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The environmental rebound effect of electric cars

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Based on:

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.

Keywords: rebound effect, electric vehicles, life cycle assessment, sustainable transportation, consumption modelling, sustainable consumption policy.

1. 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) (Sperling and Gordon 2009). 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 (Granovskii et al. 2006). 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 (Gross et al. 2009; Font Vivanco et al. 2014). Considering the increasing momentum that LCA is gaining as a support tool for environmental policy (Pothen 2010), 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 (Hertwich 2005; Spielmann et al. 2008; Thiesen et al. 2008).

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 (Sperling and Gordon 2009). We refer to the ERE as the environmental outcomes from the change in overall consumption and production due to the behavioural or other systemic response to changes in production and consumption factors (e.g., income) induced by a technical change (e.g., energy effciency in transport) in a product or process (Khazzoom 1980; Brookes 1990; Berkhout et al. 2000; Greening et al. 2000; Saunders 2000). 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 (Font Vivanco and van der Voet 2014; Goedkoop et al. 1999). 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 effciency. 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 effciency, 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 effciency of cars.

The traditional rebound effect framework, rooted in economic theory (Berkhout et al. 2000), was operationalized during the 1970s and 1980s through the so-called Khazzoom−Brookes postulate, which, following the propositions of William Stanley Jevons (1865) (the so-called Jevons paradox), stated that increased energy effciency may lead to increased energy consumption (Saunders 1992). 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 (Greening et al. 2000; Sorrell et al. 2009; Chakravarty et al. 2013). A generally accepted decomposition of the rebound effect classifies it into at least three major effects: (1) direct effect, (2) indirect effect, and (3) macro-economic or structural effect (Greening et al. 2000). Moreover, various production and consumption factors (such as income or time) can trigger rebound effects (Hofstetter and Madjar 2003), which are the financial factors (income, price, or substitution effects) most studied in the literature, particularly those related to changes in the effective prices (Santarius 2012). 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 effcient 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 re-spending effect), that is, how liberated or bound money will be reallocated or unallocated among the various consumption categories (Chakravarty et al. 2013; Freire-González 2011; Sorrell 2007; Sorrell et al. 2009). For instance, there are approaches based on Engel curves (expenditure elasticities) (Murray 2009; Chitnis et al. 2012a) or on the shifting of expenditure patterns between income groups (Alfredsson 2004; Girod 2008; Thiesen et al. 2008). 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.) (Zahavi and Talvitie 1980; Mogridge 1983; ONS 2009). Although some attempts have been made to link marginal consumption models with household demographic characteristics (Chitnis et al. 2012a; Girod 2008), 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 behaviour, 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.

2. Environmental rebound effect model. Methodology and data sources

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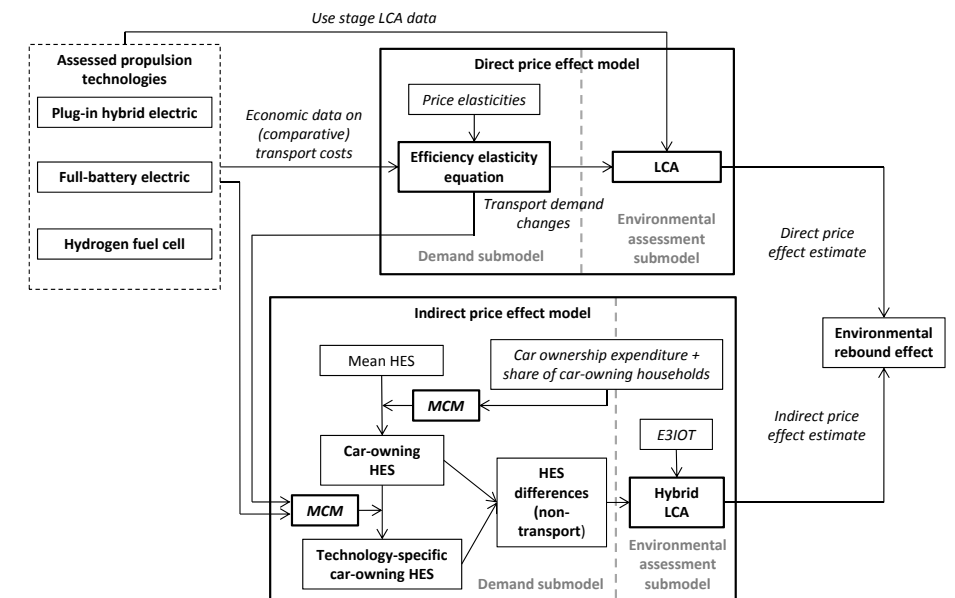
Figure 1. Overview of the proposed methodological framework to calculate the environmental rebound effect. HES: household expenditure structure, MCM: marginal consumption model, LCA: life cycle assessment. Bolded boxes represent models, and nonbolded boxes describe data, with arrows specifying data flows.

2.2 Direct price rebound effect model

Various definitions of the direct price rebound effect can be found in the literature (Becker 1965; Berkhout et al. 2000; Dimitropoulos and Sorrell; Greene et al. 1999; Juster and Stafford 1991; Khazzoom 1980; Sorrell and Dimitropoulos 2008). 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):

$$RE_d = -\eta_{P_T}(T) - 1 \tag{1}$$

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 (de Jong and Gunn 2001). As an example, if transport costs are 1% lower, by using eq 1 with the selected elasticities of transport demand, transport demand 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 (Chitnis et al. 2012a; Mizobuchi 2008; Nässén and Holmberg 2009). 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 differences related to nonfuel operating costs (e.g insurance, scrappage, etc.) would be of minor importance (Pock 2010), we consider this a valid approximation. A suitable measure for P_v is fuel efficiency (E_{fuel}) times fuel price (P_{fuel}):

$$P_v = E_{fuel} \cdot P_{fuel} \tag{3}$$

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:

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

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.

2.3 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.

2.3.1 Marginal Consumption Model

Marginal consumption modelling aims at estimating how liberated or bound income will be reallocated or unallocated by consumers. Concretely, we aim at modelling 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 (Eurostat 2014c, 2014b), and an extract of these is presented in Supporting Information S2. Second, we will consider technology choices by modelling the mean EU27 HES to reflect the spending behaviour 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:

$$HES_{t,m} = \%_{h,c} \cdot HES_{t,c} + \%_{h,nc} \cdot HES_{t,nc} \tag{5}$$

$$HES_{t,nc} = \frac{\%_{t,nc}}{\%_{t,c}} \cdot HES_{t,c} \tag{6}$$

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

$$HES_{t,c} = \frac{HES_{t,m}}{\%_{h,c} + \left(\%_{h,nc} \cdot \frac{\%_{t,nc}}{\%_{t,c}} \right)} \tag{7}$$

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 (Eurostat 2014a), 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) (2009) 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 non-car-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 non-car-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 modelling of the rest of consumption categories (other than motor transport), we will derive marginal budget shares (MBS) 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. (2008), 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 for the study of the rebound effect by Murray (2013), Chitnis et al. (2012b), Druckman et al. (2011) and Brännlund et al. (2007), among others. 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

$$HES_{r,c}(+) = HES_r + HES_r \times MBS(+) \tag{8}$$

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

with

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

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 modelled, 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):

$$HES_c = HES_t + HES_r \tag{10}$$

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

$$HES_{s,t} = HES_{c,t} + \Delta C_t \tag{11}$$

$$\Delta C_t = \Delta P_t + RE_d(i) \tag{12}$$

Where ΔC_t is the change in motor transport costs, ΔP_t the change in TCO costs (fixed and variable costs) per kilometre 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 modelled 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 ($HES_{c,r}$):

$$RE_i(i) = HES_{m,r} - HES_{s,r} \tag{13}$$

2.3.2 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) as

$$ERE_i = RE_i(i) \times EII \tag{14}$$

with

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

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 (Duchin 1996; Huppes et al. 2006; Isard et al. 1968; Leontief 1970; Leontief and Ford 1972). Our model is based on the E3IOT database (Universiteit Leiden 2014a), 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 (Universiteit Leiden 2014b), 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 (Heijungs and Suh 2002; Heijungs et al. 2006). 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

$$ERE = ERE_d + \sum_{c=1}^{m} ERE_i \tag{15}$$

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

$$\%RE = \left(\frac{PS - AS}{PS}\right) * 100 \tag{16}$$

with

$$AS = PS - (PS + RE) \tag{17}$$

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 behaviour when PS < 0 because the magnitude of the reference that is used to study the relative change (in this case, PS) also changes. An appropriate solution to this is to express the denominator in absolute terms as

$$\%ERE = \left(\frac{PS - AS}{|PS|}\right) * 100\% \tag{18}$$

2.4 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 to corresponds 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 (Sorrell and Dimitropoulos 2007; Chitnis et al. 2012b). Specific technologies (e.g., commercial car models) 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.

3. 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:
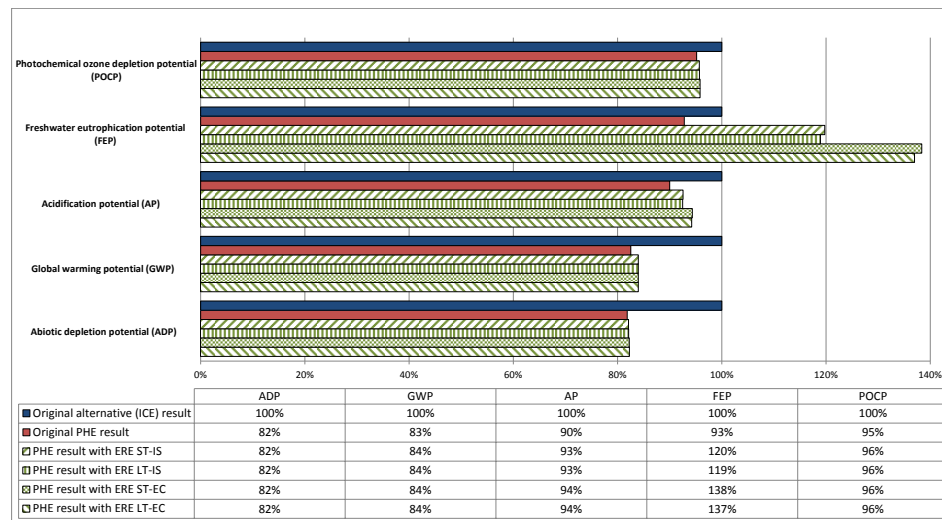
- **Baseline scenario**: Original relevant alternative (ICE) result.

- **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.

3.1 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.

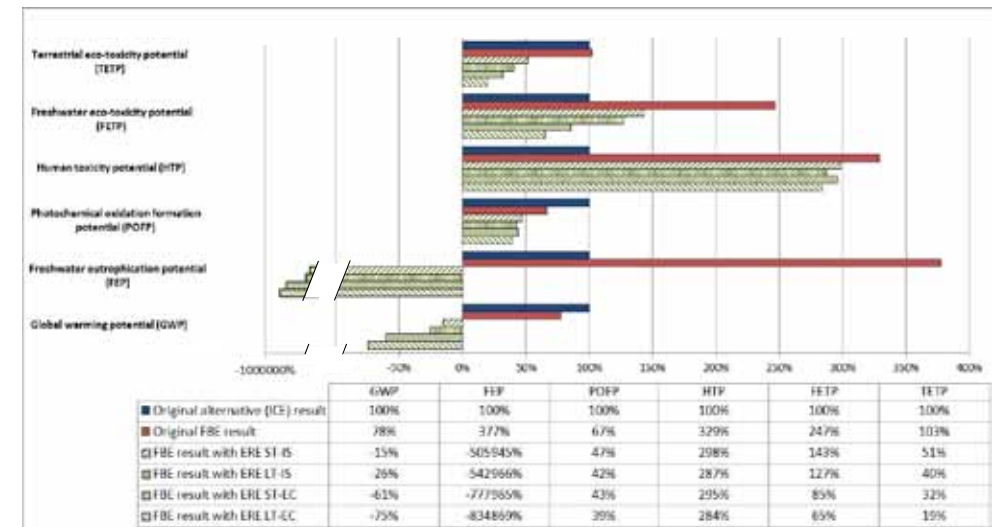|	ADP	GWP	AP	FEP	POCP
Original alternative (ICE) result	100%	100%	100%	100%	100%
Original PHE result	82%	83%	90%	93%	95%
PHE result with ERE ST-IS	82%	84%	93%	120%	96%
PHE result with ERE LT-IS	82%	84%	93%	119%	96%
PHE result with ERE ST-EC	82%	84%	94%	138%	96%
PHE result with ERE LT-EC	82%	84%	94%	137%	96%

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.

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 effect [Saunders 2000]). 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 burdens (Hahn et al. 2008) 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 non-alcoholic 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.

3.2 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.

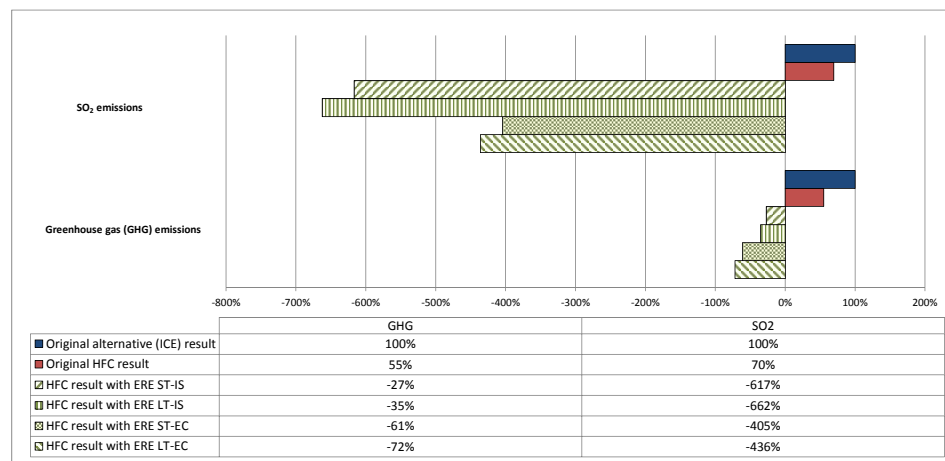|	GWP	FEP	POFP	HTP	FETP	TETP
Original alternative (ICE) result	100%	100%	100%	100%	100%	100%
Original FBE result	78%	377%	6.7%	329%	247%	103%
FBE result with ERE ST-IS	-15%	505945%	47%	298%	143%	51%
FBE result with ERE LT-IS	26%	542666%	42%	287%	127%	40%
FBE result with ERE ST-EC	-61%	-777565%	43%	295%	85%	32%
FBE result with ERE LT-EC	-75%	-834869%	39%	284%	65%	19%

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.

3.3 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 SO_2 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 SO_2 emissions are respectively 81% and 92% lower than those from general consumption (see Table S8-1 in Supporting Information S8).

	GHG	SO2
■ Original alternative (ICE) result	100%	100%
■ Original HFC result	55%	70%
☑ HFC result with ERE ST-IS	-27%	-617%
▨ HFC result with ERE LT-IS	-35%	-662%
▨ HFC result with ERE ST-EC	-61%	-405%
▨ HFC result with ERE LT-EC	-72%	-436%

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.

3.4 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 (Chitnis et al. 2012a). 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 findings of similar studies (Chitnis et al. 2012a) 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 overestimated if generalized.

4. 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 modelling of the direct and indirect rebound effects in terms of demand have a moderate impact on the ERE estimates. Concretely, choices regarding the calculation of the price elasticities, the re-spending modelling, 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 re-spending, 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 modelling 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 (Tukker et al. 2006), 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" (Sorrell and Dimitropoulos 2007; Sorrell et al. 2009). In general, approaches using a life cycle perspective and multiple environmental indicators (Font Vivanco and van der Voet 2014) 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 (Girod and de Haan 2010). 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 socioeconomic 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 (Sorrell 2007; Maxwell et al. 2011) suggest a policy mix including economic instruments, such as carbon/energy pricing or bonus-malus schemes, to mitigate the rebound effect.

Acknowledgements

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4

Supporting information

Supporting information which is not included here may be found in the online version of this article (http://pubs.acs.org/doi/suppl/10.1021/es5038063) and is available upon request.

Supporting information S1. Definition of the direct price rebound effect

Direct price rebound effect estimates in literature typically start from the household production function of Becker for energy services (Becker 1965). It provides a useful framework to estimate the direct price rebound effect from households, and the predictions of the model have been largely confirmed by empirical research (Juster and Stafford 1991). In this framework, an energy service is a service that consumers effectively demand to satisfy their wants and needs (e.g. transport, thermal comfort, etc.), more than energy itself (only indirectly demanded). The useful work is a feature of energy services and the way it can be measured (typically passenger or weight per kilometers in transport).

Starting from this framework, and in the context of energy services, some authors establish the efficiency elasticity of demand for energy as a direct measure of the direct price rebound effect. However, there are also other variables that under certain hypotheses can be considered a measure of the direct price rebound effect.

Assuming that $\varepsilon = T/E$ (the efficiency of an energy system [ε] equals to the energy service [in this case, a transport service such as passenger transportation] [T] achieved per unit of energy consumed [E]) and $P_T = P_E/\varepsilon$ (the price of the energy service [transport cost] [P_T] equals the price of energy [P_E] per unit of efficiency), the next expression can be obtained (Sorrell and Dimitropoulos 2008):

$$\eta_\varepsilon(E) = \frac{\partial E}{\partial \varepsilon}\frac{\varepsilon}{E} = \frac{\partial (T/\varepsilon)}{\partial \varepsilon}\frac{\varepsilon}{E} = \left[T\frac{\partial (1/\varepsilon)}{\partial \varepsilon} + \frac{1}{\varepsilon}\frac{\partial T}{\partial \varepsilon}\right]\frac{\varepsilon}{E} = \left[-T\varepsilon^2 + \frac{1}{\varepsilon}\frac{\partial T}{\partial \varepsilon}\right]\frac{\varepsilon^2}{T} = \frac{\varepsilon}{T}\frac{\partial T}{\partial \varepsilon} - 1 = \eta_\varepsilon(T) - 1 \quad (S1-1)$$

Equation S1-1 is the most common definition of the direct price rebound effect for a particular energy service in the literature (Sorrell 2007). That is, the efficiency elasticity of demand for energy (the direct price rebound effect) ($\eta_\varepsilon[E]$) equals the efficiency elasticity of demand for the transport energy service ($\eta_\varepsilon[T]$) minus one. Thus, the energy savings due to improvements in energy efficiency will correspond to the predictions of the mathematical models when the efficiency elasticity of demand for transport equals to zero ($\eta_\varepsilon[T] = 0$). In such a case, the efficiency elasticity of demand for energy is -1 ($\eta_\varepsilon[E] = -1$) and a positive rebound effect implies $\eta_\varepsilon(T) > 0$, so $|\eta_\varepsilon(E)| < 1$.

From this perspective, if $\eta_\varepsilon(T) > 1$ (elastic demand), or $\eta_\varepsilon(E) > 0$, we are considering a special case in which an energy efficiency improvement will cause an increase in energy consumption. This case is called backfire in the literature (Saunders 2000).

Assuming that consumers respond equally to increases (decreases) in energy efficiency in transport than to decreases (increases) on transport prices (symmetry assumption), the direct price rebound effect can be considered as a price elasticity. Under this assumption, the effect on the total cost

and, therefore, the demand for energy services (S) should be symmetrical. Assuming that income levels and prices of other goods remain constant, we can write the demand for energy services only as a function of price of transport ($S = f[P_T]$) and therefore, energy prices and energy efficiency. So the demand for energy, can be set as $E = S(P_T)/\varepsilon$ now given by: $E = f[P_E/\varepsilon]/\varepsilon$. Assuming that energy prices are exogenous, i.e., they do not depend on energy efficiency (exogeneity assumption) (Sorrell and Dimitropoulos 2008), the next expression can be derived:

$$\eta_\varepsilon(E) = -\eta_{P_T}(T) - 1 \qquad\qquad (S1-2)$$

A version of this definition has been used by many researchers to estimate the direct price rebound effect (Sorrell and Dimitropoulos 2008; Berkhout et al. 2000; Khazzoom 1980), since it is easier to apply than equations using efficiency, because of greater variation in the independent variable and data availability. Under these assumptions, the efficiency elasticity of demand for energy ($\eta_\varepsilon[E]$) is equal to the price of transport elasticity of demand for transport.

Again, a new development can be obtained through the symmetry condition (that is, consumers have similar responses to energy efficiency improvements than to reductions of energy prices) (Sorrell and Dimitropoulos 2008):

$$RE_d = \eta_\varepsilon(E) = -\eta_{P_T}(E) - 1 \qquad\qquad (S1-3)$$

This expression shows the direct price rebound effect, RE_d, based on the own price elasticity of energy demand for transport. This new definition allows estimates of the direct price rebound effect of many energy services when there is no data on energy efficiency or the useful work.

Supporting information S4. Description of the marginal consumption modelling approaches

This supporting information describes the two approaches used to model marginal consumption, namely the income-shifting (IS) and the Engel curves (EC) approaches.

S4.1. Income-shifting approach

The IS approach relates marginal liberated or bound money with marginal changes from one income group to the adjacent higher or lower income group, taking implicitly into consideration the different cross elasticities between consumption categories. Following the method described by Thiesen et al. (2008), we have calculated the marginal budget shares (MBS) for each consumption category and income quintile using household mean consumption expenditure (HMCE) data for the EU27 member states and for the year 2005 by detailed classification of individual consumption according to purpose (COICOP) level (division, group and class) and income quintiles from Eurostat (2014) (see Tables S4-1 and S4-2).

Table S4-1. Marginal budget shares (MBS) for increased income by COICOP category and income quintile (IQ) using the income-shifting approach.

COICOP category	MBS (+)					
	1st IQ	2nd IQ	3rd IQ	4th IQ	5th IQ[1]	Mean
CP01 Food and non-alcoholic beverages	0.04	0.03	0.03	0.01	0.01	0.03
CP02 Alcoholic beverages, tobacco and narcotics	0.03	0.04	0.05	0.03	0.03	0.03
CP03 Clothing and footwear	0.07	0.09	0.08	0.08	0.08	0.08
CP04 Housing, water, electricity, gas and other fuels	0.05	0.04	0.04	0.04	0.04	0.04
CP05 Furnishings, household equipment and routine maintenance of the house	0.11	0.08	0.09	0.12	0.12	0.10
CP06 Health	0.09	0.05	0.06	0.10	0.10	0.08
CP07.1 Motor vehicle transport	0.11	0.11	0.09	0.11	0.11	0.10
CP07.2 Other transport	0.11	0.11	0.09	0.11	0.11	0.10
CP08 Communications	0.05	0.05	0.05	0.04	0.04	0.05
CP09 Recreation and culture	0.10	0.10	0.08	0.08	0.08	0.09
CP10 Education	0.06	0.11	0.15	0.11	0.11	0.11
CP11 Restaurants and hotels	0.10	0.09	0.10	0.09	0.09	0.10
CP12 Miscellaneous goods and services	0.09	0.08	0.09	0.09	0.09	0.09
Total	**1.00**	**1.00**	**1.00**	**1.00**	**1.00**	**1.00**

[1] Because there is no upper income group, MBS for the fifth income quintile cannot be calculated and have been assumed to be equal to those from the fourth income quintile.

Table S4-2. Marginal budget shares (MBS) for decreased income by COICOP category and income quintile using the income-shifting approach.

COICOP category	MBS (-)					
	1st IQ[1]	2nd IQ	3rd IQ	4th IQ	5th IQ[1]	Mean
CP01 Food and non-alcoholic beverages	-0.05	-0.05	-0.04	-0.03	-0.02	-0.03
CP02 Alcoholic beverages, tobacco and narcotics	-0.04	-0.04	-0.04	-0.05	-0.04	-0.04
CP03 Clothing and footwear	-0.07	-0.07	-0.09	-0.08	-0.08	-0.08
CP04 Housing, water, electricity, gas and other fuels	-0.05	-0.05	-0.05	-0.05	-0.05	-0.05
CP05 Furnishings, household equipment and routine maintenance of the house	-0.10	-0.10	-0.08	-0.09	-0.10	-0.10
CP06 Health	-0.09	-0.09	-0.06	-0.07	-0.09	-0.08
CP07.1 Motor vehicle transport	-0.10	-0.10	-0.11	-0.09	-0.10	-0.10
CP07.2 Other transport	-0.10	-0.10	-0.11	-0.09	-0.10	-0.10
CP08 Communications	-0.06	-0.06	-0.06	-0.06	-0.05	-0.06
CP09 Recreation and culture	-0.09	-0.09	-0.10	-0.08	-0.08	-0.09
CP10 Education	-0.07	-0.07	-0.10	-0.13	-0.10	-0.10
CP11 Restaurants and hotels	-0.09	-0.09	-0.09	-0.10	-0.09	-0.09
CP12 Miscellaneous goods and services	-0.09	-0.09	-0.08	-0.09	-0.09	-0.09
Total	**-1.00**	**-1.00**	**-1.00**	**-1.00**	**-1.00**	**-1.00**

[1] Because there is no lower income group, MBS for the first income quintile cannot be calculated and have been assumed to be equal to those from the second income quintile.

S4.2. Engel curves approach

In short, Engel curves describe how expenditure on a given consumption category varies with household income. Total expenditure is usually taken as a proxy of total income "to separate the problem of allocating total consumption to various goods from the decision of how much to save or dissave out of current income" (Lewbel 2006). A basic functional form of the Engel curve describes real expenditure (q) on product i with respect to total expenditure (y) as:

$$q_i = g_i(y) \qquad (S4-1)$$

On the other hand, the Engel curve can also be expressed as proportional expenditure changes with respect to total income, thus describing the MBS (Goldberger 1969) as

$$MBS_i = w_i = \frac{\partial q_i}{\partial y} \qquad (S4-2)$$

where w_i is the fraction of y that is spent on product or consumption category i. MBS thus provide a way to model the indirect effect by describing how will the liberated or bound income be (un) allocated by consumers among the consumption categories.

From all the functional forms that Engel curves can adopt, we will opt for the linear form because of its simplicity and good statistical fit (Murray 2013; Chitnis et al. 2012). Using the linear form, the MBS can be calculated using Equations S4-1 and S4-2 as

$$q_i = \alpha_i + \beta_i y \qquad (S4-3)$$

$$MBS_i = w_i = \beta_i \qquad (S4-4)$$

where α and β are unknown parameters.

The mean MBS can be calculated by using expenditure and income data from all income groups, whereas MBS for each income quintile can be approximated by using the targeted income group data as well as the upper or lower income groups for the calculation of the MBS(+) and MBS(-) respectively. All MBS values can be found in tables S4-3 and S4-4.

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Table S4-3. Marginal budget shares (MBS) for increased income by COICOP category and income quintile (IQ) using Engel curves.

COICOP category	MBS (+)					
	1st IQ	2nd IQ	3rd IQ	4th IQ	5th IQ	Mean
CP01 Food and non-alcoholic beverages	0.14	0.11	0.08	0.04	0.04	0.13
CP02 Alcoholic beverages, tobacco and narcotics	0.01	0.02	0.02	0.01	0.01	0.02
CP03 Clothing and footwear	0.05	0.07	0.07	0.07	0.07	0.06
CP04 Housing, water, electricity, gas and other fuels	0.24	0.21	0.20	0.17	0.17	0.24
CP05 Furnishings, household equipment and routine maintenance of the house	0.07	0.06	0.07	0.10	0.10	0.07
CP06 Health	0.04	0.03	0.03	0.05	0.05	0.04
CP07.1 Motor vehicle transport	0.10	0.12	0.12	0.14	0.14	0.10
CP07.2 Other transport	0.04	0.05	0.05	0.06	0.06	0.04
CP08 Communications	0.03	0.03	0.03	0.02	0.02	0.03
CP09 Recreation and culture	0.10	0.12	0.11	0.11	0.11	0.10
CP10 Education	0.01	0.01	0.02	0.02	0.02	0.01
CP11 Restaurants and hotels	0.06	0.07	0.08	0.08	0.08	0.06
CP12 Miscellaneous goods and services	0.10	0.10	0.12	0.13	0.13	0.10
Total	**1.00**	**1.00**	**1.00**	**1.00**	**1.00**	**1.00**

Table S4-4. Marginal budget shares (MBS) for decreased income by COICOP category and income quintile (IQ) using Engel curves.

COICOP category	MBS (-)					
	1st IQ	2nd IQ	3rd IQ	4th IQ	5th IQ	Mean
CP01 Food and non-alcoholic beverages	-0.22	-0.14	-0.11	-0.08	-0.04	-0.13
CP02 Alcoholic beverages, tobacco and narcotics	-0.03	-0.01	-0.02	-0.02	-0.01	-0.02
CP03 Clothing and footwear	-0.05	-0.05	-0.07	-0.07	-0.07	-0.06
CP04 Housing, water, electricity, gas and other fuels	-0.33	-0.24	-0.21	-0.20	-0.17	-0.24
CP05 Furnishings, household equipment and routine maintenance of the house	-0.04	-0.07	-0.06	-0.07	-0.10	-0.07
CP06 Health	-0.03	-0.04	-0.03	-0.03	-0.05	-0.04
CP07.1 Motor vehicle transport	-0.06	-0.10	-0.12	-0.12	-0.14	-0.10
CP07.2 Other transport	-0.03	-0.04	-0.05	-0.05	-0.06	-0.04
CP08 Communications	-0.04	-0.03	-0.03	-0.03	-0.02	-0.03
CP09 Recreation and culture	-0.06	-0.10	-0.12	-0.11	-0.11	-0.10
CP10 Education	-0.01	-0.01	-0.01	-0.02	-0.02	-0.01
CP11 Restaurants and hotels	-0.04	-0.06	-0.07	-0.08	-0.08	-0.06
CP12 Miscellaneous goods and services	-0.07	-0.10	-0.10	-0.12	-0.13	-0.10
Total	**-1.00**	**-1.00**	**-1.00**	**-1.00**	**-1.00**	**-1.00**

Supporting information S6. Environmental and economic data of the selected specific technologies

Table S6-1. Environmental and economic data of the selected specific technologies for the environmental rebound effect calculation.

Table S6-1 see next pages $\longrightarrow$

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Table S6-1. Environmental and economic data of the selected specific technologies for the environmental rebound effect calculation.

Propulsion technology	Technology specification	Environmental assessment		Economic assessment		Comments
		Life cycle environmental indicators		Fixed costs (P_f)	Variable costs (P_v)	
		Indicator (CML 2001)	Value and unit per km, all stages (use stage [EI_u])[h]			
Plug-in hybrid electric	Mercedes-Benz S400 Hybrid (Gasoline)	ADP	1.67 (1.42) gr SB eq.	0.284 euro/km[a]	0.121 euro/km[b]	Total lifetime use of 300,000 km and fuel consumption of 7.9 litres/100 km[h]. Car lifetime of 12 years (Pridmore et al. 2010).
		GWP	269.33 (226.24) gr CO_2 eq.			
		AP	0.33 (0.17) gr SO_2 eq.			
		FEP	0.03 (0.01) gr phosphate eq.			
		POCP	0.06 (0.04) gr ethane eq.			
Internal combustion (comparable alternative)	Mercedes-Benz S350 (Gasoline)	ADP	2.04 gr SB eq.	0.254 euro/km[a]	0.153 euro/km[b]	Total lifetime use of 300,000 km and fuel consumption of 10 litres/100 km[h].
		GWP	326.33 gr CO_2 eq.			
		AP	0.37 gr SO_2 eq.			
		FEP	0.04 gr phosphate eq.			
		POCP	0.06 gr ethane eq.			
		Indicator (ReCiPe)[d]	Value and unit per km, all stages (use stage [EI_u])(Hawkins et al. 2012) [e]			
Full-battery electric	Li-FePO$_4$ battery	GWP	190.00 (104.00) gr CO_2 eq.	0.483 euro/km (van Vliet et al. 2011)[f]	0.032 euro/km[c]	Total lifetime use of 140,000 km, energy requirement of 0.623 MJ/km and car lifetime of 10 years (van Vliet et al. 2011).
		FEP	0.20 (0.09) gr P eq.			
		POFP	0.43 (0.23) gr NMVOC eq.			
		HTP	240.00 (78.00) gr 1,4-DCB eq.			
		FETP	3.70 (1.43) gr 1,4-DCB eq.			
		TETP	0.08 (0.07) gr 1,4-DCB eq.			
Internal combustion (comparable alternative)	Mixed gasoline + diesel engine[g]	GWP	245.00 gr CO_2 eq.	0.124 euro/km (van Vliet et al. 2011)[f]	0.091 euro/km[b]	Car lifetime of 12 and 15 years for gasoline and diesel cars respectively (Pridmore et al. 2010). Average yearly use: 11,416 km and 19,053 km respectively (Ntziachristos et al. 2008). Total lifetime use: 136,992 km and 285,795 km respectively. Market share of 49.1% and 50.9%, respectively[a].
		FEP	0.05 gr P eq.			
		POFP	0.65 gr NMVOC eq.			
		HTP	73.00 gr 1,4-DCB eq.			
		FETP	1.50 gr 1,4-DCB eq.			
		TETP	0.08 gr 1,4-DCB eq.			
		Indicator (pressure level)	Value and unit per km, all stages (use stage [EI_u]) (Sorensen 2004)[j]			
Hydrogen fuel cell	Mercedes-Benz f-cell	GHG	110.10 (68.06) gr CO_2 eq.	0.267 euro/km[53]	0.026 euro/km	Total lifetime use of 300,000 km, energy requirement of 0.65 MJ/km and car lifetime of 15 years (Sorensen 2004). Hydrogen price of 0.04 euro/MJ (Meyer 2012).
		Sulphur dioxide (SO_2)	0.12 (0.00[j]) gr SO_2			
Internal combustion (comparable alternative)	Mercedes-Benz A 200 CDI BlueEfficiency (Diesel)	GHG	200.00 gr CO_2 eq.	0.090 euro/km[a]	0.084 euro/km[b]	Total lifetime use of 300,000 km (Sorensen 2004). Fuel consumption of 5.8 litres/km[i].
		Sulphur dioxide (SO_2)	0.17 gr SO_2			

ADP: abiotic depletion potential, AP: acidification potential, FEP: freshwater eutrophication potential, FETP: freshwater eco-toxicity potential, GHG: greenhouse gas emissions, GWP: global warming potential, HTP: human toxicity potential, PE: primary energy, POFP: photochemical oxidation formation potential, POCP: photochemical ozone creation potential, TETP: terrestrial eco-toxicity potential

[a] Recommended ex-factory retail price by the manufacturer for Europe, including regular sales taxes. Prices obtained from *http://www.cars-of-europe.com*.

[b] EU27 average fuel retail prices (including taxes) for gasoline (1.530 euro/litre) and diesel (1.448 euro/litre) obtained from Europe's Energy Portal (*http://www.energy.eu*) for September 2013.

[c] EU27 average household electricity retail price (in purchasing power standard, including taxes and from a 2.500 to 5.000 KWh consumption range [EU27 average]) for the second semester of the year 2012 (0.055 euro/MJ) obtained from Eurostat (2013).

[d] Hierarchical scenario values. Because the ReCiPe method contains a higher resolution regarding the environmental interventions (e.g. with respect to the associated compartments or the population density) than the E3IOT, a precautionary approach has been applied by choosing the absolute lowest value in case of differing values. From the ten impact categories considered in the study, only the six described have been able to be calculated due

to differences in the format of the environmental interventions flows between the ReCiPe method and the E3IOT.

[e] Current European electricity mix conditions for the calculation of electricity production impacts.

[f] Purchase costs of Li-FePO$_4$ battery electric cars have not been able to be calculated from the information provided in Hawkins et al. (2012) due to the fact that (1) they consider modelled cars using adaptations of existing gliders and powertrains rather than real models and (2) studied battery technologies are in a relatively inceptive stage, with currently no commercial models in the market. As an approximation, the purchase cost of electric cars from van Vliet et al. (2011) have been used.

[g] The alternative is a mix of comparable gasoline and diesel internal combustion vehicles (same glider as the electric counterpart) according to the market shares of gasoline and diesel cars in Europe.

[h] The original result, in C eq. units, has been transformed to CO_2 eq. units using the mass ratio.

[i] Data from *http://www.cars-of-europe.com*.

[j] Information not provided by the data source.