

The Remarkable Environmental Rebound Effect of Electric Cars: A Microeconomic Approach

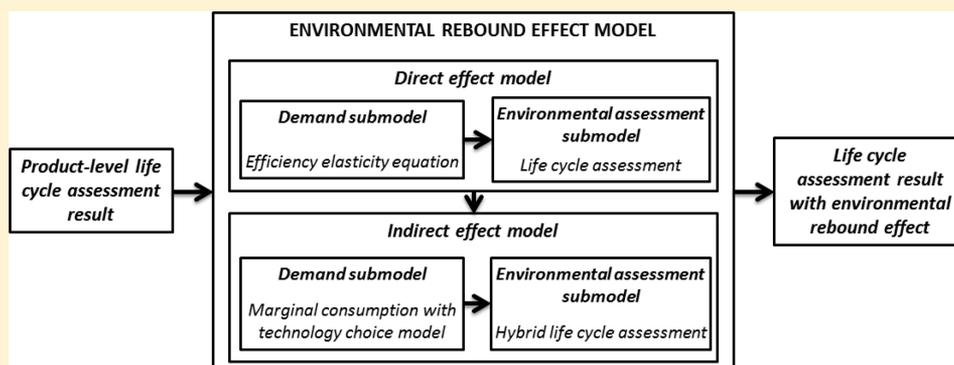
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S Supporting Information



ABSTRACT: This article presents a stepwise, refined, and practical analytical framework to model the microeconomic environmental rebound effect (ERE) stemming from cost differences of electric cars in terms of changes in multiple life cycle environmental indicators. The analytical framework is based on marginal consumption analysis and hybrid life cycle assessment (LCA). The article makes a novel contribution through a reinterpretation of the traditional rebound effect and methodological refinements. It also provides novel empirical results about the ERE for plug-in hybrid electric (PHE), full-battery electric (FBE), and hydrogen fuel cell (HFC) cars for Europe. The ERE is found to have a remarkable impact on product-level environmental scores. For the PHE car, the ERE causes a marginal increase in demand and environmental pressures due to a small decrease in the cost of using this technology. For FBE and HFC cars, the high capital costs cause a noteworthy decrease in environmental pressures for some indicators (negative rebound effect). The results corroborate the concern over the high influence of cost differences for environmental assessment, and they prompt sustainable consumption policies to consider markets and prices as tools rather than as an immutable background.

INTRODUCTION

New electric propulsion technologies, especially hybrid, battery electric, and fuel cell engines, are increasingly being evaluated from an environmental perspective, because there is hope that their expected market diffusion may mitigate sustainability concerns (e.g., greenhouse gas emissions [GHG] or urban smog) over the current automotive regime based on internal combustion engines (ICE).¹ Life cycle assessment (LCA) and LCA-based tools have been broadly used to determine detailed environmental profiles of these propulsion technologies at the product-level, the results of which are being compared to those for ICE.² However, LCA-based studies have been criticized for failing to consider the rebound effect, which may have a notable influence on the environmental profile of products but may even alter the overall direction of environmental impacts.^{3,4} Considering the increasing momentum that LCA is gaining as a support tool for environmental policy,⁵ advice derived from LCA-based studies must be aligned with achieving absolute environmental improvements. Therefore, many authors suggest

that policy-relevant LCA-based results of new technologies need to be assessed along with possible rebound effect estimates.^{6–8}

In this paper, we aim at quantifying the environmental rebound effect (ERE) through an LCA-based analysis for plug-in hybrid electric (PHE), full-battery electric (FBE), and hydrogen fuel cell (HFC) cars. The three technologies have been chosen for being representative of electric propulsion technologies and for being relevant in terms of the market diffusion that is being foreseen.¹ We refer to the ERE as the environmental outcomes from the change in overall consumption and production due to the behavioral or other systemic response to changes in production and consumption factors (e.g., income) induced by a technical change (e.g.,

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energy efficiency in transport) in a product or process.^{9–13} The ERE primarily differs from the traditional energy rebound effect in that a wide range of environmental aspects can be addressed instead of energy use alone.^{14,15} This reinterpretation has an effect not only on how the rebound effect is measured (multiple environmental indicators) but also on the definition of the technical change, which is not solely related to energy efficiency. Instead, we can assess the rebound effect of innovative products on the basis of technical changes concerning various environmental aspects, such as GHG or toxicity efficiency, that is, units of environmental pressure per unit of function or service. This supports the study of the ERE of the proposed propulsion technologies, because these are generally aimed at environmental improvements (mainly GHG emissions) rather than strictly at increasing the energy efficiency of cars.

The traditional rebound effect framework, rooted in economic theory,¹¹ was operationalized during the 1970s and 1980s through the so-called Khazzoom–Brookes postulate, which, following the propositions of William Stanley Jevons¹⁶ (the so-called Jevons paradox), stated that increased energy efficiency may lead to increased energy consumption.¹⁷ In the context of transport, it has been studied since the 1980s, mainly within energy and transport economics, and the cluster of empirical evidence gathered ever since suggests that its magnitude is relevant.^{12,18,19} A generally accepted decomposition of the rebound effect classifies it into at least three major effects: (1) direct effect, (2) indirect effect, and (3) economy-wide or structural effect.¹² Moreover, various production and consumption factors (such as income or time)²⁰ can trigger rebound effects, which are the financial factors (income, price, or substitution effects) most studied in the literature, particularly those related to changes in the effective prices.²¹ The direct and indirect price rebound effects (from hereon in combination referred to as the microeconomic rebound effect) are currently the most commonly studied. In the context of transport, the microeconomic rebound effect refers to the assumption on the cost change as a result of a more efficient vehicle. At the individual level, the total income does not change, and the assumption is that all of it is eventually spent. If costs are saved on fuel, the direct price rebound effect assumes that the money saved will be spent on the same product, in this case, additional travel. The indirect price rebound effect corresponds to the spending of the saved money in other consumption categories.

The literature offers a multitude of approaches to model marginal consumption (also known as the respending effect),^{18,19,22,23} that is, how liberated or bound money will be reallocated or unallocated among the various consumption categories. For instance, there are approaches based on Engel curves (expenditure elasticities)^{24,25} or on the shifting of expenditure patterns between income groups.^{8,26,27} However, they generally derive changes in consumption using mean household expenditure structures (HES), hence offering less accurate rebound estimates. For instance, when calculating the microeconomic rebound effect caused by a technical change in a passenger car using mean HES statistical data, information from consumers who do not own a car will be included. Empirical evidence describes a notable influence of car ownership on the HES due to all the associated fixed and variable costs (e.g., vehicle purchase, fuel, maintenance, insurance, taxes, etc.).^{28–30} Although some attempts have been made to link marginal consumption models with

household demographic characteristics,^{25,27} they generally lack detail on product technology aspects. As a first step to integrate such technological aspects, we will attempt to calculate the mean HES of a household that chose a specific car technology. While this exercise would still not address changes in car ownership or spending behavior, it could be a step forward from previous mean-based analyses to introduce technology aspects. Moreover, the (environmental) rebound effect of new electric propulsion technologies has not been assessed before, hence novel insights would be obtained.

This article has the following two aims:

- The main aim is to develop a general microeconomic model to appraise the ERE combining LCA-based methods with a marginal consumption model based on technology choices.
- A second aim is to apply the model to three electric propulsion technologies (plug-in hybrid electric [PHE], full-battery electric [FBE] and hydrogen fuel cell [HFC] engines) in Europe using existing LCA data at the product level.

■ ENVIRONMENTAL REBOUND EFFECT MODEL. METHODOLOGY AND DATA SOURCES

Overview of the Proposed Method. Figure 1 presents a graphical overview of the proposed methodological framework (models and required input data) to calculate the ERE. The framework is basically composed of the direct and indirect price ERE models, which, at the same time, are composed of two submodels each. The first submodel (demand submodel) calculates changes in demand according to price differences (efficiency elasticity equation and marginal consumption model for the direct and indirect effect, respectively). The second submodel (environmental assessment submodel) translates the units from demand to environmental indicators through LCA and Hybrid LCA, respectively.

Direct Price Rebound Effect Model. Various definitions of the direct price rebound effect can be found in the literature.^{9,11,31–35} In the context of transport, one of the most commonly used by researchers is the one that defines the direct price rebound effect, RE_d , based on the own (transport) price elasticity (η_{p_t}) of transport demand (T) (a detailed description of the assumptions and mathematical equations behind this relationship can be found in Supporting Information S1):

$$RE_d = -\eta_{p_t}(T) - 1 \quad (1)$$

For the own price elasticity of transport demand, we will derive two scenarios for completeness by using short-term (ST) and long-term (LT) price elasticities of transport demand for vehicle-kilometres (vkm). LT elasticities describe greater responsiveness of users (e.g., decisions on household location) in the long run, which could overestimate direct effect estimates. On the other hand, ST elasticities capture only short-term decisions, which could underestimate the direct effect. By considering both scenarios, we aim at studying whether such considerations have a relevant impact on the direct effect estimates. The values chosen for ST and LT elasticities are -0.16 and -0.26 , respectively, which correspond to average values obtained from a survey on various studies conducted for passenger car transport in Europe.³⁶ As an example, if transport costs are 1% lower, by using eq 1 with the selected elasticities of transport demand, transport demand

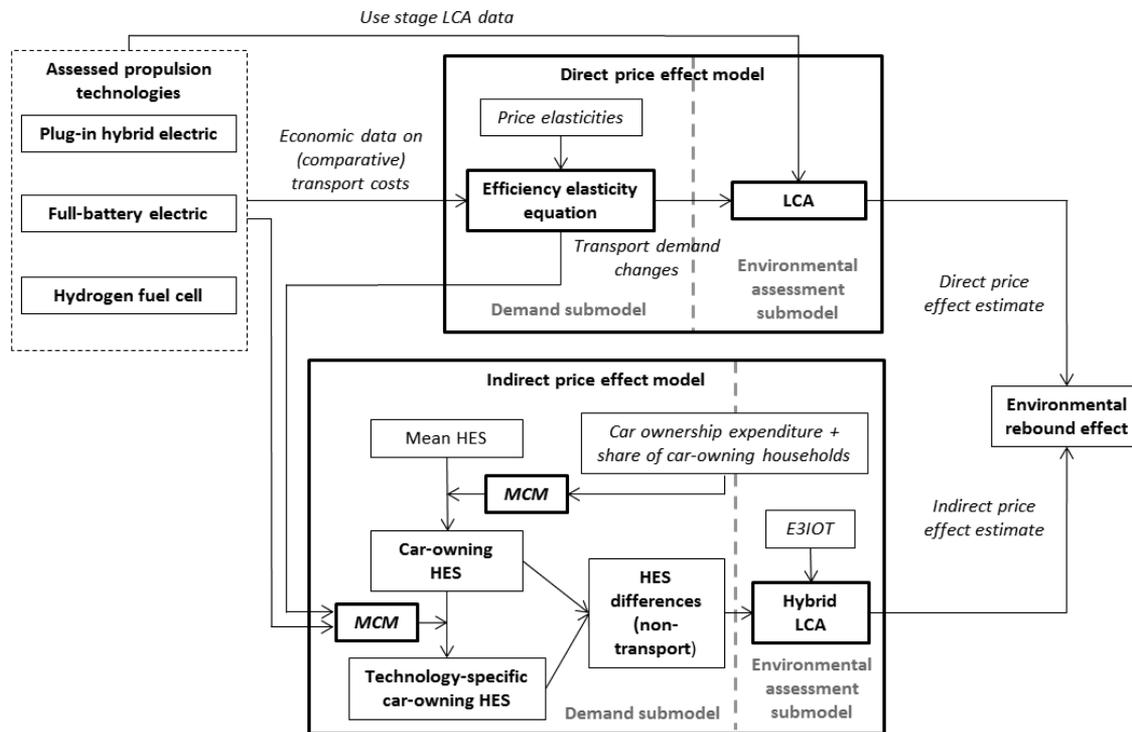


Figure 1. Overview of the proposed methodological framework to calculate the environmental rebound effect. HES: household expenditure structure, MCM: marginal consumption model, LCA: life cycle assessment. Bolded boxes represent models, and nonbolded boxes describe data, with arrows specifying data flows.

would increase by 0.16% and 0.26% for the ST and LT scenarios, respectively.

On the other hand, the transport costs, P_T , can be determined on the basis of all the costs incurred throughout the whole life cycle of the car (including capital costs), that is, the total cost of ownership (TCO). The use of the TCO is consistent with the life cycle approach of our model and the inclusion of capital costs in rebound studies is an established area of research.^{25,37,38} P_T can be defined as the sum of the fixed transport costs (P_f) and the variable transport costs (P_v):

$$P_T = P_f + P_v \tag{2}$$

Consistent with the LCA functional unit, we recalculate costs on the basis of 1 vkm. A suitable measure for P_f is the relative vehicle price, that is, the purchase price divided by the expected vkm during the vehicle lifespan. Because the relative cost differences related to nonfuel operating costs (e.g. insurance, scrappage, etc.) would be of minor importance,³⁹ we consider this a valid approximation. A suitable measure for P_v is fuel efficiency (E_f) times fuel price (P_f):

$$P_v = E_f \cdot P_f \tag{3}$$

Direct price effect estimates using this approach are described as changes in transport demand as a percentage from the initial transport demand, which can be easily translated into demand units (in this case, vkms). However, rebound effects can be expressed in various ways, for instance, as a change in a certain environmental indicator. To this end, demand units can be converted into environmental indicator units by means of LCA data from the use stage of a given transport mode, in this case expressed in impact units per vkm:

$$ERE_d = RE_d \cdot EI_u \tag{4}$$

Where ERE_d is the direct price ERE in environmental units, ER_d is the previously calculated direct price rebound effect in demand units and EI_u is the environmental impact per demand unit from the use stage. A list of the EI_u values used can be found in Table S6-1 in Supporting Information S6.

Indirect Price Rebound Effect Model. The indirect price rebound effect model is divided into two sub models: a marginal consumption model and a model that translates income changes into changes in environmental indicators by means of hybrid LCA.

Marginal Consumption Model. Marginal consumption modeling aims at estimating how liberated or bound income will be reallocated or unallocated by consumers. Concretely, we aim at modeling the allocation of income once the direct effect has taken place: the direct rebound effect shows a certain increase (or decrease) in money spent on transport and the remaining liberated or bound income then is assumed to be spent outside the transport consumption. For this, we will calculate a reference HES (ICE car) and an alternative HES (electric car). The difference between the two will describe the changes in income allocation.

First, we determine the mean HES of our consumer group, that is, how money is spent among the different consumption categories by households. For this, we use Eurostat’s “household mean consumption expenditure” (HMCE) data. Concretely, we use HMCE data for the EU27 and member states for the year 2005 by detailed classification of individual consumption according to purpose (COICOP) level (division, group, and class) and income quintiles,^{40,41} and an extract of these is presented in Supporting Information S2. Second, we will consider technology choices by modeling the mean EU27 HES to reflect the spending behavior of (ICE) car-owning households. This new HES will be used as a reference instead

of the mean HES. For this, we will calculate the income spent on the motor transport category of a car-owning household. This can be calculated by means of the following system of linear equations:

$$HES_{t,m} = \%_{h,c} \cdot HES_{t,c} + \%_{h,nc} \cdot HES_{t,nc} \quad (6)$$

$$HES_{t,nc} = \frac{\%_{t,nc}}{\%_{t,c}} \cdot HES_{t,c} \quad (7)$$

where $HES_{t,m}$ is the expenditure on motor transport from the mean HES, $\%_{h,c}$ is the percentage of households that own a car, $HES_{t,c}$ is the expenditure on motor transport from a car-owning household, $\%_{h,nc}$ is the percentage of households that do not own a car, $HES_{t,nc}$ is the expenditure on transport from a household without a car, $\%_{t,nc}$ is the percentage of the total HES from a car-owning household spent on motor transport, and $\%_{t,c}$ is the percentage of the total HES from a household without a car spent on motor transport. By solving the system of equations, $HES_{t,c}$ can be calculated as

$$HES_{t,c} = \frac{HES_{t,m}}{\%_{h,c} + \left(\%_{h,nc} \cdot \frac{\%_{t,nc}}{\%_{t,c}} \right)} \quad (8)$$

The values of $\%_{h,c}$ and $\%_{t,nc}$ can be obtained from the European Community Household Panel (ECHP), a panel survey on living conditions during the period 1994–2001,⁴² which is the most recent data available on this topic. Concretely, the data set on household car ownership per income quintile for the year 2001 in the EU15 (see Supporting Information S3). The values of $\%_{t,c}$ and $\%_{t,nc}$ can be approximated using statistical data for the U.K. from the Office for National Statistics (ONS),³⁰ because it is the most recent and close to European conditions data source available. According to this data, during the years 1999 and 2000, U.K. car-owning and noncar-owning households spent 24.7% ($\%_{t,c}$) and 2.5% ($\%_{t,nc}$), respectively, in transport from the total budget. As an approximation, we will apply these percentages to the motor transport instead of the entire transport category, thus assuming that the differences only affect the former. As more precise data are lacking, we also assume that total expenditure from car-owning and noncar-owning households is equal. Although both the ECHP and ONS data are fairly old and might be outdated to some extent, we believe it is the best way to approximate the current conditions.

Regarding the modeling of the rest of consumption categories (other than motor transport), we will derive marginal budget shares (MBS)²⁴ for each (that is, the share of marginal income that will be allocated to each consumption category) by applying two different approaches for completeness. The first approach is an income-shifting (IS) model as proposed by Thiesen et al.,⁸ which uses marginal shifts between income groups to model short-term changes in consumption patterns. This approach has been mainly used in the environmental assessment literature. The second approach is based on Engel curves (EC) or expenditure elasticities, which describe changes in expenditure on products in response to changes in total income. This approach is common in rebound and economic literature and has been applied by Murray,⁴³ Chitnis et al.,⁴⁴ Druckman et al.,⁴⁵ or Brännlund et al.⁴⁶ For a detailed description of the IS and EC approaches and a list of the calculated MBS values, see Supporting Information S4. Once the MBS have been calculated, the HES of the rest of

consumption categories for car-owning household ($HES_{r,c}$) can be calculated as

$$HES_{r,c}(+) = HES_r + HES_r \times MBS(+) \quad (9)$$

$$HES_{r,c}(-) = HES_r + HES_r \times MBS(-) \quad (10)$$

With:

$$HES_{r,c} = \begin{bmatrix} c_1 \\ c_2 \\ \vdots \\ c_m \end{bmatrix} \text{ and } MBS = \begin{bmatrix} MBS_1 \\ MBS_2 \\ \vdots \\ MBS_m \end{bmatrix}$$

where $HES_{r,c}$ is a column vector representing the household expenditure structure of all consumption categories (c) except motor transport, and m is the number of consumption categories, The positive (+) and negative (−) signs describe an increase and a decrease in income, respectively.

Once the expenditure not related to motor transport has been modeled, the car-owning HES (HES_c) for the EU27 can be determined by integrating the previously calculated $HES_{t,c}$ and $HES_{r,c}$ in the same column vector (note that $HES_{t,c}$ is presented as a column vector where the rest of consumption categories have zero values in order to make the vector addition possible):

$$HES_c = HES_t + HES_r \quad (11)$$

A third and last step regards modeling the HES_c so that it illustrates the spending behavior of those households that own a car with a specific propulsion technology. To calculate a technology specific car-owning HES ($HES_{s,t}$), we first have to calculate the change in income spent in motor transport ($HES_{s,t}$) as

$$HES_{s,t} = HES_{c,t} + \Delta C_t \quad (12)$$

$$\Delta C_t = \Delta P_t + RE_d(i) \quad (13)$$

Where ΔC_t is the change in motor transport costs, ΔP_t the change in TCO costs (fixed and variable costs) per kilometer and $RE_d(i)$ the direct price rebound effect in terms of yearly change in income. $RE_d(i)$ can be derived from RE_d by multiplying it by the transport costs per km (P_T). The rest of the consumption categories from the HES_s ($HES_{s,r}$) can be modeled again with the marginal consumption model (eqs 9 and 10).

Finally, the indirect price rebound effect expressed as an income change, $RE_i(i)$, can be calculated by the difference in expenditure in consumption categories other than motor transport between a technology-specific car-owning HES ($HES_{s,r}$) and the car-owning HES ($HES_{c,r}$):

$$RE_i(i) = HES_{m,r} - HES_{s,r} \quad (14)$$

Environmental Impact Intensity of Consumption. The indirect price rebound effect in terms of income changes can be translated into environmental indicator changes, ERE_i , by quantifying the environmental impact intensity (EII) (that is, the environmental impact per monetary unit) of each of the consumption categories (m):

$$ERE_i = RE_i(i) \times EII \quad (15)$$

with

$$ERE_i = \begin{bmatrix} ere_1 \\ ere_2 \\ \vdots \\ ere_m \end{bmatrix}, RE_i(i) = \begin{bmatrix} i_1 \\ i_2 \\ \vdots \\ i_m \end{bmatrix} \text{ and } EII = \begin{bmatrix} eii_1 \\ eii_2 \\ \vdots \\ eii_m \end{bmatrix}$$

Where *ere* and *i* are the indirect price rebound effect in environmental and income units, respectively, and *eii* is the environmental impact intensity for all consumption categories.

To calculate the ERE_i , we use detailed environmentally extended input-output analysis (EEIOA), which combines high-resolution input-output tables (IOT) with broad environmental extensions calculated using LCA data.^{47–51} Our model is based on the E3IOT database,⁵² which contains a high resolution, environmentally extended IOT (EEIOT) for Europe which covers production, consumption and waste management sectors.

Using CMLCA, a LCA software developed by the Institute of Environmental Sciences (CML) at Leiden University,⁵³ the environmental interventions per monetary unit corresponding to the different consumption categories can be calculated. Because CMLCA is fully matrix based, its combination with the E3IOT makes it a true hybrid LCA approach.^{54,55} In order to be compatible with the marginal consumption approach described in the previous section (which is based on consumption categories according to the COICOP classification), comprehensive environmental data archive (CEDA) consumption activities from the E3IOT must be converted into COICOP (division level) categories. The correlation between the CEDA and the COICOP categories has been established according to Supporting Information S5. By using this approach, we have determined the EII for all consumption categories and environmental indicators studied, and these are presented in Supporting Information S8.

The ERE , expressed as a change in environmental indicator units, can be then calculated as

$$ERE = ERE_d + \sum_{m=1}^{c-1} ERE_i \tag{16}$$

Lastly, the (environmental) rebound effect (RE) is generally expressed as a percentage of the environmental savings that are “taken back” as

$$\%RE = \left(\frac{PS - AS}{PS} \right) * 100 \tag{17}$$

with

$$AS = PS - (PS + RE) \tag{18}$$

where PS are the potential or engineered environmental savings from the studied technology with respect to its alternative considering only their technological characteristics (in our case, through product-based LCA) and AS are the actual savings including the rebound effect. Here, we encounter another complicating factor. Traditional formulations of the rebound effect are focused on dealing with one-dimensional efficiency improvements, and therefore, PS values are always positive. In the context of the ERE defined in this paper, negative PS values can take place when other environmental impacts, not targeted by the main efficiency improvement, get worse compared to the baseline scenario. For example, an improvement in GHG emissions could be linked to a larger emission of toxic substances. Equation 17 behaves appropriately when $PS > 0$, but it reverses its behavior when $PS < 0$ because the magnitude

of the reference that is used to study the relative change (in this case, PS) also changes.⁵⁶ An appropriate solution to this is to express the denominator in absolute terms as

$$\%ERE = \left(\frac{PS - AS}{|PS|} \right) * 100\% \tag{19}$$

Selected Case Studies. The results of selected product-level LCA studies in which rebound effects have not been considered will be used as a reference in order to test the described methodology. Three propulsion technologies for passenger cars have been selected as case studies: PHE, FBE, and HFC engines. The baseline scenario to which these innovative technologies will be compared will correspond to comparable alternatives equipped with ICE engines. By comparable we mean that, apart from the engine technology, the rest of the features of the car will be as similar as possible. As the literature suggests, a high comparability will minimize the risk of biases in the calculation of the rebound effect, for example by over-/underestimating changes in capital costs.^{44,57} Specific technologies (e.g., commercial car model) have been chosen by matching and/or maximizing the following four criteria: (1) Completeness and state of the art of the LCA data, (2) European scope of the LCA results (to keep consistency with the HMCE and the E3IOT boundaries), (3) compatibility of the environmental indicators with the environmental extensions of the E3IOT, and (4) availability of economic data for both the assessed technology and the comparable alternative.

The selected car models correspond to a Mercedes Benz S400 Hybrid (PHE), a Li-FePO₄ battery prototype (FBE), and a Mercedes-Benz f-cell (HFC). A summary of the main environmental and economic data needed for the rebound effect models, including alternative car models and hypotheses, can be found in Table S6-1 in Supporting Information S6. The studied models generally present a better environmental profile than their alternatives according to the LCA data. As for the transport costs, the PHE model is slightly cheaper to drive (about 1% cheaper) due to a decrease in the variable costs that offsets the higher capital costs. Regarding the FBE and HFC models, the capital costs are much higher, causing a notable increase in overall transport costs (about 58% and 41% more expensive, respectively). Because the input data is exogenous and dependent on complying with these four criteria, the case studies may not be fully comparable. For instance, car features (e.g., range or power) or environmental indicators may not be fully consistent between specific technologies. Nevertheless, general conclusions can still be drawn by testing our proposed method on these case studies.

RESULTS

In this section, we present the main results for the three studied propulsion technologies. Only the ERE results as changes in environmental indicators will be presented. For the intermediate results on HES, direct and indirect price rebound effect estimates and ERE magnitudes, we refer to Supporting Information S7. Because two different approaches will be used to calculate both the direct and the indirect effects, the ERE estimates will be presented using four scenarios for completeness. Additionally, the baseline and the original scenarios will be presented. The scenarios are defined as following:

- **Baseline scenario:** Original relevant alternative (ICE) result.
- **Original scenario:** Original result for the new propulsion technology without ERE.
- **ERE scenario 1 (ST-IS):** Short-term price own elasticity of transport demand (ST) and income-shifting (IS) approaches.
- **ERE scenario 2 (ST-EC):** ST and Engel curve (EC) approaches.
- **ERE scenario 3 (LT-IS):** Long-term price own elasticity of transport demand (LT) and IS approaches.
- **ERE scenario 4 (LT-EC):** LT and EC approaches.

Further sensitivity analysis of the calculations according to income groups will be presented also.

Plug-In Hybrid Electric Technology. The results for the assessed PHE passenger car are presented in Figure 2. They describe a general moderate positive ERE for the assessed environmental indicators. The magnitude of the ERE is generally lower than 50% and less than 5% for the ADP and GWP indicators (see Table S7-5 in Supporting Information S7). When environmental impacts are higher than the original LCA result, we speak of a positive rebound effect. A positive rebound effect counteracts the environmental benefits from the new technology, and thus it means that the overall environmental problems get worse. A negative rebound effect occurs when the rebound effect reinforces the environmental benefits, and thus the environmental impacts get better.

As can be seen in Figure 2, in the case of PHE cars, we obtain a positive rebound effect: the environmental improvement due to the PHE technology is partly undone by the rebound effect. The indirect effect is the main driver of the ERE with a contribution higher than 75% for all indicators (see Table S7-5 in Supporting Information S7). The reason for such a moderate and positive effect is that the use of the PHE car entails a slight decrease in transport costs compared with its relevant alternative (see Table S6-1 in Supporting Information S6). The freshwater eutrophication potential (FEP) indicator presents an exception to this general trend with a magnitude of 374% to 633%, superseding all environmental savings (backfire effect¹³). This can be explained by the fact that FEP emissions per € released during the life cycle of the studied PHE car are lower than the rest of consumption categories and 99% lower than those from general consumption (see Table S8-1 in Supporting Information S8). Such a low EII can be interpreted as a combination of (1) the use of state-of-the-art manufacturing processes and eco-design principles aimed at minimizing environmental burdens⁵⁸ and (2) high capital costs (luxury car brand). Thus, the FEP emissions from the PHE car are comparatively small with respect to those from the consumption categories in which the liberated income is spent. For instance, food and nonalcoholic beverages present high FEP emissions due to the extensive use of fertilizers in food production, among other factors (see Table S8-1 in Supporting Information S8). Consequently, each liberated income unit has a high potential to offset environmental improvements, and little income liberated can have a large impact. The increase in the FEP impact category from the ERE also causes the PHE results to be comparatively higher than its relevant alternative, thus reversing the original trend.

Full Battery Electric Technology. Figure 3 shows the results for the assessed FBE passenger car. The results describe, in contrast to the PHE technology, a generally notable negative

impact of the ERE on the original results, that is, an overall improvement in the environmental scores. The ERE magnitude varies considerably among indicators and is driven by the indirect effect (see Table S7-6 in Supporting Information S7). As explained before, FBE technologies are still in early development stages and have no defined market niche, and thus the purchasing costs are still relatively much higher than their ICE alternatives. The considerable magnitude of the ERE is thus related mainly to the important change in capital costs. Of the six environmental indicators assessed, two (FEP and global warming potential [GWP]) have a larger magnitude than the initial results, thus reversing the sign of the original results (from a positive to a negative score). This means that the constrained income from the use of a relatively more costly FBE car entails an overall negative environmental score (thus avoiding emissions from the whole consumption basket). Such notable magnitude is mainly driven by the indirect effect once the bound income is unallocated from consumption categories with relative higher FEP and GWP emission intensities (e.g., food or housing). Concretely, FEP and GWP emissions from the use of the FBE car are 99% and 79% lower than those from general consumption (see Table S8-1 in Supporting Information S8). Similarly to the PHE case study, this can be interpreted as a combination of green production technologies and eco-design as well as high capital costs. This would explain why bound income units have such a notable impact in avoiding emissions. Moreover, such negative contribution of the ERE causes the FBE car to score lower than its alternative in the terrestrial eco-toxicity potential (TETP) and freshwater eco-toxicity potential (FETP) indicators in some scenarios, whereas the score was comparatively higher according to the original results.

Hydrogen Fuel Cell Technology. The main results for the assessed HFC passenger car are presented in Figure 4. The results describe a considerable negative impact of the ERE on the original results, which enhances the environmental savings of this technology with respect to its ICE alternative. By type of effect, the indirect effect is the main driver with a contribution higher than 90% for all scenarios and indicators (see Table S7-7 in Supporting Information S7). It is worth noting that the direct effect in terms of SO₂ has not been able to be calculated due to lack of use stage LCA data from the original data source. As in the case of the FBE technology, such a notable magnitude can be explained by a combination of high capital costs of HFC technologies and the lower EII of the studied HFC car with respect to other consumption categories. Specifically, GHG and SO₂ emissions are respectively 81% and 92% lower than those from general consumption (see Table S8-1 in Supporting Information S8).

Sensitivity Analysis According to Income Groups. Just as in the methodological choices, the selection of the income group that will use the studied technologies can influence rebound effect estimates as well, as the literature suggests.²⁵ To study to what extent such choices may influence our results, we have calculated the rebound estimates according to income quintiles for each indicator and technology, and we have compared them to those from the mean income group (see Supporting Information S9). The results reveal various relevant insights: First, the income group chosen is found to have generally little influence on the rebound estimates. Second, the EC approach is found to be more responsive to income changes than the IS approach. Third, lower income groups present higher rebound estimates. This trend is consistent with the

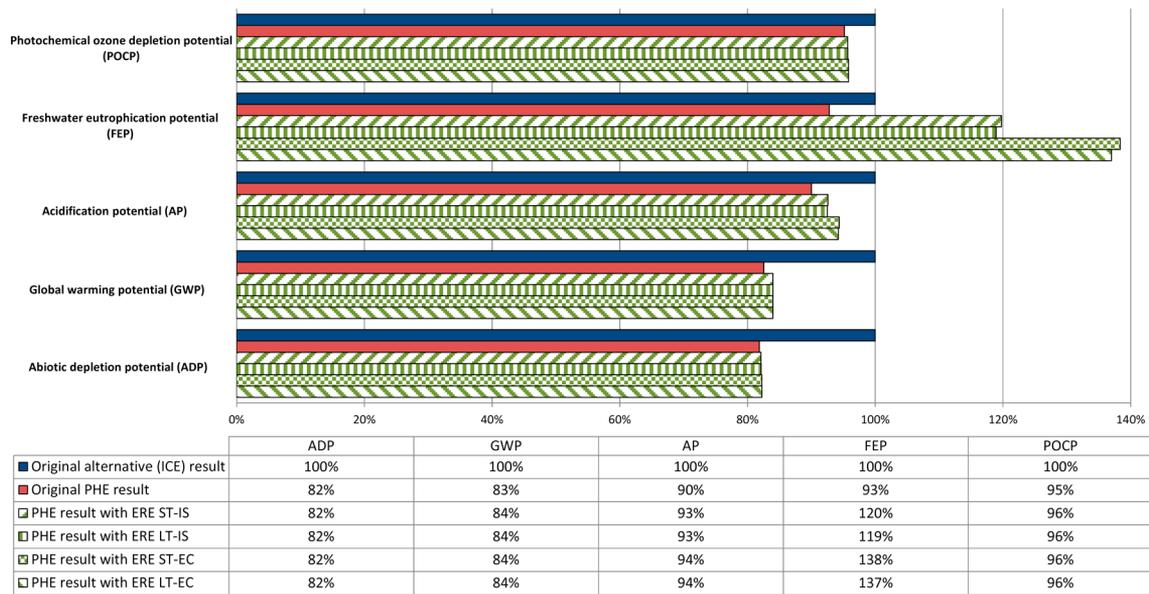


Figure 2. Normalized life cycle environmental impacts of the use of a plug-in hybrid electric (PHE) passenger car considering the environmental rebound effect (ERE) (as a percentage from the environmental impact of the relevant alternative). ICE: internal combustion engine.

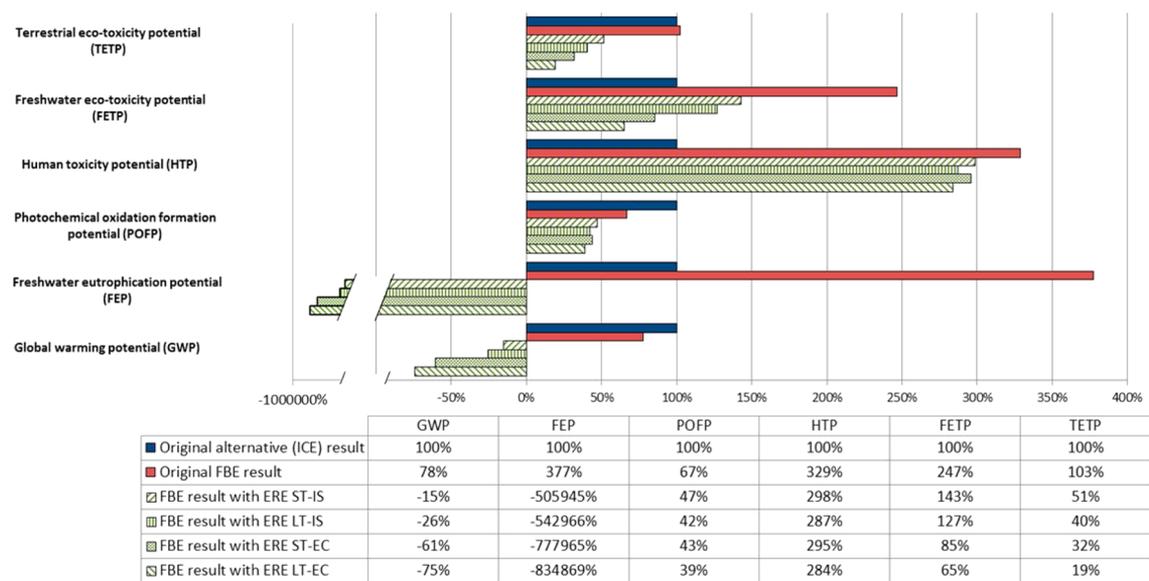


Figure 3. Normalized life cycle environmental impacts of the use of a full-battery electric (FBE) passenger car considering the environmental rebound effect (ERE) (as a percentage from the environmental impact of the relevant alternative). ICE: internal combustion engine.

findings of similar studies²⁵ and is explained by the fact that income changes in lower income groups are allocated to consumption categories with a higher EII, such as housing or food. Considering that we have studied car models with high capital costs and that these would be generally purchased by high income households, it is thus likely that, by using average income data, our rebound estimates may be slightly over-estimated if generalized.

DISCUSSION

In this article, we studied the environmental rebound effect (ERE) of different types of electric cars. The ERE is found to have an overall appreciable impact on product-level LCA estimates. It is much more influential than the technology improvement itself. For the assessed PHE car, the ERE is marginally positive due to a small decrease in the cost of using

this technology. On the other side, the use of the studied FBE and HFC cars entails a notable increase in transport costs (mainly due to the higher capital costs) that translates into a noteworthy negative ERE. As a result, the decrease in total consumption partially or completely offsets the environmental pressures from the use of these technologies. Sometimes this occurs even to the extent of causing negative environmental pressures for some indicators, that is, an overall environmental performance improvement of the consumption basket. From a comparative point of view, the ERE also induces changes in how the new technologies score with respect to their alternatives.

From the results of the sensitivity analysis, we can conclude that methodological choices in the modeling of the direct and indirect rebound effects in terms of demand have a moderate impact on the ERE estimates. Concretely, choices regarding the

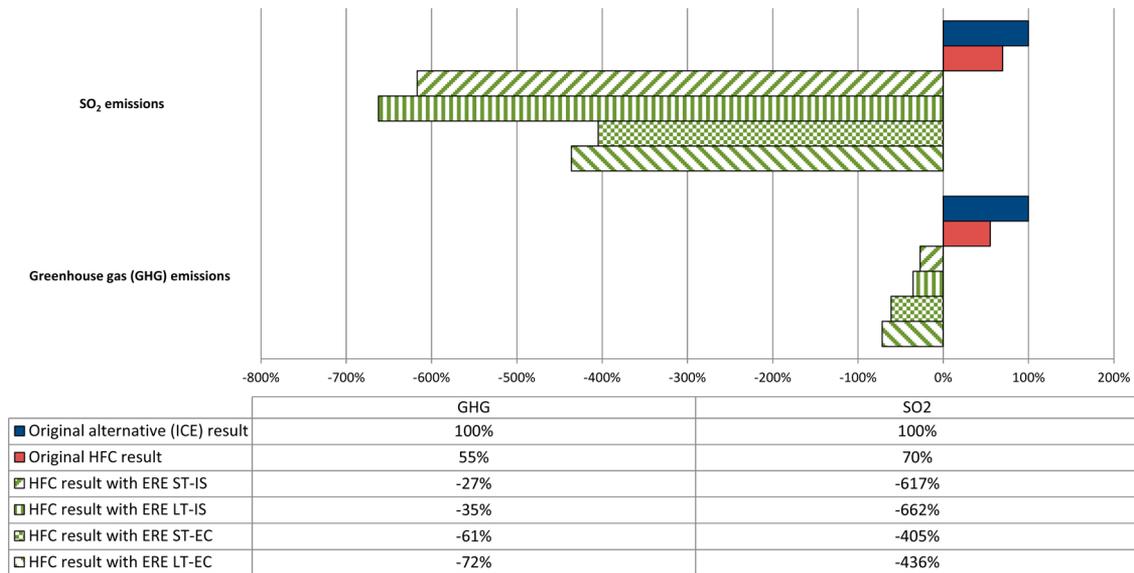


Figure 4. Normalized life cycle environmental impacts of the use of a hydrogen fuel cell (HFC) passenger car considering the environmental rebound effect (ERE) (as a percentage from the environmental impact of the relevant alternative). ICE: internal combustion engine.

calculation of the price elasticities, the responding modeling, and the income groups studied do not have a notable influence. With regard to the choice of using an income shifting model or the use of an Engel curve approach based on expenditure elasticities to model responding, we recommend the Engel curve approach as it is more responsive to income changes and it allows for higher consistency in allocating marginal income, with no negative expenditure values (see Table S7-2 in Supporting Information). Even though the introduction of technology choices such as car ownership is expected to improve the accuracy of the rebound estimates, it is also likely to entail a modest change in the overall results. Conversely, the EII of the studied technologies with respect to the rest of consumption is the main driver of the magnitude of our results. Indeed, the studied technologies have for most indicators a lower impact per euro than most of the rest of consumption categories, which explains to a great extent why liberated or bound income units have such a notable effect on increasing or decreasing overall emissions. The relevance of differences in the EII on final results calls for a further study of their drivers, for instance by introducing country-wise specifications (e.g., energy mix) or increasing the detail of the consumption modeling to account for varying impact intensities across products. Uncertainty analyses, when possible, are also recommended.

Some rebound magnitudes calculated in this study are considerably higher than those generally described in the traditional rebound effect literature, which are rarely higher than 100%. An important reason for such discrepancy is that rebound studies in the context of transport generally focus on incremental technology changes such as fuel shifts in ICE, whereas the ERE concept allows for broader technology changes, which can lead to higher cost changes. A number of other methodological choices can be also responsible for such discrepancies. Concretely, there are three significant methodological differences from other approaches. First, we have presented the rebound estimates for multiple environmental indicators instead of just energy-based indicators. When the environmental profile of the product of investigation is very different from that in other sectors, rebound effects from a reallocation of expenditures can be very high, as was the case

for FEP and TETP for FBE cars. Because evidence suggests that energy use per economic input is more uniform across economic sectors than other environmental indicators (e.g., phosphate) due to its transversal use in the economy,⁵⁹ we should expect rebound effects for some impact categories to be more extreme when money is reallocated to products with higher impact intensities. Second, by looking at the whole life cycle of products, we can account for environmental loads that would otherwise remain hidden, for instance, from the resource extraction or end-of-life stages. Third, by using the TCO to determine cost differences between technologies, we account for capital costs (vehicle purchase), which are often treated as “sunk costs”.^{18,57} In general, approaches using a life cycle perspective and multiple environmental indicators¹⁴ present larger and more varying rebound values compared to those found in the energy economics literature. In our opinion, such differences represent a step forward for environmental assessment that justifies the reinterpretation of traditional rebound definitions.

Even when the results are for car-specific models and depend on a number of assumptions which may not pertain entirely, they quite strongly indicate that price effects matter. They corroborate other findings that price differences can strongly change traditional LCA estimates.⁶⁰ For electric propulsion technologies, traditional LCA estimates alone are not a good guide to base policy on. The results also bring up some issues for policy to consider: If increases in prices offer better environmental results than technological advances, why simply not make the more environmentally challenging products more expensive? How do we achieve relevant market diffusion of expensive technologies if cheaper alternatives exist? Can we achieve similar levels of utility by consuming better, more expensive products? Of course, the complex nature of socio-economic systems prompts caution about appropriate policies. However, they invite to consider markets and prices as an active element of policy rather than a mere immutable background. In this sense, some authors^{23,61} suggest a policy mix including economic instruments, such as carbon/energy pricing or bonus-malus schemes, to mitigate the rebound effect.

■ ASSOCIATED CONTENT

📄 Supporting Information

Further details on methods, background data sets, and intermediate results. This material is available free of charge via the Internet at <http://pubs.acs.org/>.

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Notes

The authors declare no competing financial interest.

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