicate absence of variation.

¹⁴ The ‘nofuel’ scenario is infeasible for AIM/CGE; the GCAM model shows a large decrease in transport emission intensity, but with a larger decrease for the rest of the economy than in other models.

363 models that assume CCS, only three reach such market shares for biofuels in 2100 (AIM/CGE, GCAM,
364 REMIND-MAGPIE with 41%, 43% and 58% respectively).

365 4 Discussion

366
367 High levels of carbon removal could be achieved indirectly in the transport sector with a higher
368 electrification rate and a high market share of BECCS in the power sector (or equivalently with hydrogen).
369 Section 3.1 shows that only a small amount of bioenergy corresponds to the electrification of transport due
370 to the large scale of power production with other low-carbon technologies and considering the relatively
371 limited supply potential of biomass feedstocks. However, the capture rate of electricity generation (or
372 hydrogen) through biomass gasification is higher than for lignocellulosic fuel production. A higher
373 electrification rate of transport in our scenarios would likely decrease the importance of lignocellulosic
374 fuels and increase the role of bioenergy in transport electrification.

375 The observed decrease in battery costs during the past decade (Edelenbosch et al., 2018), supported by
376 dedicated policies in many countries, has triggered an unexpected growth in EV sales (EVs accounted for
377 2.6% of total car sales in 2019, (IEA, 2020b), the largest contributions being in China, the United States,
378 Europe and Canada). Several IAMs now project that transport electrification will provide a larger
379 contribution to emission reductions compared to previous assessments (Zhang et al., 2020; Edelenbosch et
380 al., 2017; Zhang et al., 2016) and some recent electrification studies predict massive adoption of battery
381 electric vehicles leading to a two-thirds decrease in gasoline and diesel demand in the U.S. by 2050 (Mai et
382 al., 2018).

383 These recent advances in electrification technologies are not reflected in our study which does not consider
384 complementary measures in transport beyond those already included in each respective model, thus likely
385 underestimating the potential for EV with respect to biofuels and related carbon removal. Batteries and
386 support for electric vehicle charging are opening up for widespread EV adoption and thus increasing
387 opportunities for achieving deep transport decarbonization (Muratori and Mai, 2021; Nadel et al., 2019;
388 Edelenbosch et al., 2017). A broader policy package including the role of consumers in end-use technology
389 may lead to emission reduction in passenger road transport compliant with a 2°C target, as shown in
390 Mercure et al. (2018). More generally, policies oriented towards the adoption and diffusion of end-use
391 technologies result in higher electrification rates for transport, contrasting with previous IAM studies
392 (Muratori et al., 2020b; Venturini et al., 2019; Ramea et al., 2018; Mercure et al., 2018; McCollum et al.,
393 2017).

394 5 Conclusions

395
396 This study has assessed the role of biomass in reducing transport sector emissions during the 21st century
397 by analyzing a set of harmonized scenarios. In mitigation scenarios, all models project continued reliance on
398 petroleum fuels until 2050 and continued significant use of fossil fuels by 2100, often offset by negative
399 emissions (mostly from BECCS). Results show that CCS availability is more important in driving biofuel
400 market share in transport than the competition with other low carbon fuels, with, however, a greater role
401 in freight services than in passenger transport because of the relative potential for electricity or hydrogen.

402 The diversity of modeling frameworks in the 10 IAMs considered provides general insights into the role of
403 bioenergy in cost-effective transport decarbonization:

404 **Biomass only enters the energy mix in significant quantities for three models in Baseline.** The phase-in of
405 biofuels in Baseline scenarios is mostly driven by increasing oil prices and the competitiveness of
406 alternatives to the internal combustion engine.

407 **Lignocellulosic fuel is the predominant bioenergy pathway for transport mitigation.** In mitigation
408 scenarios, the use of bioenergy in transport represent 42 EJ/yr on average (ranging from 5 to 85 EJ/yr) in
409 2100, mostly in the form of lignocellulosic liquid. Only small amounts of bioenergy are present in transport
410 *via* electricity or hydrogen because of the limited end-use technologies for long-haul use. The level of
411 lignocellulosic fuels in transport is sensitive to the availability of other low-carbon alternatives in each
412 transport sub-sector, with a greater contribution to freight than to passenger transport.

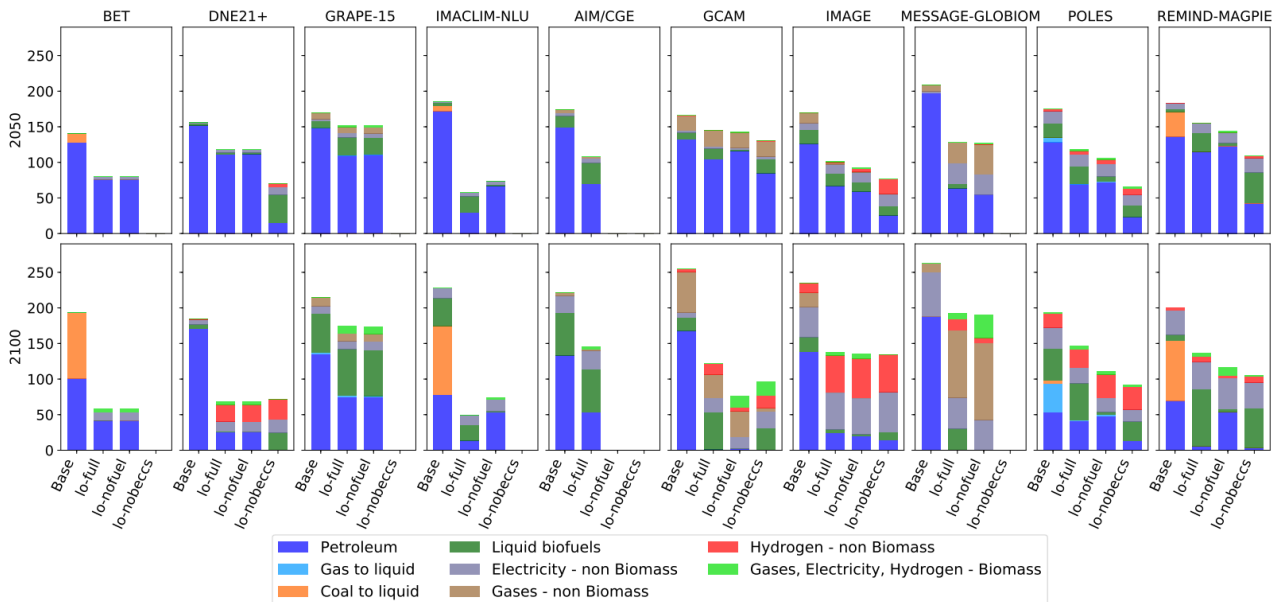
413 **Lignocellulosic fuels allow for further decrease in transport emission intensity.** Cumulative direct
414 emissions from the transport sector account for half of the emission budget (between 300 and 670 of the
415 1,000 GtCO₂). However, accounting for indirect emissions from fuel conversion processes, including carbon
416 removal from BECCS, the transport carbon intensity decreases as much as other energy sectors.

417 **The availability of CCS is a key determinant of bioenergy's role in transport decarbonization.** The
418 production of lignocellulosic fuels, hydrogen and electricity all compete for limited biomass feedstocks. If
419 BECCS technologies are assumed to be feasible, bioenergy is really valuable in providing carbon removal, so
420 that lignocellulosic fuels are attractive for transport decarbonization only on the assumption of an upgrade
421 with CCS. The average market share of biofuels is 21% in 2100 among models that consider CCS in the
422 biofuel conversion process compared to 10% for models that do not and where biomass feedstock is
423 directed instead towards electricity generation to provide carbon removal. Like most low-carbon
424 technologies in transport, lignocellulosic fuel requires policies targeted towards R&D and supporting
425 regulations in order to be deployed on a large scale (Mulholland et al., 2018), and research should consider
426 CCS in the conversion process in order to increase the chance of bioenergy being a plausible low-carbon
427 alternative in transport mitigation pathways.

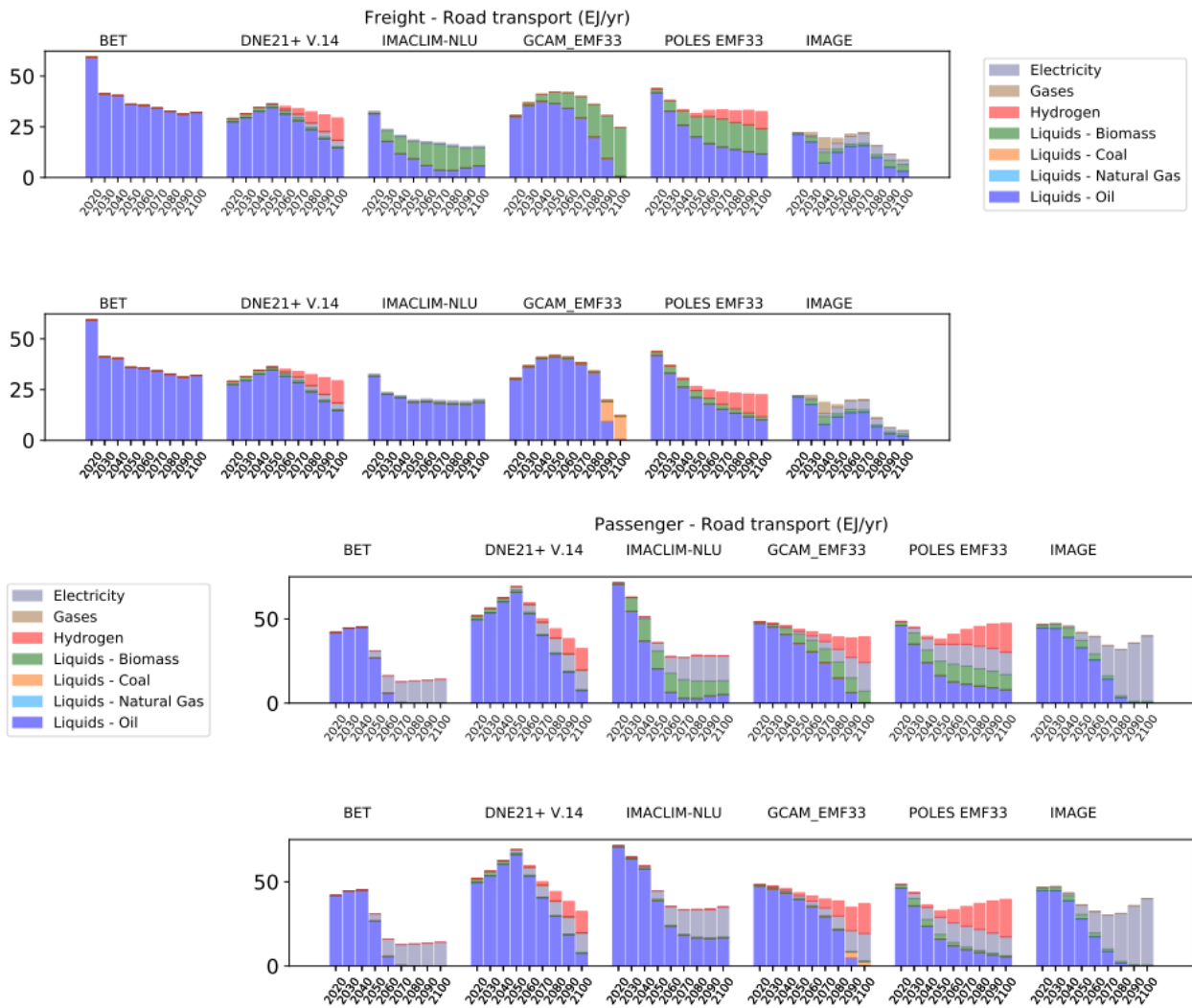
428 **Lignocellulosic fuels are very attractive for transport decarbonization if BECCS not feasible.** Most IAM
429 scenarios assume BECCS in the technological portfolio, which drives biomass usage towards carbon removal
430 regardless of the energy sector. On the contrary, if BECCS is not feasible, biomass is found to be critical in
431 lowering transport emissions with lignocellulosic fuels. In our scenarios, transport emission intensity shrinks
432 by the same percentage as other energy sectors in 2100 when BECCS is not available for any energy
433 carriers.

434 Several limitations affect the results of our paper and the EMF-33 study. First, only the benefits of using
435 bioenergy for climate change mitigation are considered, whereas the large scale deployment of bioenergy
436 crops raises concerns with respect to several externalities such as induced land-use emissions, food security
437 and prices, water use and the impact on biodiversity (Stoy et al., 2018; Fajardy and Mac Dowell, 2017;
438 Lotze-Campen et al., 2014) or to BECCS technologies themselves (Low, S. and Schäfer 2020; Muratori et al.
439 2016; Fuss et al. 2014). Even if IAMs often include land-use management measures in order to limit the
440 negative impacts of biomass feedstock production, a deeper analysis of the tradeoffs regarding the use of
441 lignocellulosic fuels and those externalities are likely to limit its attractiveness for mitigating transport
442 emissions. Secondly, the EMF-33 study only consider a carbon budget for fossil fuels and industrial

443 emissions, so that only BECCS can contribute negatively to this budget. While afforestation also competes
 444 for land with biomass feedstock production, any other negative emissions technologies, such as direct air
 445 capture (Realmonde et al., 2019), could contribute to offset residual emissions from the transport sector.
 446 Thirdly, we only described the detailed energy mix for road transport as it accounts nowadays for 74% of
 447 transport emissions. Further studies should assess the role of biofuels in the different transport mode, and
 448 the optimal allocation across those modes, especially regarding the evolution of international trade and the
 449 specific constraints concerning the adoption of bio-kerosene in air transport and the issue of corrosion
 450 from bio-based fuels in long distance shipping. Finally, the role of lignocellulosic fuel in mitigating transport
 451 emissions should also be assessed considering recent technology trends, especially with respect to electric
 452 vehicles, and complementary policies concerning technological adoption (Mercure et al., 2018; McCollum
 453 et al., 2017; Pettifor et al., 2017). This research agenda for IAMs includes better representation of
 454 sociological and technological factors, and their interactions, that drive transport demand and emissions
 455 reduction, modal choices, emerging mobility trends (e.g., telework, ride-hailing) as well as new
 456 technologies and business models (Muratori et al. 2020b). The EMF-33 study provides useful scenarios for
 457 assessing the role of biofuels in transport, but since the EMF-33 scenarios were designed (Bauer et al.
 458 (2018), major changes have occurred with respect to transportation, most notably the rise of electric
 459 vehicles (IEA, 2020b), and the sector is evolving rapidly (Mai et al., 2020). Further research should explore
 460 the potential role of bioenergy to decarbonize the transport sector with respect to these gaps and
 461 limitations.



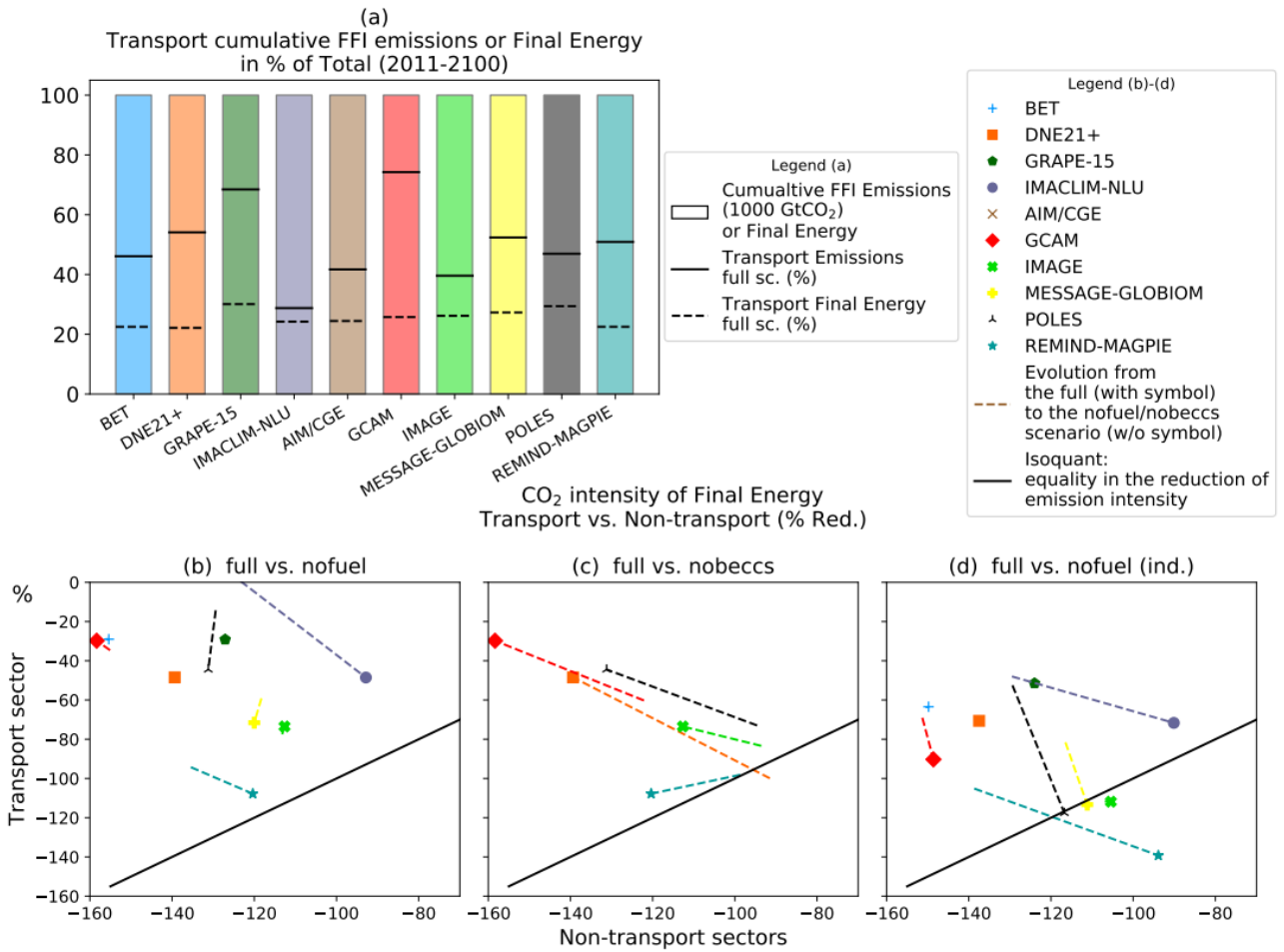
462
 463 *Figure 1: Final energy mix for transport by fuel (EJ/yr) for the different models and scenarios, in 2050 and*
 464 *2100. Use of bioenergy via hydrogen, electricity and gases is aggregated into a single category (light green).*



465

Figure 2: Final energy mix of road transport for freight and passenger mobility (bar chart), for the 'full' (top) and 'nofuel' (bottom) scenarios. The lines indicate final energy trends for the overall passenger and freight modes (not only road). Trends are normalized to the first year. Solid lines indicate the trend of the 'full' scenario, dashed lines the trend of the 'nofuel' scenario.

466



467
 468 *Figure 3: (a) Contribution of transport emissions to the 1,000 GtCO₂ cumulative emission budget (solid lines: direct combustion emissions; dashed lines: accounting for emissions from energy conversion processes. (b)*
 469 *Percentage reduction in emission intensities of transport final energy (y-axis) and non-transport final energy (x-axis), in 2100 compared to the baseline. Two scenarios are shown: 'nofuel' (no symbol) and 'full' (with*
 470 *symbol). (c) Percentage reduction in emission intensities of transport final energy for the 'nobeccc' (no symbol) and 'full' scenarios (with symbol). (d) Percentage reduction in emission intensities of transport final*
 471 *energy when accounting for emissions from energy conversion processes, for the 'nofuel' (no symbol) and 'full' scenarios (with symbol). Symbols with no line attached indicate absence of variation.*
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481 **Table 1**

Models ¹⁵		AIM/CGE	BET	DNE21+	REMIND-MAGPIE	GCAM	GRAPE-15	IMACLIM-NLU	IMAGE	MESSAGE-GLOBIOM	POLES
General algorithm ¹⁶		CGE-RD	CGE-IT	PE-IT	CGE-IT	PE-RD	CGE-IT	CGE-RD	PE-RD	PE-IT	PE-RD
Climate policy integration		Emission constraint	Budget constraint	Budget constraint	Tax	Tax	Budget constraint	Tax	Tax	Tax	Tax
Service demand	Level of demand – passengers ¹⁷	D	D	X	Yes	D	GDP/cap	D	D	D	D
	Endogenous passenger modal shift	No	No	No	Yes	Yes	No	Yes	Yes	No	Yes
	Level of demand - freight	D	D	X	D	D	GDP/cap	D	D	X	X
	Endogenous freight modal shift	No	No	No	No	Yes (Fairly inelastic)	No	Yes	Yes	No	No
Fuel and technology	Bioenergy for Electricity, Liquids, Hydrogen ¹⁸	E+ LC*+	E*+ LC* H*	E*+ LC* H*+	E+ LC*+ H+	E*+ LC*+ H*+	E+ LC* H*	E+ LC* H+	E*+ LC* +H*+	E*+ LC*+ H*+	E*+ LC*+ H*+
	First generation biofuels ¹⁹	Yes	No	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
	Vehicle cost	D	X	X	D	X	X	D	X	No	D
	Vehicle efficiency	D	X	X	X	X	X	D	X	No	X
	Technological competition	Logit	Flexible	Flexible	Flexible	Logit	Flexible	Logit	Logit	Flexible	Logit

¹⁵ References for model documentation: AIM/CGE: (Fujimori et al., 2017), BET: (Tsutsui et al., this issue), DNE21+: (Sano et al., 2015), GCAM: (Calvin et al., 2017), GRAPE: (Kato et al., 2017), IMACLIM-NLU (Waisman et al., 2012), IMAGE: (van Vuuren et al., 2017), MESSAGE-GLOBIOM: (Fricko et al., 2017), POLES:(Keramidas et al., 2017), REMIND-MAGPIE: (Baur et al., 2020).

¹⁶ Computable general equilibrium (CGE); Partial equilibrium (PE); Recursive-Dynamic (RD); Iterative (IT)

¹⁷ X, stands for exogenous and D for endogenous. D- means endogenous, but not explicit.

¹⁸ E, L and H indicate respectively electrification, liquid fuels and hydrogen availability for passenger transport. ‘*’ indicates it is also available for freight (In MESSAGE there is no distinction between passenger and freight).

‘+’ indicates that CCS is available along with energy carrier production from biomass. For GCAM: No electricity nor hydrogen for trucks, but only for trains.

¹⁹ First generation biofuels are modelled through cost competition in all models except IMACLIM-NLU and REMIND-MAGPIE, in which exogenous scenarios are prescribed.

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483

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