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

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General introduction and research questions

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It is true that at the best we see dimly into the future, but those who acknowledge their duty to posterity will feel impelled to use their foresight upon what facts and guiding principles we do possess.

(William Stanley Jevons, 1865)

They say a little knowledge is a dangerous thing, but it's not one half so bad as a lot of ignorance.

(Terry Pratchett, 1987)

1. On transport, sustainability and innovation

Historical developments in the accessibility, quality and efficiency of transport systems have been and continue to be key drivers to much of our social progress. The invention of the automobile and the railway or the increases in speed and comfort, to name a few, have transformed in multiple ways critical aspects of our society and daily lives, such as employment distribution, social interactions and the availability of goods and services. Yet all this social progress has come at a price: transport is directly or indirectly associated to many of the environmental challenges we face nowadays, such as global warming, air pollution and resources depletion. For instance, transport is responsible for more than 20% of energy-related greenhouse gas (GHG) emissions leading to climate change worldwide (OECD/IEA, 2014). It is also the sector in which these emissions have grown faster in the last decade (Kahn Ribeiro et al., 2007). Transport is also an important source of air pollution, especially in urban areas, which poses threats to human health (e.g. respiratory problems and cardiovascular diseases) (Brunekreef and Holgate, 2002) and biodiversity (Barker and Tingey, 1992). For example, the transport sector originates around 40% of total nitrogen oxides emissions and almost 20% of both total particulate matter and non-methane volatile organic components emissions in OECD countries (OECD, 2015). Moreover, transport is also behind several negative social impacts, such as fatalities and injuries, as well as economic costs, for instance those derived from traffic congestion and economic externalities (Litman and Burwell, 2006; Maddison et al., 1996). Fulfilling aspirations of a sustainable future thus largely depends on our ability as a society to transform our current transport systems.

The design of appropriate environmental strategies to transform transport systems calls for the understanding of one of the most simple yet insightful equations used in the context of environmental assessment, the IPAT equation:

$$\text{Environmental impact (i)} = \text{Population (p)} \cdot \text{Affluence (a)} \cdot \text{Technology (t)} \quad (1)$$

The IPAT equation, introduced first by Ehrlich and Holdren (1971, 1972), is a mathematical identity that explains environmental impacts as a product of population size, affluence levels and technology. Population is expressed as a number of inhabitants, while affluence is normally expressed as gross domestic product (GDP) per capita and technology is expressed as environmental impacts per GDP.¹ Although more sophisticated variants of the IPAT equation have been devised (Alcott, 2010; Chertow, 2000), its strength relies on its conceptual simplicity rather than its mathematical rigor, and it has even been coined as the “master equation” of industrial ecology (Graedel and Allenby, 1995). In essence, the IPAT equation conveys the idea that a decrease in any of the right-side elements will be followed by a decrease in the environmental impact, and so three general “environmental conservation strategies” can be derived: population control, sufficiency and technological improvements (Girod et al., 2014). Among these, the later strategy has undoubtedly been the historical flagship of environmental policy, recently channelled through the ‘decoupling’ concept (van der Voet et al., 2005). Such preference is based on many aspects, among which two stand out: the prevailing perception of technology as the ultimate solution as well as the unwillingness to renounce to the *dolce vita* in developed countries by arbitrarily constraining affluence (Meadows et al., 1972). Strategies focusing on technology generally aim to achieve similar levels of economic output (e.g. in the context of transport, mobility) with a lower use of resources and/or lower generation of emissions and waste. This goal can be attained mainly through two essentially different approaches: structure and pure efficiency changes. On the one hand, structure changes target shifts in consumption and production so that a comparable output is delivered by less environmentally problematic sources (e.g. by replacing a car for public transportation). On the other hand, pure efficiency changes aim at delivering the same output by generating less environmental pressures (e.g. increased fuel efficiency). In any case, the effectiveness of technology-oriented strategies is not straightforward and immutable, as the determinants of the IPAT equation do not work separately (Alcott, 2010). These strategies are thus a co-product of social, economic and regulatory conditions, and particularly of the process of innovation.

Innovation has been traditionally defined as the process of introducing new ideas into the economic realm, for instance by means of new products, processes, markets, sources of supply for inputs and industrial organization (Schumpeter, 1934). Innovation helps to reduce existing trade-offs between the environment and the economy, allowing policy targets to be achieved at lower costs and facilitates the setting of higher policy targets. However, the classical definition of innovation has been re-interpreted by modern social and economic theories under the premise that it suffers from a certain “techno-economic bias”. This bias would overlook changes in non-technological objects, such as new social relationships or normative instruments (Rennings, 2000) as well as the social dimension of innovation (Roth, 2009). Through this broader understanding of innovation, its transformative potential becomes even more explicit. Under this new paradigm, innovation can be understood through a three-dimensional framework, also called the “innovation triangle” (see Figure 1), which decomposes innovation into an object, a time and a social dimension (Johannessen et al., 2001; Roth, 2009). Moreover, the recognition of a social dimension of innovation provides an element of social attribution, through which innovations are considered as socially advantageous (Pohlmann, 2005; Dijk, 2010). When the social attribution relates to the environmental advantage of an innovation, this is in some cases regarded as an eco-innovation (Kemp and Pearson, 2007).

1. Some authors use the quantity of goods and services consumed instead of GDP as a proxy for affluence, since it is highly correlated to actual levels of consumption, and thus to environmental impacts (Alcott, 2010).

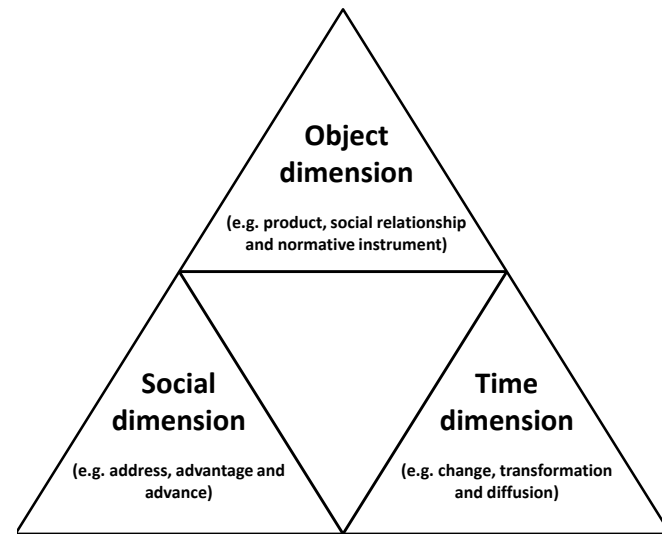


Figure 1. The three dimensions of innovation: the innovation triangle. Based on Roth (2009).

Different understandings of eco-innovation have led to sparse definitions, albeit they all converge in adding an additional environmental layer to innovation (Andersen, 2008). Among the different definitions of eco-innovation, two basic strands of literature stand out: those based on motivation and those based on performance (Kemp and Pearson, 2007). Definitions based on motivation are geared towards the aim to decrease environmental pressures, and are generally focused on the technical aspects of the innovation (e.g. material composition, efficiency, etc.), thus disregarding other behavioural and systemic aspects (e.g. user behaviour and economic functioning). The automotive industry is a good example of the application of motivation-driven eco-innovation, and product-based features and environmental profiles (e.g. fuel efficiency and CO₂ emissions per kilometre) usually support claims of environmental superiority, which materialize in words such as “eco”, “green” and “clean” that brand car’s bodies and swamp consumers through marketing campaigns. On the other hand, definitions based on performance focus on the effective environmental improvements that take place from the use of the innovation, and generally invoke broader system boundaries to capture behavioural and systemic aspects. According to Kemp and Pearson (2007), performance-based eco-innovation is preferred since it deals with the desired end (environmental improvements). It also avoids disregarding those “normal” innovations that do not aim for environmental improvements but these are nonetheless achieved (*ibidem*). Moreover, a generally disregarded yet emerging aspect of eco-innovation relates to the life cycle perspective on the environmental pressures, that is, looking at all the pressures incurred through the entire life cycle of the innovation. To support claims of eco-innovation, a variety of environmental assessment tools are applied, among which approaches based on the principles of industrial ecology stand out, particularly those based on life cycle assessment (LCA) (Dangelico and Pujari, 2010). A general introduction to these methods is provided in the following section.

2. On industrial ecology and eco-innovation

Industrial ecology focuses, broadly speaking, on the study of the material and energy throughputs in the physical economy or the ‘technosphere’, and their environmental repercussions and broader sustainability issues. Because sustainability issues arise from the complex integration and interaction between human and natural systems, industrial ecologists require a systems-based and multidisciplinary perspective (Allenby, 2006). A system’s perspective is based on the understanding of the systemic aspects of both society and nature, which are seen as a set of interconnected elements within a defined boundary (Bertalanffy, 1968). Moreover, systems can overlap, develop emerging properties as well as constitute nested entities in which the elements of a system can be systems at the same time, thus building complex system structures. The human-natural system can be regarded as a singularly complex structure because it is constituted by multiple overlapping and constantly evolving subsystems, such as biotic, abiotic, social, economic and normative systems, among many other. Because of this, the understanding of sustainability issues irremediably calls for a multidisciplinary approach in which multiple fields of knowledge and disciplinary perspectives are needed, for instance biology, geology, physics, economics and sociology. The industrial ecology perspective is operationalized by means of a set of tools that fit different analytical purposes, among which LCA and LCA-based methods enjoy a wide popularity.

The LCA method is designed to calculate the environmental impacts incurred during all the stages of a product’s life cycle, that is, from the extraction of raw materials to the final disposal of the waste product. LCA has its roots in the analysis of material and energy flows in industry during the 1970s and 1980s, especially resource requirements and waste flows, for the main purpose of gaining competitive advantage (Boustead, 1996; Hunt et al., 1996; Oberbacher et al., 1996). From there on, LCA became a very popular analytical technique, and it was provided with sound principles and an analytical framework that decomposed the method into four main interdependent phases: goal and scope definition, inventory analysis, impact assessment and interpretation (see Figure 2) (Guinée et al., 2002). In the first phase, the research question(s) addressed and the technical details underlying the study are defined, for instance, the functional unit, the system boundaries and the allocation methods. Following, the relevant material and energy flows from and to nature for a product system are systematically compiled in a “life cycle inventory”. The inventory flows are then translated into environmental impacts of interest (e.g. global warming and human eco-toxicity) by means of characterization methods during the impact assessment phase. Lastly, the impact results are interpreted through a systematic process, by which potential issues are identified and conclusions are derived. The interpretation process is also implemented throughout the entire LCA to ensure the overall quality of the assessment. The basic principles of LCA have more or less endured until the present, yet the creativity and ingenuity of practitioners to deal with broader sustainability issues has led to constant development in the application, breadth and depth of LCA (Guinée et al., 2010).

LCA was initially applied to the comparative study of the environmental impacts from consumer products (e.g. “does product A present an environmental advantage with respect to product B?”). However, LCA is currently evolving towards sectorial and economy-wide sustainability assessments (e.g. “will the diffusion of technology A through the economy entail an environmental advantage?”) (Guinée et al., 2010). Moreover, LCA is deepening its scope to go beyond technological relations,

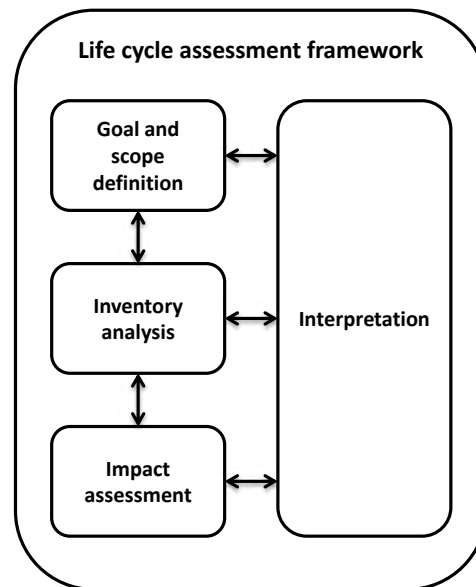


Figure 2. Phases included in a life cycle assessment. Based on ISO (1997).

and economic mechanisms and behavioural responses are increasingly being included (ibidem). In this sense, some authors claim that LCA will be progressively integrated into the so-called life cycle sustainability analysis (LCSA), which encompasses the three dimensions of sustainability (environmental, social and economic) as well as meso and macro scales of analysis (Guinée and Heijungs, 2011). To operationalize this new framework, existing and new tools are being combined with LCA in novel ways, such as life cycle costing (LCC) (Hunkeler et al., 2008) and environmentally-extended input-output analysis (EEIOA) (Leontief, 1970; Miller and Blair, 2009). In the context of the environmental assessment of eco-innovation, that is, the study of whether innovation effectively leads to an environmental advantage, LCA-based tools have been and continue to be widely used, partly due to the high technology detail and the multiple possibilities for analysis they offer (Berkhout, 1996).

LCA embraces industrial ecology's systems thinking by including economic processes from multiple life cycle stages within the so-called 'product system'. However, a broadening of such system's perspective may be valuable in the context of eco-innovation assessment. To illustrate this point, let us consider the case of electric vehicles. Electric vehicles such as hybrid (which combine an internal combustion engine with an electric motor) and full battery electric cars (which have a single electric motor powered by a battery) have been proposed as a solution to mitigate various environmental issues ranging from climate change to noise and air pollution (Sperling and Gordon, 2009). Hawkins and colleagues (2012) provide a review of 51 comparative LCA studies of hybrid and full battery electric cars, from which just a few take into consideration certain systemic aspects outside the product level. Some examples of such systemic aspects are use patterns related

to the charging cycles of the battery, driving behaviour and induced changes in energy systems (e.g. vehicle-to-grid systems) (ibidem). From this illustrative case, which could be generalized to the application of LCA in general, it can be interpreted that comparative LCAs in the context of eco-innovation rarely set the boundaries of the analysis outside the product-level, and therefore systemic aspects of interest are generally disregarded. This "systems myopia" (Leathers, 1988) can be understood by factors ranging from the difficulty to obtain relevant data or the application of complex modelling, but most importantly, on a systemic lack of understanding of the interplay of products within broader system structures, and the co-production mechanisms leading to environmental impacts that derive from such interplay (Laurenti et al., 2014; 2015). In the next section, we describe such system structures and co-production process for the case of transport.

3. On transport system structures and causal effects

Transport studies, a multidisciplinary field that emerged from disciplines such as geography, civil engineering and urban planning, defines transport as a system that provides mobility to people and goods (and in a broader sense, also information) by means of a combination of three interconnected elements: operations, vehicles and infrastructure (Hutchinson, 1974; Rodrigue et al., 2013). These three elements are thus necessary and inseparable from the concept of transport. Moreover, the consideration of transport as a system implicitly assumes the interconnectedness between its elements, and thus changes in one element can cause the rest to re-adapt and change (Meadows, 2008; Skyttner, 2005). Let us consider, for instance, a transport system consistent of a worker that commutes from a household to a work office (operation), a passenger car (vehicle) and a urban road network (infrastructure). Let us suppose that the work office is now re-located much closer to the household. *Ceteris paribus*, the vehicle and the infrastructure should remain the same, yet the worker might choose to shift from the passenger car to a bicycle due to the now reduced distance to work. Alternatively, let us suppose that the worker decides to renovate his or her gasoline car for a full battery electric car. In this new scenario, the worker might decide, in view of the perceived reduction of the environmental burdens associated with driving the car, to drive further distances to fulfil other existing or new needs, such as go shopping or take a more scenic (and longer) route to work. These are just a few examples from many possible, which show that a transport system behaves as a unit rather than as the sum of the behaviours of its elements (Meadows, 2008; Skyttner, 2005). Because the behaviour of the transport system is inherently linked to its environmental outcome, a failure to account for such dynamic aspects can lead to misguided conclusions about the overall effects of changes in the transport elements (e.g. technological changes in vehicles). In this sense, Graedel and colleagues (2002:444) note that industrial ecologists have "overemphasized cars as products and underemphasized the transport system of which the car is such a major part". Moreover, transport systems can be considered to be part of larger socio-technical systems (Elzen et al., 2004), which makes the study of their behaviour even more complex.

Socio-technical systems theory was developed from the premise that societal functions are not achieved by means of technological artefacts alone (e.g. the use of a vehicle to achieve mobility), but rather through multiple linkages between these and heterogeneous elements, such as scientific

elements and legislative artefacts (Hughes, 1987). Therefore, the appropriate unit of analysis of societal functions would be a system in which artefacts work within a specific social context (Fleck, 1993). Under this framework, the social elements of transport systems would go beyond simple operations as approached by the basic definition from transport studies, but also include normative, scientific and cultural elements. For instance, Geels (2004: 3) defines a socio-technical system as “a cluster of elements, including technology, regulation, user practices and markets, cultural meaning infrastructure maintenance networks, supply networks”. In the context of transport, a socio-technical system can be defined as in Figure 3. Furthermore, the comprehensiveness of the socio-technical systems framework offers better insights into the potential feedback loops from changes in the elements of a given system.

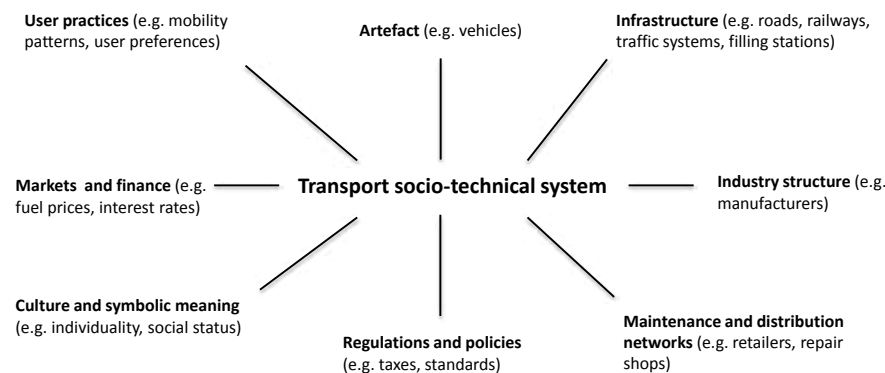


Figure 3. Transport socio-technical system and its elements. Based on Geels (2002).

As stated previously, the interplay between the system’s elements resulting from the introduction of an eco-innovation can be key determinants of its overall environmental performance. As a first step to operationalize such interplay into an environmental modelling exercise (for instance, LCA), it is important to describe the relevant causal effects derived from a change in a system’s element. To this end, various tools can be used, such as causal loop diagrams (CLD), policy structure diagrams and subsystem diagrams (Morecroft, 1982). Among these, CLD have become popular in system behaviour analysis, mainly due to their simplicity to provide basic and visual overviews of loop structures (ibidem). Continuing with the case of the introduction of a full battery electric car, Figure 4 describes potential causal effects within the transport socio-technical system by applying the CLD method. As shown by this figure, many causal effects can be triggered by the introduction of an eco-innovation, including multiple-order effects that ripple through the transport and potentially to other socio-technical systems.² Drawing from the multiple possible effects, some attempts have been directed towards classification in the context of environmental assessment, and general categories such as “technology spill over” “behaviour change”, “supply chain effects” and “rebound effects” have been theorized (Huppes et al., 2011; Miller and Keoleian, 2015). Among these, the study of rebound effects enjoys widespread popularity due to the general agreement on their high capacity to detrimentally alter environmental outcomes (Jenkins et al., 2011; Sorrell, 2007). In the next

section, the theoretical foundations of the rebound effect and the implications in the context of the environmental assessment of innovation are described.

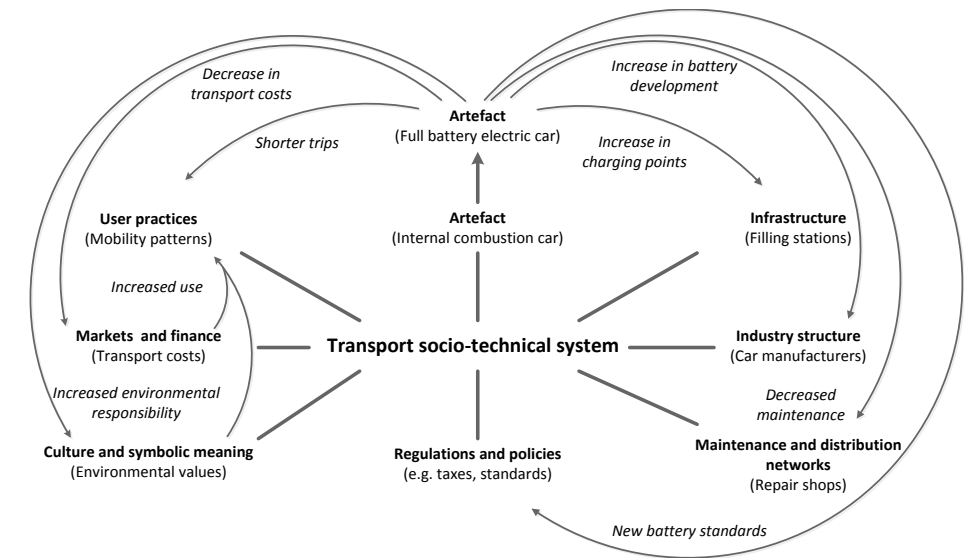


Figure 4. Causal loop diagram describing potential causal effects from the introduction of full battery electric cars.

4. On rebound effects and the study of the unexpected

The origin of the so-called rebound effect can be traced back to the seminal works of the English economist William Stanley Jevons, particularly his much-cited book “The Coal Question” (Jevons, 1865). In this book, Jevons argued that efficiency gains related to the use of coal by engines actually lead to increased overall coal consumption rather than a decrease as conventional wisdom would suggest. In his own words:

It is wholly a confusion of ideas to suppose that the economical use of fuel is equivalent to a diminished consumption. The very contrary is the truth.

(Jevons 1865: 103)

Such a seemingly counter-intuitive argument, later on branded as the “Jevon’s Paradox” (Wirl, 1997; Giampietro and Mayumi, 1998), stemmed from a combination of effects related mainly to profitability, new inventions and uses, and consumer behaviour (Alcott, 2005). Regarding the argument on profitability, Jevons wrote:

[I]f the quantity of coal used in a blast-furnace, for instance, be diminished in comparison with the yield, the profits of the trade will increase, new capital will be attracted, the price

² Figure 4 shows, in an illustrative way, a simplified representation of potential causal effects, which are rarely unidirectional. For instance, the development of electric cars may trigger the creation of new battery standards in the same way as new standards can induce technology development. Thus, co-production aspects must be dealt with carefully to avoid deterministic solutions.

of pig-iron will fall, but the demand for it increase; and eventually the greater number of furnaces will more than make up for the diminished consumption of each.

(Jevons 1865: 104-105)

According to Berkhout and colleagues (2000), this argument implied that, following an increase in energy efficiency, producers could shift the production factor mix and/or reduce the unit production costs and thus the market price, the outcome of both effects being additional demand. On the argument on new inventions and uses, Jevons wrote:

[T]he progress of any branch of manufacture excites new activity in most other branches, and leads indirectly, if not directly, to increased inroads upon our seams of coal.

(Jevons 1865: 105)

From this argument, some authors derived the underlying idea that, because end-uses compete for the same overall budget, other end-uses not targeted by the efficiency improvement will also be affected (Khazzoom, 1980). Lastly, on the argument on consumer behaviour, Jevons stated:

We are growing rich and numerous upon a source of wealth of which the fertility does not yet apparently decrease with our demands upon it. Hence the uniform and extraordinary rate of growth which this country presents. We are like settlers spreading in a rich new country of which the boundaries are yet unknown and unfelt.

(Jevons 1865: 154)

This argument implies a seemingly trivial but essential idea behind the Jevons' Paradox that relates to the previous two arguments: price elasticities of demand are generally positive and demand is generally unsaturated, hence (1) price reductions (profitability argument) will lead to increased demand for the improved products as well as for other products (new uses argument) (Alcott, 2005). Using the CLD method, the manifold feedbacks stemming from these three arguments in the context of improved efficiency of steam engines as described by Jevons are depicted in Figure 5.

Jevons' propositions, however, encountered early critiques (some of which still remain) among scholars such as Mundella (1878), which acknowledged the correlation between increased efficiency and increased demand but challenged the causality established by Jevons, arguing that it was not supported by sufficient empirical evidence. Indeed, Jevons' case was not an empirical one but was mostly based on theoretical arguments (Alcott, 2005). The lack and difficulty to obtain empirical support combined with the fact that Jevons shifted his work towards other economic issues³ caused the concerns raised in *The Coal Question* to remain largely unattended in the following years.

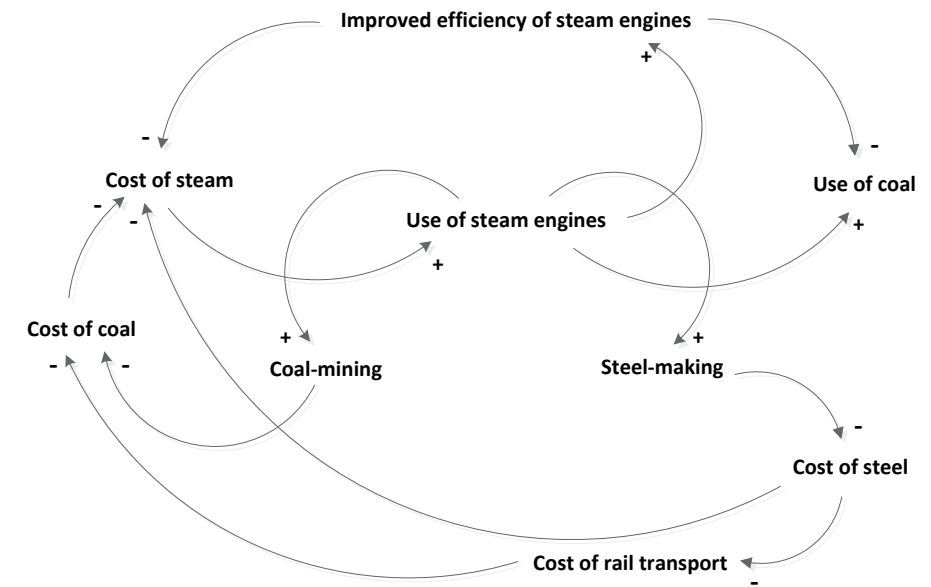


Figure 5. Feedbacks from the improved energy efficiency of steam engines. Based on Sorrell (2009).

Jevons' controversial ideas draw the attention of scholars during the 1900s, such as Coppé (1939) and Gordon (1958), and others such as Hotelling (1931) and Domar (1962) also observed the converging trends of efficiency and resource use. However, it was not until the 1970s, during an energy crisis that ravaged major industrial economies with shortages and rising prices of oil, that Jevons' theories were revived in an intense debate between energy economists over the efficacy of energy efficiency policies in curbing oil consumption. Brookes (1979) first questioned the work by Leach and colleagues (1979) on the grounds that energy savings calculations did not account for a number of economic aspects, such as shifts in production factors and energy-activity dependencies via prices. Later, Khazzoom (1980) also criticized the work of Lovins (1977) in a similar way. It was precisely Khazzoom who coined the term "rebound effect" for the first time, referring to the increase in demand for energy services due to the decrease in the unit price of energy from an energy efficiency improvement in household appliances (ibidem). In the words of Khazzoom:

It overlooks the fact that changes in appliance efficiency have a price content. Consequently, the feedback from the engineering to the behavioral sector is completely missing. [...] What these theoreticians failed to see is that with increased productivity comes a decline in the effective price of commodities, and that in the face of lower effective prices, demand does not remain stagnant at its former level (of 100 units), but tends to increase.

(Khazzoom 1980: 22-23)

3. The ideas behind *The Coal Question* still remained in some comments he did in posterior works, albeit with no significant addition of empirical support (Black, 1877).

The underlying ideas behind the argumentations of Khazzoom and Brookes were later on labelled as the “Khazzoom-Brookes postulate” by Saunders (1992), and were widely recognized as the stepping stone to the posterior debate on the rebound effect. Indeed, during the 1990s, and fuelled by the increasing concerns on climate change, a comprehensive debate unleashed between energy economists, some of which were divided among two contrasting positions (Herring, 2008): those who defended that the energy savings from energy efficiency policies would be completely offset due to the rebound effect (Brookes, 1979; Saunders, 1992) and those who defended that the rebound effect would offset but a share of the energy savings achieved (Schipper and Grubb, 2000). Notable contributions to this debate also include the works of Greene and colleagues (1999), Lovins (1988), Greening and colleagues (2000), Saunders (2000), Schipper and Meyers (1992), Howarth (1997), Wirl (1997) and Binswanger (2001). The debate thus focused on the empirical nature of the rebound effect, with each contributor wielding estimates based on a panoply of theoretical assumptions regarding the temporal and spatial scope, definitions, treatment of economic variables, etc. (Sorrell, 2009).

Aside from the empirical debate, efforts were also dedicated to classification, and the so-called “rebound effect” was decomposed into multiple single effects that spanned through the economic and temporal dimensions. For this reason, some authors prefer to speak of “rebound effects” (Herring and Sorrell, 2009). Probably, the most widely accepted classification is that of Greening and colleagues (2000), who decomposed the rebound effect into four main effects:

Direct effect: when an improvement of the energy efficiency of providing an energy service lowers the unit price of the service, an increase in demand follows.

Indirect effect: because of saturation in the levels of demand for the energy service, a share of the effective income gained from the decrease in the unit price of the service will be allocated to other goods and services.

Macroeconomic effect: changes in demand at the microeconomic level (individuals, households and firms) can trigger a number of macroeconomic effects that can cause further changes in overall demand.

Transformational effect: technical improvements in energy efficiency can lead to broader changes in socio-technical systems, for instance in consumer’ preferences, social institutions and the organization of production, which can lead to further changes in overall demand.

Among these effects, the direct, indirect and macroeconomic effects have been widely accepted in the rebound literature, whereas the transformational effects remain generally disputed over the difficulties to discern among all the potentially confounding factors and therefore establish causality between broad socio-technical changes and specific technical changes (Greening et al., 2000). Furthermore, these three main effects have been further decomposed into specific economic effects that apply to both the consumption and the production side (see Table 1). The combination of microeconomic and macroeconomic effects is generally known as the “economy-wide” rebound effect (Herring and Sorrell, 2009).

Table 1. Classification and definition of the single effects that make up the economy-wide energy rebound effect. Based on Jenkins et al. (2011).

Type of effect		Consumption side	Production side
Micro-economic	Direct	Income effect: After the price of an energy service falls, consumers may respond to the increase in effective income by increasing the demand for the same service.	Output effect: Producing firms can respond to a fall in the price of an energy service by increasing the demand for the service, resulting in an increase in their output.
		Substitution effect: The lower price of an energy service can make consumers prioritize this over other goods and services.	Substitution effect: Producers may prioritize the now cheaper energy service over other inputs to production.
	Indirect	Re-spending effect: Saturation for the demand of an energy service may cause consumers to spend the remaining effective income in other goods and services.	Re-investment effect: Limits to the use of an energy service as input to production may lead producers to other investments in production.
Macroeconomic		Market price effect: Aggregate increases in demand for an energy service at the microeconomic level can cause a decrease in the service’s market price, inducing extra demand for the same service. Composition effect: Other economic sectors using the energy service as an input of production can decrease its production costs, resulting in a decrease in the market price and extra demand for their goods and services. Moreover, the increase in outputs needed to produce the energy service can lead to additional decreases in the output’s market price and extra demand for those. Growth effect: Increases in energy productivity can, <i>ceteris paribus</i> , spur greater economic output and growth, either through sectorial reallocation of growth or overall growth via an increase in total factor productivity.	

The study of rebound effects, however, has not always pertained exclusively to the domain of energy economics, and already during the 1990s it drew the attention of multiple other disciplines concerned with sustainability issues, such as ecological and evolutionary economics, urban planning and sociology (Walnum et al., 2014). Industrial ecologists, well aware of the systemic nature of sustainability issues and the importance of economic mechanisms, also started to theorize on ways to include rebound effects in the environmental assessment of products and technologies (Ekvall, 2000; Goedkoop et al., 1999; Hertwich, 2005). Among the multiple research possibilities that this new perspective offered, considerable efforts were devoted to the study of potentially detrimental effects from the introduction of new products which presumably offered an environmental advantage (motivation-based eco-innovation) within the context of LCA. Notable contributions to this field of research include the works of Alfredsson (2004), Takase et al. (2005), Thiesen et al. (2008) and Spielmann et al. (2008), among others. These works offer many valuable insights to understand the reasons why motivation-driven eco-innovation does not always deliver the expected environmental gains. However, the definitions and theoretical frameworks used in these studies were not always fully aligned with those of the traditional energy rebound effect.

Indeed, industrial ecologists found the original energy rebound effect framework insufficient to describe all the effects that were of interest (Hertwich, 2005; Takase et al., 2005). For instance, what happens when the technical change does not target decreases in energy but in other environmental pressures such as air emissions and/or waste? Have prices full explanatory power over consumption and production decisions? Can broader definitions of efficiency, beyond changes in the ratio between inputs and outputs, be used in the context of rebound effects? The traditional energy rebound effect framework could not accommodate these concerns, and multiple novel insights unfolded, leading to a sparse collection of theories and definitions. Among these insights, some scholars coined the term “environmental rebound effects” (Goedkoop et al., 1999; Murray, 2013; Spielmann et al., 2008), mainly to refer to rebound effects dealing with multiple environmental pressures (resources, emissions and waste) instead of energy use alone. However, the design of an adequate theoretical framework consistent with conventional rebound theories and the full extent of research possibilities that this novel concept can unfold are currently far from being fully explored.

5. Problem statement, research questions and outline of the thesis

The macro-environmental impact of innovations in transport systems depends largely on systemic aspects that go beyond the product level, particularly economic and behavioural responses to technical change channelled through so-called rebound effects. In the rebound effect context, do proclaimed eco-innovations in transport effectively deliver environmental improvements? And what is the role of industrial ecology in the study of rebound effects?

The aim of this dissertation is to investigate the role of rebound effects in shaping the environmental performance of transport eco-innovation, and to investigate the value of applying concepts and methods from the realm of industrial ecology and other sustainability sciences. To fulfil this aim, the following research questions are addressed:

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

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

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

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

This thesis is structured in nine chapters as described in Figure 6.

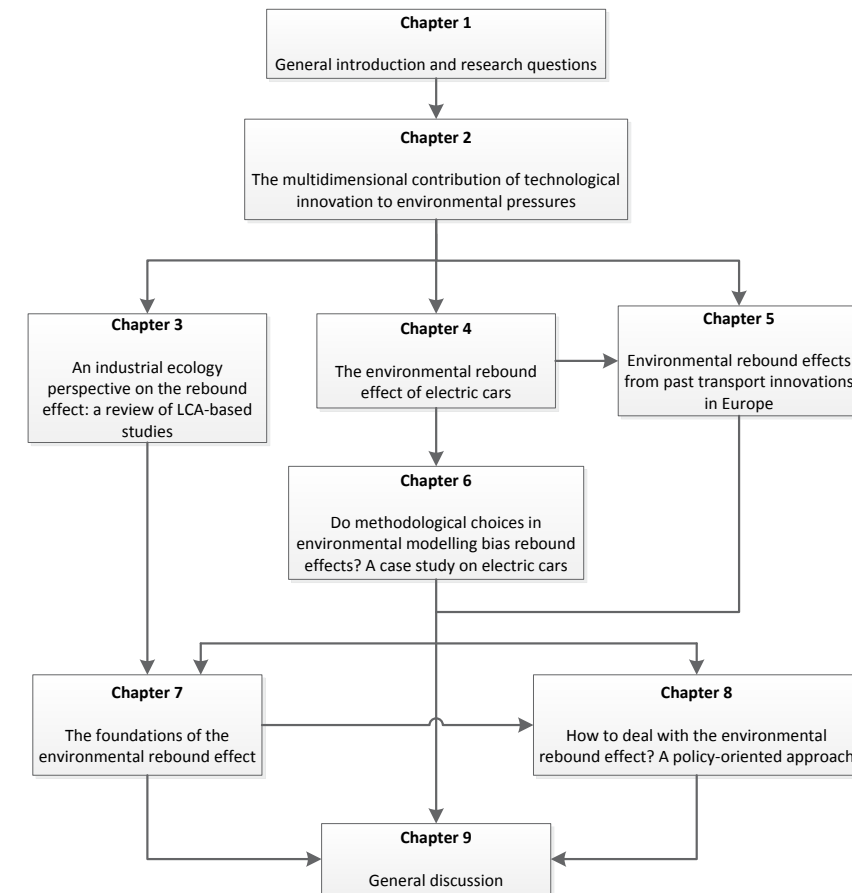


Figure 6. Outline of the thesis.

Chapter 2 explores the limitations of comparative LCA at the product level in the context of transport eco-innovation, and exemplifies such limitations with a case study on diesel passenger cars in Europe. To this end, a general framework for macroenvironmental assessment is presented, through which product-level LCA results are scaled-up to the macroeconomic level using the IPAT equation concept. Furthermore, this framework is used in combination with decomposition analysis to assess the multidimensional contribution of technological innovation to changes in environmental pressures, that is, the combined effect on both technology and demand once assumed that a rebound effect will take place from the increased fuel efficiency of diesel engines.

Following, **chapter 3** analyses in detail the issue of rebound effects within the realm of industrial ecology. By means of a comprehensive literature review, it examines the theoretical and methodological implications of the inclusion of rebound effects in environmental assessments, and exerts this knowledge to describe the advantages with respect to the traditional energy rebound

effect framework. Moreover, the concept of environmental rebound effects is introduced and discussed.

In **chapters 4, 5 and 6**, various case studies investigate the role of price-based environmental rebound effects in the context of transport eco-innovation. The methodological approach is based on a combination of environmental assessment methods and econometric tools, and a particular emphasis is placed on exploring the benefits of applying industrial ecology tools, specifically LCA. The case studies are used to test eco-innovation claims of various transport products and services in the European context. Chapter 6 offers additional insights on how methodological choices in environmental modelling can bias rebound effects.

Based on the knowledge base gained from the previous chapters, **chapter 7** attempts to delineate the foundational aspects of the environmental rebound effect. In addition, this chapter discusses the value of the environmental rebound effect in the context of environmental and broader sustainability assessments and whether it offers valuable insights in order to harmonize the existing rebound effect discourses into a general, all-inclusive conceptual framework.

Chapter 8 explores and discusses options to deal with rebound effects, focusing on which could be more effective for attaining effective environmental gains. Drawing from practical cases and simulations from the literature, a number of policy pathways are mapped, and the advantages and disadvantages of each pathway are discussed. Furthermore, this chapter also analyses the status of the rebound effect in the policy agenda in the European context, and investigates the explanatory factors behind policy inaction.

Lastly, **chapter 9** offers a general discussion guided by the research questions and exposes the concluding remarks, including limitations of this thesis and further research.

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