The rebound effect through industrial ecology's eyes : the case of transport eco-innovation

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Title: The rebound effect through industrial ecology's eyes : the case of transport eco-innovation
Issue Date: 2016-03-03

General discussion

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1. Introduction

This thesis investigates the value of applying concepts and methods from the realm of industrial ecology to the study of the rebound effect. This thesis departs from the original definition from neoclassical energy economics for the rebound effect, which focuses on the increase in the supply of energy services as a result of improvements in technological efficiency causing a decrease in the effective price of energy services (Greening et al. 2000). This definition, however, can be considered too narrow in the context of the complex sustainability issues that are industrial ecology's bread-and-butter (Hertwich 2005). By applying concepts and methods from industrial ecology, this thesis reveals both the feasibility and value of definitional refinements of the classical definition. A revised definition is proposed, based on the environmental rebound effect (ERE) concept (Goedkoop et al. 1999; Spielmann et al. 2008; Murray 2013), which focuses on the lifecycle environmental consequences of overall demand changes as a result of technical efficiency improvements in products liberating or bounding consumption and production factors. Whereas results following the classical energy rebound effect are often in the range of zero to 80% (and often below 30%) (Greening et al. 2000; Sorrell 2007; Jenkins et al. 2011), those following the ERE typically assume a wide range of values (including values far above 100% and below -100%).[25]

This thesis contributes to the study of rebound effects in four ways: it advances theoretical frameworks and methods for estimating (environmental) rebound effects, it discusses the limitations of existing definitions and methods, it examines the extent to which rebound effects are treated in policy and how to deal with them, and engages in original empirical analysis by calculating the rebound effects for ten innovations in passenger transport in Europe. Such contributions together offer a renewed perspective on this critical yet contested issue. While the size and consequent impact of rebound effects is highly case-dependent, the general insights gained can be generalized to some extent to other sectors and regional contexts. By answering the research questions put forward in the introductory section, such contributions and their implications are further discussed. Figure 1 shows how the chapters of this thesis are related to each of the research questions.

2. Answers to the research questions

Q1. Is life cycle assessment a good basis for the macro-level environmental assessment of transport eco-innovation?

Life cycle assessment (LCA) was conceived mainly as a decision supporting tool (Guinée et al. 2002), and recently has received increasing attention in the context of environmental policy (Pothen 2010). While first applications were developed for industry, for purposes such as the minimisation of waste from packaging (Hunt et al. 1996), the uses of LCA have proliferated rapidly (Guinée et al.2010).

25. The percentage refers to the environmental gains that are 'taken back' due to the rebound effect, with a 100% meaning that all environmental gains are nullified and a -100% meaning that these are doubled.

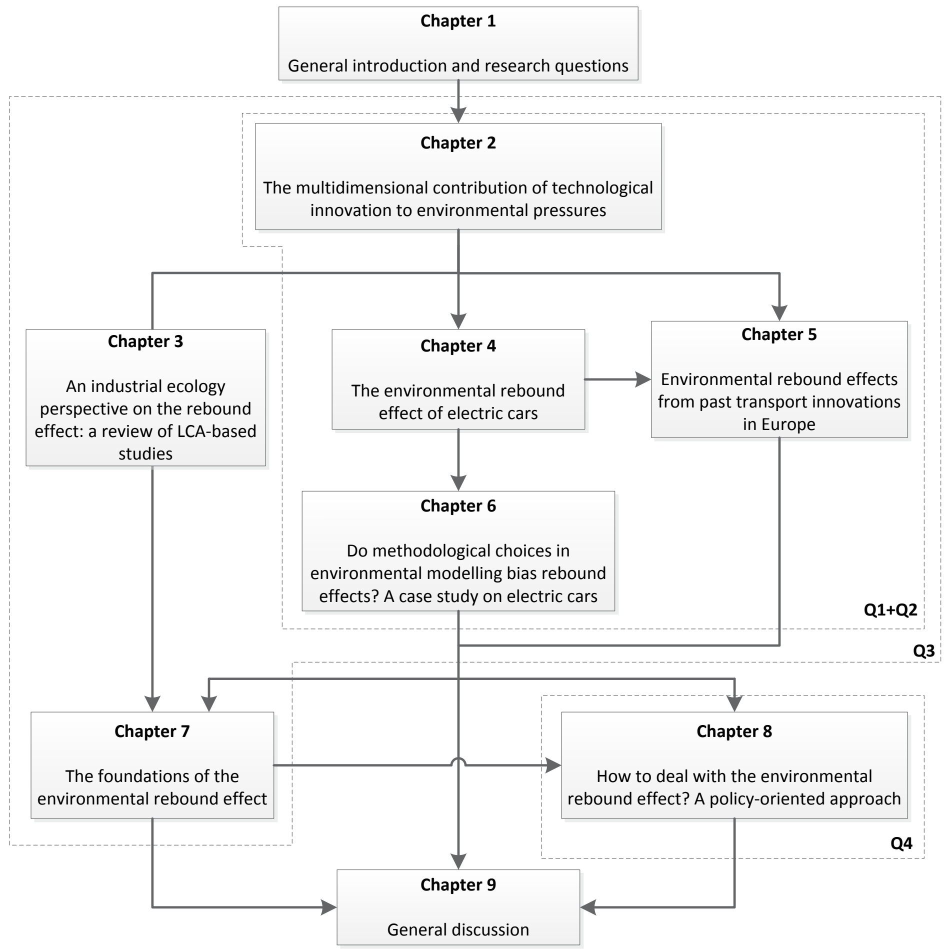

Figure 1. Outline of the thesis and relation with the research questions (Q).

Nowadays, LCA clusters a plethora of uses, including policy design and evaluation, and is an integral part of key policies, such as integrated product policy (IPP). In this regard, the European Commission (EC) (2003: 10) concluded, in its Communication on IPP, that "LCAs provide the best framework for assessing the potential environmental impacts of products". In line with this, LCA is often used to investigate claims of environmental superiority of so-called eco-innovation (Dangelico and Pujari 2010). However, the use of LCA for environmental policy raises a number of still unresolved issues (Guinée et al. 2010). Among these issues, a topic of special concern is the shift from functional-unit-based (micro-level of individual products) to real-world improvements (macroeconomic level) (ibidem). In doing so, LCA studies should incorporate dynamic effects derived from the interaction between products and surrounding socio-technical systems, such as technology displacement, behaviour changes and rebound effects (Miller and Keoleian 2015).

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However, these side-effects are insufficiently addressed in LCA studies in general (van der Voet et al. 2010; Heijungs et al. 2009) and also specifically in the case of transport (Hawkins et al. 2012).

The results of empirical analyses presented in **Chapters 2**, **4**, **5** and **6** show how overlooking rebound effects stemming from price mechanisms may notably overestimate the macro-level environmental performance of presumed eco-innovations such as diesel engines and car sharing schemes. While the results show a wide range of outcomes, from a slight to a complete offsetting of environmental savings due to the rebound effect, they indicate that price effects matter, and that price differences can strongly influence product-level LCA estimates when including rebound effects. Similar results can be found in the literature when consumption factors other than prices are studied in the rebound effect context, for instance time and socio-psychological costs (Jalas 2002; Girod et al. 2011). The divergence between micro and macro level results leads to two important points of discussion. First, when supported by LCA, does the concept of eco-innovation apply equally at both product and macro scales of analysis? Second, if indeed rebound effects greatly influence environmental profiles of products, why does functional-unit-based LCA still have wide acceptance in policy design?

Eco-innovation has been defined both in terms of motivation and performance (Kemp and Pearson 2007), that is, whether environmental improvements are expected or effectively achieved. Motivation-driven eco-innovation is better aligned with objectives to reduce the environmental burdens per functional unit (e.g. CO_2 emissions per kilometre), which predominate at the corporate level (Herva et al. 2011). This interpretation would be better aligned with functional-unit or product-based LCA, which would generally ignore indirect effects taking place once the innovation diffuses through the economy, such as rebound and other causal effects (Miller and Keoleian 2015). On the other hand, performance-based eco-innovation seems to be better aligned with governmental objectives of absolute environmental improvements, and so macro-level LCA, including rebound and other indirect effects, would be more suitable. However, the discrepancies between micro and macro level LCA results exemplify that eco-innovation claims depend greatly on the scale of analysis: what can be considered an eco-innovation at the factory gate can become an environmentally detrimental product once it permeates the economy. Such relativity makes eco-innovation a rather ill-defined concept in the context of achieving absolute environmental improvements.

A possible way forward to restore meaning to the eco-innovation concept involves a reformulation so that the concept relates exclusively to the product-level environmental performance. This involves a departure from overpromising objectives such as the reduction of environmental burdens or sustainability targets (Klemmer et al. 1999) to more realistic expectations on resource efficiency. Eco-innovation has a powerful meaning for end-consumers (Pujari 2006; Jansson et al. 2010), and so balancing the expectations surrounding eco-innovation would in turn lead to more informed decisions by consumers seeking to reduce their environmental footprint. Indeed, claims of environmental superiority leave little room to question the counterproductive consequences of resource efficiency. By raising awareness on such consequences, consumers can choose, for instance, higher quality products such as transport services with increased comfort and more durable goods

instead of cheaper alternatives that invoke rebound effects. As regards the management of eco-innovation by policymakers, claims of environmental superiority supported by product-level LCA should be complemented with broader analysis that consider rebound and other indirect effects when designing policies and targets. This would be in line with the principles underlying the life cycle sustainability analysis (LCSA) framework (Guinée and Heijungs 2011), in particular the need to combine the technology richness of LCA with economic and social assessment tools in order to capture economic and social responses to technical change. Meaningful eco-innovation assessment and management relies deeply on a careful consideration of such responses.

On the subject of the role of LCA in policy, as illustrated by the case of the IPP in Europe, product-level LCA enjoys widespread popularity in the policy domain for assessing the environmental performance of innovation. While not addressing this issue in detail, **Chapter 8** offers valuable insights on this topic while analysing the reasons for the predominance of efficiency-based principles in the design and evaluation of environmental policy. An example of this are CO_2 emissions per vehicle-kilometre targets in Europe (ICCT 2014). This chapter offers a number of reasons for such predominance, such as the lower costs and greater ease with which relative improvements can be achieved (compared to absolute reductions) and the affinity with prevailing discourses of managerial and business efficiency (Princen 2005; Levett 2009; Schaefer and Wickert 2015). The use of product-level LCA, which yields results in in the form of intensive variables (e.g. emissions per kilometre), is much aligned with discourses based on efficiency, and so would be seen as an adequate tool for policymakers. However, as the results of this thesis point out, whether these objectives will effectively deliver real-world environmental improvements will depend highly on economic conditions such as fuel prices and tax levels (Ajanovic et al. 2015). In light of the relevance of such conditions, overcoming the prevailing efficiency dogma or "efficiencysm" (Schaefer and Wickert 2015) in public management is a key element of a genuine pursuit of a sustainable future. In this sense, environmental targets and environmental policy in general must give way to a critical re-interpretation of the role of technological efficiency, which may not always be fully aligned with prime environmental strategies and objectives. This re-interpretation also involves questioning the role of product-level LCA, which has proven to be a valuable yet insufficient basis to inform policy in light of rebound effects.

Answering research question **Q1** by way of summary, LCA offers a valuable approach to assess the environmental impacts of transport eco-innovation. Specifically, the use of multiple indicators in combination with a systems perspective allows to identify trade-offs within supply chains and environmental pressures. These features have made LCA popular as a policy support tool, together with the fact that relative values and intensive variables are better aligned with prevailing discourses of managerial and business efficiency. However, LCA has been criticized for failing to account for aspects that go beyond the product level, such as economic and behavioural responses. This thesis contributes to this line of thinking by offering evidence that such responses in the context of technical change, channelled here through the rebound effect concept, are key to support claims of eco-innovation at the macro-level. A shift towards the use of LCSA would maintain the technology detail of LCA while incorporating causal effects of interest, thus providing a better policy support tool.

Q2. Does transport eco-innovation effectively deliver environmental benefits when taking into account rebound effects?

In this thesis, rebound effects are calculated for ten transport innovations that diffused through Europe to investigate to which extend the rebound effect influences product-level LCA results. **Chapter 4** provides results for plug-in hybrid electric (PHE), full-battery electric (FBE) and hydrogen fuel cell (HFC) cars, and **Chapter 6** expands on the latter two. **Chapter 2** yields estimates for diesel cars, and **Chapter 5** expands on this innovation as well as bicycle sharing systems (BSS), car sharing schemes (CSS), catalytic converters in passenger cars, direct fuel injection (DFI) systems in passenger cars, high speed rail (HSR) systems and park-and-ride (P+R) schemes. While all the studied innovations present an overall improved environmental performance with respect to their alternatives according to LCA results, the inclusion of price rebound effects notably influences such relative performance overall. The results show a wide range of rebound estimates. Considering the overall trends from the various environmental indicators used, three out of the ten studied innovations describe a negative rebound effect or an overall improvement of environmental pressures (P+R, FBE and HFC cars), three (catalytic converters, PHE cars and DFI) describe the classical example of a partial offsetting of environmental savings and, most importantly, four (BSS, CSS, HSR and diesel cars) describe a backfire effect, that is, cases in which the rebound effect completely offsets environmental savings. A summary table with all the rebound effect sizes found is presented in Table 1. It is important to note that the size of rebound effects varies according to the environmental indicators used, and that only average values (instead of ranges with uncertainty and historical results) are presented for simplicity.

A number of reasons have been found to support the occurrence of backfire effects. To better understand these, it is important to highlight the three basic effects or components that make up a microeconomic and consumption-side rebound effect. First, the ‘efficiency effect’, related to the environmental savings from the initial efficiency improvement. Second, a ‘demand effect’, by which changes in consumption factors (e.g. income) induced by the efficiency improvement lead to changes in overall demand. Third, an ‘environmental effect’, through which changes in demand are translated into relevant environmental indicators.

Regarding the ‘efficiency effect’, applying a life cycle perspective can decrease the expected environmental savings by taking into account trade-offs occurring during the production and end-of-life stages. For instance, by accounting for the resources used and emissions from the production and recycling of electric batteries. When the environmental savings are moderate, these can be more easily offset by additional environmental pressures from extra demand. This is the case, for example, of diesel cars, which offer modest carbon emission reductions with respect to their gasoline counterparts. This is the result of considering various aspects that offset fuel efficiency improvements at the use stage, such as increased use of resources in the manufacturing of the engine, which needs to endure a higher compression ratio and torque, and increased size and power of the average vehicle.

As regards the ‘demand effect’, large decreases in the total cost of ownership (TCO), as is the case of BSS or CSS, can lead to notable increases in real income and additional expenditure. Furthermore, in line with the literature (Mizobuchi 2008), changes in TCO can be amplified by including capital

Table 1. Summary of the size of the rebound effect associated with the studied transport innovations.

Innovation	Rebound effect size (as a % of the initial environmental savings that are ‘taken back’)										
	Photochemical ozone depletion	Photochemical oxidation formation	Freshwater eutrophication	Acidification	Global warming	Abiotic depletion	Terrestrial eco-toxicity	Freshwater eco-toxicity	Human toxicity	Land use change	Abiotic resources depletion
Plug-in hybrid electric car	10%		366%	26%	3%	1%					
Full battery electric car		-71%	-239,944%		-545%		-2,535%	-97%	-17%		
Hydrogen fuel cell car				-1,970%	-231%						
Diesel car					7,189%						
Direct fuel injection					63%						
Catalytic converter	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
High speed trains					215%					91%	227%
Car sharing					135%						
Bicycle sharing					899%						
Park-and-ride					-1,500%						

costs. This is the case, for example, of electric cars, which have a notably higher purchasing costs than those equipped with an internal combustion engine. Such purchasing costs, in the current economic conditions, importantly offset economic savings from the use stage.

Lastly, relating to the 'environmental effect', when the environmental profile of the innovation under investigation is very different from that in other sectors, rebound effects from a reallocation of expenditures can be very high. This phenomenon takes place particularly when other environmental indicators other than energy are studied, as the energy use per economic input is more uniform across economic sectors than other environmental indicators (Tukker et al. 2006). Phosphate emissions are an illustrative example of this, as these take place extensively during the production of food products but to a much lesser extent in the transport and other sectors. Consequently, relatively small additional expenditure on food products can offset to a large degree the initial phosphate savings. This explains, for example, why the rebound effect from FBE cars in terms of freshwater eutrophication is so remarkable, while it is modest for other indicators such as human toxicity.

Studies analysing rebound effects rarely find backfire effects in the context of energy use and related carbon emissions (Sorrell 2007; Druckman et al. 2011; Turner 2012). This thesis, however, evidences that for environmental pressures and using multiple indicators such backfire effects can be more common than previously thought in the European context. Moreover, there are grounds for supposing that the same conditions that favour such backfire effects, such as fuel prices and tax levels, are equally plausible in other regional contexts. Such conditions are more likely when calculations focus on specific products and technologies rather than heterogeneous economic sectors (as is done in a large share of the literature), because products and technologies can present notably different environmental and economic profiles than the sectorial mix. Moreover, by increasing the resolution of analyses, rebound assessments become more meaningful for policymakers, as products and technologies that need policy attention can be readily identified.

This thesis also explores a number of potential sources of bias when calculating the size of rebound effects. This exercise is key to control for highly sensible variables, and expands the current knowledge base in various ways. The results of **Chapter 4** indeed show that, in line with the literature (Murray 2013; Chitnis et al. 2012; Chitnis et al. 2014), the household demand model used and the income groups considered can notably underestimate or overestimate the rebound effect size. The results also show that models often used in the field of industrial ecology, such as the use of proportional expenditure patterns (Briceno et al. 2004; Takase et al. 2005) and the income shifting approach (Thiesen et al. 2008; Alfredsson 2004; Girod 2008) offer a less scientifically sound approach than those traditionally applied within economics, for instance econometric estimates such as expenditure and cross-price elasticities. Further efforts should thus be dedicated to improve the knowledge transfer from the economics literature dealing with rebound effects to industrial ecology and related sustainability sciences. Moreover, the results from **Chapter 6** describe a high influence of methodological choices in environmental modelling, concretely the environmental assessment models and the environmental input-output databases used to calculate, respectively, the previously defined 'efficiency' and 'environmental' effects. Such choices would have a biasing effect comparable to that introduced by methodological choices made to determine

changes in demand or the 'demand effect' (Murray 2013; Chitnis et al. 2014; Chitnis et al. 2012; Druckman et al. 2011). This represents a novel addition to the rebound effect literature, which has traditionally focused on the latter.

Answering research question **Q2** by way of summary, transport eco-innovation does not always live up to the expectations of environmental improvement when taking into account rebound effects. These cases are described as backfire effects in the literature, and so far evidence has supported these only in a few cases. This thesis, however, evidences that the application of concepts and methods from industrial ecology for the study of rebound effects make the occurrence of backfire effects more likely. This finding has important implications for eco-innovation management and environmental policy in general. In any case, because of the emergence of this approach, further research, including the study of sources of bias and the application to other sectors and regional contexts, is needed to confirm the validity of such finding.

Q3. Are concepts and methods from the industrial ecology domain valuable to study rebound effects?

While the study of rebound effects traditionally pertained to the domain of neoclassical energy economics, the concept has lured the interest of other disciplines due to the potential to increase the behavioural realism of environmental assessments. Among the various existing disciplinary understandings, that from industrial ecology or the so-called 'environmental rebound effect' (ERE) concept (Goedkoop et al. 1999; Spielmann et al. 2008; Murray 2013) has remained largely unnoticed, leading scholars from industrial ecology and other disciplines to largely neglect its potential value. This thesis attempts to reveal the value of the ERE concept by means of literature review and empirical application to the case of transport eco-innovation. **Chapter 3** offers insights into the origins of the ERE concept within the industrial ecology field, and **Chapter 7** further expands by mapping the relationship of the ERE with other disciplinary perspectives and its value towards a general framework. Furthermore, **Chapters 4**, **5** and **6** operationalize the ERE concept by means of case-based environmental scientific analysis. Bringing together the contributions of these chapters, we describe the evolution of the rebound effect concept within industrial ecology. Next, we emphasize the value of the ERE concept for the specialized rebound effect literature as well as for the broader environmental assessment literature.

During the 1990s, industrial ecologists argued about the value and possibilities to integrate rebound effects within environmental assessments mainly in the context of LCA (Goedkoop et al. 1999; Weidema 1993). During the early 2000s, the first empirical applications emerged, showing that broader definitions than those used within energy economics were needed in order to include other effects of interest (Hertwich 2005). This included mostly the study of multiple environmental indicators (Takase et al. 2005), but also a reinterpretation of the technological improvements that lead to rebound effects (Alfredsson 2004; Weidema et al. 2008) as well as the consumption and production factors that can be liberated or bound due to the latter (Hofstetter and Madjar 2003; de Haan et al. 2005; Weidema and Thrane 2007; de Haan 2008).

Below, the value of the ERE perspective is summarized in four main points.

First, while classical rebound effect definitions focus on energy, the ERE goes beyond energy use by dealing with environmental pressures in a broader sense, that is, including emissions, resources and waste. In doing so, multiple rebound effect sizes can be calculated, and trade-offs between indicators can be easily identified. Moreover, this feature permits to study innovations that do not target (exclusively) energy reductions. For example, electric cars aim at reducing carbon emissions as well as other air pollutants and noise. Assessments applying the ERE perspective can thus yield more comprehensive insights into the impact of rebound effects.

Second, classical rebound effect definitions focus on a rather narrow and engineering-based interpretation of efficiency, understood as the ratio between fixed technical inputs and outputs – 'process efficiency'– (Schaefer and Wickert 2015). Under the ERE umbrella, however, efficiency changes are understood more broadly, as the resources, emissions and waste generated to provide a given function – 'environmental efficiency'. The inclusion of such 'enviromental efficiency' in the definition of the rebound effect allows to study broader technical changes such as alternative car powertrains and organizational innovation (e.g. car sharing schemes).

Third, industrial ecologists have embraced and further developed modern notions of consumption theory. Such renewed perspective is built on the premise that consumption is not fully explained by income levels and prices, as neoclassical economics and an important share of the rebound literature suggest. For instance, it is also explained by costs that are culturally and socially defined, for instance following environmental values and attitudes (Hofstetter and Madjar 2003; Jackson 2005). Also, by other consumption factors such as time, information, technology availability and technical definitions (Hofstetter and Madjar 2003; Weidema and Thrane 2007; de Haan 2008). **Chapters 3** and **7** describe that, according to an important body of literature from industrial ecology and other sustainability sciences, all these consumption factors could theoretically lead to rebound effects, and could therefore be included in broader definitions. Following an expanded definition, relevant types of rebound effects that would otherwise remain unnoticed can be included in the environmental assessment and evaluation of eco-innovation and environmental policy.

Fourth and last, classical rebound effect approaches from energy economics generally focus on direct energy use from highly aggregated economic activities. By using a life cycle perspective and multiple environmental indicators to calculate the environmental profiles of both the innovations under study and their alternatives, the ERE approach allows to identify trade-offs within supply chains and between environmental pressures. Furthermore, by increasing the technology detail of analyses by means of LCA, it is possible to focus on specific products and technologies.

These four points together represent a valuable evolution from classical approaches from neoclassical energy economics to study rebound effects, and can potentially lead to more comprehensive and meaningful knowledge for tackling key environmental issues such as climate change and resource depletion. The inclusion of these four points in the definition of the rebound effect, or what we label as the ERE perspective, entails a broadening of the classical definition. In this sense, **Chapter 7** puts forward a definition for the ERE that focuses on the environmental consequences as a result of

technical efficiency changes liberating or limiting consumption and production factors. However, **Chapters 3** and **7** rise concerns over the lack of articulation of clear definitions within industrial ecology, which have caused this perspective and its value to remain largely unnoticed. Indeed, the different insights that we have gathered under the ERE umbrella stem from scattered and often inconsistent definitions. For instance, some definitions focus simply on the environmental diversity of rebound effect indicators, while others go beyond by including a wide range of improvement options, including non-technical ones. In this sense, **Chapter 7** attempts to formulate clear and consistent boundaries for the ERE, and also proposes the operationalization of the ERE as a valuable basis for a general framework that harmonizes all disciplinary understandings. This exercise proves to be both feasible and valuable, uncovering the full potential of the ERE perspective for rebound effect analysis.

Chapter 7 also rises concerns over the risks associated with broader definitions for the rebound effect. Concretely, broader definitions can overlap with other cause-effect mechanisms such as technology displacement or supply chain effects (Miller and Keoleian 2015), thus evolving towards a broader but ill-defined causal effect. The risk is that the term 'rebound effect' becomes a catch-all for a wide set of causal effects, thus losing part of its original meaning. The proposed general framework tries to avoid such excessive broadening by means of clear boundaries and rules, yet the achievement of its intent in practice remains to be seen.

Answering research question **Q3** by way of summary, the application of concepts and methods from industrial ecology to study rebound effects offer more comprehensive results and broader applicability with respect to the original approaches from energy economics. Such contribution can be considered highly valuable in the context of environmental assessment, for instance by making possible to assess specific products and technologies and to identify trade-offs between supply chains and environmental pressures.

Q4. **What policies are available to mitigate the unwanted consequences of rebound effects? Which policies are the most effective?**

The empirical results from this thesis show, in line with the specialized literature, that rebound effects can significantly thwart the expected environmental gains from eco-innovation and environmental policy. In this context, **Chapter 8** is dedicated to investigate which policy pathways are available and which can be more effective to deal with the unwanted consequences of rebound effects. A total of thirteen consumption-side specific pathways are described and analysed in this context, which are classified into five general categories – policy design, sustainable consumption and behaviour, innovation, environmental economic policy and new business models–. The specific policy pathways include broader definitions and benchmarking tools, specific consumption information actions and standards as well as the promotion of product service systems. Among these, economic instruments such as carbon taxes and cap-and-trade schemes stand out in terms of rebound mitigation potential, mainly because these instruments are able to tackle three general rebound mitigation strategies simultaneously: efficiency – consuming better–, structure – consuming differently– and demand – consuming less– (Sorrell 2010). It has been argued that these three general strategies are needed in combination to tackle the exceptional environmental challenges we face (Jackson 2014). Moreover, empirical results have proven economic instruments to effectively achieve in some cases the intended environmental targets while at the same time improving key economic and social indicators (Stavins 2003). However, from the analysis of each pathway, it is concluded that there is still little evidence confirming their effectiveness for rebound mitigation. In addition, their effectiveness largely relies on adequate policy design and policy mix in order to avoid, inter alia, additional rebound effects, welfare losses and environmental trade-offs. The proposed ERE perspective can support policy design in avoiding trade-offs within supply chains and between environmental pressures in the rebound effect context, showing yet an additional facet of its value.

This thesis focuses, in line with the general literature, on the environmental dimension of the rebound effect. This approach may however unintendedly disguise the economic and social implications of the rebound effect, which must be carefully considered in policy design. The economic implications of the rebound effect relate to the stimulation of economic growth, while the social effects are associated with increases in social welfare. It is especially important to consider the effects on low income groups, where the rebound effect can be seen as a way to deal with social issues such as energy poverty (Ürge-Vorsatz and Tirado Herrero 2012). It is thus key that rebound mitigation strategies such as energy taxes target overall environmental improvements whilst considering and asymmetric distribution of economic burdens among income groups. Expanding on this, Galvin (2015) confirms empirically the value of focusing on the absolute impact of rebound effects in the design of policy goals, due to the fact that less privileged groups indeed present higher rebound effects in relative terms, yet their contribution to overall consumption of energy and CO_2 emissions is modest. This argumentation is also in line with the results presented in **Chapter 5**, where absolute macro-level values of rebound effects provided valuable insights into their relative importance. Furthermore, dealing with the rebound effect from a multidimensional perspective is especially challenging for developing countries, where higher levels of unmet demand and energy poverty are present (Boardman 1991; Chakravarty et al. 2013; Orasch and Wirl 1997; Roy 2000). But perhaps one of the biggest challenges in the rebound effect debate relates to overcoming the appeal for policymakers of achieving both environmental and economic gains simultaneously.

The rebound effect has been argued to stimulate economic growth by means of increases in productivity and overall consumption (Greening et al. 2000; Madlener and Alcott 2009; Sorrell 2007). Such economic growth, in combination with the achievement of relative environmental savings (relative decoupling), may make appear certain environmental policies and targets as adequate, especially those focused on increases in efficiency (e.g. CO_2 emission targets for passenger cars). This would be in line with arguments of a certain “efficiencysm” doctrine in public management (Schaefer and Wickert 2015), described also in Chapter 8. In the context of a GDP-driven economic growth paradigm, overcoming such doctrine to effectively deal with rebound effects may thus require of transformative changes in the prevailing rational approach to public policy and in socio-economic structures (Sorrell 2010; Levett 2009). For example, introducing a long-term and systems perspective in public management, which would be consistent with the proposal to progressively shift from an ‘LCA mindset’ to an ‘LCSA mindset’, as proposed

previously when addressing research question **Q1**. Also, by introducing alternative economic frameworks, for instance influenced by the ‘degrowth’ (Martínez-Alier et al. 2010) and ‘agrowth’ concepts (van den Bergh 2011b).

A way forward to achieve environmental targets in the rebound effect context may be to focus on strategies that are focused on the desired ends (e.g. reduction of GHG emissions) rather than on potentially problematic means (e.g. efficiency-based eco-innovation), in line with the arguments set forward by a growing yet relatively small share of the literature (Sorrell 2010; Alcott 2010; van den Bergh 2011a). In the context of economic instruments, cap-and-trade and similar schemes would be preferred to other instruments such as carbon taxes or subsidies, because a specific ceiling for key environmental pressures can be set. However, as **Chapter 8** points out, inadequate formulations of these ‘ceiling-type’ schemes may overlook critical aspects such as trade-offs between economic sectors, regions and environmental pressures, thus impeding the achievement of global targets. Yet again, the ERE perspective and the concepts and methods from industrial ecology in a broader sense may prove useful in the design and evaluation of these instruments.

Answering research question **Q4** by way of summary, there are multiple policy options available to mitigate undesired rebound effects, which target different actors and pertain to different strategies. Among these, economic instruments stand out due to their proven effectiveness and the capacity to tackle multiple environmental conservation strategies simultaneously. While the effectiveness of the various options is currently unclear according to existing empirical evidence, their assessment from an industrial ecology perspective brings various relevant considerations, such as additional rebound effects and trade-offs between economic sectors, regions and environmental pressures.

3. Limitations and further research

This thesis attempts to contribute novel insights for the study of rebound effects from new products and technologies, specifically for the case of transport. To this end, a conceptual and analytical framework is designed based on the ‘environmental rebound effect’ (ERE) perspective, which is largely inspired by concepts and methods from industrial ecology. More specifically, this thesis approaches price-related and consumption-side microeconomic rebound effects from passenger transport innovations. Because of the limited scope, however, a number of aspects remain open for further research.

First, production-side rebound effects could shed light into the effect of output, substitution and re-investment effects at the firm level (Jenkins et al. 2011). For instance, to which degree reductions in production costs from more efficient transport services lead to increases in overall output, production factors and capital stocks, and their associated environmental consequences. The literature demonstrates this type of effects are possible to study for the case of energy as a production factor (Saunders 2013), yet more complete datasets of production inputs, which typically focus on capital, labour, energy and materials, are missing to study other production factors such as transport services. Future efforts can thus be directed towards the compilation of more complete and detailed information on production factors.

Second, prices and income levels have been the most studied consumption factors in the rebound effect literature (Santarius 2012). This is mostly explained due to the availability of data and analytical frameworks such as expenditure data and household demand models. Time costs and socio-psychological costs as consumption factors have also been empirically applied (Jalas 2002; Girod et al. 2011), yet their utilisation remains scarce. Other consumption factors have been theorised but have never been empirically tested, such as information, skills and technical definitions (Hofstetter and Madjar 2003; Weidema and Thrane 2007; de Haan 2008). Further development of analytical approaches such as those based on quasi-experimental data may shed light into the relevance of these factors in the rebound effect context.

Third, macroeconomic rebound effects related to market price, composition and growth effects can also be studied, which would shed light into relevant effects related to changes in endogenous prices, market structure, income distribution and factor supply, among other (Jenkins et al. 2011; Sorrell 2007; Dimitropoulos 2007). The literature offers four main types of models to approach such effects (Dimitropoulos, 2007): neoclassical growth models, macro-econometric models, computable general equilibrium (CGE) models and hybrid macro-economic models. Among these, hybrid macro-economic models combining the main structure of traditional CGE models with econometrically-based behavioural parameters and bottom-up environmental models are becoming very popular among researchers because of their robustness and possibilities for environmental assessment (Allan et al., 2007). Some examples of hybrid macro-economic models are the NEMO model (Koopmans, 1997), the MDM E3 model (Barker et al., 2007), and the EXIOMOD model (Ivanova 2014). A logical next step would be to further integrate concepts and methods from industrial ecology into hybrid macro-economic models in order to increase the technology detail and environmental completeness of economy-wide rebound effect assessments.

Fourth, rebound effects can be interpreted as a specific type of causal effect taking place at the intersection between technology, economic conditions and social behaviour. In this context, some authors have theorised the existence of multiple other causal effects, such as technology displacement, social behaviour and resource scarcity (Miller and Keoleian 2015). Further research can offer insights on whether such effects are relevant for environmental assessment. Moreover, future efforts in classification can be expected to better define the rebound effect boundaries and mitigate the sometimes ill-defined nature of rebound effects, improving at the same time communication between disciplines.

Lastly, while this thesis has focused on specific innovations, it is also possible to investigate rebound effects from policies such as environmental taxes, which can ultimately lead to technological change. In this sense, some authors make a conceptual distinction between rebound effects in the context of an efficiency improvement that arises from a technology breakthrough, in which all other product attributes are held constant, and a policy-induced improvement in which costs and other product attributes typically change (Gillingham et al. 2015). This type of assessment is scarce in the literature, which has traditionally focused on technological advancements in specific economic

sectors and products, and would offer valuable insights into the effectiveness of environmental policies and targets.

4. Final thoughts

Our collective ingenuity has made possible the ever-increasing advancement of people's quality of life and social progress. The myriad of innovations that have historically improved the accessibility, quality and efficiency of transport as well as many other daily aspects bear witness to this. However, the occurrence of rebound effects and other detrimental causal effects rises compelling concerns on whether such a scarce resource is being fully harnessed. Making the most out of our treasured ingenuity in the actual environmental context calls for a paradigm shift with respect to the role of innovation, which can no longer be seen as the ultimate solution to all problems. While increases in technological efficiency will always play an important role, we must give way to alternative innovative ideas. Such paradigm shift is gaining momentum within the scientific community, and various discourses that challenge the traditional 'technoptimism' can be observed. The rebound effect discourse, but also the degrowth and evolutionary economics discourses, to name a few, are starting to articulate common understandings and gaining ground. Such concerns, however, have not permeated yet the public management arena, where traditional discourses of business efficiency still prevail. Reaching out to the policy arena is essential for such a paradigm shift, and the scientific community must contribute even greater compelling arguments if the pursuit is genuine.

The rebound effect debate is far from resolved, and scholars bring to the attention on a daily basis their findings about the empirical nature of rebound effects, often following rather reductionist arguments on whether these are overall big or small. Much knowledge has been gained since the pioneering works of William Stanley Jevons, in which bold claims stated that technological efficiency would irremediably lead to increased resource use. The current knowledge base offers a broad spectrum of sizes of rebound effects, showing how heterogeneous these actually are. This thesis reaffirms such diversity, and contributes novel insights into the relevance of technology detail and environmental completeness for the rebound effect debate. It is my intuition that further research in the field will show even greater diversity of sizes and influencing variables. In this context, both extremes of the debate – either systematically downplaying or overplaying the importance of rebound effects– will progressively lose credibility, giving way to more informed and ad hoc solutions to the rebound effect issue.

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