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

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# 38 The contribution of bioenergy to the 39 decarbonization of transport: a multi- 40 model assessment

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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 33<sup>rd</sup> 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 21<sup>st</sup> 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 GtCO<sub>2</sub>). 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 fleet<sup>1</sup> 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 transport<sup>2</sup>. 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

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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 biomass<sup>3</sup>, 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 fuel<sup>4</sup> (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

<sup>3</sup> Through gaseification or anaerobic digestion of biomass feedstocks.

<sup>4</sup> 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

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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 IAMs<sup>5</sup>. 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 materials<sup>6</sup>.

193 Apart from the Baseline we evaluate three climate sensitivity scenarios using an intertemporal carbon  
194 budget constraint of 1,000 GtCO<sub>2</sub> over the period 2011-2100 which account for CO<sub>2</sub> 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 CO<sub>2</sub> 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 GtCO<sub>2</sub>) 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 available<sup>7</sup> ('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

<sup>5</sup> [https://www.iamcdocumentation.eu/index.php/IAMC\\_wiki](https://www.iamcdocumentation.eu/index.php/IAMC_wiki)

<sup>6</sup> [https://static-content.springer.com/esm/art%3A10.1007%2Fs10584-018-2226-y/MediaObjects/10584\\_2018\\_2226\\_MOESM1\\_ESM.docx](https://static-content.springer.com/esm/art%3A10.1007%2Fs10584-018-2226-y/MediaObjects/10584_2018_2226_MOESM1_ESM.docx)

<sup>7</sup> 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 uses<sup>8</sup>, 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 CO<sub>2</sub> 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)<sup>9</sup>, 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 Baseline<sup>10</sup>: 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%)<sup>11</sup>. 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 GtCO<sub>2</sub> budget scenario<sup>12</sup>, 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 GtCO<sub>2</sub> target, so in the SOM we present a scenario with a 1,600 GtCO<sub>2</sub> 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

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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 GtCO<sub>2</sub> emission budget, for the ‘full’ scenario.  
328 Direct CO<sub>2</sub> emissions from combustion for transport (solid lines) range from 300 to 670 GtCO<sub>2</sub> across  
329 models, which is about half of the CO<sub>2</sub> 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 symbol<sup>13</sup>). 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 production<sup>14</sup>. 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

<sup>13</sup> Symbols with no line attached indicate absence of variation.

<sup>14</sup> 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 21<sup>st</sup> 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.

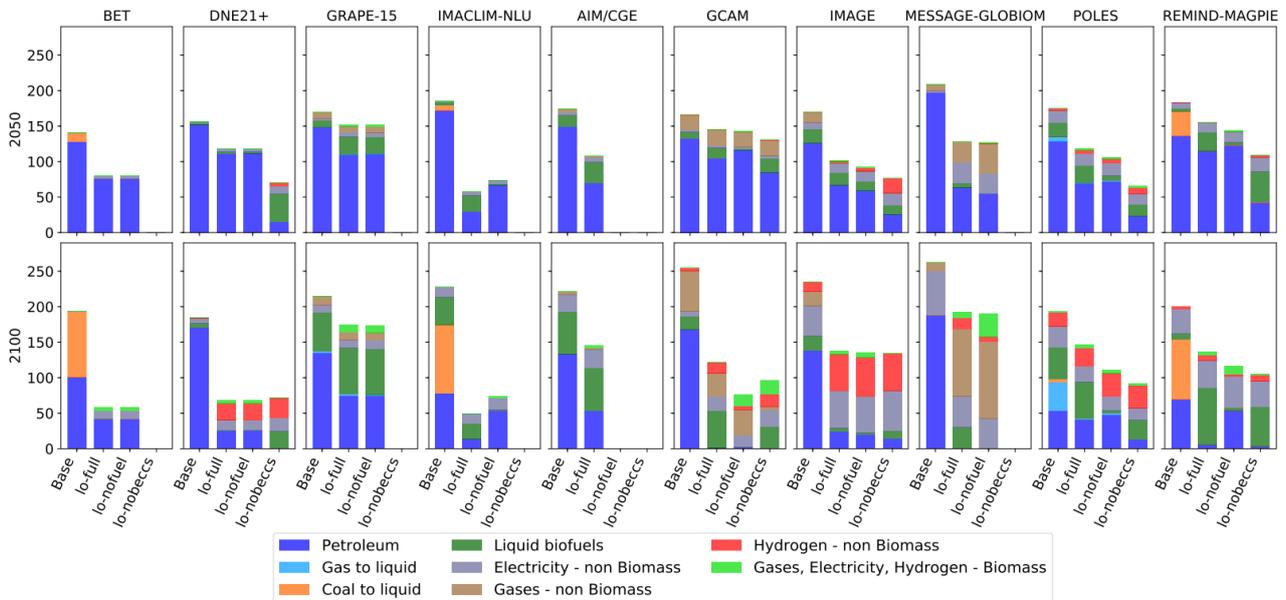
413 **Lignocellulosic fuels allow for further decrease in transport emission intensity.** Cumulative direct  
414 emissions from the transport sector account for half of the emission budget (between 300 and 670 of the  
415 1,000 GtCO<sub>2</sub>). However, accounting for indirect emissions from fuel 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.

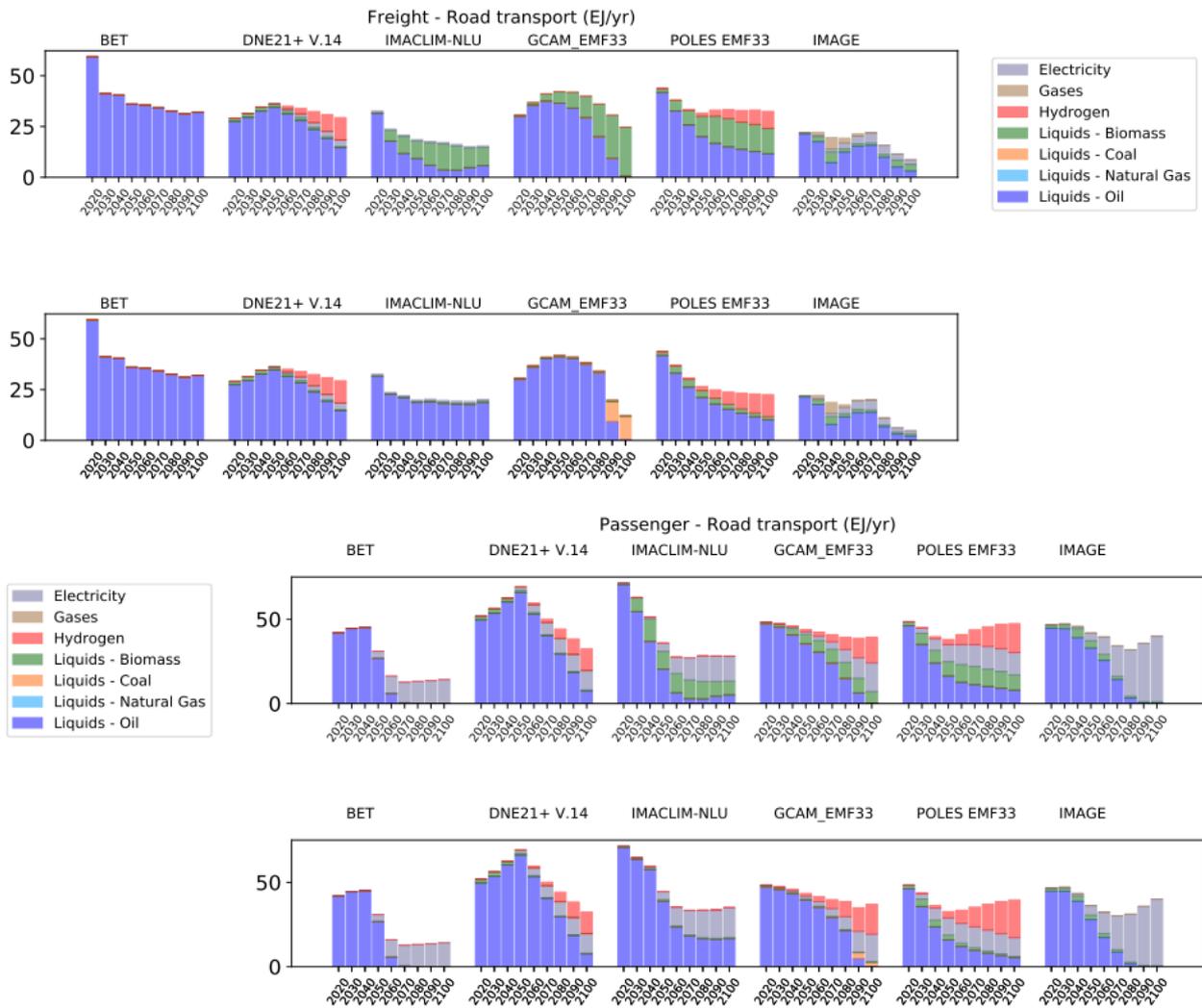
428 **Lignocellulosic fuels are very attractive for transport decarbonization if BECCS not feasible.** Most IAM  
429 scenarios assume BECCS in the technological portfolio, which drives biomass usage towards carbon removal  
430 regardless of the energy sector. On the contrary, if BECCS is not feasible, 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.



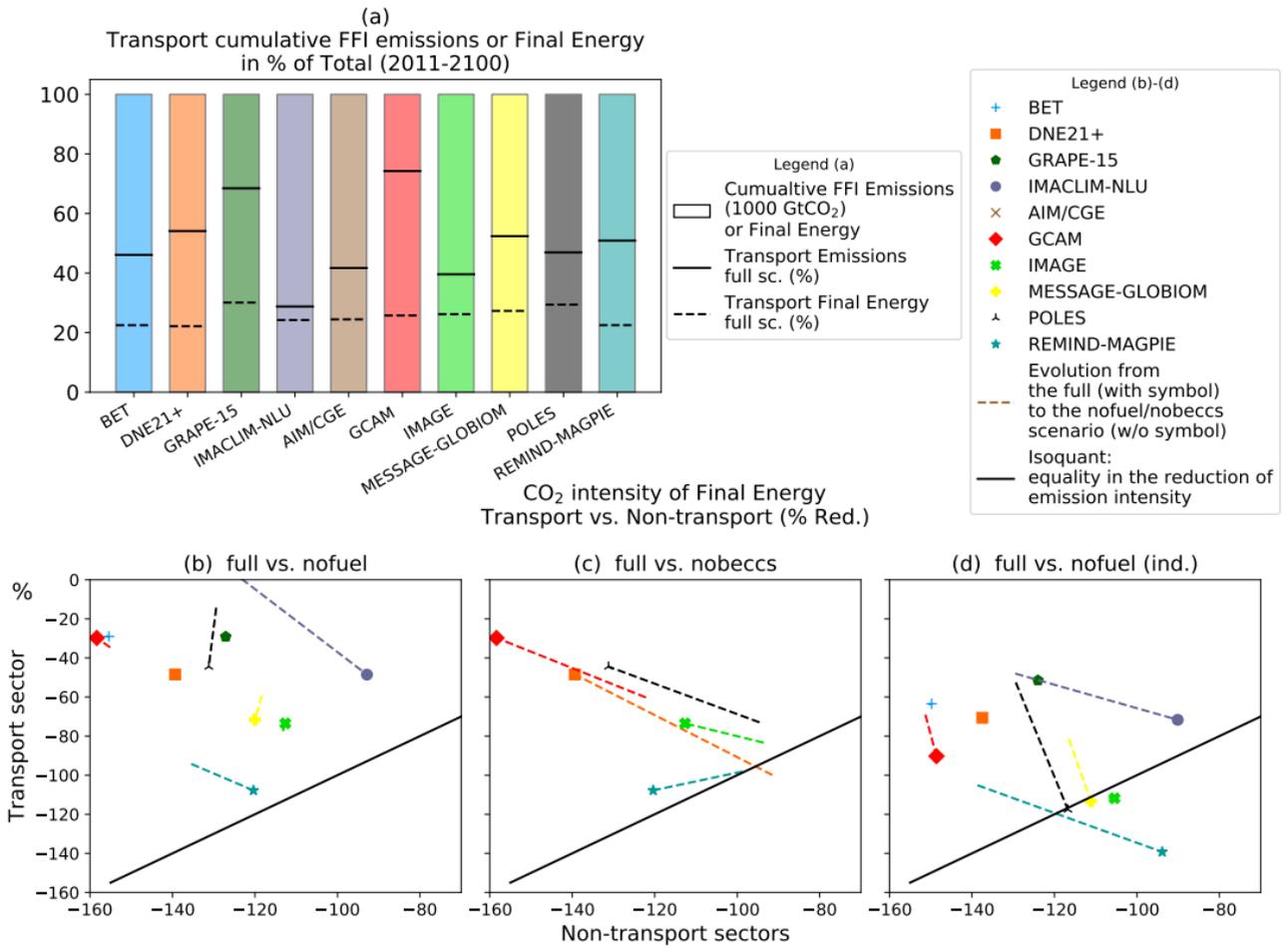
462 *Figure 1: Final energy mix for transport by fuel (EJ/yr) for the different models and scenarios, in 2050 and*  
 463 *2100. Use of bioenergy via hydrogen, electricity and gases is aggregated into a single category (light green).*  
 464



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 GtCO<sub>2</sub> 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*  
 470 *(x-axis), in 2100 compared to the baseline. Two scenarios are shown: 'nofuel' (no symbol) and 'full' (with*  
 471 *symbol). (c) Percentage reduction in emission intensities of transport final energy for the 'nobeccc' (no*  
 472 *symbol) and 'full' scenarios (with symbol). (d) Percentage reduction in emission intensities of transport final*  
 473 *energy when accounting for emissions from energy conversion processes, for the 'nofuel' (no symbol) and*  
 474 *'full' scenarios (with symbol). Symbols with no line attached indicate absence of variation.*  
 475

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481 **Table 1**

Models <sup>15</sup>		AIM/CGE	BET	DNE21+	REMIND-MAGPIE	GCAM	GRAPE-15	IMACLIM-NLU	IMAGE	MESSAGE-GLOBIOM	POLES
General algorithm <sup>16</sup>		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
<b>Service demand</b>	Level of demand – passengers <sup>17</sup>	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
<b>Fuel and technology</b>	Bioenergy for Electricity, Liquids, Hydrogen <sup>18</sup>	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 <sup>19</sup>	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

<sup>15</sup> 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).

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

<sup>17</sup> X, stands for exogenous and D for endogenous. D- means endogenous, but not explicit.

<sup>18</sup> 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.

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

482 **References**

483

484 Ahlgren, Erik O., Martin Börjesson Hagberg, and Maria Grahn. 2017. “Transport Biofuels in  
485 Global Energy-Economy Modelling - a Review of Comprehensive Energy Systems  
486 Assessment Approaches.” *GCB Bioenergy* 9 (7): 1168–80.

487 Azar, C., Lindgren, K., Obersteiner, M. *et al.* The feasibility of low CO<sub>2</sub> concentration targets and  
488 the role of bio-energy with carbon capture and storage (BECCS). *Climatic Change* **100**, 195–  
489 202 (2010). <https://doi.org/10.1007/s10584-010-9832-7>

490 Bauer, N., Klein, D., Humpenöder, F., Krieglner, E., Luderer, G., Popp, A., Strefler, J., 2020. Bio-  
491 energy and CO<sub>2</sub> emission reductions: an integrated land-use and energy sector perspective.  
492 *Climatic Change*, 163, 1675–1693. <https://doi.org/10.1007/s10584-020-02895-z>.

493 Bauer, Nico, Steven K. Rose, Shinichiro Fujimori, Detlef P. van Vuuren, John Weyant, Marshall  
494 Wise, Yiyun Cui, et al. 2018. “Global Energy Sector Emission Reductions and Bioenergy  
495 Use: Overview of the Bioenergy Demand Phase of the EMF-33 Model Comparison.”  
496 *Climatic Change*, July. <https://doi.org/10.1007/s10584-018-2226-y>.

497 Calvin, Katherine, Ben Bond-Lamberty, Leon Clarke, James Edmonds, Jiyong Eom, Corinne  
498 Hartin, Sonny Kim, et al. 2017. “The SSP4: A World of Deepening Inequality.” *Global*  
499 *Environmental Change* 42 (January): 284–96.  
500 <https://doi.org/10.1016/j.gloenvcha.2016.06.010>.

501 Cheah, Wai Yan, Tau Chuan Ling, Joon Ching Juan, Duu-Jong Lee, Jo-Shu Chang, and Pau Loke  
502 Show. 2016. “Biorefineries of Carbon Dioxide: From Carbon Capture and Storage (CCS) to  
503 Bioenergies Production.” *Bioresource Technology* 215 (September): 346–56.  
504 <https://doi.org/10.1016/j.biortech.2016.04.019>.

505 Clarke, Leon, Kejun Jiang, Keigo Akimoto, Mustafa Babiker, Geoffrey Blanford, Karen Fisher-  
506 Vanden, Jean-Charles Hourcade, et al. 2014. “Assessing Transformation Pathways.” In  
507 *Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to*  
508 *the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Edenhofer,  
509 O., R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, A. Adler, I. Baum, S.  
510 Brunner, P. Eickemeier, B. Kriemann, J. Savolainen, S. Schlömer, C. von Stechow, T.  
511 Zwickel and J.C. Minx (Eds.)]. Cambridge University Press, Cambridge, United Kingdom  
512 and New York, NY, USA.

- 513 Creutzig, F., P. Jochem, O. Y. Edelenbosch, L. Mattauch, D. P. v. Vuuren, D. McCollum, and J.  
514 Minx. 2015. “Transport: A Roadblock to Climate Change Mitigation?” *Science* 350 (6263):  
515 911–912. <https://doi.org/10.1126/science.aac8033>.
- 516 Daiglou, Vassilis, Jonathan C. Doelman, Elke Stehfest, Christoph Müller, Birka Wicke, Andre  
517 Faaij, and Detlef P. van Vuuren. 2017. “Greenhouse Gas Emission Curves for Advanced  
518 Biofuel Supply Chains.” *Nature Climate Change* 7 (12): 920–24.  
519 <https://doi.org/10.1038/s41558-017-0006-8>.
- 520 Daiglou, Vassilis, Steven K Rose, Nico Bauer, Alban Kitous, Matteo Muratori, Shinichiro  
521 Fujimori, Matthew Gidden, et al. 2020. “Bioenergy Technologies in Long-Run Climate  
522 Change Mitigation: Results from the EMF-33 Study.” *Climatic Change* (August).  
523 <https://doi.org/10.1007/s10584-020-02799-y>.
- 524 Du, Xiaodong, and Miguel A. Carriquiry. 2013. “Flex-Fuel Vehicle Adoption and Dynamics of  
525 Ethanol Prices: Lessons from Brazil.” *Energy Policy* 59 (August): 507–12.  
526 <https://doi.org/10.1016/j.enpol.2013.04.008>.
- 527 Edelenbosch, O.Y., D.L. McCollum, D.P. van Vuuren, C. Bertram, S. Carrara, H. Daly, S.  
528 Fujimori, et al. 2017. “Decomposing Passenger Transport Futures: Comparing Results of  
529 Global Integrated Assessment Models.” *Transportation Research Part D: Transport and  
530 Environment* 55: 281–293. <https://doi.org/10.1016/j.trd.2016.07.003>.
- 531 Elgowainy, A., Han, J., Ward, J., Joseck, F., Gohlke, D., Lindauer, A., Ramsden, T., Bidy, M.,  
532 Alexander, M., Barnhart, S., Sutherland, I., Verduzco, L., Wallington, T.J., 2018. Current and  
533 Future United States Light-Duty Vehicle Pathways: Cradle-to-Grave Lifecycle Greenhouse  
534 Gas Emissions and Economic Assessment. *Environ. Sci. Technol.* 52, 2392–2399.  
535 <https://doi.org/10.1021/acs.est.7b06006>.
- 536 Fajardy, Mathilde, and Niall Mac Dowell. 2017. “Can BECCS Deliver Sustainable and Resource  
537 Efficient Negative Emissions?” *Energy Environ. Sci.* 10 (6): 1389–1426.  
538 <https://doi.org/10.1039/C7EE00465F>.
- 539 Fricko, Oliver, Petr Havlik, Joeri Rogelj, Zbigniew Klimont, Mykola Gusti, Nils Johnson, Peter  
540 Kolp, et al. 2017. “The Marker Quantification of the Shared Socioeconomic Pathway 2: A  
541 Middle-of-the-Road Scenario for the 21st Century.” *Global Environmental Change* 42  
542 (January): 251–67. <https://doi.org/10.1016/j.gloenvcha.2016.06.004>.
- 543 Fujimori, Shinichiro, Tomoko Hasegawa, Toshihiko Masui, Kiyoshi Takahashi, Diego Silva  
544 Herran, Hancheng Dai, Yasuaki Hijioka, and Mikiko Kainuma. 2017. “SSP3: AIM

545 Implementation of Shared Socioeconomic Pathways.” *Global Environmental Change* 42  
546 (January): 268–83. <https://doi.org/10.1016/j.gloenvcha.2016.06.009>.

547 Fuss, Sabine, William F Lamb, Max W Callaghan, Jérôme Hilaire, Felix Creutzig, Thorben Amann,  
548 Tim Beringer, et al. 2018. “Negative Emissions—Part 2: Costs, Potentials and Side Effects.”  
549 *Environmental Research Letters* 13 (6): 063002. <https://doi.org/10.1088/1748-9326/aabf9f>.

550 Fuss, Sabine, et al. "Betting on negative emissions." *Nature climate change* 4.10 (2014): 850-853.  
551 Gota, Sudhir, Cornie Huizenga, Karl Peet, Nikola Medimorec, and Stefan Bakker. 2019.  
552 “Decarbonising Transport to Achieve Paris Agreement Targets.” *Energy Efficiency* 12 (2):  
553 363–86. <https://doi.org/10.1007/s12053-018-9671-3>.

554 Havlík, Petr, Uwe A. Schneider, Erwin Schmid, Hannes Böttcher, Steffen Fritz, Rastislav Skalský,  
555 Kentaro Aoki, et al. 2011. “Global Land-Use Implications of First and Second Generation  
556 Biofuel Targets.” *Energy Policy* 39 (10): 5690–5702.  
557 <https://doi.org/10.1016/j.enpol.2010.03.030>.

558 Hileman, J.I., and R.W. Stratton. 2014. “Alternative Jet Fuel Feasibility.” *Transport Policy* 34  
559 (July): 52–62. <https://doi.org/10.1016/j.tranpol.2014.02.018>.

560 IPCC. 2013. *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I*  
561 *to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*.  
562 Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press.  
563 [www.climatechange2013.org](http://www.climatechange2013.org).

564 International Energy Agency, 2017. *Delivering Sustainable Bioenergy*.  
565 <https://doi.org/10.1787/9789264287600-en>.

566 International Energy Agency. 2019. *CO2 Emissions from Fuel Combustion 2019*. CO2 Emissions  
567 from Fuel Combustion. OECD. <https://doi.org/10.1787/2a701673-en>.

568 International Energy Agency, 2020a. *World Energy outlook 2020*

569 International Energy Agency, 2020b, *Global EV Outlook 2020*, IEA, Paris.  
570 <https://www.iea.org/reports/global-ev-outlook-2020>

571 Johnson, Nils, Nathan Parker, and Joan Ogden. 2014. “How Negative Can Biofuels with CCS Take  
572 Us and at What Cost? Refining the Economic Potential of Biofuel Production with CCS  
573 Using Spatially-Explicit Modeling.” *Energy Procedia* 63: 6770–91.  
574 <https://doi.org/10.1016/j.egypro.2014.11.712>.

- 575 Kato, Etsushi, Ryo Moriyama, and Atsushi Kurosawa. 2017. "A Sustainable Pathway of Bioenergy  
576 with Carbon Capture and Storage Deployment." *Energy Procedia* 114 (July): 6115–23.  
577 <https://doi.org/10.1016/j.egypro.2017.03.1748>.
- 578 Kavitha, C., and Vijayasarithi Prabakaran. 2015. "An Overview of Corrosion Performance of  
579 Automotive Metals in Biodiesel." *Research Journal of Engineering and Technology* 6  
580 (January): 457. <https://doi.org/10.5958/2321-581X.2015.00071.9>.
- 581 Keramidias, Kimon, Alban Kitous, Jacques Després, Andreas Schmitz, Ana Diaz Vazquez, Silvana  
582 Mima, Peter Russ, and Tobias Wiesenthal. 2017. "POLES-JRC Model Documentation." JRC  
583 Working Papers JRC107387. Joint Research Centre (Seville site).  
584 <https://EconPapers.repec.org/RePEc:ipt:iptwpa:jrc107387>.
- 585 Kriegler, Elmar, John P. Weyant, Geoffrey J. Blanford, Volker Krey, Leon Clarke, Jae Edmonds,  
586 Allen Fawcett, et al. 2014. "The Role of Technology for Achieving Climate Policy  
587 Objectives: Overview of the EMF 27 Study on Global Technology and Climate Policy  
588 Strategies." *Climatic Change* 123 (3–4): 353–367. [https://doi.org/10.1007/s10584-013-0953-](https://doi.org/10.1007/s10584-013-0953-7)  
589 [7](https://doi.org/10.1007/s10584-013-0953-7).
- 590 Leblanc, Florian, Thierry Brunelle, Patrice Dumas, Ruben Bibas, Chloe Pelletier, and Rémy  
591 Prudhomme. This issue. "Trade-offs across energy sectors in using biomass for climate  
592 change mitigation: an integrated assessment with Imaclim-NLU."
- 593 Li, Wei, Chao Yue, Philippe Ciais, Jinfeng Chang, Daniel Goll, Dan Zhu, Shushi Peng, and Albert  
594 Jorner-Puig. 2018. "ORCHIDEE-MICT-BIOENERGY: An Attempt to Represent the  
595 Production of Lignocellulosic Crops for Bioenergy in a Global Vegetation Model."  
596 *Geoscientific Model Development* 11 (6): 2249–72. [https://doi.org/10.5194/gmd-11-2249-](https://doi.org/10.5194/gmd-11-2249-2018)  
597 [2018](https://doi.org/10.5194/gmd-11-2249-2018).
- 598 Lotze-Campen, Hermann, Martin von Lampe, Page Kyle, Shinichiro Fujimori, Petr Havlik, Hans  
599 van Meijl, Tomoko Hasegawa, et al. 2014. "Impacts of Increased Bioenergy Demand on  
600 Global Food Markets: An AgMIP Economic Model Intercomparison." *Agricultural  
601 Economics* 45 (1): 103–16. <https://doi.org/10.1111/agec.12092>.
- 602 Low, S. and Schäfer, S., 2020. Is bio-energy carbon capture and storage (BECCS) feasible? The  
603 contested authority of integrated assessment modeling. *Energy Research & Social Science*, 60,  
604 p.101326.
- 605 Sean, Low and Stefan Schäfer Stefan 2020. "Is bio-energy carbon capture and storage (BECCS)  
606 feasible? The contested authority of integrated assessment modeling." *Energy Research &  
607 Social Science* (60). <https://doi.org/10.1016/j.erss.2019.101326>. Luderer, Gunnar, Zoi

608 Vrontisi, Christoph Bertram, Oreane Y. Edelenbosch, Robert C. Pietzcker, Joeri Rogelj,  
609 Harmen Sytze De Boer, et al. 2018. “Residual Fossil CO2 Emissions in 1.5–2 °C Pathways.”  
610 *Nature Climate Change* 8 (7): 626–33. <https://doi.org/10.1038/s41558-018-0198-6>.

611 Macedo, I.C., Nassa, A.M., Cowie, A.L. Seabra, J.E.A., Marelli, L., Otto, M., Wang, M.Q., Tyner,  
612 E., 2014. “Greenhouse gas emissions from bioenergy”, in G. Souza (eds.), *Bioenergy and*  
613 *Sustainability: Bridging the Gaps*, report commissioned by SCOPE – Scientific Committee on  
614 Problems of the Environment.

615 Mai, Trieu, Paige Jadun, Jeffrey Logan, Colin McMillan, Matteo Muratori, Daniel Steinberg, Laura  
616 Vimmerstedt, Ryan Jones, Benjamin Haley, and Brent Nelson. 2018. *Electrification Futures*  
617 *Study: Scenarios of Electric Technology Adoption and Power Consumption for the United*  
618 *States*. Golden, CO: National Renewable Energy Laboratory. NREL/TP-6A20-71500.  
619 <https://www.nrel.gov/docs/fy18osti/71500.pdf>.

620 Marangoni, G., M. Tavoni, V. Bosetti, E. Borgonovo, P. Capros, O. Fricko, D. E. H. J. Gernaat, et  
621 al. 2017. “Sensitivity of Projected Long-Term CO2 Emissions across the Shared  
622 Socioeconomic Pathways.” *Nature Climate Change* 7 (2): 113–17.  
623 <https://doi.org/10.1038/nclimate3199>.

624 McCollum, David L., Charlie Wilson, Hazel Pettifor, Kalai Ramea, Volker Krey, Keywan Riahi,  
625 Christoph Bertram, Zhenhong Lin, Oreane Y. Edelenbosch, and Sei Fujisawa. 2017.  
626 “Improving the Behavioral Realism of Global Integrated Assessment Models: An Application  
627 to Consumers’ Vehicle Choices.” *Transportation Research Part D: Transport and*  
628 *Environment* 55 (August): 322–42. <https://doi.org/10.1016/j.trd.2016.04.003>.

629 McCollum, David, Volker Krey, Peter Kolp, Yu Nagai, and Keywan Riahi. 2014. “Transport  
630 Electrification: A Key Element for Energy System Transformation and Climate Stabilization.”  
631 *Climatic Change* 123 (3–4): 651–64. <https://doi.org/10.1007/s10584-013-0969-z>.

632 Mercure, J.-F., A. Lam, S. Billington, and H. Pollitt. 2018. “Integrated Assessment Modelling as a  
633 Positive Science: Private Passenger Road Transport Policies to Meet a Climate Target Well  
634 below 2 °C.” *Climatic Change* 151 (2): 109–29. <https://doi.org/10.1007/s10584-018-2262-7>.

635 Mulholland, Eamonn, Jacob Teter, Pierpaolo Cazzola, Zane McDonald, and Brian P. Ó Gallachóir.  
636 2018. “The Long Haul towards Decarbonising Road Freight – A Global Assessment to 2050.”  
637 *Applied Energy* 216 (April): 678–93. <https://doi.org/10.1016/j.apenergy.2018.01.058>.

638 Muratori, M., Mai, T., 2021. The shape of electrified transportation. *Environ. Res. Lett.* 16, 011003.  
639 <https://doi.org/10.1088/1748-9326/abcb38>.

640 Muratori, M., Bauer, N., Rose, S.K., Wise, M., Daioglou, V., Cui, Y., Kato, E., Gidden, M.,  
641 Strefler, J., Fujimori, S. and Sands, R.D., 2020a. EMF-33 insights on bioenergy with carbon  
642 capture and storage (BECCS). *Climatic Change*, 163(3), pp.1621-1637.

643 Muratori, M., Jadun, P., Bush, B., Bielen, D., Vimmerstedt, L., Gonder, J., Gearhart, C. and Arent,  
644 D., 2020b. Future integrated mobility-energy systems: A modeling perspective. *Renewable  
645 and Sustainable Energy Reviews*, 119, p.109541.

646 Muratori, Matteo, Haroon Kheshgi, Bryan Mignone, Leon Clarke, Haewon McJeon, and Jae  
647 Edmonds. 2017a. “Carbon Capture and Storage across Fuels and Sectors in Energy System  
648 Transformation Pathways.” *International Journal of Greenhouse Gas Control* 57 (February):  
649 34–41. <https://doi.org/10.1016/j.ijggc.2016.11.026>.

650 Muratori, M., Smith, S.J., Kyle, P., Link, R., Mignone, B.K. and Kheshgi, H.S., 2017b. “Role of the  
651 freight sector in future climate change mitigation scenarios.” *Environmental science &  
652 technology*, 51(6), pp.3526-3533. <https://pubs.acs.org/doi/abs/10.1021/acs.est.6b04515>.

653 Muratori, M., Calvin, K., Wise, M., Kyle, P. and Edmonds, J., 2016. Global economic  
654 consequences of deploying bioenergy with carbon capture and storage  
655 (BECCS). *Environmental Research Letters*, 11(9), p.095004.

656 Nadel, Steven. 2019. “Electrification in the Transportation, Buildings, and Industrial Sectors: A  
657 Review of Opportunities, Barriers, and Policies.” *Current Sustainable/Renewable Energy  
658 Reports* 6 (4): 158–68. <https://doi.org/10.1007/s40518-019-00138-z>.

659 Ramea, Kalai, David S. Bunch, Christopher Yang, Sonia Yeh, and Joan M. Ogden. 2018.  
660 “Integration of Behavioral Effects from Vehicle Choice Models into Long-Term Energy  
661 Systems Optimization Models.” *Energy Economics* 74 (August): 663–76.  
662 <https://doi.org/10.1016/j.eneco.2018.06.028>.

663 Realmonte, G., Drouet, L., Gambhir, A., Glynn, J., Hawkes, A., Köberle, A. C., and Tavoni, M.  
664 2019. “An inter-model assessment of the role of direct air capture in deep mitigation  
665 pathways”. *Nature Communications*, 10(1):3277. [https://doi.org/10.1038/s41467-019-10842-  
666 5](https://doi.org/10.1038/s41467-019-10842-5)

667 Riahi, Keywan, Detlef P. van Vuuren, Elmar Kriegler, Jae Edmonds, Brian C. O’Neill, Shinichiro  
668 Fujimori, Nico Bauer, et al. 2017. “The Shared Socioeconomic Pathways and Their Energy,  
669 Land Use, and Greenhouse Gas Emissions Implications: An Overview.” *Global  
670 Environmental Change* 42 (January): 153–168.  
671 <https://doi.org/10.1016/j.gloenvcha.2016.05.009>.

- 672 Rogelj, Joeri, Gunnar Luderer, Robert C. Pietzcker, Elmar Kriegler, Michiel Schaeffer, Volker  
673 Krey, and Keywan Riahi. 2015. “Energy System Transformations for Limiting End-of-  
674 Century Warming to below 1.5 °C.” *Nature Climate Change* 5 (6): 519–527.  
675 <https://doi.org/10.1038/nclimate2572>.
- 676 Rogelj, Joeri, Michiel Schaeffer, Pierre Friedlingstein, Nathan P. Gillett, Detlef P. van Vuuren,  
677 Keywan Riahi, Myles Allen, and Reto Knutti. 2016. “Differences between Carbon Budget  
678 Estimates Unravelling.” *Nature Climate Change* 6 (3): 245–52.  
679 <https://doi.org/10.1038/nclimate2868>.
- 680 Rogelj, J., D. Shindell, K. Jiang, S. Fifita, P. Forster, V. Ginzburg, C. Handa, et al. 2018.  
681 “Mitigation Pathways Compatible with 1.5°C in the Context of Sustainable Development.” In  
682 *Global Warming of 1.5°C. An IPCC Special Report on the Impacts of Global Warming of*  
683 *1.5°C above Pre-Industrial Levels and Related Global Greenhouse Gas Emission Pathways,*  
684 *in the Context of Strengthening the Global Response to the Threat of Climate Change,*  
685 *Sustainable Development, and Efforts to Eradicate Poverty*, edited by V. Masson-Delmotte,  
686 P. Zhai, H.O. Pörtner, D. Roberts, J. Skea, P.R. Shukla, A. Pirani, et al., 93–174. In Press.
- 687 Rose, S.K., Bauer, N., Popp, A. *et al.* An overview of the Energy Modeling Forum 33rd study:  
688 assessing large-scale global bioenergy deployment for managing climate change. *Climatic*  
689 *Change* **163**, 1539–1551 (2020). <https://doi.org/10.1007/s10584-020-02945-6>
- 690 Rose, Steven K., Elmar Kriegler, Ruben Bibas, Katherine Calvin, Alexander Popp, Detlef P. van  
691 Vuuren, and John Weyant. 2013. “Bioenergy in Energy Transformation and Climate  
692 Management.” *Climatic Change*, 1–17.
- 693 Rose, Steven K, Alexander Popp, Shinichiro Fujimori, Petr Havlik, Detlef P van Vuuren, John  
694 Weyant, and Marshall Wise. This issue. “Global Biomass Supply Modeling for Long-Run  
695 Management of the Climate System.”
- 696 Sano, Fuminori, Kenichi Wada, Keigo Akimoto, and Junichiro Oda. 2015. “Assessments of GHG  
697 Emission Reduction Scenarios of Different Levels and Different Short-Term Pledges through  
698 Macro- and Sectoral Decomposition Analyses.” *Technological Forecasting and Social*  
699 *Change* 90: 153–65. <https://doi.org/10.1016/j.techfore.2013.11.002>.
- 700 Schultres, A., Leimbach, M., Luderer, G., Pietzcker, R.C., Baumstark, L., Bauer, N., Kriegler, E.,  
701 Edenhofer, O., 2018. Optimal international technology cooperation for the low-carbon  
702 transformation. *Climate Policy* 18, 1165–1176.  
703 <https://doi.org/10.1080/14693062.2017.1409190>

- 704 Sims, Ralph, Roberto Schaeffer, Felix Creutzig, Xochitl Cruz-Núñez, Marcio D’Agosto, Dalia  
705 Dimitriu, Maria Josefina Figueroa Meza, et al. 2014. “Transport.” In *Climate Change 2014:  
706 Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment  
707 Report of the Intergovernmental Panel on Climate Change [Edenhofer, O., R. Pichs-  
708 Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, A. Adler, I. Baum, S. Brunner, P.  
709 Eickemeier, B. Kriemann, J. Savolainen, S. Schlömer, C. von Stechow, T. Zwickel and J.C.  
710 Minx (Eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY,  
711 USA.*
- 712 Singh, B., John Korstad, and Y.C. Sharma. 2012. “A Critical Review on Corrosion of Compression  
713 Ignition (CI) Engine Parts by Biodiesel and Biodiesel Blends and Its Inhibition.” *Renewable  
714 and Sustainable Energy Reviews* 16 (5): 3401–8. <https://doi.org/10.1016/j.rser.2012.02.042>.
- 715 Sorate, Kamalesh A., and Purnanand V. Bhale. 2015. “Biodiesel Properties and Automotive System  
716 Compatibility Issues.” *Renewable and Sustainable Energy Reviews* 41 (January): 777–98.  
717 <https://doi.org/10.1016/j.rser.2014.08.079>.
- 718 Stoy, Paul C, Selena Ahmed, Meghann Jarchow, Benjamin Rashford, David Swanson, Shannon  
719 Albeke, Gabriel Bromley, et al. 2018. “Opportunities and Trade-Offs among BECCS and the  
720 Food, Water, Energy, Biodiversity, and Social Systems Nexus at Regional Scales.”  
721 *BioScience* 68 (2): 100–111. <https://doi.org/10.1093/biosci/bix145>.
- 722 Taljegard, Maria, Selma Brynolf, Maria Grahn, Karin Andersson, and Hannes Johnson. 2014.  
723 “Cost-Effective Choices of Marine Fuels in a Carbon-Constrained World: Results from a  
724 Global Energy Model.” *Environmental Science & Technology* 48 (21): 12986–93.  
725 <https://doi.org/10.1021/es5018575>.
- 726 Tanzer, Samantha Eleanor, John Posada, Sjors Geraedts, and Andrea Ramírez. 2019.  
727 “Lignocellulosic Marine Biofuel: Technoeconomic and Environmental Assessment for  
728 Production in Brazil and Sweden.” *Journal of Cleaner Production* 239 (December): 117845.  
729 <https://doi.org/10.1016/j.jclepro.2019.117845>.
- 730 Transports, Forum International des. 2018. “Decarbonising Maritime Transport,” no. 47.  
731 <https://doi.org/10.1787/b1a7632c-en>.
- 732 Tsutsui, J., H. Yamamoto, S. Sakamoto, and M. Sugiyama. 2020. "The role of advanced end-use  
733 technologies in long-term climate change mitigation: the interlinkage between primary  
734 bioenergy and energy end-use," *Climatic Change*, 163, 1675–1693.  
735 <https://doi.org/10.1007/s10584-020-02839-7>.

- 736 van Vuuren, Detlef P., Elke Stehfest, David E.H.J. Gernaat, Jonathan C. Doelman, Maarten van den  
737 Berg, Mathijs Harmsen, Harmen Sytze de Boer, et al. 2017. “Energy, Land-Use and  
738 Greenhouse Gas Emissions Trajectories under a Green Growth Paradigm.” *Global  
739 Environmental Change* 42 (January): 237–50.  
740 <https://doi.org/10.1016/j.gloenvcha.2016.05.008>.
- 741 Venturini, Giada, Jacopo Tattini, Eamonn Mulholland, and Brian Ó Gallachóir. 2019.  
742 “Improvements in the Representation of Behavior in Integrated Energy and Transport  
743 Models.” *International Journal of Sustainable Transportation* 13 (4): 294–313.  
744 <https://doi.org/10.1080/15568318.2018.1466220>.
- 745 Victor, David Gardiner, Dadi Zhou, Essam Hassan Mohamed Ahmed, Pradeep Kumar Dadhich, Jos  
746 Gerardus Jozef Olivier, Hans-Holger Rogner, Kamel Sheikho, and Mitsutsune Yamaguchi.  
747 2014. “Introductory Chapter.” In *Climate Change 2014: Mitigation of Climate Change.  
748 Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental  
749 Panel on Climate Change [Edenhofer, O., R. Pichs-Madruga, Y. Sokona, E. Farahani, S.  
750 Kadner, K. Seyboth, A. Adler, I. Baum, S. Brunner, P. Eickemeier, B. Kriemann, J.  
751 Savolainen, S. Schlömer, C. von Stechow, T. Zwickel and J.C. Minx (Eds.)]. Cambridge  
752 University Press, Cambridge, United Kingdom and New York, NY, USA.*
- 753 Waisman, Henri, Céline Guivarch, Fabio Grazi, and Jean Charles Hourcade. 2012. “The Imaclim-R  
754 Model: Infrastructures, Technical Inertia and the Costs of Low Carbon Futures under  
755 Imperfect Foresight.” *Climatic Change* 114 (1): 101–20. [https://doi.org/10.1007/s10584-011-  
756 0387-z](https://doi.org/10.1007/s10584-011-0387-z).
- 757 Wei, Hongjian, Wenzhi Liu, Xinyu Chen, Qing Yang, Jiashuo Li, and Hanping Chen. 2019.  
758 “Renewable Bio-Jet Fuel Production for Aviation: A Review.” *Fuel* 254 (October): 115599.  
759 <https://doi.org/10.1016/j.fuel.2019.06.007>.
- 760 Wise, Marshall, Matteo Muratori, and Page Kyle. 2017. “Biojet Fuels and Emissions Mitigation in  
761 Aviation: An Integrated Assessment Modeling Analysis.” *Transportation Research Part D:  
762 Transport and Environment* 52: 244–53. <https://doi.org/10.1016/j.trd.2017.03.006>.
- 763 Why, Elaine Siew Kuan, Hwai Chyuan Ong, Hwei Voon Lee, Yong Yang Gan, Wei-Hsin Chen,  
764 and Cheng Tung Chong. 2019. “Renewable Aviation Fuel by Advanced Hydroprocessing of  
765 Biomass: Challenges and Perspective.” *Energy Conversion and Management* 199  
766 (November): 112015. <https://doi.org/10.1016/j.enconman.2019.112015>. Yeh, Sonia, Gouri  
767 Shankar Mishra, Lew Fulton, Page Kyle, David L. McCollum, Joshua Miller, Pierpaolo

768 Cazzola, and Jacob Teter. 2017. "Detailed Assessment of Global Transport-Energy Models'  
769 Structures and Projections." *Transportation Research Part D: Transport and Environment* 55  
770 (August): 294–309. <https://doi.org/10.1016/j.trd.2016.11.001>.

771 Yeh, Sonia, Gouri Shankar Mishra, Lew Fulton, Page Kyle, David L. McCollum, Joshua Miller,  
772 Pierpaolo Cazzola, and Jacob Teter. 2017. "Detailed Assessment of Global Transport-Energy  
773 Models' Structures and Projections." *Transportation Research Part D: Transport and  
774 Environment* 55 (August): 294–309. <https://doi.org/10.1016/j.trd.2016.11.001>.

775 Zhang, Runsen, and Shinichiro Fujimori. 2020. "The Role of Transport Electrification in Global  
776 Climate Change Mitigation Scenarios." *Environmental Research Letters* 15 (3): 034019.  
777 <https://doi.org/10.1088/1748-9326/ab6658>.

778 Zhang, Runsen, Shinichiro Fujimori, Hancheng Dai, and Tatsuya Hanaoka. 2018. "Contribution of  
779 the Transport Sector to Climate Change Mitigation: Insights from a Global Passenger  
780 Transport Model Coupled with a Computable General Equilibrium Model." *Applied Energy*  
781 211 (February): 76–88. <https://doi.org/10.1016/j.apenergy.2017.10.103>.

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783