

Pricing of indirect emissions accelerates low-carbon transition of US light vehicle sector

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Article

Keywords: Electric Vehicle Adoption, Life Cycle Assessment, Expected Technological Change, Gasoline Production

Posted Date: March 25th, 2021

DOI: <https://doi.org/10.21203/rs.3.rs-334331/v1>

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Version of Record: A version of this preprint was published at Nature Communications on December 1st, 2021. See the published version at <https://doi.org/10.1038/s41467-021-27247-y>.

Pricing of indirect emissions accelerates low-carbon transition of US light vehicle sector

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Submitted to Nature Communications

Words: Abstract—148/150; Main—4,248/5,000 (w/o captions)

Abstract

Large-scale electric vehicle adoption can greatly reduce emissions from vehicle tailpipes. However, analysts have cautioned that it can come with increased indirect emissions from electricity and battery production that are not commonly regulated by transport policies. We combine integrated energy modeling and life cycle assessment to compare optimal policy scenarios that price emissions at the tailpipe only, versus both tailpipe and indirect emissions. Surprisingly, scenarios that also price indirect emissions exhibit higher, rather than reduced, sales of electric vehicles, while yielding lower cumulative tailpipe and indirect emissions. Expected technological change ensures that emissions from electricity and battery production are more than offset by reduced emissions of gasoline production. Given continued decarbonization of electricity supply, results show that a large-scale adoption of electric vehicles is able to reduce CO₂ emissions through more channels than previously expected. Further, carbon pricing of stationary sources will also favor electric vehicles.

Introduction

Global transportation is the single largest energy user and energy-using emitter of CO₂ emissions, chiefly driven by light duty vehicles (LDVs) [1]. In order to curb emissions, many countries, including the United States (US), are increasingly promoting alternative fuel vehicles, which are typically characterized by lower tailpipe emissions. However, concerns over

29 potentially growing emissions from energy production and vehicle manufacturing have been
30 voiced [2, 3, 4]. These emissions occur off-site, or indirectly, and include generation of elec-
31 tricity to charge electric vehicles, in this work $\sim 66\text{--}86$ g CO₂ per electric-vehicle km driven in
32 2020, and production of vehicles, here $\sim 16\text{--}38$ g CO₂ per vehicle-km driven in 2020 (Supple-
33 mentary Table 20 and Supplementary Figure 2). It has only recently been recognized that the
34 emissions for producing gasoline can range significantly, from below 15 to ~ 320 g CO₂/kWh in
35 2015 [5, 6], compared to direct tailpipe emissions of about 250 g CO₂/kWh. Taken together,
36 indirect emissions accounted for $\sim 26\%$ of the 1.5 Gt CO₂ caused by the US LDV fleet in 2020
37 (Supplementary Table 16).

38 The introduction of the Low Carbon Fuel Standard in California shows that transport
39 policy in practice can at least partly address indirect vehicle emissions. However, not a single
40 transport policy exists to date that consistently regulates all sources of vehicle emissions along
41 the entire supply chain.¹ Fully regulating all emissions, for example through pricing, could
42 significantly change the relative costs of different vehicle propulsion options, such as battery
43 electric vehicles (BEVs) versus hydrogen fuel cell electric vehicles (HFCEVs) versus internal
44 combustion engine vehicles (ICEVs). Changing costs, in turn, could affect production decisions
45 of vehicle manufacturers, and purchase behaviors of consumers. The potential impact of these
46 relationships is unknown to date because neither model calculations, nor real-world policies,
47 have fully accounted for or priced indirect vehicle emissions.

48 Integrated energy models (IEMs) show that it will be challenging to reduce emissions
49 rapidly and far enough to reach the Paris goal [7, 8, 9, 10]. However, there is concern that
50 IEMs do not fully represent the impact of changes in one sector, such as electricity generation
51 technologies, on emissions in other sectors, such as industry or fuel supply [11, 12, 13, 14]. For
52 electricity generation, this has been investigated [15, 16, 17, 18, 19, 20], but not for vehicles.
53 Our work is the first to fully account for, and price, all life-cycle emissions that are directly
54 (within the vehicle sector) and indirectly (in other sectors) caused by US passenger vehicles.
55 We investigate whether this holistic emissions pricing influences the assessment of the benefit
56 of competitive technologies.

57 To this end, we apply an interdisciplinary approach integrating industrial ecology meth-
58 ods with integrated modelling of the entire energy-economy system. We link a detailed and
59 comprehensive vehicle life cycle assessment (LCA) model to the Energy Information Agency’s
60 National Energy Modeling System (NEMS). NEMS is the federal government’s main tool for
61 evaluating energy and climate policies integrative of all energy demand and supply sectors.
62 Among IEMs, NEMS has the advantage of representing the US passenger vehicle sector and
63 its upstream sectors in great detail [13] (also see Methods), which is a prerequisite for accu-
64 rately accounting for all vehicle emissions across the entire supply chain of the vast portfolio of
65 available technology options. Although *global* IEMs are the main tool for identifying optimal

¹We use the terms ‘supply chain emissions’ and ‘life-cycle emissions’ synonymously. Both are defined as the sum of direct, or tailpipe, emissions and indirect emissions.

66 climate change mitigation pathways, they generally do not offer the same level of technological
67 detail as national models do [11, 12, 13, 21] which may limit their ability to identify optimal
68 solutions across the range of options available in the real world. Further, while some integrated
69 assessments account for materials used in electric power plants [22, 23], others point out the
70 importance of considering efficient use of resources within integrated climate scenarios [24]. Yet,
71 material and resource efficiency have not been thought of as pollution mitigation strategies in
72 large-scale integrated energy scenarios and are therefore not well represented in the assessment
73 reports of the Intergovernmental Panel on Climate Change [25].

74 Here we address these knowledge gaps by applying a novel conceptual framework by
75 Creutzig et al. [26], which focuses on demand-side solutions to climate change mitigation.
76 We specify this framework for comprehensive climate change mitigation analysis of an impor-
77 tant demand-side sector, the US LDV sector. We illustrate a set of climate-change mitigation
78 scenarios, primarily for the vehicles sector, but also consider responses in important upstream
79 sectors, such as changes to material production, vehicle manufacturing and electricity genera-
80 tion. These responses are normally not fully captured in NEMS. Thus, we soft-link NEMS to
81 a detailed LCA model (see Methods). We assume that the production cost of electric vehicle
82 batteries and renewable electricity generators fall quickly, in line with recent estimates (see
83 Methods). We further introduce a carbon price in the transport sector in 2021 which linearly
84 increases up to 150 USD/t CO₂ (constant 2016\$) by 2050 (Supplementary Table 9). This level
85 is required for an LDV fleet commensurate with the US nationally determined contribution
86 under the Paris Agreement (see Methods). For simplicity and to provide insight, we run our
87 cases with no carbon pricing on other sectors. The difference between the two main scenarios is
88 that either emissions from (1) the tailpipe, or (2) the entire vehicle supply chain are accounted,
89 priced and optimized for. The implications are both surprising and significant. The strongest
90 effect of pricing both tailpipe and indirect emissions is that the system would be pushed to
91 an even faster phase-out of gasoline-powered vehicles, leading to a scenario minimizing both
92 tailpipe and indirect emissions.

93 Results

94 Optimal vehicle choice

95 While pricing only direct tailpipe emissions already leads to a nearly complete phase-out of
96 ICEVs (Figure 1a), the transition is accelerated under full emissions pricing (Figure 1b). In
97 addition, HFCEVs are avoided entirely under full pricing due to the high emissions penalty of
98 producing hydrogen from natural gas. Lower sales of ICEVs, HFCEVs and other powertrains
99 (mostly hybrids and flex-fuel vehicles running both on conventional liquid fuels and biofuels)
100 are compensated by higher BEV sales. This substitution pattern peaks around 2040 with about
101 2.4 million units (Figure 1c). In absolute terms, sales of ICEV light trucks are reduced the

102 most, and compensated by BEV cars and trucks. The cumulative amount of avoided ICEVs and
 103 HFCEVs amounts to nearly 29 and 9 million units. We explore a range of side cases in which
 104 (a) only energy-chain emissions instead of full life-cycle emissions are priced, (b) hydrogen
 105 production becomes carbon-neutral by 2050, (c) HFCEVs become cost-competitive with BEVs,
 106 as well as different combinations thereof. We display three of these cases in Supplementary
 107 Figure 6.

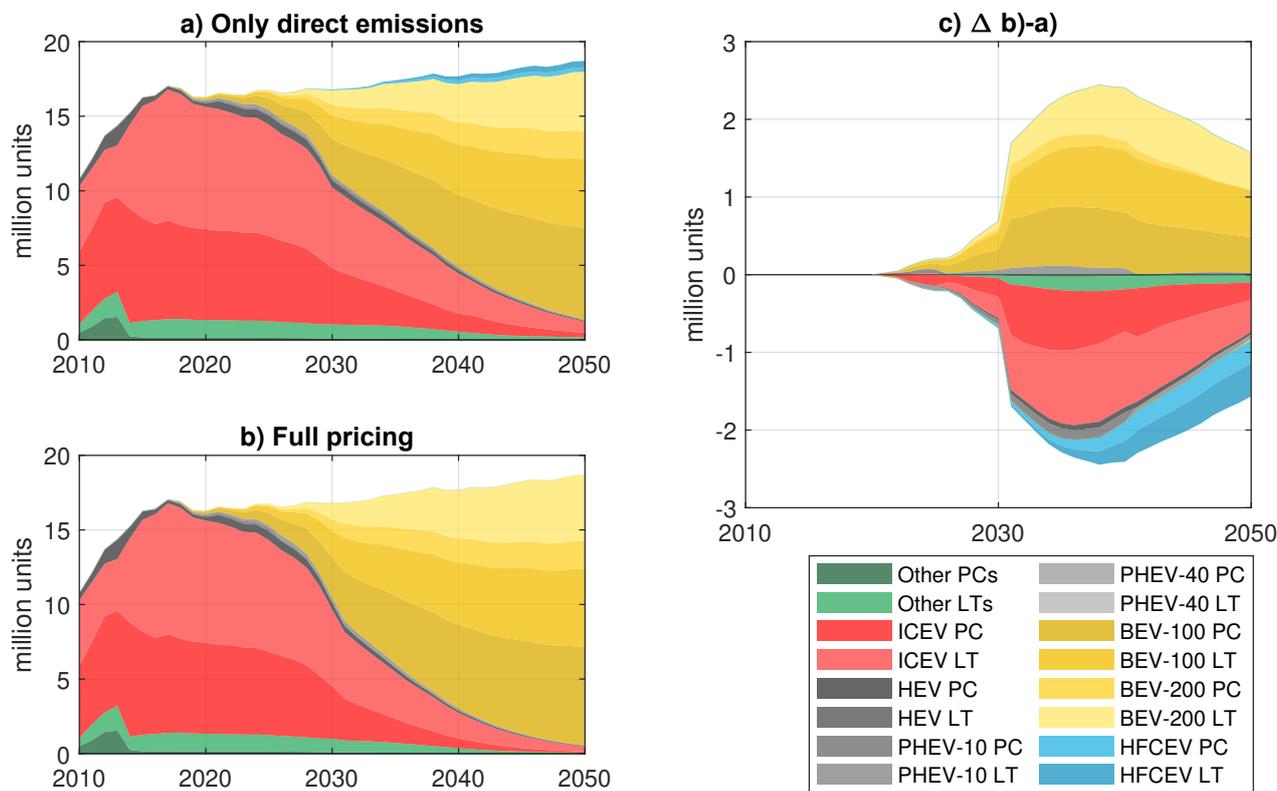


Figure 1: Optimal vehicle choice under direct-emissions-only pricing (a) and full emissions pricing (b). (c) Differences in vehicle choice between (b) and (a). PC=passenger car; LT=light truck; ICEV=internal combustion engine vehicle; HEV=hybrid electric vehicle; PHEV=plug-in hybrid electric vehicle; BEV=battery electric vehicle; HFCEV=hydrogen fuel cell electric vehicle; -10=10-mile electric range.

108 The mentioned substitutions of technologies lead to substantially lower cumulative life-
 109 cycle emissions through 2050 (- 1.6 Gt CO₂, Figure 2a and 2f), largely driven by lower fuel
 110 combustion (- 1.4 Gt CO₂, Figure 2b and 2g) and lower production of gasoline and hydrogen
 111 (- 0.5 Gt CO₂, Figure 2c and 2h). While stronger sales of BEVs lead to higher electricity
 112 emissions (Figure 2d and i), these are however relatively small compared to lower emissions from
 113 fuel production (+ 0.25 Gt CO₂ vs. - 0.5 Gt CO₂, Figure 2k). Finally, since BEVs are material
 114 intensive, an additional 30 Mt CO₂ embodied in vehicle production can be observed. However,
 115 these could be more than compensated by ambitious recycling and reuse practices (+ 0.03 vs.
 116 - 0.5 Gt CO₂, Supplementary Figure 3). We explore a range of side cases (Supplementary

117 Figure 6) which show some variation in their potential for emission reductions (also see dotted
 118 lines in Figure 2a–j) but the overall trend is robust among all cases. Accordingly, additional
 119 cumulative life-cycle emission reductions can vary between -1.4 to -1.7 Gt CO₂ across all
 120 cases (see dotted lines in Figure 2f) on top of emission reductions already achieved under
 121 pricing direct emissions only. In Figure 2k, the differences in emissions between ‘full pricing’
 122 and ‘direct-emissions-only pricing’ are once more plotted by life cycle stage, while in Figure 2l,
 123 all sources of indirect emissions, i.e. production of fuels, electricity and vehicles, are categorized
 124 as such. It becomes apparent that ‘full pricing’ not only leads to reduced tailpipe emissions,
 125 but also to lower indirect supply chain emissions, at least after about 2035.

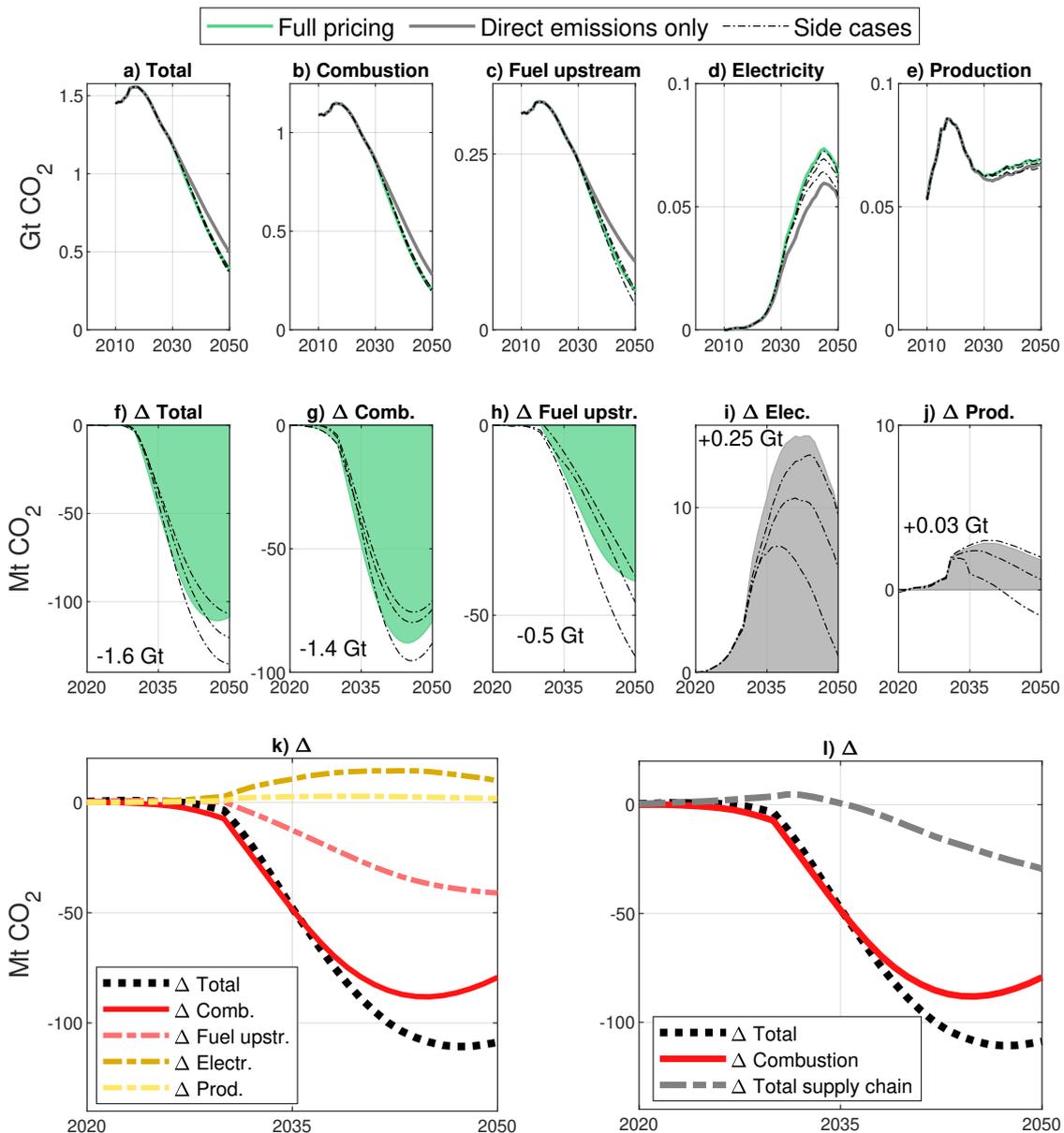


Figure 2: Life-cycle CO₂ emissions of the US light vehicle fleet, total (a) and broken down by life-cycle stage (b–e) when fully pricing emissions and when only pricing direct emissions. Differences in emissions between full and direct-emissions-only pricing (f–l). Dotted lines (a–j) illustrate results from side cases (see Supplementary Figure 6).

126 **Fleet efficiency**

127 The future of the Corporate Average Fuel Economy (CAFE) standard is currently highly un-
128 certain and we therefore do not model changes to CAFE after 2025. While the Trump admin-
129 istration enacted the Safer Affordable Fuel Efficient (SAFE) standard in 2018, which weakened
130 CAFE requirements through 2026, the Biden campaign announced a plan to consider a more
131 ambitious CAFE² but further details are unknown at the time of writing. Despite the fact that
132 CAFE is not further tightened after 2025 in our model, average real-world fuel economy [27]
133 of the fleet continues to improve greatly in all scenarios, even after 2025 (Figure 3). This can
134 be explained by the strong market penetration of BEVs. When full life-cycle emissions are
135 optimized for, average fuel economy is even higher compared to direct-emissions-only pric-
136 ing due to the accelerated penetration of BEVs. Side cases with higher shares of HFCEVs
137 however exhibit significantly lower average fuel economies (Supplementary Table 12). Other
138 fleet characteristics, such as average vehicle weight, deployment of lightweighting through ma-
139 terial substitution, segment shares, and total travel demand, are less impacted in the different
140 scenarios (Supplementary Figure 9).

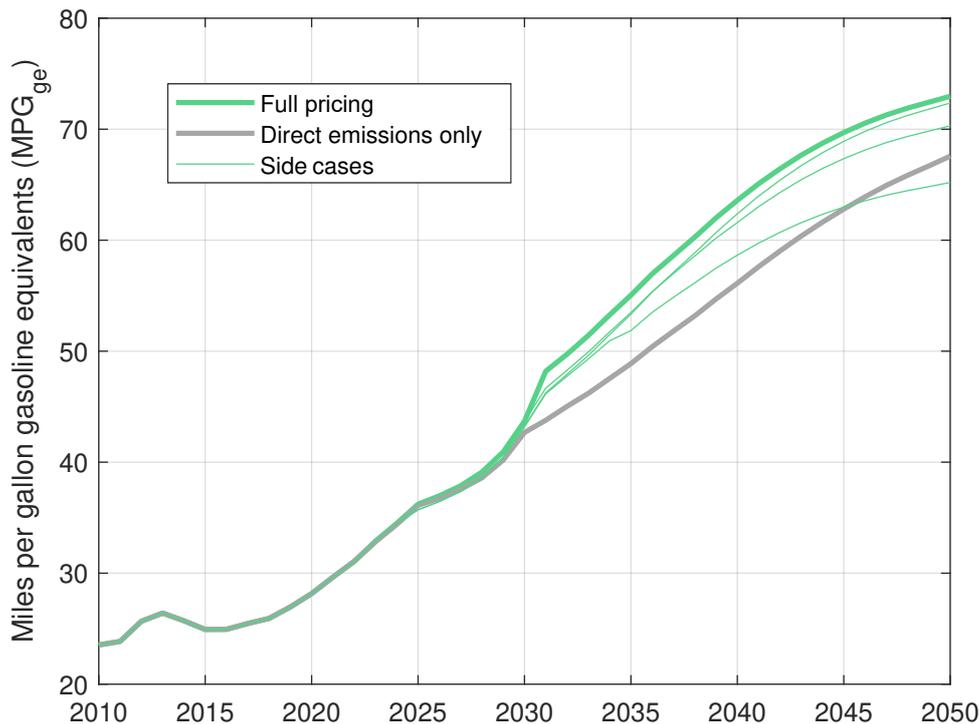


Figure 3: Average real-world fuel economy of the US light vehicle fleet when all emissions are priced and when only direct emissions are priced. The thin green lines show the range of results from the side cases.

²<https://joebiden.com/9-key-elements-of-joe-bidens-plan-for-a-clean-energy-revolution/>

141 **Resource use implications**

142 Fully pricing life cycle emissions would also have important implications on resource use (Fig-
 143 ure 4). For example, gasoline and diesel consumption in 2050 would be 29% and 32% lower than
 144 if taxing only direct emissions (26–32% and 30–39% in the side cases). Further, while hydrogen
 145 demand would be lower by 99.9% (– 98.0 to + 327.0%), electricity use would be 18% higher
 146 (2–18%). Overall, taxing supply chains would lower energy use by 7% (1–6%). Meanwhile,
 147 overall material demand would be slightly higher, by 2.1% (0.8–2.0%), with copper demand
 148 higher by 4.7% (with a range of – 0.7 to + 5.0%). These effects are largely due to higher BEV
 149 sales (by 9.1%, with a range of – 6.1% to + 9.3%, see Supplementary Table 17).

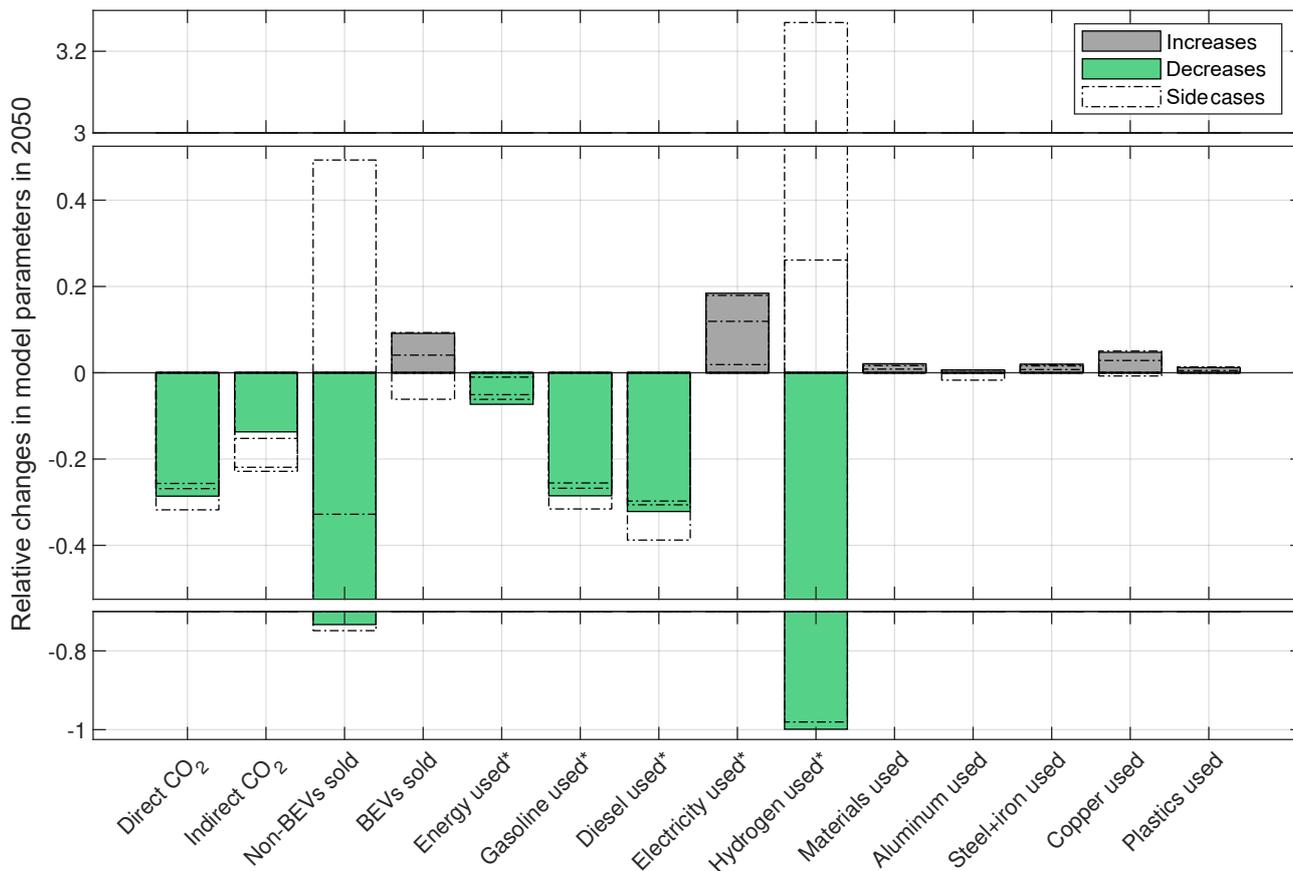


Figure 4: Changes in model parameters due to full pricing relative to direct-emissions-only pricing in 2050 (colored bars). The hollow bars show the normalized differences of the side cases relative to direct-emissions-only pricing in 2050. BEV=battery electric vehicle; *=on-board energy.

150 In absolute terms, the difference between the two main scenarios is that under full pricing,
 151 cumulative gasoline consumption through 2050 is reduced by 0.15 trillion gallons or 0.6 tril-
 152 lion liters compared to direct-emissions-only pricing. This corresponds to three years of cur-
 153 rent (2019) annual US gasoline consumption (55 million gallons/0.2 trillion liters).³ Similarly,

³https://www.eia.gov/dnav/pet/pet_cons_psup_dc_nus_mbbl_a.htm

154 0.8 PWh (trillion kWh) of hydrogen are saved, while electricity consumption is higher by
155 3.2 PWh, roughly corresponding to the current annual amount of electricity end use in the US
156 in 2019.⁴ Cumulative material use for vehicle production is moderately higher, by about 24 Mt,
157 which is chiefly driven by the larger stock of material-intensive BEVs. The higher material
158 demand is partially mitigated by a slightly lower average vehicle weight (Supplementary Fig-
159 ure 10a). Material substitutions due to vehicle lightweighting (Supplementary Figure 10b) lead
160 to a marginally higher use of aluminum and plastics, and a reduction of steel and iron. Overall,
161 the largest absolute difference is due to the higher demand for stainless steel (+ 13.2 Mt), fol-
162 lowed by copper (+ 3.1 Mt), aluminum (+ 1.6 Mt) and plastics (+ 1.2 Mt). Simultaneously, use
163 of automotive steel and cast iron is lower, by 1.0 Mt. However, more ambitious recycling and
164 reuse practices have the potential to more than offset the stronger demand for virgin materials,
165 by about 740 Mt (Supplementary Note 1).

166 Adequacy of analyzed decarbonization measures

167 Emission reductions required to halt climate change are sometimes framed through the carbon
168 budget — the amount of emissions remaining until the atmosphere reaches an identified tem-
169 perature threshold. Under the described cases, the US LDV sector would require 3–5% of the
170 global carbon budget identified by the Intergovernmental Panel on Climate Change [10], which
171 is about as much as its share of current emissions (Supplementary Table 16).

172 Discussion

173 There is remarkably little known about the extent to which indirect emissions shape cost-
174 optimal decarbonization pathways [28] and vice versa. Previous work focusing on electricity
175 supply reported a limited role of indirect emissions in optimized climate change mitigation
176 scenarios [15, 17, 16]. Here we explore the role of indirect emissions in decarbonization efforts
177 of the US passenger vehicle fleet and find that, in fact, they can significantly alter optimal
178 climate change mitigation pathways. An important difference between the electricity supply
179 sector and the LDV sector is that indirect emissions play a larger role, accounting for about
180 a quarter of total life-cycle emissions already today. In our scenarios, indirect emissions make
181 up almost half of total LDV sector CO₂ emissions in 2050 (44–49%) and about 24–29% of
182 cumulative emissions over the 2010–2050 scenario time frame (Supplementary Table 16). For
183 comparison, McDowall et al. report that indirect emissions would account for less than 10%
184 of total life-cycle power plant emissions in 2050 in an optimal decarbonization scenario of the
185 EU [16].

186 Although overall life-cycle emissions are significantly lower under full emissions pricing,
187 indirect ones are higher, most prominently due to electricity generation and battery manufac-

⁴<https://www.eia.gov/totalenergy/data/browser/?tbl=T07.06#/?f=M>

188 turing for BEVs. However, higher electricity emissions are more than offset by lower gasoline
189 supply-chain emissions stemming from exploration, transportation and refining of crude oil
190 (Figure 2k). Higher emissions from material production and vehicle assembly are relatively
191 small and could be more than offset by increased material efficiency efforts including more
192 ambitious material recycling and reuse of components.

193 While it is expected that direct emissions of BEVs are lower than those of ICEVs, it is
194 surprising that in fact non-tailpipe emissions are also lower (Figure 2l). This sheds new light
195 on the current public debate about ‘dirty’ batteries and electricity.⁵ In fact, the simultaneous
196 reduction of both direct and indirect emissions indicates a win-win situation for climate change
197 mitigation, meaning that climate policy with very high shares of BEVs represents a no-regrets
198 strategy. Our insights are therefore highly relevant for global climate and transport policies.
199 Current policies, such as performance standards or emission pricing schemes, should be broad-
200 ened in their scope in order to regulate all sources of vehicle emissions along the entire supply
201 chain or throughout the entire life cycle. Our scenarios further indicate that the US (and likely
202 other nations with suitable low-carbon electricity grids) should target deployment of BEVs and
203 largely disregard competing technologies. HFCEVs could offer a viable alternative if costs to
204 produce fuel cells and low-carbon hydrogen would fall considerably in coming years.

205 Our work represents a first step towards a holistic inclusion of dynamic life-cycle relation-
206 ships in integrated modelling frameworks. Future research could include additional potentially
207 important factors and processes, such as deployment of carbon capture and storage (CCS)
208 at fuel refineries, differences in emission intensities of hydrocarbons, synthetic liquid fuels,
209 net-negative emission pathways of energy production, and low-carbon steel production using
210 hydrogen from renewable sources. Future research could also investigate the degree to which
211 our results would differ in various regions of the world, or if additional pollutants, other than
212 direct and indirect CO₂ emissions, were internalized in optimal pollution mitigation pathways.

213 **Methods**

214 **Demand-side framework**

215 We address calls for a stronger research focus on demand-side solutions for mitigating climate
216 change [29]. Specifically, we apply and specify a novel, transdisciplinary demand-side assess-
217 ment framework focusing on an important emitting sector [30]. Our framework addresses the
218 following key areas: (1) End-use context: we focus on demand-side solutions, with the US
219 LDV fleet as a case study. (2) Technology: we use industrial ecology methods to model full life
220 cycle CO₂ emissions and costs of all major established and emerging vehicle technologies. This
221 enables us to test the potential of different technological mitigation measures along the entire
222 vehicle supply chain including powertrain switching, changes in material composition, recycling

⁵<https://www.bloomberg.com/news/articles/2018-10-16/the-dirt-on-clean-electric-cars>

223 of materials, reuse of vehicle components, and feedstock switching for fuel and electricity pro-
224 duction. (3) Policy instruments: Carbon pricing is applied to either tailpipe emissions, or the
225 entire vehicle life cycle. (4) Climate change mitigation pathways: We present climate change
226 mitigation scenarios of the US LDV sector and analyze the contribution of several mitigation
227 measures towards the US nationally determined contribution and a 2°C consistent US LDV sec-
228 tor. (5) Sustainable development: We highlight synergies with other sustainability indicators
229 such as resource use, energy use and consumer cost.

230 **Integrated energy modelling**

231 Our tool of choice is NEMS which is the model behind the well-known Annual Energy Out-
232 look [31]. In this study, we use the NEMS code run on a server at Yale University (hence-
233 forth we call it “Yale-NEMS” at EIA’s request) and slightly modified to output additional
234 results [32, 33]. Yale-NEMS sets prices so that an equilibrium is obtained where annual energy
235 supply equals energy demand through 2050. The main energy demand sectors are residential
236 buildings, commercial buildings, transport and industry. Projections of economic drivers are
237 provided exogenously while world energy prices, world energy supply and demand, and US
238 energy imports and exports are calculated endogenously. Yale-NEMS provides a full account
239 of CO₂ emissions across all industries and a range of air pollutants from vehicles and power
240 plants.

241 **Transport sector modelling**

242 The transport sector includes several modes of travel, such as LDVs, aviation, trucking, ship-
243 ping, and rail. The LDV submodule distinguishes twelve vehicle sizes, 86 fuel efficiency tech-
244 nologies, as well as sixteen alternative propulsion technologies including BEV-100 (100-mile
245 electric range), BEV-200, PHEV-10, PHEV-40, HEV, and HFCEV. Various fuel pathways are
246 modelled as well. The LDV submodule uses a discrete choice formulation to simulate both
247 the behavior of vehicle manufacturers and consumers. Consumers base purchase decisions on
248 energy prices, charger and fuel station availability, vehicle purchase prices and a range of other
249 vehicle attributes. The decision-making process of vehicle manufacturers is usually not con-
250 sidered in large-scale IEMs [2]. Thus a distinguishing feature of Yale-NEMS is that vehicle
251 manufacturers make production decisions based on technology cost, CAFE requirements and
252 potential regulatory costs. Further details on EIA’s NEMS and a direct comparison with other
253 IEMs can be found elsewhere [13].

254 Here we make several refinements to Yale-NEMS’ LDV submodule: We update vehicle
255 costs in a bottom-up fashion using detailed cost estimates for all major vehicle components,
256 such as engines, electric motors, transmissions, fuel cells, and hydrogen storage tanks [34, 35].
257 Further, costs of lithium-ion batteries start out at about 465 USD/kWh in 2016 and reach
258 floor costs of ~83 USD/kWh over the modelled time horizon due to economies of scale and

259 technological development. This cost development is within the range of recent estimates [36].

260 **Modelling upstream sectors**

261 The electricity market module considers all major fossil and renewable generators, including
262 conventional, and advanced coal and gas power plants with and without CCS, nuclear, hydro,
263 solar thermal, solar photovoltaics (PV), and on- and offshore wind power. In our scenarios
264 we assume that overnight capital costs of solar PV and onshore wind power plants fall from
265 around 1,245 and 1,230 USD/kW in 2019 down to about 370 and 540 USD/kW by 2050 due
266 to economies of scale and technological developments. This cost development is within the
267 range of recent estimates [37, 38]. As a result, new power plant capacities are mainly provided
268 by renewable electricity generators (Supplementary Figure 7), while fossil-fueled power plants
269 retire (Supplementary Figure 8). Thus, renewables provide more than half of all electricity well
270 before 2030 and more than three quarters by 2050. The remaining electricity demand in 2050 is
271 mainly met by natural gas (16%) and nuclear power (6%), while coal is almost entirely phased
272 out (1.5%, see Supplementary Figure 5 and Supplementary Table 18). A small percentage of
273 electricity from coal is generated at CCS-equipped plants. Electricity is not only produced in
274 the power supply sector but also in the residential and commercial end-use sectors — a feature
275 that sets apart Yale-NEMS from other IEMs [21] — with the main technologies being rooftop
276 solar PV and distributed natural gas. While electricity demand grows from almost four to more
277 than six trillion kWh, an increase by more than half, electricity emissions fall from almost 2,400
278 to below 290 Mt CO₂, a reduction of 88%. As a result, the carbon intensity of the electricity
279 mix falls by a factor of twelve, from 546 down to 45 g CO₂/kWh (Supplementary Figure 6 and
280 Supplementary Table 18).

281 **Determining a carbon price**

282 In all scenarios, we introduce a price on carbon in the transport sector in 2021 which linearly
283 increases up to 150 USD/t CO₂ by 2050 (constant 2016\$, Supplementary Table 9) — a level
284 required to meet the US nationally determined contribution under the Paris Agreement. The
285 US is committed to reduce CO₂ emissions by 80% by 2050 relative to 2005. We assume that
286 all sectors equally attempt to reduce their emissions by that percentage. According to the US
287 EPA, direct CO₂ emissions from the US LDV fleet amounted to 1,180 Mt in 2005 [39]. The
288 growing carbon price leads to a significant cost increase of energy carriers, especially of gasoline
289 (Supplementary Figure 4). Combined with the cost reductions of electric vehicle batteries and
290 renewable power plants, our assumed carbon price leads to reductions of direct CO₂ emissions on
291 the order of 76–84% in 2050 relative to 2005, depending on the specific scenario (Supplementary
292 Table 16).

293 **Soft-linking Yale-NEMS with LCA**

294 We soft-link Yale-NEMS to a detailed passenger vehicle LCA model [40] and iterate between
295 the LCA model and Yale-NEMS until inputs and outputs converge between both models.
296 The LCA model covers CO₂ emissions of all major technologies across the entire vehicle life
297 cycle, including fuel production and combustion, electricity generation, material production
298 and recycling, assembly and reuse of vehicle components, and lightweighting through material
299 substitution.

300 **Inputs from Yale-NEMS into LCA (first iteration)**

301 In a first iteration we calibrate the LCA model to the US case by using the following Yale-
302 NEMS outputs as calibration coefficients: (1) Vehicle baseline weights (without lightweighting,
303 Supplementary Table 1), (2) the expected degree of vehicle lightweighting (substitution of
304 conventional materials with lightweight materials, Supplementary Table 11), (3) current and
305 future on-road energy consumption (Supplementary Table 1), (4) current and future battery
306 sizes (Supplementary Table 1), (5) current and future carbon intensity of electricity generation
307 used to manufacture vehicles and charge BEVs (Supplementary Table 18), and (6) carbon
308 prices (Supplementary Table 9). Taking these variables into account, the LCA model calculates
309 per-vehicle life-cycle carbon emissions (Supplementary Figures 1 and 2) and translates these
310 into life-cycle carbon prices for each technology (Supplementary Figure 5 and Supplementary
311 Table 10).

312 **Inputs from LCA into Yale-NEMS**

313 The obtained carbon prices are then linked back to Yale-NEMS for consideration in the vehicle
314 choice procedure of the LDV submodule. Specifically, carbon prices on indirect emissions are
315 implemented in Yale-NEMS as a so-called ‘feebate’. Feebates are regarded as one of the most
316 effective policy instruments to reduce vehicle emissions [41, 42, 43]. Feebate systems impose a
317 fee on vehicles with high CO₂ emissions and grant a rebate to low-carbon vehicles. Here we
318 apply that design to both the production of vehicles and energy carriers separately, with two
319 main steps. First, if the production of any alternative vehicle technology a is more carbon-
320 intensive than the production of an ICEV, a fee is added to the purchase price of a , otherwise
321 a rebate is granted. Second, if the production of the energy source that is used in a over a ’s
322 lifetime is expected to create more CO₂ than the production of gasoline used in an ICEV,
323 then an additional fee is added to a ’s purchase price, while a rebate is provided otherwise.
324 For example, a fee is imposed on the production of BEVs, largely due to the energy- and
325 material-intensive battery. This fee is increasing with the growing carbon price (although
326 partially mitigated by the falling carbon intensity of production), from about 9–15 USD/BEV
327 in 2021 to about 120–210 USD/BEV in 2050, depending on vehicle and battery size. A rebate
328 is however granted due to the production of electricity that the BEV is expected to charge over

329 its lifetime. This rebate is growing strongly each year as electricity quickly decarbonizes —
330 from about 400 USD/BEV in 2021 to \sim 2,600 USD/BEV in 2050 (Supplementary Figure 5
331 and Supplementary Table 10). This way, these fees or credits become part of the decision-
332 making process of vehicle manufacturers and consumers, and therefore influence both vehicle
333 production and sales in Yale–NEMS.

334 Note that due to the large uncertainties involved we do not attempt to estimate the costs
335 of electric vehicle chargers [35] (especially when allocating a certain fraction of the cost of
336 public chargers to individual BEVs and PHEVs), nor do we attempt to estimate how strongly
337 consumers would discount future costs [43]. We do however acknowledge that these factors
338 could impact consumer choice. Since we wish to present our results in isolation of these factors
339 we leave it for future research to quantify the influence of these effects.

340 **Inputs from Yale–NEMS into LCA (second iteration)**

341 In a second iteration of the LCA model, total vehicle sales by technology and segment, and
342 total energy use by energy carrier are extracted from Yale–NEMS and fed back into the LCA
343 model. In addition, any vehicle characteristics, such as vehicle weights, that have been altered
344 by the the life-cycle carbon price implemented in Yale–NEMS (Supplementary Figure 10),
345 are updated in the LCA model accordingly. As a result of the second LCA model run, total
346 indirect emissions of vehicle and energy production over time are obtained (Supplementary
347 Table 16). Tailpipe emissions and emissions from electricity use are taken directly from Yale-
348 NEMS (Supplementary Table 16).

349 **Data availability**

350 The most important input data and model outputs are made available in an accompanying
351 spreadsheet file. A version of the LCA model used in this work is available in an open repository
352 at Zenodo: <https://doi.org/10.5281/zenodo.3896664>.

353 **Acknowledgements**

354 We thank Pei Huang at the Leibniz Centre for European Economic Research, Brian Andrew
355 Reed at Stanford University, and Paul Kondis at the US Energy Information Administration
356 for assistance with NEMS.

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Figures

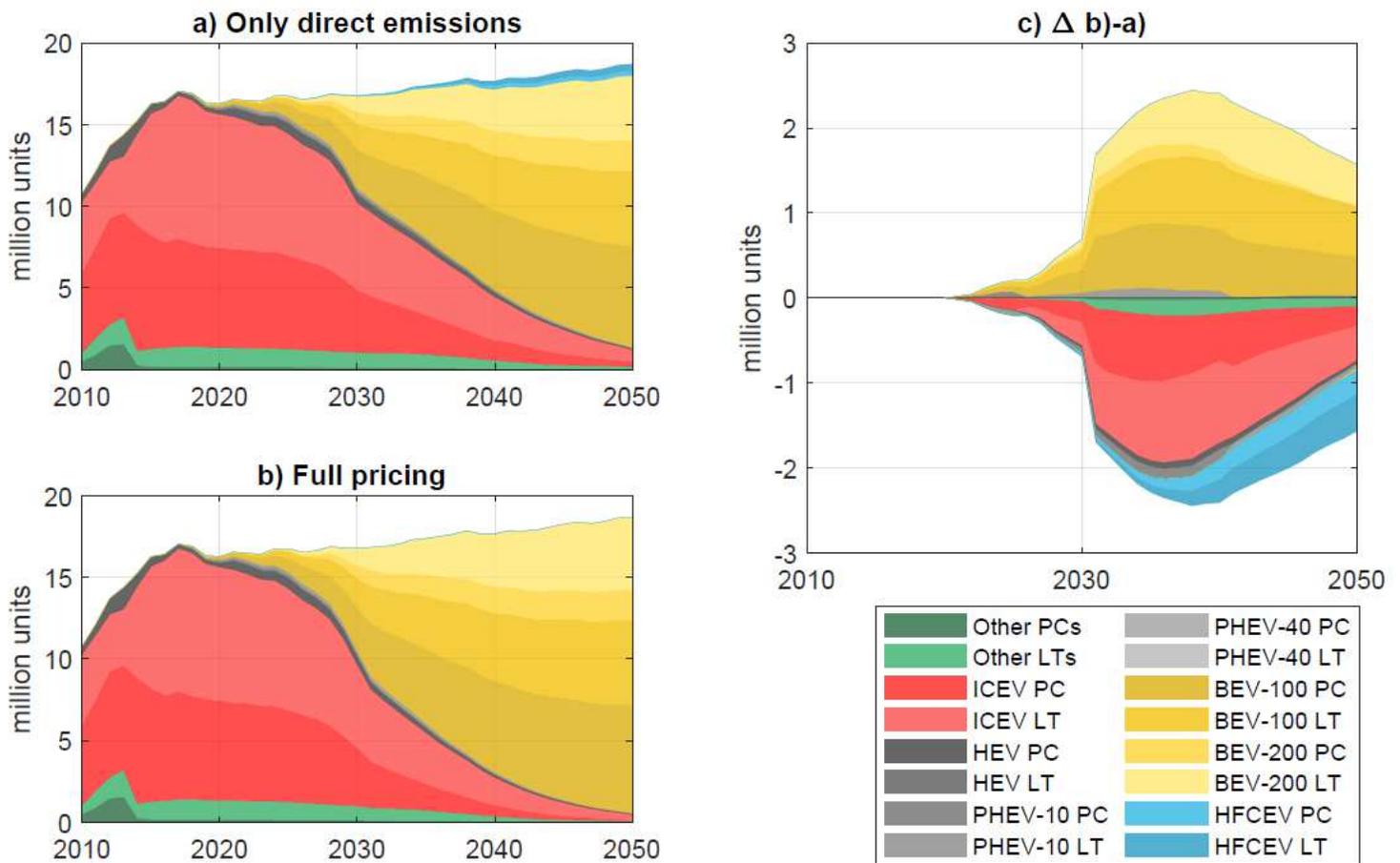


Figure 1

Optimal vehicle choice under direct-emissions-only pricing (a) and full emissions pricing (b). (c) Differences in vehicle choice between (b) and (a). PC=passenger car; LT=light truck; ICEV=internal combustion engine vehicle; HEV=hybrid electric vehicle; PHEV=plug-in hybrid electric vehicle; BEV=battery electric vehicle; HFCEV=hydrogen fuel cell electric vehicle; -10=10-mile electric range.

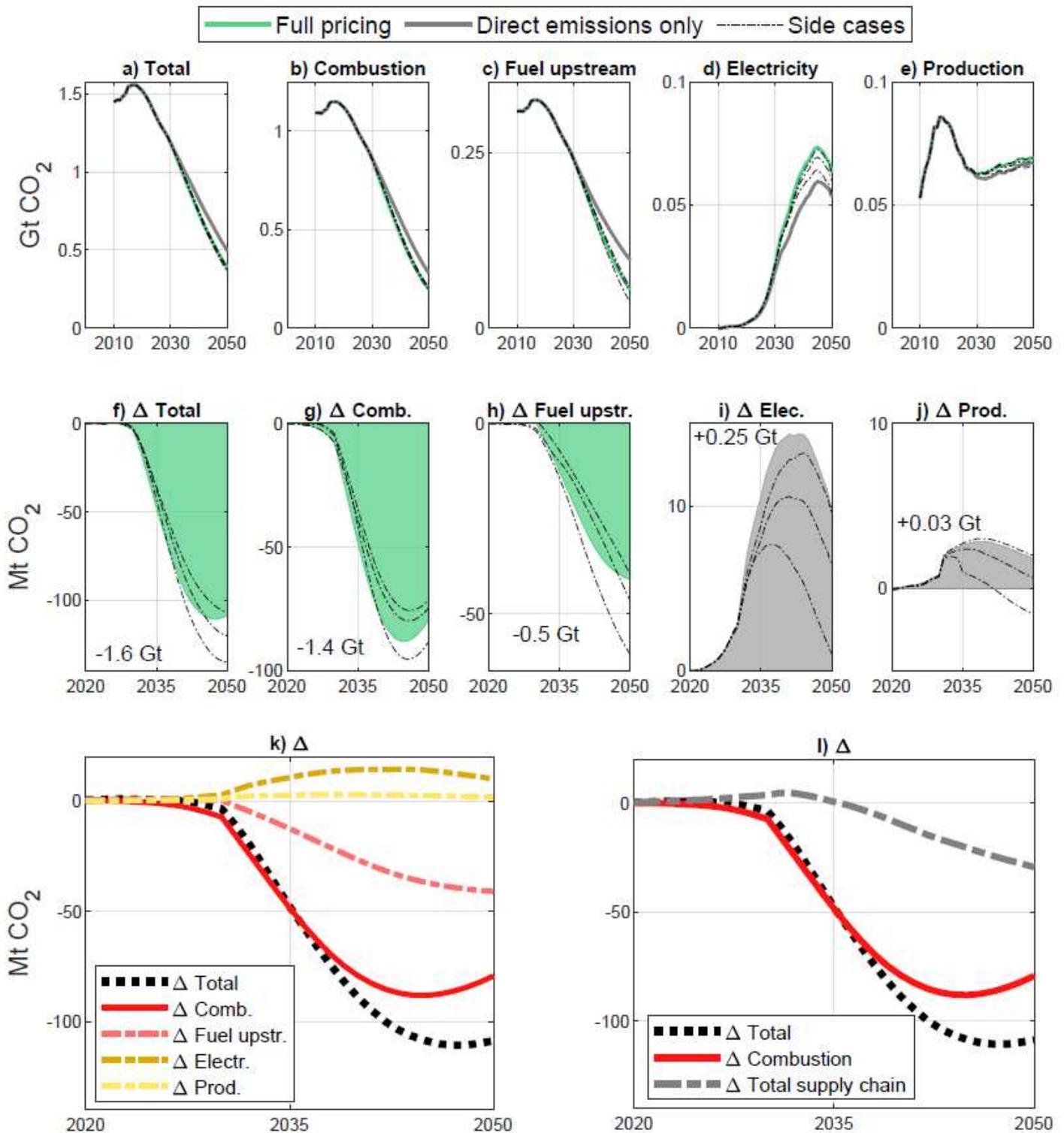


Figure 2

Life-cycle CO₂ emissions of the US light vehicle fleet, total (a) and broken down by life-cycle stage (b-e) when fully pricing emissions and when only pricing direct emissions. Differences in emissions between full and direct-emissions-only pricing (f-l). Dotted lines (a-j) illustrate results from side cases (see Supplementary Figure 6).

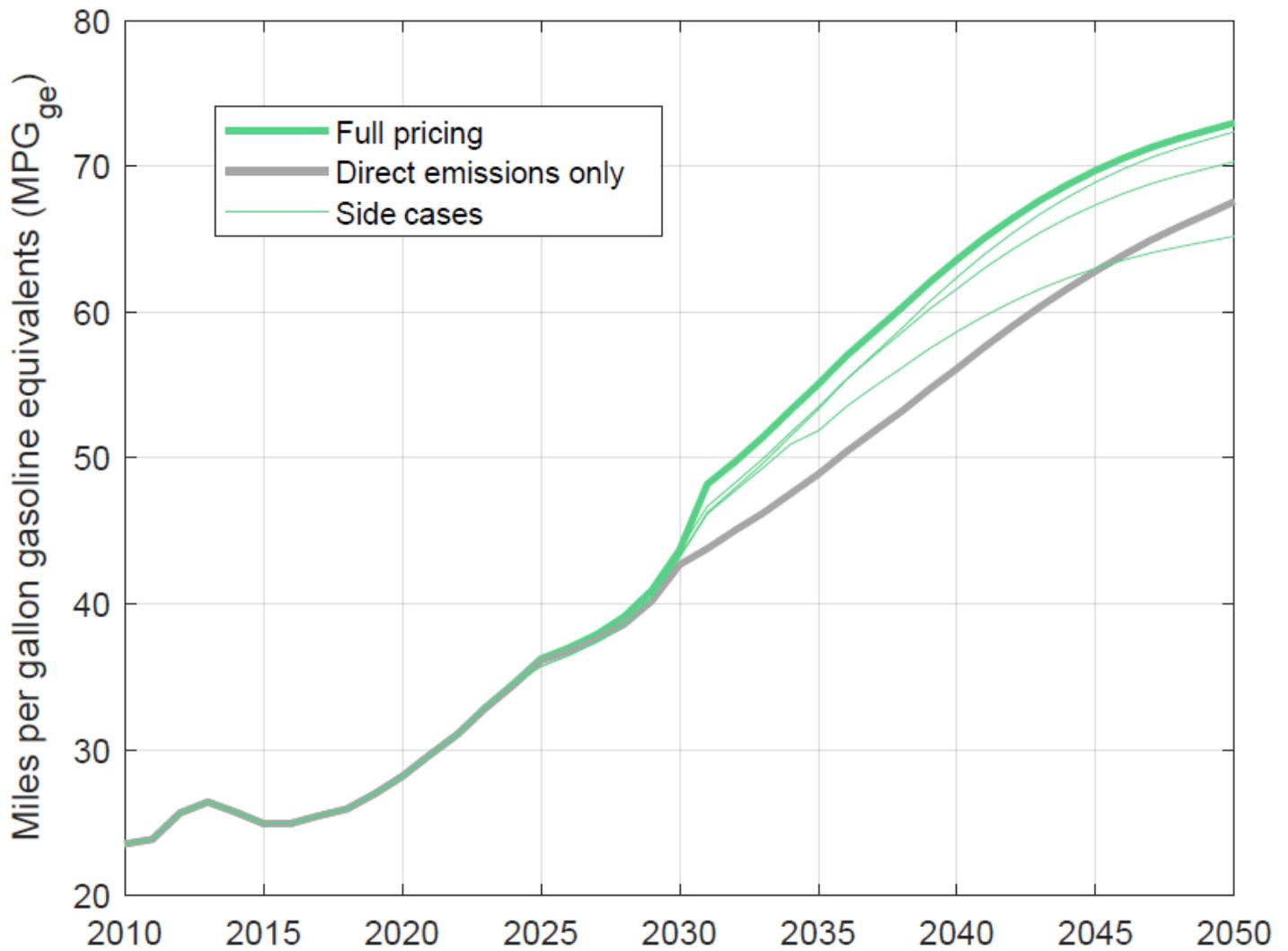


Figure 3

Average real-world fuel economy of the US light vehicle fleet when all emissions are priced and when only direct emissions are priced. The thin green lines show the range of results from the side cases.

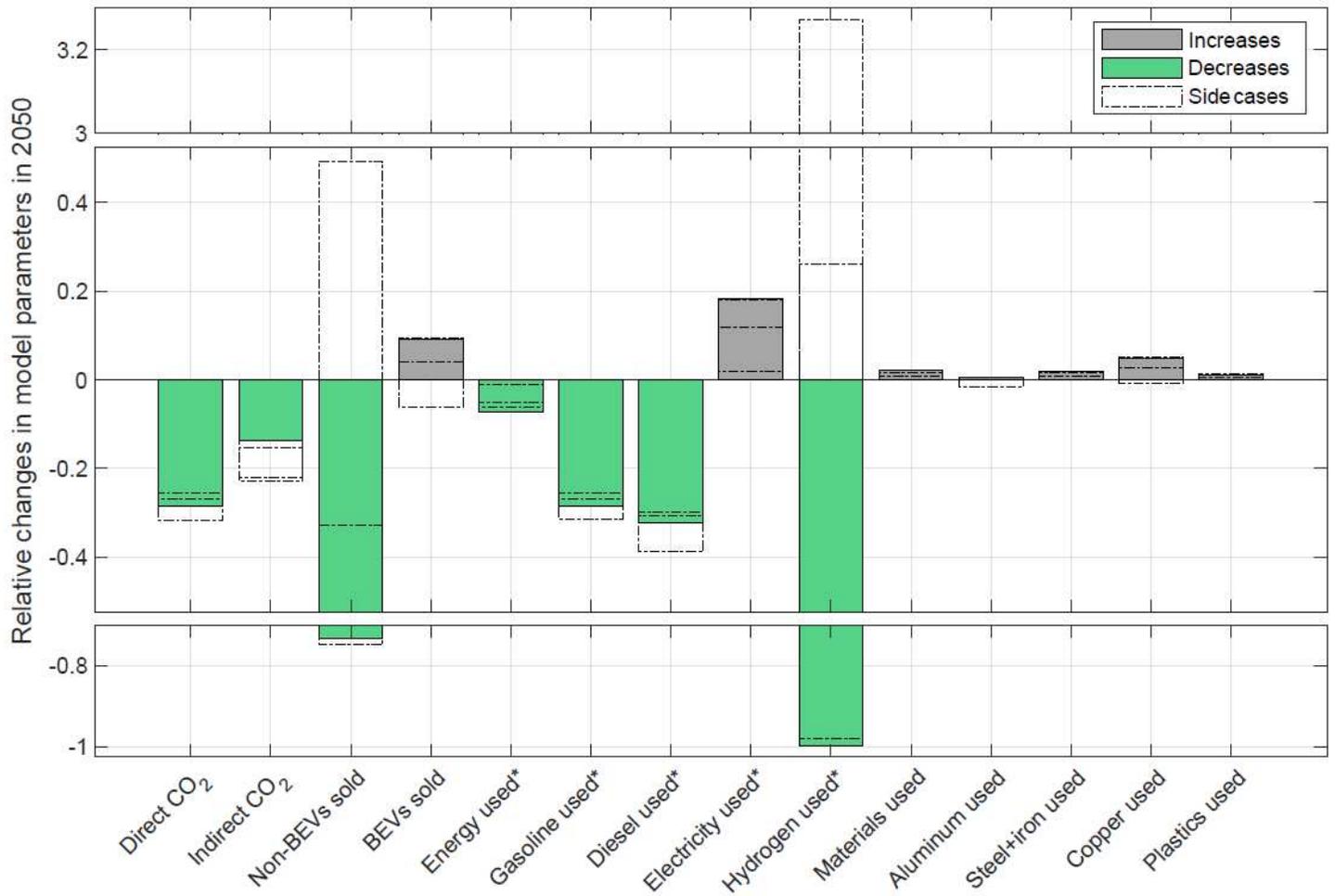


Figure 4

Changes in model parameters due to full pricing relative to direct-emissions-only pricing in 2050 (colored bars). The hollow bars show the normalized differences of the side cases relative to direct-emissions-only pricing in 2050. BEV=battery electric vehicle; *=on-board energy.

Supplementary Files

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