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

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

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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 CO_2 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 CO_2 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 potentially growing emissions from energy production and vehicle manufacturing have been voiced [2, 3, 4]. These emissions occur off–site, or indirectly, and include generation of electricity to charge electric vehicles, in this work ∼66–86 g CO_2 per electric–vehicle km driven in 2020, and production of vehicles, here ∼16–38 g CO_2 per vehicle–km driven in 2020 (Supplementary Table 20 and Supplementary Figure 2). It has only recently been recognized that the emissions for producing gasoline can range significantly, from below 15 to ∼320 g CO_2/kWh in 2015 [5, 6], compared to direct tailpipe emissions of about 250 g CO_2/kWh. Taken together, indirect emissions accounted for ∼26% of the 1.5 Gt CO_2 caused by the US LDV fleet in 2020 (Supplementary Table 16).

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

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

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

[1] We 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.

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

Here we address these knowledge gaps by applying a novel conceptual framework by Creutzig et al. [26], which focuses on demand–side solutions to climate change mitigation. We specify this framework for comprehensive climate change mitigation analysis of an important demand–side sector, the US LDV sector. We illustrate a set of climate–change mitigation scenarios, primarily for the vehicles sector, but also consider responses in important upstream sectors, such as changes to material production, vehicle manufacturing and electricity generation. These responses are normally not fully captured in NEMS. Thus, we soft–link NEMS to a detailed LCA model (see Methods). We assume that the production cost of electric vehicle batteries and renewable electricity generators fall quickly, in line with recent estimates (see Methods). We further introduce a carbon price in the transport sector in 2021 which linearly increases up to 150 USD/t CO_2 (constant 2016$) by 2050 (Supplementary Table 9). This level is required for an LDV fleet commensurate with the US nationally determined contribution under the Paris Agreement (see Methods). For simplicity and to provide insight, we run our cases with no carbon pricing on other sectors. The difference between the two main scenarios is that either emissions from (1) the tailpipe, or (2) the entire vehicle supply chain are accounted, priced and optimized for. The implications are both surprising and significant. The strongest effect of pricing both tailpipe and indirect emissions is that the system would be pushed to an even faster phase–out of gasoline–powered vehicles, leading to a scenario minimizing both tailpipe and indirect emissions.

Results

Optimal vehicle choice

While pricing only direct tailpipe emissions already leads to a nearly complete phase–out of ICEVs (Figure 1a), the transition is accelerated under full emissions pricing (Figure 1b). In addition, HFCEVs are avoided entirely under full pricing due to the high emissions penalty of producing hydrogen from natural gas. Lower sales of ICEVs, HFCEVs and other powertrains (mostly hybrids and flex–fuel vehicles running both on conventional liquid fuels and biofuels) are compensated by higher BEV sales. This substitution pattern peaks around 2040 with about 2.4 million units (Figure 1c). In absolute terms, sales of ICEV light trucks are reduced the most, and compensated by BEV cars and trucks. The cumulative amount of avoided ICEVs and HFCEVs amounts to nearly 29 and 9 million units. We explore a range of side cases in which (a) only energy–chain emissions instead of full life–cycle emissions are priced, (b) hydrogen production becomes carbon–neutral by 2050, (c) HFCEVs become cost–competitive with BEVs, as well as different combinations thereof. We display three of these cases in Supplementary Figure 6.

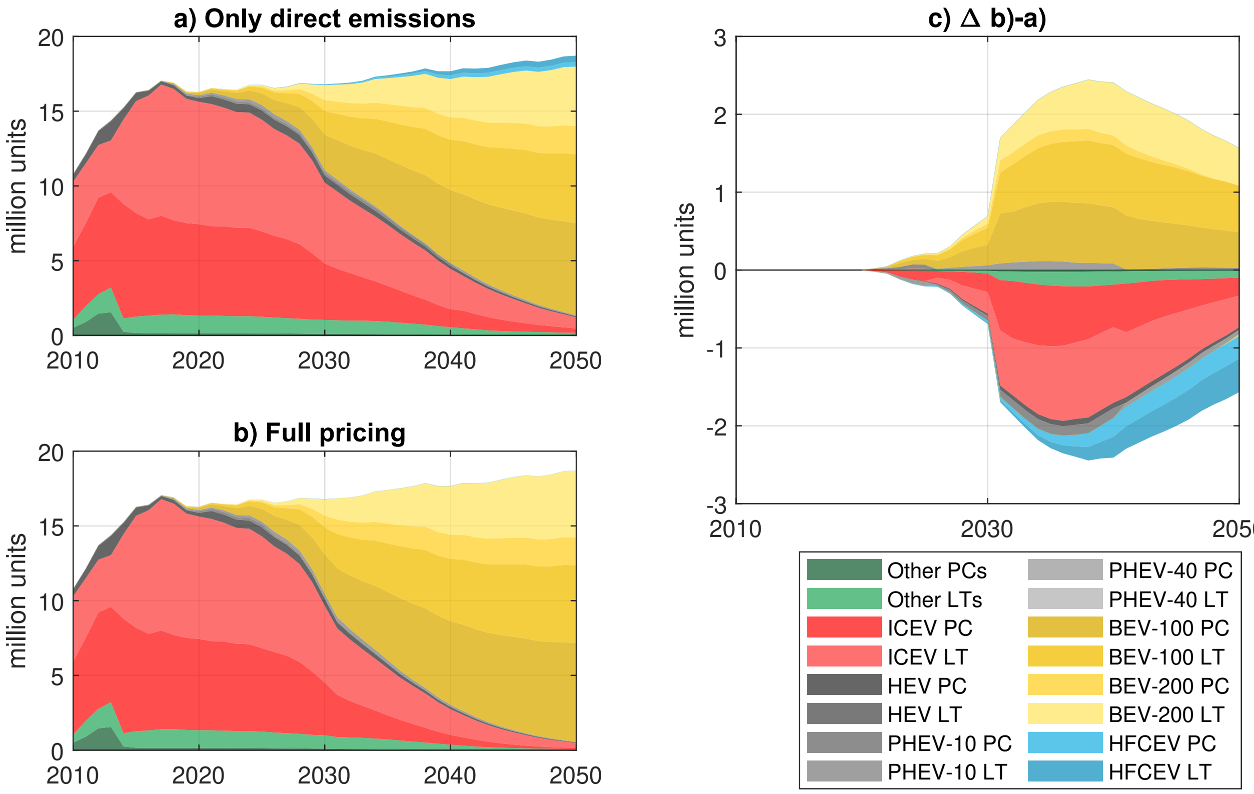

Figure 1: Optimal vehicle choice under direct–emissions–only pricing (a) and full emissions pricing (b). (c) Differences in vehicle choice between (b) and (a). PC=passenger car; LT=light truck; ICEV=internal combustion engine vehicle; HEV=hybrid electric vehicle; PHEV=plug–in hybrid electric vehicle;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

The mentioned substitutions of technologies lead to substantially lower cumulative life–cycle emissions through 2050 (– 1.6 Gt CO_2, Figure 2a and 2f), largely driven by lower fuel combustion (– 1.4 Gt CO_2, Figure 2b and 2g) and lower production of gasoline and hydrogen (– 0.5 Gt CO_2, Figure 2c and 2h). While stronger sales of BEVs lead to higher electricity emissions (Figure 2d and i), these are however relatively small compared to lower emissions from fuel production (+ 0.25 Gt CO_2 vs. – 0.5 Gt CO_2, Figure 2k). Finally, since BEVs are material intensive, an additional 30 Mt CO_2 embodied in vehicle production can be observed. However, these could be more than compensated by ambitious recycling and reuse practices (+ 0.03 vs. – 0.5 Gt CO_2, Supplementary Figure 3). We explore a range of side cases (Supplementary

Figure 6) which show some variation in their potential for emission reductions (also see dotted lines in Figure 2a–j) but the overall trend is robust among all cases. Accordingly, additional cumulative life–cycle emission reductions can vary between – 1.4 to – 1.7 Gt CO_2 across all cases (see dotted lines in Figure 2f) on top of emission reductions already achieved under pricing direct emissions only. In Figure 2k, the differences in emissions between 'full pricing' and 'direct–emissions–only pricing' are once more plotted by life cycle stage, while in Figure 2l, all sources of indirect emissions, i.e. production of fuels, electricity and vehicles, are categorized as such. It becomes apparent that 'full pricing' not only leads to reduced tailpipe emissions, but also to lower indirect supply chain emissions, at least after about 2035.

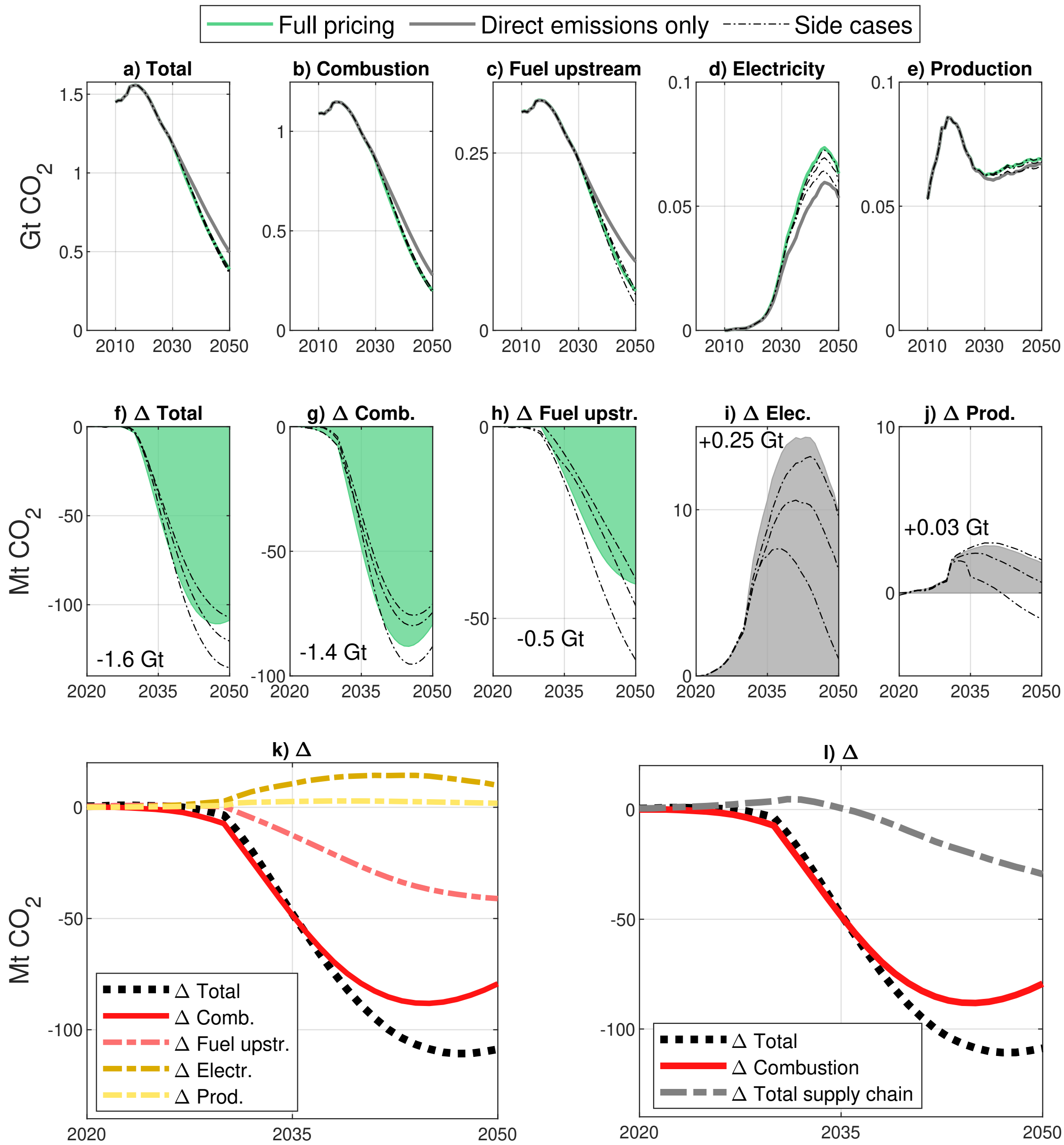

Figure 2: Life–cycle CO_2 emissions of the US light vehicle fleet, total (a) and broken down by life–cycle stage (b–e) when fully pricing emissions and when only pricing direct emissions. Differences in emissions between full and direct–emissions–only pricing (f–l). Dotted lines (a–j) illustrate results from side cases (see Supplementary Figure 6).

Fleet efficiency

The future of the Corporate Average Fuel Economy (CAFE) standard is currently highly uncertain and we therefore do not model changes to CAFE after 2025. While the Trump administration enacted the Safer Affordable Fuel Efficient (SAFE) standard in 2018, which weakened CAFE requirements through 2026, the Biden campaign announced a plan to consider a more ambitious CAFE[2] but further details are unknown at the time of writing. Despite the fact that CAFE is not further tightened after 2025 in our model, average real–world fuel economy [27] of the fleet continues to improve greatly in all scenarios, even after 2025 (Figure 3). This can be explained by the strong market penetration of BEVs. When full life–cycle emissions are optimized for, average fuel economy is even higher compared to direct–emissions–only pricing due to the accelerated penetration of BEVs. Side cases with higher shares of HFCEVs however exhibit significantly lower average fuel economies (Supplementary Table 12). Other fleet characteristics, such as average vehicle weight, deployment of lightweighting through material substitution, segment shares, and total travel demand, are less impacted in the different scenarios (Supplementary Figure 9).

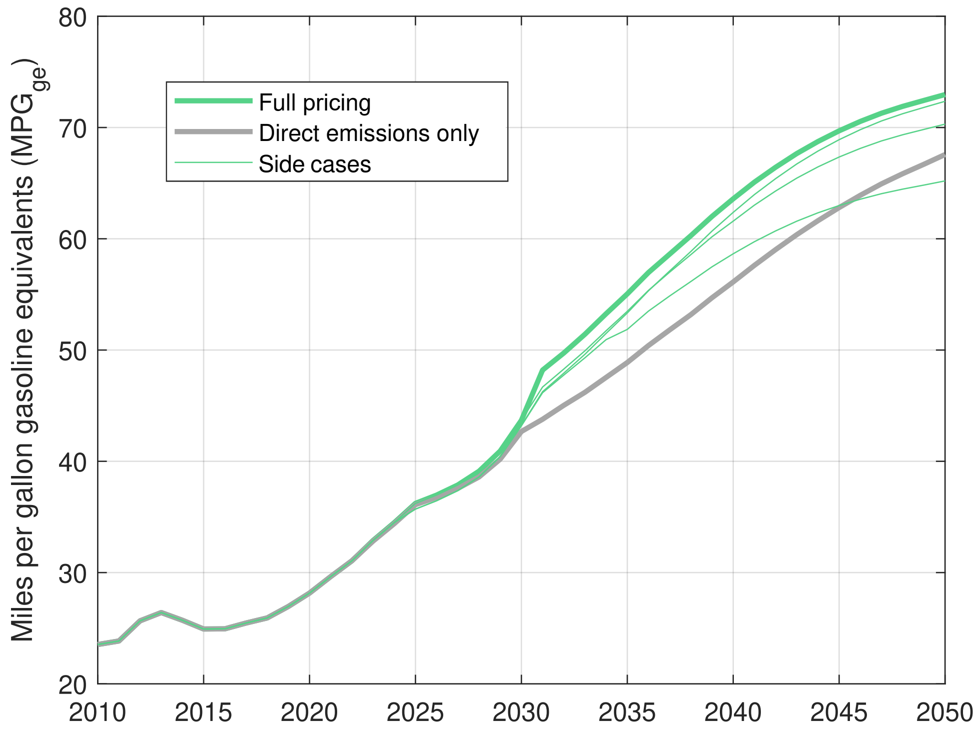

Figure 3: Average real–world fuel economy of the US light vehicle fleet when all emissions are priced and when only direct emissions are priced. The thin green lines show the range of results from the side cases.

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

Resource use implications

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

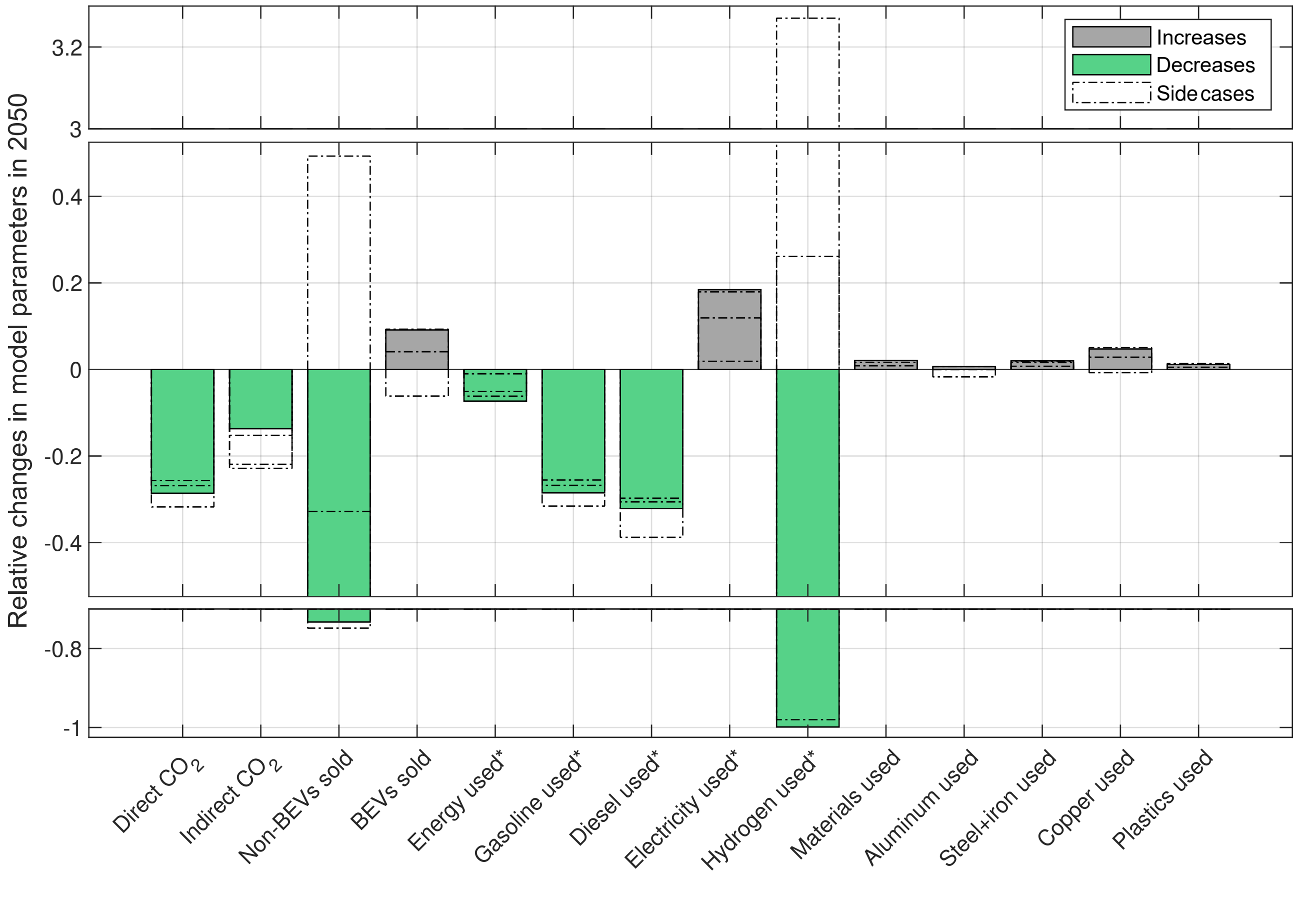

Figure 4: Changes in model parameters due to full pricing relative to direct–emissions–only pricing in 2050 (colored bars). The hollow bars show the normalized differences of the side cases relative to direct–emissions–only pricing in 2050. BEV=battery electric vehicle; *=on–board energy.

In absolute terms, the difference between the two main scenarios is that under full pricing, cumulative gasoline consumption through 2050 is reduced by 0.15 trillion gallons or 0.6 trillion liters compared to direct–emissions–only pricing. This corresponds to three years of current (2019) annual US gasoline consumption (55 million gallons/0.2 trillion liters).[3] Similarly,

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

0.8 PWh (trillion kWh) of hydrogen are saved, while electricity consumption is higher by 3.2 PWh, roughly corresponding to the current annual amount of electricity end use in the US in 2019.[4] Cumulative material use for vehicle production is moderately higher, by about 24 Mt, which is chiefly driven by the larger stock of material–intensive BEVs. The higher material demand is partially mitigated by a slightly lower average vehicle weight (Supplementary Figure 10a). Material substitutions due to vehicle lightweighting (Supplementary Figure 10b) lead to a marginally higher use of aluminum and plastics, and a reduction of steel and iron. Overall, the largest absolute difference is due to the higher demand for stainless steel (+ 13.2 Mt), followed by copper (+ 3.1 Mt), aluminum (+ 1.6 Mt) and plastics (+ 1.2 Mt). Simultaneously, use of automotive steel and cast iron is lower, by 1.0 Mt. However, more ambitious recycling and reuse practices have the potential to more than offset the stronger demand for virgin materials, by about 740 Mt (Supplementary Note 1).

Adequacy of analyzed decarbonization measures

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

Discussion

There is remarkably little known about the extent to which indirect emissions shape cost–optimal decarbonization pathways [28] and vice versa. Previous work focusing on electricity supply reported a limited role of indirect emissions in optimized climate change mitigation scenarios [15, 17, 16]. Here we explore the role of indirect emissions in decarbonization efforts of the US passenger vehicle fleet and find that, in fact, they can significantly alter optimal climate change mitigation pathways. An important difference between the electricity supply sector and the LDV sector is that indirect emissions play a larger role, accounting for about a quarter of total life–cycle emissions already today. In our scenarios, indirect emissions make up almost half of total LDV sector CO_2 emissions in 2050 (44–49%) and about 24–29% of cumulative emissions over the 2010–2050 scenario time frame (Supplementary Table 16). For comparison, McDowall et al. report that indirect emissions would account for less than 10% of total life–cycle power plant emissions in 2050 in an optimal decarbonization scenario of the EU [16].

Although overall life–cycle emissions are significantly lower under full emissions pricing, 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

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

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

Our work represents a first step towards a holistic inclusion of dynamic life–cycle relationships in integrated modelling frameworks. Future research could include additional potentially important factors and processes, such as deployment of carbon capture and storage (CCS) at fuel refineries, differences in emission intensities of hydrocarbons, synthetic liquid fuels, net–negative emission pathways of energy production, and low–carbon steel production using hydrogen from renewable sources. Future research could also investigate the degree to which our results would differ in various regions of the world, or if additional pollutants, other than direct and indirect CO_2 emissions, were internalized in optimal pollution mitigation pathways.

Methods

Demand–side framework

We address calls for a stronger research focus on demand–side solutions for mitigating climate change [29]. Specifically, we apply and specify a novel, transdisciplinary demand–side assessment framework focusing on an important emitting sector [30]. Our framework addresses the following key areas: (1) End–use context: we focus on demand–side solutions, with the US LDV fleet as a case study. (2) Technology: we use industrial ecology methods to model full life cycle CO_2 emissions and costs of all major established and emerging vehicle technologies. This enables us to test the potential of different technological mitigation measures along the entire 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

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

Integrated energy modelling

Our tool of choice is NEMS which is the model behind the well–known Annual Energy Outlook [31]. In this study, we use the NEMS code run on a server at Yale University (henceforth we call it "Yale–NEMS" at EIA's request) and slightly modified to output additional results [32, 33]. Yale–NEMS sets prices so that an equilibrium is obtained where annual energy supply equals energy demand through 2050. The main energy demand sectors are residential buildings, commercial buildings, transport and industry. Projections of economic drivers are provided exogenously while world energy prices, world energy supply and demand, and US energy imports and exports are calculated endogenously. Yale–NEMS provides a full account of CO_2 emissions across all industries and a range of air pollutants from vehicles and power plants.

Transport sector modelling

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

Here we make several refinements to Yale–NEMS' LDV submodule: We update vehicle costs in a bottom-up fashion using detailed cost estimates for all major vehicle components, such as engines, electric motors, transmissions, fuel cells, and hydrogen storage tanks [34, 35]. Further, costs of lithium–ion batteries start out at about 465 USD/kWh in 2016 and reach floor costs of ∼83 USD/kWh over the modelled time horizon due to economies of scale and technological development. This cost development is within the range of recent estimates [36].

Modelling upstream sectors

The electricity market module considers all major fossil and renewable generators, including conventional, and advanced coal and gas power plants with and without CCS, nuclear, hydro, solar thermal, solar photovoltaics (PV), and on– and offshore wind power. In our scenarios we assume that overnight capital costs of solar PV and onshore wind power plants fall from around 1,245 and 1,230 USD/kW in 2019 down to about 370 and 540 USD/kW by 2050 due to economies of scale and technological developments. This cost development is within the range of recent estimates [37, 38]. As a result, new power plant capacities are mainly provided by renewable electricity generators (Supplementary Figure 7), while fossil–fueled power plants retire (Supplementary Figure 8). Thus, renewables provide more than half of all electricity well before 2030 and more than three quarters by 2050. The remaining electricity demand in 2050 is mainly met by natural gas (16%) and nuclear power (6%), while coal is almost entirely phased out (1.5%, see Supplementary Figure 5 and Supplementary Table 18). A small percentage of electricity from coal is generated at CCS–equipped plants. Electricity is not only produced in the power supply sector but also in the residential and commercial end–use sectors — a feature that sets apart Yale–NEMS from other IEMs [21] — with the main technologies being rooftop solar PV and distributed natural gas. While electricity demand grows from almost four to more than six trillion kWh, an increase by more than half, electricity emissions fall from almost 2,400 to below 290 Mt CO_2, a reduction of 88%. As a result, the carbon intensity of the electricity mix falls by a factor of twelve, from 546 down to 45 g CO_2/kWh (Supplementary Figure 6 and Supplementary Table 18).

Determining a carbon price

In all scenarios, we introduce a price on carbon in the transport sector in 2021 which linearly increases up to 150 USD/t CO_2 by 2050 (constant 2016$, Supplementary Table 9) — a level required to meet the US nationally determined contribution under the Paris Agreement. The US is committed to reduce CO_2 emissions by 80% by 2050 relative to 2005. We assume that all sectors equally attempt to reduce their emissions by that percentage. According to the US EPA, direct CO_2 emissions from the US LDV fleet amounted to 1,180 Mt in 2005 [39]. The growing carbon price leads to a significant cost increase of energy carriers, especially of gasoline (Supplementary Figure 4). Combined with the cost reductions of electric vehicle batteries and renewable power plants, our assumed carbon price leads to reductions of direct CO_2 emissions on the order of 76–84% in 2050 relative to 2005, depending on the specific scenario (Supplementary Table 16).

Soft–linking Yale–NEMS with LCA

We soft–link Yale–NEMS to a detailed passenger vehicle LCA model [40] and iterate between the LCA model and Yale–NEMS until inputs and outputs converge between both models. The LCA model covers CO_2 emissions of all major technologies across the entire vehicle life cycle, including fuel production and combustion, electricity generation, material production and recycling, assembly and reuse of vehicle components, and lightweighting through material substitution.

Inputs from Yale–NEMS into LCA (first iteration)

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

Inputs from LCA into Yale–NEMS

The obtained carbon prices are then linked back to Yale–NEMS for consideration in the vehicle choice procedure of the LDV submodule. Specifically, carbon prices on indirect emissions are implemented in Yale–NEMS as a so–called 'feebate'. Feebates are regarded as one of the most effective policy instruments to reduce vehicle emissions [41, 42, 43]. Feebate systems impose a fee on vehicles with high CO_2 emissions and grant a rebate to low–carbon vehicles. Here we apply that design to both the production of vehicles and energy carriers separately, with two main steps. First, if the production of any alternative vehicle technology a is more carbon–intensive than the production of an ICEV, a fee is added to the purchase price of a, otherwise a rebate is granted. Second, if the production of the energy source that is used in a over a's lifetime is expected to create more CO_2 than the production of gasoline used in an ICEV, then an additional fee is added to a's purchase price, while a rebate is provided otherwise. For example, a fee is imposed on the production of BEVs, largely due to the energy– and material–intensive battery. This fee is increasing with the growing carbon price (although partially mitigated by the falling carbon intensity of production), from about 9–15 USD/BEV in 2021 to about 120–210 USD/BEV in 2050, depending on vehicle and battery size. A rebate is however granted due to the production of electricity that the BEV is expected to charge over its lifetime. This rebate is growing strongly each year as electricity quickly decarbonizes — from about 400 USD/BEV in 2021 to ∼2,600 USD/BEV in 2050 (Supplementary Figure 5 and Supplementary Table 10). This way, these fees or credits become part of the decision–making process of vehicle manufacturers and consumers, and therefore influence both vehicle production and sales in Yale–NEMS.

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

Inputs from Yale–NEMS into LCA (second iteration)

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

Data availability

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

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References

[1] IEA. CO_2 emissions from fuel combustion: Overview. International Energy Agency, Paris, 2020.

[2] Xin He, Shiqi Ou, Yu Gan, Zifeng Lu, Steven Victor Przesmitzki, Jessey Lee Bouchard, Lang Sui, Amer Ahmad Amer, Zhenhong Lin, Rujie Yu, et al. Greenhouse gas consequences of the China dual credit policy. *Nature Communications*, 11(1):1–10, 2020.

[3] Muhammad Imran Khan, Mehdi Shahrestani, Tasawar Hayat, Abdul Shakoor, and Maria Vahdati. Life cycle (well-to-wheel) energy and environmental assessment of natural gas as transportation fuel in Pakistan. *Applied Energy*, 242:1738 – 1752, 2019.

[4] Timothy Searchinger, Ralph Heimlich, Richard A Houghton, Fengxia Dong, Amani Elobeid, Jacinto Fabiosa, Simla Tokgoz, Dermot Hayes, and Tun-Hsiang Yu. Use of US croplands for biofuels increases greenhouse gases through emissions from land-use change. *Science*, 319(5867):1238–1240, 2008.

[5] Mohammad S Masnadi, Hassan M El-Houjeiri, Dominik Schunack, Yunpo Li, Jacob G Englander, Alhassan Badahdah, Jean-Christophe Monfort, James E Anderson, Timothy J Wallington, Joule A Bergerson, et al. Global carbon intensity of crude oil production. *Science*, 361(6405):851–853, 2018.

[6] Liang Jing, Hassan M El-Houjeiri, Jean-Christophe Monfort, Adam R Brandt, Mohammad S Masnadi, Deborah Gordon, and Joule A Bergerson. Carbon intensity of global crude oil refining and mitigation potential. *Nature Climate Change*, pages 1–7, 2020.

[7] Gunnar Luderer, Zoi Vrontisi, Christoph Bertram, Oreane Y. Edelenbosch, Robert C. Pietzcker, Joeri Rogelj, Harmen Sytze De Boer, Laurent Drouet, Johannes Emmerling, Oliver Fricko, Shinichiro Fujimori, Petr Havlík, Gokul Iyer, Kimon Keramidas, Alban Kitous, Michaja Pehl, Volker Krey, Keywan Riahi, Bert Saveyn, Massimo Tavoni, Detlef P. Van Vuuren, and Elmar Kriegler. Residual fossil CO_2 emissions in 1.5-2°C pathways. *Nature Climate Change*, 8(7):626–633, July 2018.

[8] Arnulf Grubler, Charlie Wilson, Nuno Bento, Benigna Boza-Kiss, Volker Krey, David L. McCollum, Narasimha D. Rao, Keywan Riahi, Joeri Rogelj, Simon De Stercke, Jonathan Cullen, Stefan Frank, Oliver Fricko, Fei Guo, Matt Gidden, Petr Havlík, Daniel Huppmann, Gregor Kiesewetter, Peter Rafaj, Wolfgang Schoepp, and Hugo Valin. A low energy demand scenario for meeting the 1.5°C target and sustainable development goals without negative emission technologies. *Nature Energy*, 3(6):515–527, June 2018.

[9] Detlef P. van Vuuren, Elke Stehfest, David E. H. J. Gernaat, Maarten van den Berg, David L. Bijl, Harmen Sytze de Boer, Vassilis Daioglou, Jonathan C. Doelman, Oreane Y. Edelenbosch, Mathijs Harmsen, Andries F. Hof, and Mariësse A. E. van Sluisveld. Alternative pathways to the 1.5C target reduce the need for negative emission technologies. *Nature Climate Change*, 8(5):391–397, May 2018.

[10] Joeri Rogelj, Drew Shindell, Kejun Jiang, Solomone Fifita, P Forster, Veronika Ginzburg, Collins Handa, Haroon Kheshgi, Shigeki Kobayashi, Elmar Kriegler, et al. Mitigation pathways compatible with 1.5°C in the context of sustainable development. Ch. 2 in: Special Report on Global Warming of 1.5°C. Intergovernmental Panel on Climate Change, 2018.

[11] Stefan Pauliuk, Anders Arvesen, Konstantin Stadler, and Edgar G. Hertwich. Industrial ecology in integrated assessment models. *Nature Climate Change*, 7(1):13–20, jan 2017.

[12] Felix Creutzig, Alexander Popp, Richard Plevin, Gunnar Luderer, Jan Minx, and Ottmar Edenhofer. Reconciling top-down and bottom-up modelling on future bioenergy deployment. *Nature Climate Change*, 2(5):320–327, 2012.

[13] Paul Wolfram and Edgar Hertwich. Representing vehicle-technological opportunities in integrated energy modeling. *Transportation Research Part D: Transport and Environment*, 2019.

[14] Graham Palmer. A Biophysical Perspective of IPCC Integrated Energy Modelling. *Energies*, 11(4):839, 2018.

[15] Michaja Pehl, Anders Arvesen, Florian Humpenöder, Alexander Popp, Edgar G. Hertwich, and Gunnar Luderer. Understanding future emissions from low-carbon power systems by integration of life-cycle assessment and integrated energy modelling. *Nature Energy*, 2:939–945, 2017.

[16] Will McDowall, Baltazar Solano Rodriguez, Arkaitz Usubiaga, and José Acosta Fernández. Is the optimal decarbonization pathway influenced by indirect emissions? Incorporating indirect life-cycle carbon dioxide emissions into a European TIMES model. *Journal of Cleaner Production*, 170:260–268, 2018.

[17] Joana Portugal-Pereira, Alexandre C. Köberle, Rafael Soria, André F. P. Lucena, Alexandre Szklo, and Roberto Schaeffer. Overlooked impacts of electricity expansion optimisation modelling: The life cycle side of the story. *Energy*, 115:1424–1435, November 2016.

[18] Hannah E. Daly, Kate Scott, Neil Strachan, and John Barrett. Indirect co_2 emission implications of energy system pathways: Linking IO and TIMES models for the UK. *Environmental Science & Technology*, 49(17):10701–10709, 2015. PMID: 26053304.

[19] K Scott, H Daly, J Barrett, and N Strachan. National climate policy implications of mitigating embodied energy system emissions. *Climatic Change*, 136(2):325–338, 2016.

[20] Laurent Vandepaer, Evangelos Panos, Christian Bauer, and Ben Amor. Energy system pathways with low environmental impacts and limited costs: Minimizing climate change

impacts produces environmental cobenefits and challenges in toxicity and metal depletion categories. *Environmental Science & Technology*, 54(8):5081–5092, 2020.

[21] David EHJ Gernaat, Harmen-Sytze de Boer, Louise C Dammeier, and Detlef P van Vuuren. The role of residential rooftop photovoltaic in long-term energy and climate scenarios. *Applied Energy*, 279:115705, 2020.

[22] Antoine Boubault, Seungwoo Kang, and Nadia Maïzi. Closing the TIMES integrated assessment model (TIAM-FR) raw materials gap with life-cycle inventories. *Journal of Industrial Ecology*, 2018.

[23] Gunnar Luderer, Michaja Pehl, Anders Arvesen, Thomas Gibon, Benjamin L Bodirsky, Harmen Sytze de Boer, Oliver Fricko, Mohamad Hejazi, Florian Humpenöder, Gokul Iyer, et al. Environmental co-benefits and adverse side-effects of alternative power sector decarbonization strategies. *Nature Communications*, 10(1):1–13, 2019.

[24] Sebastian Rauner, Nico Bauer, Alois Dirnaichner, Rita Van Dingenen, Chris Mutel, and Gunnar Luderer. Coal-exit health and environmental damage reductions outweigh economic impacts. *Nature Climate Change*, 10(4):308–312, 2020.

[25] Max W Callaghan, Jan C Minx, and Piers M Forster. A topography of climate change research. *Nature Climate Change*, 10(2):118–123, 2020.

[26] Felix Creutzig, Joyashree Roy, William F. Lamb, Inês M. L. Azevedo, Wändi Bruine de Bruin, Holger Dalkmann, Oreane Y. Edelenbosch, Frank W. Geels, Arnulf Grubler, Cameron Hepburn, Edgar G. Hertwich, Radhika Khosla, Linus Mattauch, Jan C. Minx, Anjali Ramakrishnan, Narasimha D. Rao, Julia K. Steinberger, Massimo Tavoni, Diana Ürge Vorsatz, and Elke U. Weber. Towards demand-side solutions for mitigating climate change. *Nature Climate Change*, 8(4):260–263, April 2018.

[27] D. L. Greene, A. Khattak, J. Liu, J. L. Hopson, X. Wang, and R. Goeltz. How do motorists' own fuel economy estimates compare with official government ratings? A statistical analysis. Howard H. Baker Jr. Center for Public Policy, 2015.

[28] Anders Arvesen, Gunnar Luderer, Michaja Pehl, Benjamin Leon Bodirsky, and Edgar G Hertwich. Deriving life cycle assessment coefficients for application in integrated assessment modelling. *Environmental Modelling & Software*, 99:111–125, 2018.

[29] Charlie Wilson, Arnulf Grubler, Kelly S. Gallagher, and Gregory F. Nemet. Marginalization of end-use technologies in energy innovation for climate protection. *Nature Climate Change*, 2:780, October 2012.

[30] Felix Creutzig, Joyashree Roy, William F Lamb, Inês ML Azevedo, Wändi Bruine De Bruin, Holger Dalkmann, Oreane Y Edelenbosch, Frank W Geels, Arnulf Grubler,

Cameron Hepburn, et al. Towards demand-side solutions for mitigating climate change. *Nature Climate Change*, 8(4):260, 2018.

[31] USEIA. Annual energy outlook 2020. U.S. Energy Information Administration, 2020.

[32] Kenneth Gillingham and Pei Huang. Is abundant natural gas a bridge to a low-carbon future or a dead-end? *The Energy Journal*, 40(2), 2019.

[33] Kenneth Gillingham and Pei Huang. The long-run environmental and economic impacts of electrifying waterborne shipping in the United States. *Environmental Science & Technology*, 2020.

[34] NAS. Transitions to alternative vehicles and fuels. National Academy of Sciences, 2013.

[35] Paul Wolfram and Nic Lutsey. Electric vehicles: Literature review of technology costs and carbon emissions. International Council on Clean Transportation, 2016.

[36] O. Y. Edelenbosch, A. F. Hof, B. Nykvist, B. Girod, and D. P. van Vuuren. Transport electrification: the effect of recent battery cost reduction on future emission scenarios. *Climatic Change*, Sep 2018.

[37] IRENA. Future of solar photovoltaic: Deployment, investment, technology, grid integration and socio-economic aspects (a global energy transformation: paper). International Renewable Energy Agency, Abu Dhabi, 2019.

[38] IRENA. Future of wind: Deployment, investment, technology, grid integration and socio-economic aspects (a global energy transformation: paper). International Renewable Energy Agency, Abu Dhabi, 2019.

[39] USEPA. Inventory of U.S. greenhouse gas emissions and sinks: 1990–2016. U.S. Environmental Protection Agency, 2018.

[40] P. Wolfram, Q. Tu, N. Heeren, S. Pauliuk, and E. Hertwich. Material efficiency and climate change mitigation of passenger vehicles. *Journal of Industrial Ecology*, 2020.

[41] F. Nemry, K. Vanherle, W. Zimmer, A. Uihlein, A. Genty, J.M. Rueda-Cantuche, I. Mongelli, F. Neuwahl, L. Delgado, F. Hacker, S. Seum, M. Buchert, and W. Schade. Feebate and scrappage policy instruments – environmental and economic impacts for the EU27. European Commission Joint Research Centre, Institute for Prospective Technological Studies, 2009.

[42] Cambridge Econometrics. The effectiveness of CO_2–based feebate systems in the European passenger vehicle market context – an analysis of the Netherlands and the UK. Cambridge Econometrics. A report for the International Council on Clean Transportation, 2013.

[43] David L Greene, Philip D Patterson, Margaret Singh, and Jia Li. Feebates, rebates and gas-guzzler taxes: a study of incentives for increased fuel economy. *Energy Policy*, 33(6):757–775, 2005.

Figures

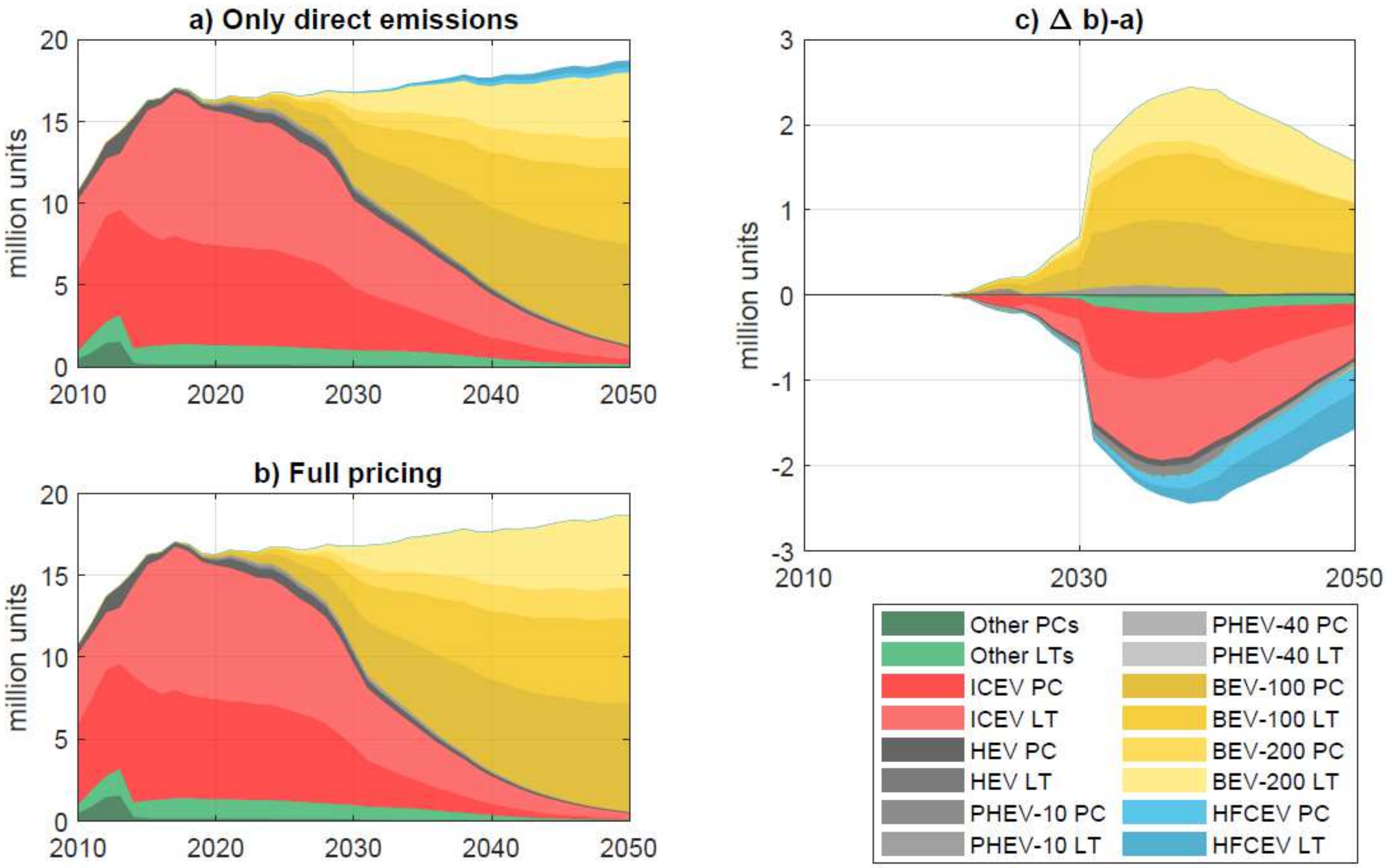

Figure 1

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.

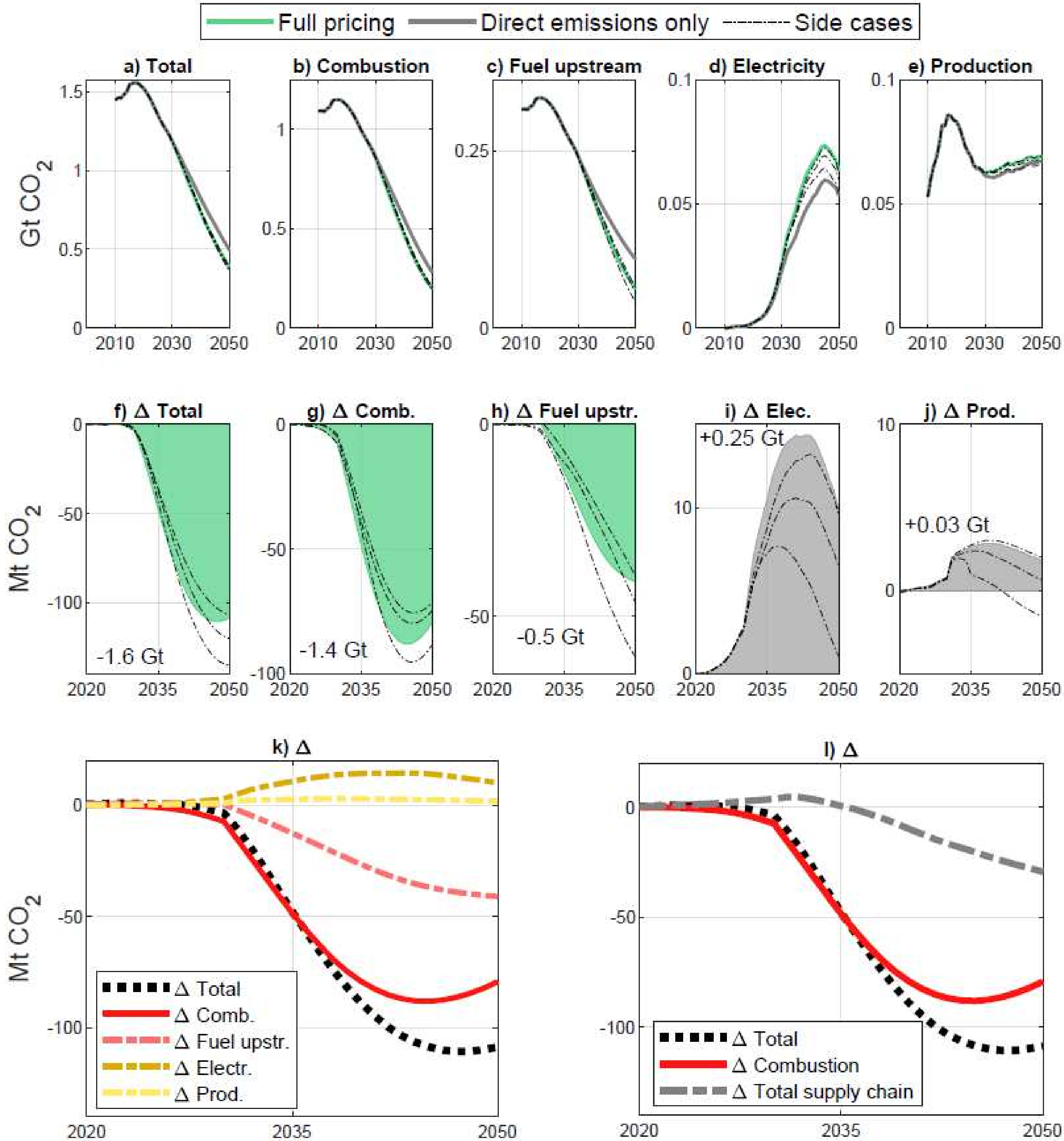

Figure 2

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).

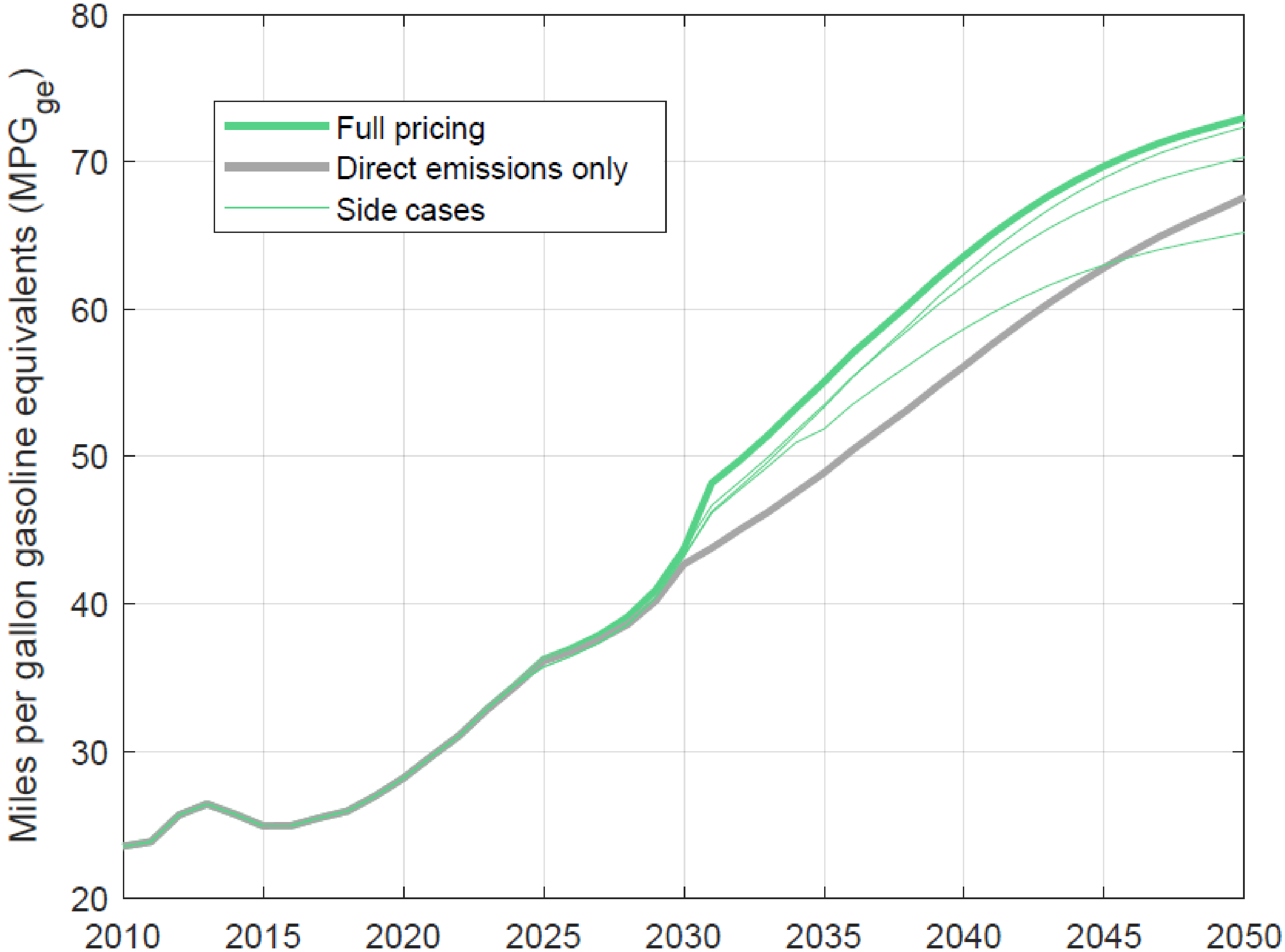

Figure 3

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.

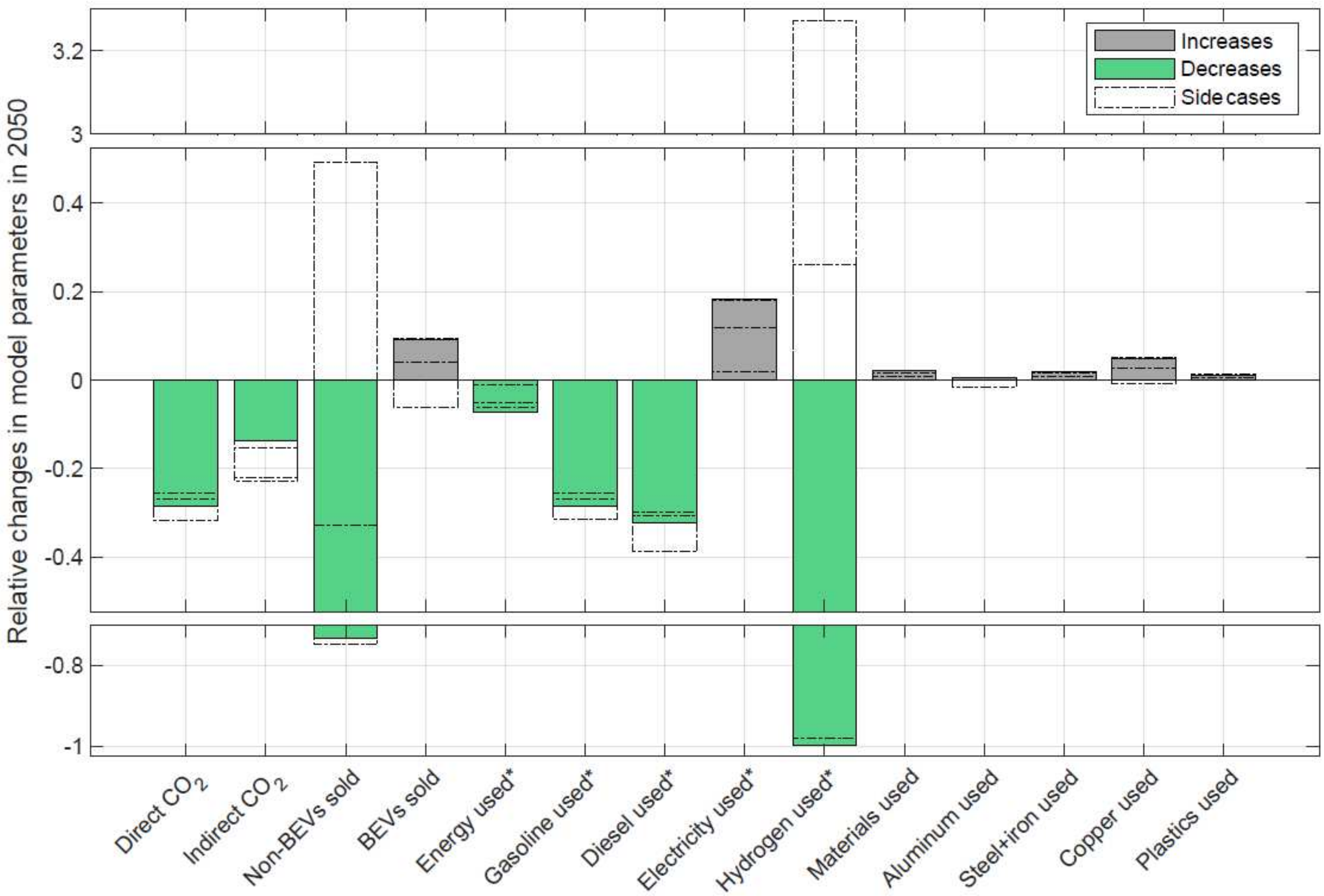

Figure 4

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

This is a list of supplementary files associated with this preprint. Click to download.

- USLDVNEMSSI.pdf
- WolframESM.xlsx