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Material efficiency and climate change mitigation of passenger vehicles

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Abstract

A transition to electric vehicles and renewable energy is currently underway but may not be rapid enough in order to reach ambitious climate change mitigation targets. Therefore, additional, preferably instantaneous, measures are needed for quick emission reductions, which is where material efficiency (ME) could constitute a promising solution. ME strategies include but are not limited to vehicle lightweighting through material substitution, increased recycling of materials, reuse and remanufacturing of vehicle components, vehicle downsizing (switching to a smaller vehicle), and more intensive use by means of increased vehicle occupancy through sharing practices. While recent analyses have focused on a narrow subset of ME strategies, we find striking differences in the overall potential of different measures to decrease vehicular carbon footprints. Downsizing and more intensive use offer the largest mitigation potential but strongly depend on consumer behavior and are highly sensitive to modeling assumptions. Combined, the analyzed strategies can achieve emission reductions of up to 57% over the life cycle of a single vehicle, which is comparable to up to 83% achieved through a shift to low-carbon energy supply. ME can cut carbon footprints of already efficient vehicles charging renewable electricity by half again. This makes ME both an excellent short-term solution for climate change mitigation targeting the light-vehicle sector but also an important complementary strategy to the long-term transition toward electric vehicles and renewable energy supply. This article met the requirements for a gold-gold *JIE* data openness badge described at http://jie.click/badges.

KEYWORDS
carbon footprinting, climate change, electric vehicles, industrial ecology, life-cycle assessment (LCA), materials efficiency

1 | INTRODUCTION

Climate change mitigation requires a rapid transition toward low-carbon energy supply and demand (IPCC, 2018; Wilson, Grubler, Gallagher, & Nemet, 2012). The shift to electric vehicles and renewable energy supply is already underway in many regions of the world and can potentially lead to significant emissions reductions (IEA, 2019). However, vehicles and power plants have long lifetimes, typically around 10+ and 40+ years (Erickson, Kartha, Lazarus, & Tempest, 2015), causing considerable lag in the turnover of the current stock of equipment (Keith, Houston, & Naumov, 2019; Seto et al., 2016). In addition, alternative vehicle technologies face several barriers, such as lacking infrastructure, high battery cost, and consumer skepticism (NAS, 2015). As a result, sizeable reductions in GHG emissions may not be achieved for decades to come (Hill, Heidrich, Creutzig, and Blythe, 2019; OPEC, 2019) which could threaten compliance with the 1.5°C and 2°C global warming targets. Therefore, additional measures are needed that can accelerate reductions in GHG emissions, which is where ME promises to be a viable solution. Measures, such as lightweighting or downsizing, can be more easily integrated with existing automotive supply chains (Shanmugam et al., 2019) and their implementation often requires short leadtimes (Lutsey, 2012). We there fore analyze to what extent ME strategies could decrease emissions from conventional and electrified light vehicles and compare these to possible emissions cuts from renewable energy supplied to the light-vehicle sector.

1.1 | Material efficiency for vehicles

ME strategies are broadly defined as a set of technical measures and/or policy interventions that can lead to a significant reduction in the use of materials (Allwood, Ashby, Gutowski, & Worrell, 2011; Hertwich et al., 2019; Hertwich, Lifset, Pauliuk, & Heeren, 2020). Common ME strategies described in the literature include lightweighting, recycling, remanufacturing, downsizing, and more intensive use (Allwood et al., 2011). There can be synergies or trade-offs between GHG emissions from materials and from operational energy use. On the one hand, vehicle downsizing can reduce material use and simultaneously improve fuel economy. On the other hand, materials used for lightweighting usually require more energy to produce than steel. Further, the potential effects of ME strategies can be described at a more detailed technology scale, or at a broader economy–environment scale (Wolfram & Hertwich, 2019). Below we define each strategy and discuss some of the existing literature on each measure starting from the lowest scale (individual technology) and ending at the highest (systemic) level:

- *Lightweighting* usually refers to a substitution of heavier materials, such as steel, with lighter materials, such as aluminum, increasing a vehicle's fuel economy. However, this often entails increasing emissions from vehicle production (Kim & Wallington, 2013). Yet, higher production impacts can be mediated by powertrain resizing for performance equivalency (Kim and Wallington, 2013) and by deploying recycled materials (Kim, McMillan, Keoleian, & Skerlos, 2010). Life-cycle assessments (LCAs) of individual vehicles and entire fleets have focused on the effects of electrification and lightweighting under regional conditions (He et al., 2020; Milovanoff et al., 2019 Wu et al., 2019). Economy-wide studies recently incorporated the effects of lightweighting on fuel economy improvements of the vehicle fleet, often in combination with other strategies, such as fuel economy or biofuel targets, but have not taken into account the increase in emissions from materials production (Heywood et al., 2015; USEIA, 2019).
- *Recycling* is defined here as the use of recycled materials in the production of vehicles. Recycling of end-of-life vehicles is quite common in many countries around the world (Sakai et al., 2014) but recovered materials often are not functionally recycled, meaning that they are used for lower-quality applications. Kim et al. (2010) assessed to what degree open- and closed-loop recycling could offset increased vehicle production emissions from lightweighting an individual vehicle. Employing a global fleet model, Modaresi, Pauliuk, Løvik, and Müller (2014) capture the effects of vehicle lightweighting and recycling on total industrial emissions. Oda, Akimoto, and Tomoda (2013) estimate the future global availability of secondary steel for construction and transport equipment. Finally, certain whole-system models represent recycling technologies albeit not specific to vehicles. For example, the AIM/Enduse model considers recycling of paper and electronics (Akashi & Hanaoka, 2012).
- *Remanufacturing* commonly requires disassembling, refurbishing, repairing, cleaning, and reassembling of used vehicle components, such as engines or tires, to produce a "like-new" product. This can reduce the life-cycle energy embodied in a diesel engine by about 70–90% compared to a newly manufactured one (Liu, Jiang, & Zhang, 2013; Sutherland, Adler, Haapala, & Kumar, 2008). However, remanufactured components may not benefit from efficiency improvements in the same way as new ones do, if at all, causing a trade-off between savings in embodied energy and higher use-phase energy needs (Sutherland et al., 2008). Sato, Furubayashi, and Nakata (2019) estimate the energy and emission benefits from reuse and recycling in the Japanese automotive sector and find a potential reduction of 2.8 kg CO_2 per kg of vehicle. McKenna, Reith, Cail, Kessler, and Fichtner (2013) estimate the overall potential for energy savings from reuse practices in the German automotive sector to be 2.5–5% of the sector's total energy use in 2010. The effects of increased recycling and reuse at a global scale are demonstrated in IEA (2017)'s Energy Technology Perspectives.
- *More intensive use* is defined here as an increasing vehicle occupancy. Chester and Horvath (2009) demonstrate the sensitivity of life-cycle emissions per passenger kilometer due to changes in vehicle occupancy. Based on an integrated transport land-use model, Yin, Liu, Coulombel, and Viguié (2018) find that ridesharing could lead to a 25–75% increase in vehicle occupancy in the Paris region. Integrated and economic models impose fuel and/or carbon taxes onto the vehicle sector (Kim, Edmonds, Lurz, Smith, & Wise, 2006; Zhang, Fujimori, Dai, & Hanaoka, 2018), which

can reduce demand of personal motorized transport. This demand reduction in turn can be an implicit result of more intensive use (carpooling or ridesharing) or mode switching, or trip avoidance.
- *Downsizing* in a broader sense can be defined as a switch from a larger vehicle segment to a smaller one, for example, from a light truck to a sports utility vehicle (SUV). Dhingra and Das (2014) apply the downsizing concept in a narrower sense to study the effects of reduced size on efficiency and life-cycle emissions of an individual engine. The U.S. Annual Energy Outlook is based on an integrated energy model which captures the effects of taxes and fuel economy standards on segment switching within the US vehicle fleet (USEIA, 2019).

In conclusion, the engineering literature has focused on a narrow portfolio of ME strategies and vehicle types and is often conducted at an individual-technology level, and sometimes at fleet level. Integrated models often take a national or global perspective at the expense of resolution and thus, apart from downsizing and lightweighting, do not explicitly consider ME, and do not establish the link between service demand, material demand, and emissions embodied in materials. Here we set out to bridge the two perspectives by analyzing an extensive set of ME strategies applied to a broad array of vehicle types available in the global market and by explicitly considering emissions embodied in material production under different energy supply scenarios.

1.2 | Carbon emissions return on investment

The oil crises during the 1970s required highly economical usage of energy sources and thus popularized the use of the energy return on investment (EROI) indicator. EROI measures the amount of energy delivered by a technology ('energy out') per unit of life-cycle energy required to deliver that energy ('energy in'), and is therefore useful for comparing the "energy pay-off" of technological alternatives (Arvesen & Hertwich, 2015; Brockway, Owen, Brand-Correa, & Hardt, 2019; Palmer, 2017). EROI has been used ambiguously in the past due to the many different ways of measuring energy, such as primary versus final energy (Arvesen & Hertwich, 2015; Brockway et al., 2019). In addition, EROI counts every unit of energy input and output equally, be it sourced from renewable or fossil fuel energy carriers.

However, the pressing challenge of climate change mitigation (Figueres et al., 2017) calls for a novel unambiguous indicator that accounts for the carbon intensity of energy sources. Carbon emissions return on investment (CEROI) measures the life-cycle GHG emissions benefit during vehicle operation ('Δ carbon out') per unit of additional life-cycle GHG emission burden during vehicle production ('Δ carbon in'). To the best of our knowledge this indicator has not yet been described or tested in the literature. Only Kim et al. (2010) and Patterson, Gurr, Marion, and Williams (2012) presented a related indicator, emissions payback time (EPBT), investigating after how many years additional vehicle supply chain emissions from lightweighting and electrification would pay off through reduced operational emissions. Shanmugam et al. (2019) developed a sustainable return on investment (SROI) indicator for vehicle lightweighting, analyzing the trade-off between external costs to society and costs to manufacturers.

By introducing the concept of CEROI and providing a first application of the concept, we aim at filling another gap identified in the literature. Specifically, we analyze the CEROI of vehicle lightweighting under both current and low-carbon electricity supply.

2 | METHODS AND DATA

2.1 | Life-cycle assessment

For our analysis we choose four common vehicle segments (microcars, passenger cars, minivans/SUVs, and light trucks) as well as six mature and emerging powertrain technologies (internal combustion engine vehicles running on either gasoline or diesel [ICEV-g/-d], hybrid electric vehicles [HEV], plug-in hybrid electric vehicles [PHEV], battery electric vehicles [BEV], and hydrogen fuel cell electric vehicles [HFCEV]), representing a good approximation of both existing and potentially popular future vehicles types in the global market. While today there is also a considerable number of ICEVs running on compressed natural gas, these vehicles may not play a prominent role in the future according to IEA scenarios (IEA, 2017).

As shown in Equation (1), vehicle carbon footprints (from hereon "footprint," E) are evaluated on a life-cycle basis considering embodied emissions from vehicle production, that is, vehicle supply chain emissions (F_{vc}), and emissions from production and use of energy carriers, that is, energy cycle emissions (F_{ec}).

$$E = F_{vc} + F_{ec} \tag{1}$$

Vehicle supply chain impacts are calculated using a detailed and comprehensive LCA model, largely based on data points from the GREET2 model (Burnham, Wang, & Wu, 2006; Sullivan, Burnham, & Wang, 2010; Wang et al., 2017) and the ecoinvent life-cycle inventory database v3.5, model "allocation, cut-off by classification" Wernet et al. (2016) (see section S1.1 in Supporting Information for details). The vehicle supply chain is divided into two phases: (1) material production, F_{mat}, and (2) vehicle assembly, F_{ass} (Equation (2)). The former includes all processes from raw material

TABLE 1 Life-cycle emission factors of average global production processes of materials under current and future low-carbon energy supply in kg CO_2e per kg material. The last column indicates the reduction in GHG emissions due to low-carbon energy (Burnham et al., 2006; Ekman Nilsson et al., 2017; Hopewell, Dvorak, & Kosior, 2009; Kim et al., 2010; Vandepaer et al., 2020; Wang et al., 2017)

		Current	Low carbon	Unit	Reduction (%)
Automotive steel	Virgin	2.46	2.04	kg CO_2e kg^{-1}	17
	Recycled	0.98	0.82		
Stainless steel	Virgin	4.67	3.22	kg CO_2e kg^{-1}	31
	Recycled	1.87	1.29		
Cast iron	Virgin	1.85	1.73	kg CO_2e kg^{-1}	7
	Recycled	0.61	0.57		
Wrought aluminum	Virgin	11.90	4.80	kg CO_2e kg^{-1}	60
	Recycled	1.79	0.72		
Cast aluminum	Virgin	11.90	4.80	kg CO_2e kg^{-1}	60
	Recycled	1.79	0.72		
Copper, electric grade	Virgin	5.22	2.67	kg CO_2e kg^{-1}	49
	Recycled	1.00	0.51		
Plastics	Virgin	2.13	2.11	kg CO_2e kg^{-1}	1
	Recycled	1.40	1.39		

TABLE 2 Life-cycle emission factors of average global energy supply under current and future low-carbon energy supply in g CO_2e per kWh generated (Burnham et al., 2006; Edwards et al., 2014; Riahi et al., 2019; Wernet et al., 2016; Wolfram & Hertwich, 2019; Wolfram & Lutsey, 2016;)

	Current	Low carbon	Unit	Reduction (%)
Electricity grid mix	750	60	g CO_2e kWh^{-1}	92
Assembly energy mix	503	151	g CO_2e kWh^{-1}	70
Heat, coal	659	659	g CO_2e kWh^{-1}	0
Heat, natural gas	218	218	g CO_2e kWh^{-1}	0
Hydrogen	460	460	g CO_2e kWh^{-1}	0
Gasoline	328	328	g CO_2e kWh^{-1}	0
Diesel	304	304	g CO_2e kWh^{-1}	0

mining to the finished material in the form of metal sheets, ingots, and billets, or plastic pellets, resins, and slabs. The second phase includes all material transformation processes needed to produce the final vehicle, including battery assembly, metal and plastic forming, welding, gluing, painting, and other processes. As shown in Equation (3), emissions from material production equate to the Hadamard product (indicated by the $\circ$ symbol) of X_{mat}, a matrix that contains the material composition of vehicle archetypes, and f_{mat}, a matrix containing life-cycle emission factors of material production (cf. Table 1). Material emission intensities under low-carbon energy supply are based on the work by Vandepaer, Panos, Bauer, and Amor (2020) and have been provided by the authors on request. Vandepaer et al. derived emission factors of virgin low-carbon materials by integrating future low-carbon energy mixes from integrated assessment modeling into the respective life-cycle inventories of these virgin materials.[1]

Similarly, emissions from vehicle assembly are derived as the Hadamard product of energy spent on vehicle assembly, X_{ass}, and the life-cycle emission factors of the energy mix used for the assembly stage, f_{en} (cf. Table 2, Equation (4)).

$$F_{vc} = F_{mat} + F_{ass}, \tag{2}$$

$$F_{mat} = X_{mat} \circ f_{mat}, \tag{3}$$

$$F_{ass} = X_{ass} \circ f_{en}. \tag{4}$$

[1] For further information on the integration of energy mixes from integrated assessment models into LCA, please refer to the work by (Beltran et al., 2018; Cox, Bauer, Beltran, van Vuuren, & Mutel, 2020; Knobloch et al., 2020).

Energy cycle emissions include emissions from vehicle operation as well as upstream processes, such as oil drilling, fuel transportation, electricity generation and transmission and are derived following Equation (5). Operational energy use factors, X_{en}, are based on drive-cycle simulations using FASTSim (Future Automotive Systems Technology Simulator, cf. Section 2.3) (Brooker, Ward, & Wang, 2013; Brooker et al., 2015). Life-cycle emission factors of the energy carriers used during the operational phase are specified in Table 2. We assume an average vehicle lifetime mileage, parameter α, of about 180,000 km.

$$F_{ec} = X_{en} \text{ of }_{en} \times \alpha. \tag{5}$$

Our functional unit is one person driving a vehicle over its entire lifetime of 180,000 km. Impact results are therefore presented as footprints per passenger over the vehicle lifetime, E_{pp}, in t CO_2e person^{-1} (Equation (6)). This means that our results present the footprint of each passenger over the entire vehicle lifetime, having the advantage of capturing the reductions in footprints from increased vehicle occupancy.[2] We estimate an average global occupancy of 1.5 passengers per vehicle (Wolfram, Tu, Hertwich, & Pauliuk, 2020). Therefore, vehicle footprints derived from Equations (1)–(5), are divided by the amount of passengers per vehicle, parameter β (1.5 in the default case and 2.0 in the more intensive use scenario).

$$E_{pp} = \frac{E}{\beta}. \tag{6}$$

2.2 | Definition of vehicle archetypes

Vehicle archetypes represent differences in vehicle segment, technology, and production design. We model four vehicle segments (microcar, passenger car, minivan/SUV, light truck), six technologies (ICEV-g, ICEV-d, HEV, PHEV, BEV, HFCEV), and two production designs (conventional and lightweight). The conventional ICEV-g light truck and passenger car are modeled off of the Ford F-150 and the Toyota Corolla, each being the worldwide highest-sold vehicle in their segment in 2018.[3] The microcar is modeled off of the Suzuki Alto, the highest-selling car in India between 2004 and 2018.[4] The minivan/SUV has been modeled off of the Wuling Hongguang, which is the most popular vehicle in China.[5] Several data points on performance, weight, and dimensions of each of these vehicles have been collected from manufacturer homepages and additional online sources. When different options exist, we average their characteristics. For example, the Ford F-150 is sold as a 2WD and a 4WD option, considerably differing in curb weight, fuel tank capacity, driving range, fuel consumption, and vehicle dimensions. Since sales shares between the two options are unknown, we average between them. The selected vehicles, which are all ICEVs, serve as the foundation for other powertrains. To model alternative powertrains off of ICEVs, components are added, removed, or scaled as needed (Wolfram & Wiedmann, 2017). The masses of individual components are determined using variable and fixed masses from Bauer, Hofer, Althaus, Del Duce, and Simons (2015). The resulting component and total vehicle masses are illustrated in Figure 1b. The vehicle mass breakdown by material is derived from the GREET2 model (Burnham et al., 2006; Wang et al., 2017) and illustrated in Figure 1c,d. For more details, please refer to Section S1.2 in Supporting Information and Wolfram et al. (2020).

2.3 | Drive-cycle simulations

Vehicle characteristics are used as input data for drive-cycle simulations in FASTSim (Brooker et al. 2015). Specific inputs include vehicle mass, motorization, energy storage, vehicle dimensions, and drag coefficient for each vehicle segment and powertrain. Operational energy use is determined over EPA's US06 drive cycle. While various drive cycles are used across different countries, they all exhibit some divergence between official and real-world fuel consumption (Tietge, Diaz, Yang, & Mock, 2017). FASTSim however automatically corrects any drive cycle for real-world conditions (USEPA, 2018). This built-in correction increases energy consumption by about 30–40% depending on technology. For lightweighted vehicle archetypes, we assume that power components are resized for performance equivalency in accordance with the literature. Specifically, peak power is reduced incrementally until the acceleration of conventional and lightweighted vehicle archetypes match (Brooker et al., 2013). Additional weight reduction can be achieved through downsizing of components, which is a consequence of primary weight savings by material substitution. For the powertrain, we assume an additional 50% weight reduction compared to the 100% initial reduction (Kim & Wallington, 2013).

[2] Footprints can also be expressed as emission intensities per vehicle-kilometer (cf. Section S3 in Supporting Information).
[3] https://www.best-selling-cars.com/global/2018-full-year-international-global-top-selling-car-models/
[4] https://economictimes.indiatimes.com/industry/auto/cars-uvs/maruti-suzuki-alto-crosses-35-lakh-cumulative-sales-mark/articleshow/63171749.cms
[5] https://www.goodwood.com/grr/road/news/2018/4/axons-automotive-anorak-chinas-best-selling-cars/

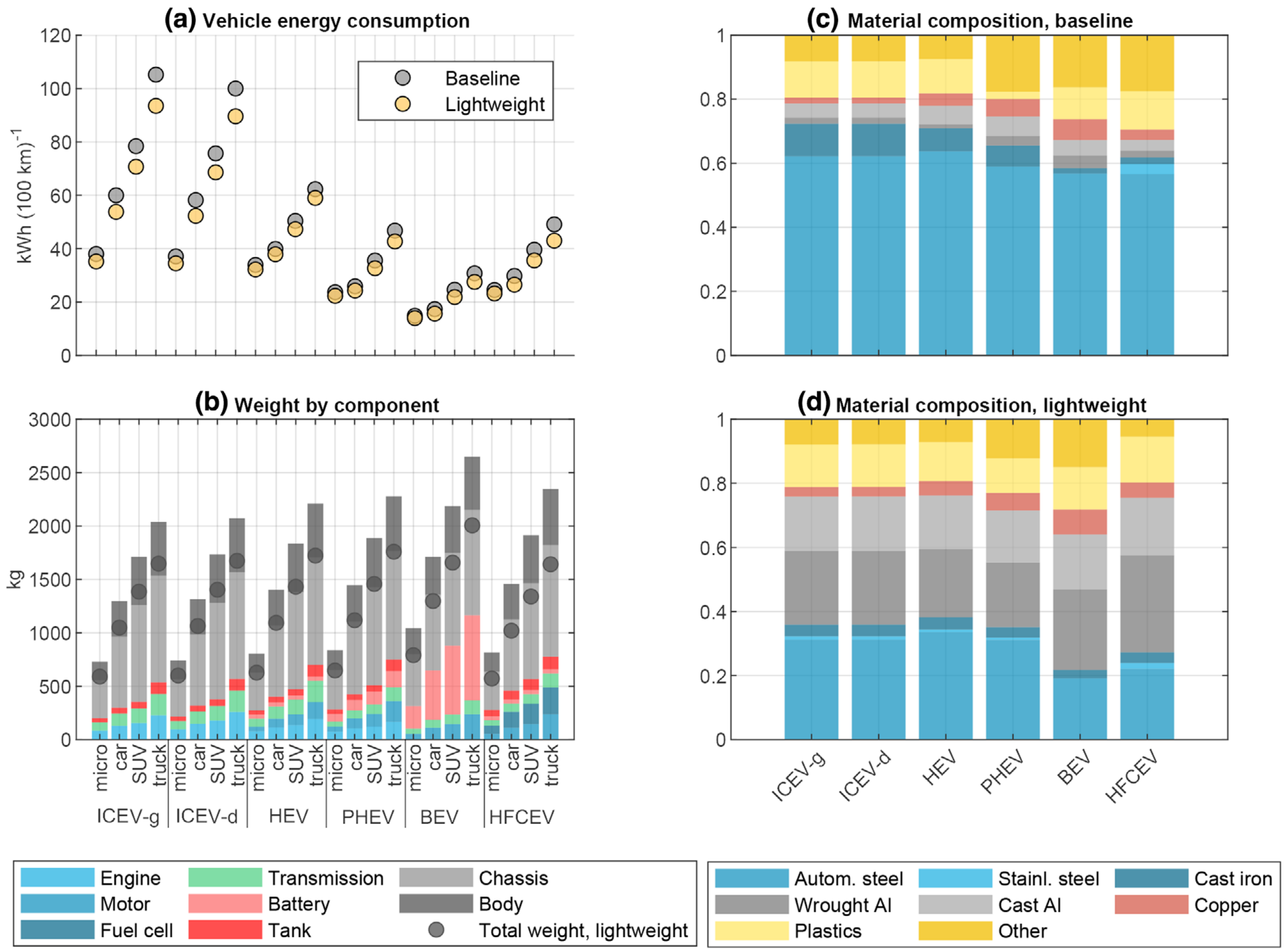

FIGURE 1 Characteristics of vehicle archetypes. (a) Drive-cycle energy consumption of baseline and lightweight vehicles. A PHEV utility factor of 0.5 is assumed. (b) Baseline vehicle weight by component. Circles indicate total weights of lightweight vehicles. (c) Material composition of baseline vehicles. (d) Material composition of lightweight vehicles. Underlying data used to create this figure can be found in a data repository at https://doi.org/10.5281/zenodo.3896664

2.4 | Modeling of ambitious material efficiency strategies

Analyzed strategies include (a) vehicle lightweighting through material substitution, (b) material recycling, (c) components remanufacturing, (d) more intensive use, and (e) downsizing. In addition, we analyze (f) the effects of a simultaneous implementation of all ME strategies as well as (g) a combined implementation of all strategies but lightweighting. The implementation levels of these measures should be regarded as ambitious, yet plausible, and are roughly in line with the storylines of very optimistic climate change mitigation scenarios, such as SSP1 (O'Neill et al., 2017) and LED (Grubler et al., 2018).

- *Lightweighting*: Compared to the baseline material composition, we assume an increase in the content of aluminum by 10–28% and a reduction in the steel content by 25–31%, depending on powertrain. These assumptions are largely based on the aggressive lightweighting scenario in Burnham et al. (2006) (refer to Section S1.2 in Supporting Information for details). We further investigate the trade-offs of lightweighting, that is, the relationship of additional carbon invested upfront (in the vehicle supply chain), and carbon saved in the energy cycle, which we term "carbon emissions return on investment" (CEROI).
- *Recycling*: The recycled content is assumed to amount to about 11–85% by weight depending on material (refer to Section S1.2 in Supporting Information for details), thereby reducing material-related energy expenditures. These rates are already high and can be seen as upper boundaries as materials in end-of-life vehicles are usually downcycled for use in less demanding applications (Hertwich et al., 2019; Ortego, Valero, Valero, & Iglesias, 2018). Emission factors of recycled materials are illustrated in Table 1.
- *Remanufacturing*: We infer from Liu et al. (2013) that each kg of remanufactured equipment reduces energy needs of material production by about 98% and assembly energy needs by about 40%. We assume that the share of recovered materials through remanufacturing amounts to

roughly 9–19% by weight depending on powertrain and component. These rates are based on current practices in Japan where the combined rate of remanufacturing and recycling is already very high, about 82% by weight (Sato et al., 2019) (see Section S1.2 in Supporting Information for details).

- *Downsizing* is defined as customers switching to a smaller vehicle segment, that is, light truck→van/SUV; van/SUV→passenger car; passenger car→microcar. No further downsizing is available for microcars in our model. Downsizing reduces vehicle weight by 16–44% and fuel consumption by 9–37%, depending on vehicle segment and powertrain (cf. Figure 1). Nudging consumers to drive smaller cars would require an immense effort to reverse the current trend of vehicles becoming increasingly bigger (USEPA, 2018).
- *More intensive use* implies an increase in vehicle occupancy from 1.5 to 2.0 passengers, lowering vehicle- and energy-cycle emissions per passenger by a constant 25%, regardless of energy mix, powertrain, or vehicle segment. Such increase in vehicle occupancy is roughly in line with the LED scenario (Grubler et al., 2018) and would require very high usage rates of ridesharing services.

2.5 | Carbon emissions return on investment

Among all of the ME strategies analyzed in this work, only lightweighting is suited for a CEROI analysis because of the trade-off between inputs (increased vehicle supply chain emissions) and outputs (reduced energy cycle emissions). All other measures either yield reduced vehicle supply chain emissions at constant energy cycle emissions (remanufacturing and recycling) or complementary emission reductions in both the energy cycle and the vehicle supply chain (downsizing and more intensive use), which mathematically does not allow for a CEROI calculation. We therefore define CEROI as the fraction of additional vehicle supply chain emissions, ΔF_{vc}, and reduced energy cycle emissions, ΔF_{ec}, due to vehicle lightweighting (LW) compared to the baseline (BL) vehicle (Equation (7)).

$$\mathrm{CEROI} = -\frac{\Delta F_{\mathrm{out}}}{\Delta F_{\mathrm{in}}} = -\frac{\Delta F_{\mathrm{ec}}}{\Delta F_{\mathrm{vc}}} = -\frac{F_{\mathrm{ec}}^{\mathrm{BL}} - F_{ec}^{LW}}{F_{\mathrm{vc}}^{\mathrm{BL}} - F_{\mathrm{vc}}^{\mathrm{LW}}}. \tag{7}$$

3 | RESULTS

3.1 | Vehicle carbon footprints

Under current energy supply, the ICEV-g light truck has the highest total footprint with 46.7 t CO_2e person^{-1} (Figure 2a). With 10.6 t CO_2e person^{-1}, the PHEV microcar can achieve the lowest footprint when applying all ME strategies, and is closely followed by its ICEV-d and HEV counterparts. PHEVs, despite their higher weight, achieve a higher fuel economy than HEVs due to their more efficient powertrain (larger electric motor and smaller combustion engine). Due to the "dirty" electricity mix (global average of 750 g CO_2e/kWh), the BEV only achieves 11.6 t CO_2e person^{-1}.

Assuming a low-carbon energy supply mix, the footprint of the ICEV-g light truck falls from 46.7 to 44.6 t CO_2e person^{-1} (Figure 2b), as the vehicle supply chain benefits from the lower-carbon energy supply. An increasing share of renewable electricity is used to produce materials and assemble vehicles (Section S1.1 in Supporting Information). Meanwhile, production of gasoline is left unchanged, meaning that the carbon intensity of gasoline remains constant. In contrast, BEVs fully capitalize on the low-carbon energy supply, cleaning up both the energy cycle and the vehicle supply chain. Hence, the lower end of the range of footprints shown in Figure 2 is fully dominated by BEVs. For example, the BEV microcar reaches a footprint of 2.9 t CO_2e person^{-1}, which further falls to 1.7 t CO_2e person^{-1} after applying all ME strategies.

3.2 | Contribution of energy cycles and vehicle supply chains

The relative contribution of vehicle supply chains and energy cycles to total footprints strongly varies, depending on powertrain, vehicle segment, energy supply, and implemented ME strategies. Under current energy supply, the vehicle supply chain can contribute as little as 9% ('ICEV-g micro all but lightweighting') or as much as 34% ('BEV car lightweighting') (compare Figure 3a,e). Assuming low-carbon energy, these two extreme points become even more extreme with a 5% contribution from the vehicle supply chain to the ICEV-g footprint, and a 73% contribution to the BEV. The decreasing energy cycle contribution to the footprint of the ICEV-g is due to the assumption that the carbon intensity of crude oil remains unchanged. Therefore, mitigation of energy cycle emissions cannot be achieved for gasoline or diesel, whereas the vehicle supply chain can still source low-carbon energy and therefore reduce impacts. As a result, for ICEVs and HEVs the emissions share of the vehicle supply chain decreases while the energy cycle share grows (compare pairs a–g, b–h, and c–i in Figure 3). Fully relying on electricity as a power source, only BEVs can truly capitalize on the "cleaner" grid so that energy cycle emissions strongly shrink. As a result, mitigation of the energy cycle is even greater than that

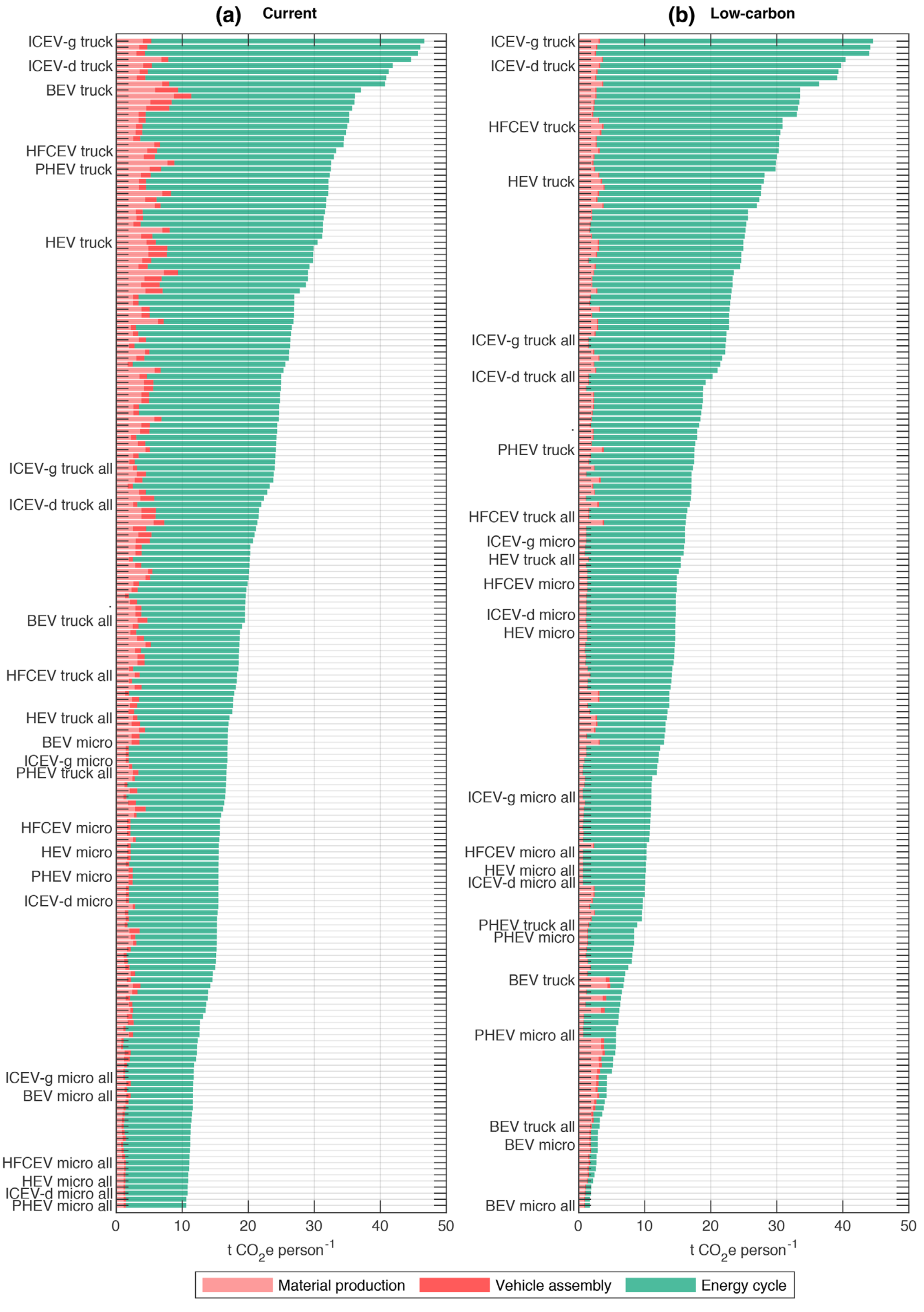

FIGURE 2 Vehicle carbon footprints in ascending order. (a) Current global energy supply mix; (b) low-carbon energy supply mix. Labels are shown only for microcars and trucks, and for no ME and all ME strategies. ICEV, internal combustion engine vehicle; HEV, hybrid electric vehicle; PHEV, plug-in hybrid electric vehicle; BEV, battery electric vehicle; HFCEV, hydrogen fuel cell electric vehicle; -g, gasoline; -d, diesel. Underlying data used to create this figure can be found in a data repository at https://doi.org/10.5281/zenodo.3896664

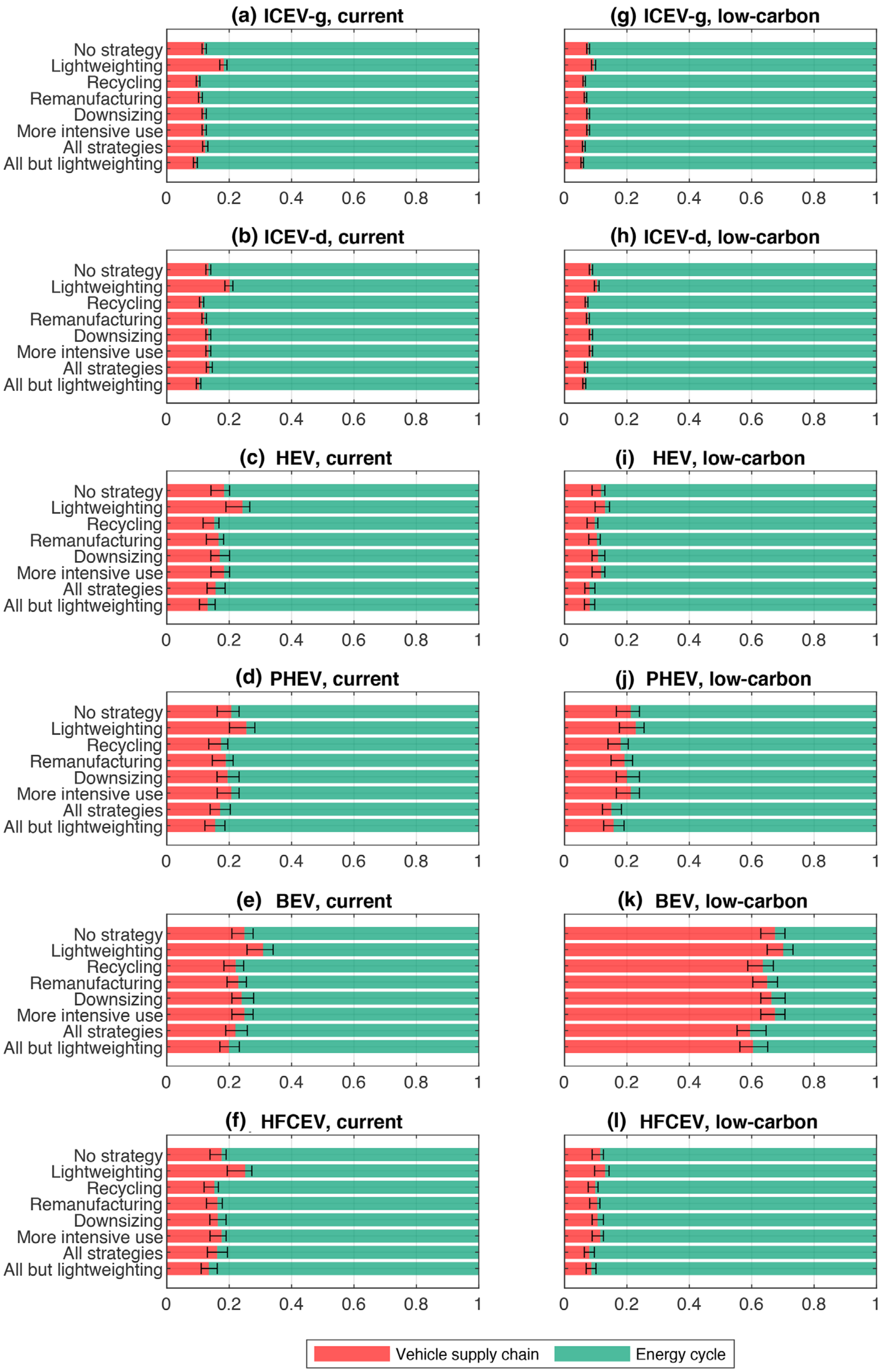

FIGURE 3 Share of vehicle supply chain (=material production + vehicle assembly) to total vehicle carbon footprints (=vehicle supply chain + energy cycle). Left: Under current global energy supply mix. Right: Under low-carbon energy supply mix. Whiskers indicate the range of results across vehicle segments. 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; -g, gasoline; -d, diesel. Underlying data used to create this figure can be found in a data repository at https://doi.org/10.5281/zenodo.3896664

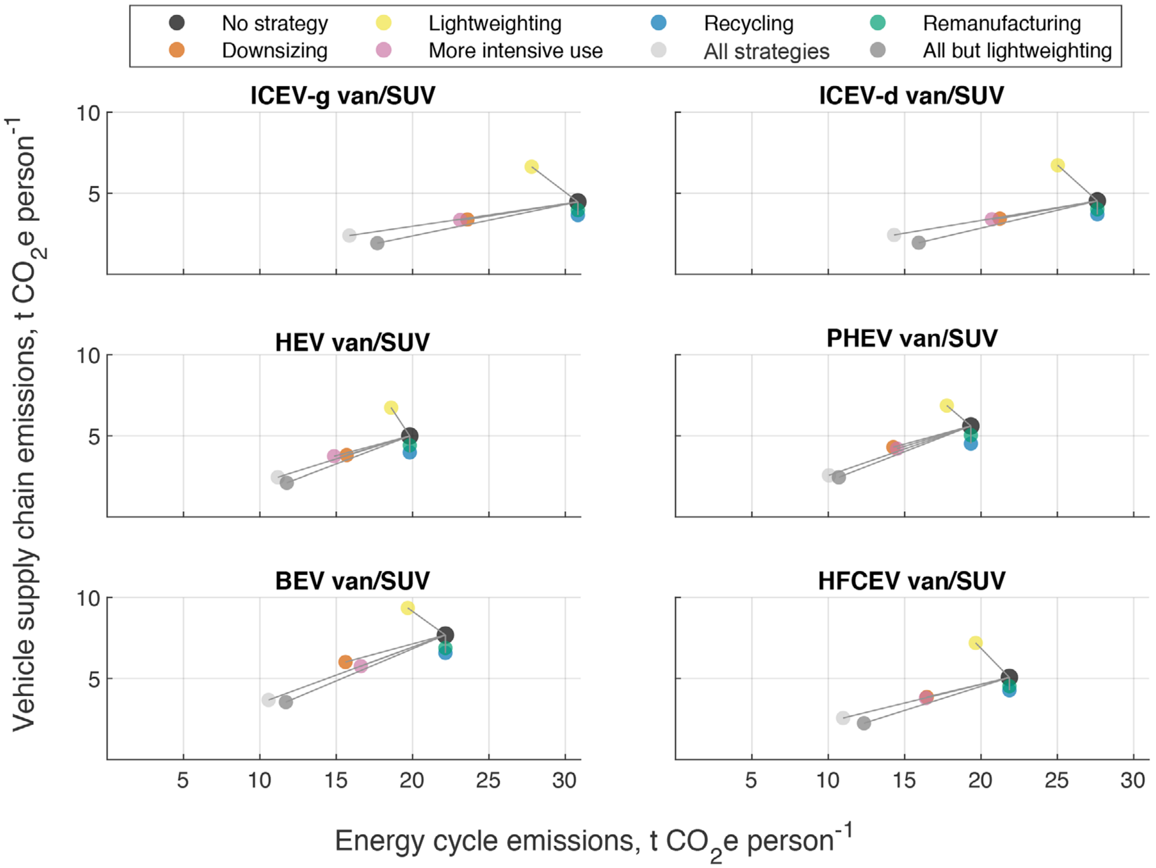

FIGURE 4 Effect of different material efficiency strategies on energy chain and supply chain emissions of vans/SUVs under current energy supply. "Recycling" is partially covered by "Remanufacturing" and "More intensive use" is partially covered by "Downsizing." SUV, sports utility vehicle; ICEV, internal combustion engine vehicle; HEV, hybrid electric vehicle; PHEV, plug-in hybrid electric vehicle; BEV, battery electric vehicle; HFCEV, hydrogen fuel cell electric vehicle; -g, gasoline; -d, diesel. Underlying data used to create this figure can be found in a data repository at https://doi.org/10.5281/zenodo.3896664

of the vehicle supply chain, which still depends on fossil fuels to a much larger degree. Hence, the share of vehicle supply chain emissions further increases for BEVs, while the energy cycle share grows smaller (compare Figure 3e,k). The changes for PHEVs and HFCEVs can go in either direction but are minor since reductions in vehicle supply chain and energy cycle emissions are about equal under low-carbon energy (compare pairs d–j and f–l in Figure 3).

3.3 | Mitigation through material efficiency

We find striking differences in the overall potential of different ME strategies to reduce footprints (vehicle supply chain + energy cycle emissions). Under current energy supply, lightweighting achieves modest, and sometimes slightly negative, footprint reductions ranging from –3 to +4% (–0.8 to +2.0 t CO_2e person^{-1}). Reductions are particularly high for ICEV-g, ICEV-d, BEV and HFCEV vans, SUVs and light trucks. Reductions for micro and passenger cars are typically found at the other end of the range and can be slightly negative, which indicates a small increase in footprints (more in Section 3.4). Although lightweighting can reduce energy chain emissions (by 5–12% or 0.7–4.6 t CO_2e person^{-1}), vehicle production impacts can simultaneously increase (by 21–49% or 0.6–2.6 t CO_2e person^{-1}), which explains the small or sometimes negative reductions in total footprints. Figure 4 shows the absolute mitigation potential of ME for vans/SUVs while Figures S1– S4 in Supporting Information show absolute and relative mitigation results for all powertrains.

Recycling and remanufacturing can mitigate vehicle supply chain impacts by about 6–20% or 0.2–1.3 t CO_2e person^{-1}, whereas energy cycle discharges are not affected. As a result, total footprints are only marginally reduced, by about 1–4%. The benefit of recycling is constrained by the limited recycled content in vehicles, which is a result of the high performance required of materials in this application. As a result, most materials from end-of-life vehicles are downcycled. Remanufacturing components, such as engines, also prevents the deployment of new, more efficient ones, causing a trade-off between production and operational pollution. This opportunity cost has not been modeled here and would further diminish the

TABLE 3 Individual and combined potential of material efficiency strategies and low-carbon energy supply to reduce vehicle carbon footprints. 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

	ICEV (%)	HEV (%)	PHEV (%)	BEV (%)	HFCEV (%)
Material efficiency	30–57	30–45	32–49	31–52	29–50
Low-carbon energy	4–6	6–8	45–46	80–83	5–7
Combined	35–59	35–50	63–74	90–92	35–55

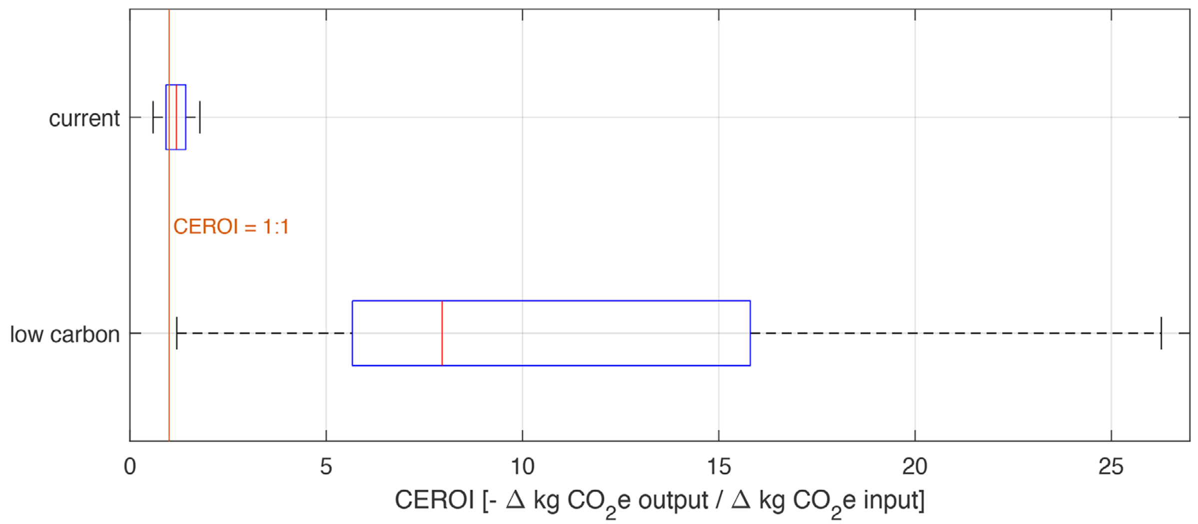

FIGURE 5 Carbon emissions return on investment (CEROI) of lightweighting different vehicle types under current and low-carbon energy supply. Whiskers indicate the range of results across different vehicle segments and technologies. Underlying data used to create this figure can be found in a data repository at https://doi.org/10.5281/zenodo.3896664

abatement potential from remanufacturing. In order to avoid overestimating the GHG mitigation potential of remanufacturing we therefore limited the degree of its application (Section S1.2 in Supporting Information).

More intensive use and downsizing can yield the largest impact mitigation. While more intensive use can reduce footprints by 25% or 3.9–11.7 t CO_2e person^{-1}, downsizing offers reductions on the order of 17–38% or 3.1–11.4 t CO_2e person^{-1}. Both strategies act positively on both the energy cycle and the vehicle supply chain.

All strategies taken together can cut footprints by 29–57% (4.6–22.7 t CO_2e person^{-1}) with particularly high reductions for larger vehicle segments and conventional powertrains. Implementing all strategies except for lightweighting leads to similar overall footprint alleviation (27–54% or 4.3–21.1 t CO_2e person^{-1}) but differs in the sense that it acts more strongly on the energy cycle and less so on the vehicle supply chain.

Footprints can also be cut by switching from the current energy supply to low-carbon energy supply, by 4–83% (0.8–30.2 t CO_2e person^{-1}) in particular, which is comparable in magnitude to the overall potential of above analyzed ME strategies (28–57% or 4.6–22.7 t CO_2e person^{-1}). While footprint reductions from low-carbon energy supply are very heterogeneous, with large reductions for BEVs and low reductions for ICEVs, footprint reductions from ME are strongly homogeneous among all technologies (Table 3). This shows that ME is a very suitable mitigation strategy not only for electric vehicles but for all technologies. In addition, by comparing the last two rows of Table 3, we can assert that even when taking future low-carbon energy supply as a starting point instead of the current one, a further substantial drop in footprints is possible thanks to ME.

The corresponding results for ME under low-carbon energy are illustrated in Figures S2 and S4 in Supporting Information. Most notably, lightweighting becomes a more important strategy as it can yield footprint reductions ranging from 0.4–10% or 0.01–4.1 t CO_2e person^{-1} compared to -3–4% or -0.8–2.0 t CO_2e person^{-1} under current energy supply (more details in Section 3.4).

3.4 | Trade-offs of lightweighting

Generally, lightweighting can lead to favorable results, meaning that additional GHG emissions in the vehicle supply chain are more than compensated for by GHG savings in the energy cycle. Figure 5 shows that lightweighting leads to a CEROI roughly ranging between 0.6:1 and 1.8:1, with a median of about 1.2:1, when current average energy supply is assumed. This means that on average one additional kg of CO_2e invested during vehicle production shrinks energy cycle emissions by about 1.2 kg CO_2e. However, in some cases, increased GHG emissions in the vehicle production phase outweigh savings in the use phase, leading to a CEROI below 1:1.

Assuming low-carbon energy supply, however, a CEROI of about 25:1 and higher can be achieved. This is largely due to the assumed constant carbon intensity of gasoline and diesel, while vehicle production benefits from low-carbon energy supply. Thus, it "pays off" to "invest" more carbon upfront. If the carbon intensity of crude oil further increases in the future (Wallington et al., 2017), the CEROI could become even higher, meaning that for gasoline- and diesel-powered cars lightweighting could be even more favorable than illustrated by our computations.

3.5 | Sensitivity of results

Our results indicate that the mitigation potential of ME exhibits significant variation over different vehicle technologies and segments as well as energy supply. Here we further highlight the sensitivity of selected results to two fundamental model parameters, vehicle occupancy and vehicle lifetime. For example, assuming a longer vehicle lifetime of 210,000 km instead of 180,000 km, an increase of about 17%, increases total life-cycle emissions of the ICEV-g truck under current energy supply by 15%, while the footprint of a micro BEV under low-carbon energy supply is increased by only 7%. Conversely, a shorter lifetime of 150,000 km reduces use-phase emissions and increases the share of vehicle production emissions further, for example, from 73% (Figure 3k) to 77% in the case of a lightweight BEV car under low-carbon energy. Meanwhile, assuming that more intensive use increases ridership from 1.5 to 1.75 passengers per vehicle, instead of from 1.5 to 2.0, which is a 13% reduction, increases respective life-cycle emissions of all vehicle types in the more intensive use scenario by the same percentage regardless of the emissions intensity of energy supply.

4 | DISCUSSION

4.1 | Discussion of results, limitations, and future work

Our results indicate that downsizing and more intensive use can potentially yield the largest footprint cuts. However, their successful implementation relies strongly on consumer behavior and is therefore highly uncertain. Today's potential for downsizing and more intensive use is significant, however. For example, with 1.5 passengers per vehicle (ORNL/FHWA, 2018), vehicle occupancy in the United States is quite low. In addition, the US share of SUVs and light trucks almost tripled between 1975 and 2017 (USEPA, 2018), suggesting that larger vehicles are a recent consumer preference rather than a necessity. However, nudging consumers toward more efficient practices will require political intervention. Such intervention in turn could trigger rebound effects, which can reduce or even negate achieved emission reductions. For instance, more efficient vehicles have been found to be driven further than less efficient ones (direct rebound) (Gillingham, Kotchen, Rapson, & Wagner, 2013). In addition, cost savings from owning and driving more efficient vehicles may be spent on increased air travel or other highly polluting activities (indirect rebound) (Briceno, Peters, Solli, & Hertwich, 2005). None of the mentioned mechanisms have been analyzed in this work, however, since our model lacks the necessary economic considerations.

Our results and modeling assumptions are largely consistent with the literature cited throughout this paper. For example, Elgowainy et al. (2018) estimate that a current ICEV LDV emits about 280 g CO_2e/vkm over its lifetime, which falls right into the range of our reported 140–389 g CO_2e/vkm,[6] depending on vehicle segment. Depending on powertrain, lightweighting reduces vehicle weight by 18–24%, which is consistent with Bandivadekar et al. (2008), who find that about a 20% vehicle weight reduction is possible with aggressive material substitution. Secondary weight reduction is particularly high for BEVs due to the high initial weight of the large battery, a finding that is confirmed by Hofer, Wilhelm, and Schenler (2014). Ambrose, Kendall, Lozano, Wachche, and Fulton (2020) estimate that vehicle production could contribute as much as two thirds to the life-cycle GHG emissions of a future BEV charged by renewable electricity, while here we find a range from roughly two thirds to three quarters (Figure 3k).

The individual contributions to GHG mitigation from lightweighting, recycling and remanufacturing are modest. This is at least true under current global energy supply, whereas regional conditions could support stronger mitigation effects. For instance, economies whose energy supply is "cleaner" than the global average, can produce lower carbon aluminum and thus enable stronger emission benefits from lightweighting (Milovanoff et al., 2019). We show that larger emission reductions are also possible globally in a hypothetical future with low-carbon energy supply. For recycling, an economy-wide perspective considering downcycling of materials recovered from end-of-life vehicles may reveal stronger system-wide climate benefits (Modaresi et al., 2014) compared to our results. Conversely, the potential of remanufacturing may be lower than estimated in this

[6] Convert results from Figure 2 as follows: g CO_2e/vkm = t CO_2/person × 1/180,000 vehicle/vkm × 1.5 persons/vehicle × 1,000,000 g/t.

work if a fleet model is employed which considers efficiency improvements of vehicle vintages. The reason therefore would be that remanufactured engines do not benefit from efficiency improvements as new ones do, therefore leading to trade-offs between operational and embodied energy and carbon (Sutherland et al., 2008). In addition, we assume that remanufacturing restores vehicle components to "like-new" conditions, which is not necessarily the case in reality (Hertwich et al., 2019). To alleviate the effects of these two issues, we limit the degree to which remanufacturing is deployed (Section S1.2 in Supporting Information).

Even stronger reductions in vehicle footprints may be possible through additional deployment of other low-carbon technologies not analyzed in this work. For instance, carbon capture and storage could save the majority of carbon dioxide discharged from coal and natural gas power plants (Singh, Stromman, & Hertwich, 2011), while biofuels (Wang, Dunn, Han, & Wang, 2015), synthetic fuels (Heywood et al., 2015), and other low-carbon fuels (Elgowainy et al., 2018) could further alleviate pollution from combustion processes. Similarly, emissions from steel production could be further decreased by direct iron reduction using renewable hydrogen (Bhaskar, Assadi, & Nikpey Somehsaraei, 2020; Vogl, Åhman, & Nilsson, 2018). However, many, if not all of these technologies are not yet commercially available, which makes their future deployment uncertain.

4.2 | Relevance for integrated modeling

Integrated energy models can be broadly defined as models of national or global energy demand and supply within the broader economic–environmental system (Debnath & Mourshed, 2018; Krey et al., 2019; Pfenninger, Hawkes, & Keirstead, 2014). These models are commonly used to investigate emission pathways as a function of mitigation efforts (Grubler et al., 2018; Luderer et al., 2019; Pietzcker et al., 2014; van Vuuren et al., 2018) and have become more and more detailed in the way they portrait mitigation mechanisms and consumer behavior (Mercure, Lam, Billington, & Pollitt, 2018; van den Berg et al., 2019; Venturini, Tattini, Mulholland, & Gallachóir, 2019). The industrial ecology literature has pointed out that explicit linking of service demand to material demand constitutes another important building block toward a holistic evaluation of climate change mitigation pathways (Creutzig et al., 2018; Pauliuk & Hertwich, 2016; Rao, Min, & Mastrucci, 2019). Following this new direction of research, we apply industrial ecology methodology in order to derive important data points for use within or in combination with integrated models. Most notably, we have defined 48 different vehicle archetypes representing the global vehicle market. These archetypes can be readily used to replace or detail existing descriptions of global average vehicles in integrated models and may be further customized to represent regional differences. Integrated modeling teams may choose to only incorporate vehicle fuel consumption or fuel cycles, or consider the complete vehicle life cycle including material production, vehicle assembly, and ME options. Doing so could significantly change the technology mix optimization procedure in integrated models and could illustrate yet unknown mitigation pathways for the light-vehicle sector and its supply chain. Further research on the optimal level of vehicle-technological detail in integrated models is needed.

4.3 | Policy implications

In order to stay within reach of climate targets, an annual personal footprint budget of roughly 1–2 t CO_2e has been hypothesized by environmental and consumer organizations (Bilharz, 2014; Verbraucherzentrale, 2010). This ambitious threshold is currently involuntarily met only by the poorest of nations, whereas rich countries by far overshoot that target (WB, 2010). Here we show that stringent ME and low-carbon energy application can achieve a personal vehicle footprint roughly as low as 2 t CO_2e over the vehicle lifetime. Assuming an average vehicle lifetime of about 15 years, that value translates to an annual footprint of 130 kg CO_2e per person, which would make up 13% of a personal carbon budget of 1 t CO_2e per year, leaving the majority of the budget for other purposes, such as housing or diet. This indicates that the current demand level of personal motorized transport is compatible with ambitious climate targets only under two major conditions: (1) consumers must switch to more energy- and material-efficient vehicles, for example, smaller or shared electrified vehicles, and (2) the energy used to charge these vehicles must be highly decarbonized.

Various policy measures exist which can help consumers switch, such as taxes or feebates. Yet, as a prerequisite for consumers to make that transition, appropriate vehicles must be offered by manufacturers, which in turn may need incentives to do so, such as tighter fuel economy and low-carbon fuel standards. In order to reduce vehicle supply chain emissions next to energy cycle emissions, however, requires existing regulatory frameworks to be complemented by an additional vehicle production standard, which regulates emissions embodied in vehicle production. Alternatively, existing standards could be replaced by a life-cycle standard which regulates all upstream and direct emissions. Tailpipe emission regulations in different countries around the world are targeting 95–99 g CO_2e per vehicle-km between 2020 and 2025. Some vehicle options already achieve these targets today even under real-world conditions (see Section S3 in Supporting Information), highlighting the scope for further tightening of existing standards.

Smaller, material-efficient vehicles may offer important side effects for sustainability, such as reduced stress on road and parking space, lower consumer costs, higher energy security, and increased safety for non-motorized road users.

Finally, in line with Shanmugam et al. (2019), we note that lightweighting, recycling, and remanufacturing may be more easily integrated within traditional automotive supply chains compared to fuel-side initiatives, and depend less upon consumer acceptance, if at all, compared to consumer-oriented policies. Despite their lower potential to reduce vehicle footprints, these measures should therefore be implemented regardless.

5 | CONCLUSIONS

This work is the first to provide a comprehensive overview of the potential of ME to mitigate vehicle emissions under a vast range of conditions. We also offer the first analysis of the carbon return on investment of vehicle lightweighting. Our results indicate striking differences in the overall potential of different ME strategies to abate footprints. When implemented together, ME can yield sizeable reductions of up to 57%, comparable to mitigation of up to 83% achieved through low-carbon energy supplied to vehicles. Moreover, ME can halve the emissions of an electric car run on low-carbon electricity.

Our analysis illustrates the importance of considering specific conditions when choosing the most suitable portfolio of mitigation options. Lightweighting should not be seen as a "one-fits-all" solution as its "carbon pay-off" highly depends on other vehicle characteristics and energy supply of material production. Recycling and remanufacturing lead to modest reductions, while downsizing and more intensive use can have the largest reduction effect on footprints. However, policy incentives will be required in order to nudge consumers toward more efficient behavior. Rebound effects, which have not been evaluated in this work, can diminish the footprint alleviation potential of these strategies. An economy-wide approach will be needed to capture these effects. Conversely, our results offer a valuable starting point for economy-wide and integrated models, which usually lack the connection between climate change mitigation and material use.

According to our results, vehicle production would contribute a larger share of the life-cycle impacts of electric vehicles in a low-carbon energy future. Hence, we argue that more attention should be paid to vehicle supply chain emissions in regulatory frameworks. For example, existing fuel economy and low-carbon fuel standards could be complemented by vehicle production standards.

While low-carbon energy supply reduces footprints of electric vehicles more than that of other vehicles, ME is suited to reduce footprints of all analyzed technologies more equally. Thus we conclude that ME is highly suited as an immediate strategy to reduce emissions in the short term until full proliferation of plug-in and fuel cell electric vehicles in combination with renewable energy supply may be achieved. In addition, ME is a useful companion to the long-term transition toward low-carbon technology as it can further cut the footprint of low-carbon vehicles in half.

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CODE AND DATA AVAILABILITY

The data that supports the results of this study as well as the MATLAB code used to generate the results can be found in an open repository on Zenodo: https://doi.org/10.5281/zenodo.3896664. FASTSim, which has been used for drive-cycle simulations, is freely available at https://www.nrel.gov/transportation/fastsim.html

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of the article.

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