



Rebounds Are Structural Effects of Infrastructures and Markets

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The promise of energy efficiency brings us to a lighter world, to a world that has less “losses” or dissipation. Energy efficiency is the realm of engineers, for whom machines can be described as quantitative inputs and outputs. The world of machines is supposed to be progressively “dematerialised” through various improvements in resource efficiency. Of course, we observe exactly the reverse: a multiplication of machines and growing resource exploitation. The possibility that improved efficiency leads to a world with more objects and more activities is called the Jevons paradox. In this paper, I explore this paradox through various academic disciplines (neoclassical economics, ecology, technology, sociology), taking seriously the way these disciplines not only analyse but also construct their proper worlds. The description of rebound effects is intimately linked to energy demand issues and to the understanding of how this demand is created and uncontrolled. A good description of rebound effects requires understanding how temporal and spatial aspects affect energy demand. The main argument of the paper is then the following: rebounds are systemic effects when saved energy is used elsewhere, at another time. Rebounds arise faster when infrastructures and markets enable energy to circulate, and when energy consumers are in competition. Rebounds participate then to the concentration of power. In conclusion, energy efficiency is a big business that actualises many materializations, machines and infrastructures, ever more high performance artifacts, always more productive.

Keywords: interdisciplinarity, practice theory, power, complex adaptive system

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INTRODUCTION: DISCIPLINARY ONTOLOGIES OF ENERGY EFFICIENCY

The political idea of conserving energy was central in the 1970s but has been progressively erased in favor of the idea of “energy efficiency,” more and more present from the 1990s (Lutzenhisser, 2014) and much in line with neoliberal policies based on innovation. Today, public policies advocate the many virtues of energy efficiency measures: they can attenuate greenhouse gas emissions, enhance energy security and increase energy productivity. Energy efficiency appears as the less contested “resource” to mitigate global warming since nuclear energy, carbon capture and storage, biofuels and, to a lesser extent, renewables, all entail important environmental issues. However, historical trends show that energy consumption increases with energy efficiency improvement. This is sometimes “explained” by rebound effects, although questions abound about their quantification and even their description.

The IPPC (2014) recommends a series of energy efficiency measures to combat climate change, and mentions the possibility of rebound effects, although declaring that the size of the rebound is

controversial. Rebounds refer to *effects following the energy efficiency improvement of a technological system*: energy consumption does not decrease (or even increase) as much as what is expected from an engineering model. The fact that the energy savings are lower than the forecast is usually explained by economic and behavioral responses (e.g., saved income, reduced costs, increased demand) to the use of a more efficient technology. Rebound effects are often invoked when energy efficiency measures are critically analyzed¹. However, they are difficult to define precisely, and even more to quantify. The magnitude (and even existence) of macroeconomic rebound effects (wide economy rebounds) in particular has been subject to controversy within the economic discipline. Some economists argue that in some cases consumption rebound can exceed 100% of the theoretical energy savings and then completely erases the expected gains. This case is usually called “backfire.”

There is no satisfactory classification of rebound effects, which have mostly been analyzed by neoclassical economists (Van den Bergh, 2011) but have also been observed and described with concepts from a wide range of disciplines. I suggest that controversies about rebound effects come from the fact that they can arise at different scales of time and space, and that each discipline captures specific rebound mechanisms as they frame and construct differently their objects of inquiry. We will see that an energy efficiency change can have an effect on energy consumption but also on the way activities are structured and even on the economic growth. Rebounds can be local and almost immediate, or they can be propagated through the whole economy. My object of inquiry concerns the mechanisms that are called rebounds, i.e., which arise after an improvement of energy efficiency. Yet the unfolding of rebound effects requires the clarification of energy efficiency and consumption. I glance first through the efficiency concept to show its deep ambiguity with productivity, before questioning the notion of energy.

Energy efficiency is defined differently in each discipline, notably because energy and efficiency have different meanings (Schlomann et al., 2015). Efficiency has to be distinguished from efficacy. Whilst efficacy means the ability to produce a desired result, efficiency relates the achievement of a result to the means used to reach this result. Efficacy is evaluated in terms of success or failure, whereas efficiency is assessed as a relationship between an objective and the resources used to carry it through. Efficiency takes then different forms according to disciplines and how they emphasize specific resources. Efficiency can be applied to energy, but also to money in economics (and is then called cost), to human work (productivity), to land (yield), to time (rate or speed) and even to materials or systems. In the case of energy, to be efficient means to perform a task with minimum energy input. Engineers define energy efficiency as the ratio of the intended energy output for a specific task or service to the energy input (Patterson, 1996). In broader terms, being energy efficient implies the ability to perform more with the same amount of energy input or, alternatively, to achieve

the same result with less energy. In the former case, efficiency is equivalent to productivity. In the latter case, the rebound issue amounts to knowing whether the conserved energy will be used or not. For example, if energy efficiency improvements are large enough to decrease energy prices, demand will raise and what is conserved locally will be consumed elsewhere, provided that there are enough energy sources. The fact that energy efficiency can be improved locally (e.g., device, household, factory) while global energy consumption increases is due to the relational characteristic of efficiency.

Energy efficiency is a ratio and indicates thus a level of energy consumption relatively to an activity. As a policy indicator, energy efficiency tells nothing on the absolute level of consumption. Energy efficiency and energy conservation lead to distinct policies (Harris et al., 2008). Policies based on efficiency and relative decoupling between resource use and economic growth do not prevent the increase use of resource. Absolute decoupling can be achieved only if resource efficiency increases faster than economic throughput (Jackson, 2009). Energy efficiency is well defined in thermodynamics where the output is the useful energy, and is then relatively easy to be measured in a laboratory. But its definition becomes ambiguous when the service (i.e., output) is not easily translated in terms of kWh. Energy efficiency is more suited to the analysis of an industry that produces goods or services in series than to a household. For example, a sense of comfort or cosiness is a service or output, but is hard to quantify.

The notion of energy has also different meaning in disciplines. As we shall see in more details, energy is considered as followed: (1) in neoclassical economics, a commodity or a production function expressed as prices or costs; (2) in ecology, exergy, and unidirectional energy flows measured in physical units; (3) in technology, the chain of energy conversions; (4) in sociology of practices, an ingredient of any human activity. These perspectives don't match with a compartmentalized approach in which each discipline would describe a particular cycle of the energy flow. Theoretical approaches incommensurable, but they can display mechanisms that are play in other framings. In each discipline, entities are endowed with specific properties and processes are organized along specific patterns. A discipline can be seen as a process of attributing properties to specific entities. A theory qualifies certain entities and at the same time disqualifies or neglects others (Wallenborn, 2007).

A theoretical frame is like a projector that sheds light on some actors while leaving others in the shadow or behind the scene. On stage, actors have certain characteristics that make them interact with others in specific ways. On an ontological scene, each entity is active, participates in the action, even by its mere resistance or presence. Each theoretical framework endows particular properties to the entities through constraints that it constructs. For example, we will see that in the neoclassical economic ontology, firms, and individuals maximize their profit or utility. Mathematical formalism is constructed to deal with price elasticity or factors of production. On the ecological scene, entities are organisms that evolve by natural selection. Living beings in an ecosystem reproduce themselves by consuming material and energy resources. In the technological framework,

¹Of course, energy efficiency can have many positive effects like health benefits, poverty alleviation, or improving productivity (IEA, 2014), but it should then be clear that its aim is not to reduce energy consumption.

the machines are powered by an external energy source and are coordinated within infrastructures. Machine efficiencies are constantly improved and stabilized through standards that allow them to circulate. In social practice theory, units of analysis are performances that tie body, skill, material objects and meanings. Practices are entities that evolve across time and space.

In other words, each discipline establishes its own ontology, namely a way of enunciating beings that need to be considered. An ontology values certain beings to the detriment of others. In a given ontology, the entities and their relations are conceived in a determined way. An ontology is not a “worldview” because a discipline does not embrace the whole world, but instead makes special beings exist. Each theoretical framework is based on assumptions about the composition of the world and the processes that take place there. This paper does not deviate from the rule. To understand how energy consumption is staged in different theoretical frameworks, I make the assumption that it is possible to highlight simple ontologies that uncover mechanisms that are present in several approaches. All theories are not commensurable, in the sense that there is not always a meta-criterion that makes it possible to compare them. But they all concern the composition of a common world. The world is even actively constructed by (mainstream) disciplines. Interdisciplinarity requires the ability to link the various disciplinary ontologies, at least locally at the entity level. This implies that ontologies already consist of relationships. As we will see in particular for the framing of the neoclassical economy, if an ontology does not understand the relations between the entities, only the individual beings can be described (Debaise, 2017). In this case, the ontology is truncated and excludes all becoming, process or individuation. In summary, each disciplinary ontology selects the relevant entities and their relationships that fit with the rebound effect issue.

Interdisciplinary approaches of rebound effects are rather scarce. Fortunately, there are some works that explore the rebound effects in various disciplinary frameworks. For example, the book *The Myth of Resource Efficiency* (Polimeni et al., 2008) studies the rebound effects in an ecological framework and applies methods from analyses of complex adaptive systems. This important book, although rarely quoted, shows that there are two types of efficiency (based on time and energy) that lead to distinct effects rebounds. The temporal issue of rebound effects is analyzed in some other publications (Binswanger, 2001; Sorrell and Dimitropoulos, 2008). And rebounds in social practices are partially described (Herring, 2011; Winther and Wilhite, 2015). Many ethnographic investigations have displayed users who leave efficient lamps lit, or how a new fridge pushes the old into the cellar to keep cool a few bottles. However, almost all analysis of rebounds are centered on individuals and do not usually say how energy flows. Thus, the role of infrastructure in the formation and spread of rebound effects is systematically ignored. An objective of this article is to try to correct this deficiency.

In a nutshell, this paper aims at describing rebound effects in various disciplinary ontologies. It is the result of a larger work, that can only be summarized here. As a consequence, the paper is mainly conceptual and endeavors to use a large variety of references within many scientific disciplines. Space is

restricted and examples are limited to what is strictly required by the description of general rebound mechanisms. Therefore I start with the following underlying assumption: some disciplines display mechanisms that can be generalized to other domains of inquiry. In the next sections, four disciplinary ontologies are explored to understand various meanings of rebound effects. The identified mechanisms are synthesized in a penultimate section, just before I draw conclusions about the way human societies could fight rebounds.

ECONOMICS: MAXIMIZATION OF UTILITY AND PROFIT

The exploration begins with the neoclassical economics because it is usually in this discipline that rebound effects are defined and tentatively quantified. More than 95% of papers discussing rebound effects are framed within the neoclassical economics. And the usual typology of rebounds are directly inspired by this theory, as we shall see. The origin of the debate on rebound effects come from Khazzoom (1980) and Brookes (1990), works that were grouped under the name “Khazzoom-Brookes postulate” by Saunders (1992). This postulate says that when energy price is constant, energy efficiency gains will increase energy consumption beyond what it would have been without these gains—so this is the assumption of a “backfire.” As indicated in a report by the House of Lords, “the “Khazzoom-Brookes postulate,” while not proven, offers at least a plausible explanation of why in recent years improvements in “energy intensity” at the macroeconomic level have stubbornly refused to be translated into reductions in overall energy demand” (House of lords Science and Technology Committee, 2005).

The neoclassical school was established around the problem of value in deciding that its determination results from a market equilibrium between supply and demand. While the classical economists were mainly interested in the productive forces, working conditions and relations between wages and profits, neoclassical adopted the micro-economic point of view that individual behaviors determine the whole economic system. This ontology has been developed to be above all mathematical and it relies on balance problems between agents seeking to maximize the satisfaction of preferences. The axioms of neoclassical ontology are described by Arnsperger and Varoufakis (2006): methodological individualism, methodological instrumentalism and equilibration. These axioms and other hypotheses allow economists to mathematize acts of trade in sophisticated equations. Mathematics is not here simply a statistical manipulation of figures, but formulates how entities relate to each other according to their attributed properties. Problems of maximization (of profit or utility) are solved thanks to variation calculation and other tools borrowed from physics.

For instance, the production function specifies the output of a firm, an industry, or an entire economy for all combinations of factors, which usually include capital and labor—and to which some add raw material and energy. These factors are given monetary value and can then be combined and weighted. In doing so, economists say that factors are substitutable. Energy

is thus a factor of production among others and is in principle substitutable. The production function can be optimized to yield maximum return of capital investment. For instance, capital and labor are monetarised so that their relative distribution can be optimized, and it is possible to calculate the best combination of workers and machines to maximize profit. Factors are similar for firms and individuals but outputs are different: the former aim at increasing production and profit while the latter search for services. Therefore, in neoclassical economics, energy efficiency is defined as the ratio of either product or service by energy consumption. Energy efficiency is not however directly measurable, and only derived from data on price elasticity and energy intensity (i.e., energy required to produce a GDP unit or energy required to produce utility that has a certain monetary value).

The literature on rebound effects is full of considerations on how they should be organized into types. Economists do not agree on the classification of the mechanisms that may explain the rebounds (Gavankar and Geyer, 2010). Nevertheless, they agree to identify two types of effects: the decrease in costs related to a particular activity (direct effect) and the productivity increase of the entire entity considered, due to the reorganization of production factors or an increase of activities following an increased budget available (indirect effect). These effects can be analyzed from the perspective of either producers or consumers. The direct effect is often divided into an income effect (increase in apparent income) and a substitution effect (lower implicit price of energy service), but this distinction is an artifact of the neoclassical theory for it does not make sense for consumers. Rebounds occur when the increase in production and consuming activities cause in return an increase in energy consumption.

After two decades of controversy, researchers have accepted the existence of the rebound effect. Today, the debate focuses on the magnitude of the rebound and economists attempt to quantify the effects by all possible means of econometrics—which are limited when dealing with large ensembles composed of many households and firms. One can begin to make calculations if one has reliable data on the energy efficiency of specific machines, on the energy consumption and on the associated utility produced. The main neoclassical instruments are elasticity and marginal cost, which is assumed to be the price of producing the service.

Since there is no consistent data on energy efficiency, rebounds are generally derived from an estimate of the price elasticity of the service (Binswanger, 2001). Reliable econometric studies cover only cases where a single service is taken into account, such as personal transportation, residential heating, and few other areas². They estimate the magnitude of direct rebound effects between 5 and 50%, depending on the methods and data used and 10–30% as a best guess (Sorrell, 2007). The analysis of these very simple cases is thus reassuring: rebound effects do not impede energy savings through technological development. But the model of the single service works only if services are actually well separated or, in economic terms, if the substitution between

services is very limited. For example, this model cannot deal with a person who saves money through efficient heating and spends it on traveling more. It implicitly assumes also that investment in efficient machines is reversible, so that households (or businesses) adjust their capital at an optimal level when their income or energy prices vary. Moreover, contrary to what these models assume, price and energy elasticities are generally not constant and are generally higher in periods of increased energy prices compared to periods when the price drops. Recently Chitnis and Sorrell (2015) have estimated that cumulated direct and indirect rebounds amount to 41–78%.

The controversy among economists relate essentially to macroeconomic (or economy-wide) effects. These comprehend transformational, productivity and market mechanisms—as exhibited in the Jevons' case (see below, the technological ontology). Despite the fame of Jevons, his book was rarely quoted until the 1980s, when began the deployment of energy efficiency policies in response to the oil shocks of the 70s. From the 1980s, neoclassical economists (Daniel Khazzoom, Leonard Brookes and Harry Saunders) investigate the link between efficiency improvements and energy consumption growth. Saunders' (1992) work demonstrates that, in the framework of neoclassical growth theory, efficiency improvements at the micro level (desirable for economic reasons) necessarily lead to an increase in energy consumption at the macro level. However, even in the neoclassical framework, it is possible to challenge the theoretical results of Saunders. Indeed, Saunders' model is based on questionable assumptions such as the choice of the production function.

The trouble with estimating rebound effects (especially macroeconomic ones) comes from the difficulties to mathematize complex systems. I point here to two main epistemological problems: the dynamical and coupling features of the economic system³. Firstly, the roots of the neoclassical theory lie in classical physics. Mirowski has shown how neoclassical mathematical formalism borrows line to line from the classical physics formalism and this imposed particular properties to utility, which I Summarize here. Classically, the utility represents the subjective pleasure or satisfaction in the consumption of a product. In neoclassical ontology, utility is a mathematical function whose second derivative must exist. The utility operates in the product space. Changes in the value denote different combinations of products. The increase and decrease of the value are identified to variations of well-being. To build a mathematical function with appropriate properties, preferences must have very peculiar properties (Tiffany, 2011). Hence, utility operates in a world without friction, where it is conserved throughout time. Usefulness and consumer satisfaction of a given service are considered as constant. Utility is not produced through appropriation or learning process, but only translated into price and instantly balanced within a constrained budget. The notion of utility is then very strange. On one hand, it is purely subjective since the agents set instantaneously the value of anything that interests them. On the other, it obeys to pure and eternal ideas of mathematics that fix the value of things. Time and history

²Saunders (2013) has attempted to measure direct rebounds in industry, and show that they might be important. His methodology however rests upon criticisable methodology: see (Jenkins et al., 2011).

³I could also have added the problems of system boundaries and causality.

are outside the picture for the neoclassical ontology cannot describe the dynamic evolution of the systems (Chen, 2005). Many attempts have been tried to integrate time and dynamics in economic formalism, but they remain marginal (Fisk, 2011).

Secondly, direct and indirect rebound effects are estimated with the assumption that efficiency is improved leaving untouched all the other variables. Baselines are however difficult to establish because energy efficiency is inseparable from other changes, whether technological, economic or societal. Rebound effects link energy intensity, energy consumption, and economic activities. These variables are designed as independent in neoclassical models and prospective scenarios, and they appear then as weakly coupled. If we take the direct and indirect rebounds effect as a model for all rebounds, then we are not able to properly conceive macroeconomic rebounds. Direct and indirect rebounds are framed within microeconomics and they can describe how saved energy is used in other activities via cost mechanisms. Relationships between saved and used energy are then linear, like on a balance or communicating vessels. When a quantity of energy disappears here, the same quantity appears there. However, we will see that ecological and technological ontologies show that rebounds are not necessarily linear redistributions but can also be mechanisms that produce and link heterogeneous activities within complex systems. Macroeconomic rebounds refer to assemblages of producers and consumers, humans and machines, connected by infrastructures, and interacting together with feedback loops. In this case rebounds appear as emergent phenomena (Jenkins et al., 2011). It is then probable that neoclassical models, based on the substitution of factors of production, are far away from a reality in which activities are tied through energy consumption. “The economy-wide rebound effect represents the net effect of a number of different mechanisms that are individually complex, mutually interdependent and likely to vary in importance from one type of energy efficiency improvement to another” (Sorrell, 2007).

Econometric studies analyse the contribution that energy efficiency makes to economic growth, but often these researches aggregate different types of energy carriers based on their heat content (primary energy) and therefore neglect energy substitution effects (e.g., coal to electricity). The quality of energy, namely its useful content, is generally not considered. For instance, electricity has a higher quality than coal because it can do many more things and is available in many places. What is important for users is the ability to use easily energy to perform various tasks. Polimeni et al. (2008) provide econometric estimates for a number of countries and different time periods in considering the substitution of energy of various qualities. They show then that Jevons mechanisms are widespread in industrialized societies. This supports the hypothesis that a better quality of energy (such as electricity) is a major cause of economic growth. With better quality of energy, one can also understand that agents are more closely tied and that the activities may extend more easily. An important attribute of energy is its capacity to circulate and made available to uses. For example, electricity is more ubiquitous than petrol, which is more fluid than coal.

To sum up, neoclassical economics usually consider three kinds of rebounds, corresponding to two theories: (1) single entities similar to elastic monads; aggregated entities, that are more or less substitutable. Both theories are based on contestable assumptions. Neoclassical economists argue that energy cannot produce large effects because its prices determine only marginally the costs of production and consumption. But if we consider that any activity can occur only through energy consumption, we better understand that a small amount (assessed in monetary units) can cause large effects. The neoclassical formalism considers that the consumption of energy is weakly coupled to economic activities, while the opposite is probably true (Voudouris et al., 2015). This formalism can only deal with static rebounds, and cannot analyse how activities are transformed. The maximization of profit and utility accelerate the flow of capital and the creation of new energy uses, but neoclassical economists cannot describe this productivity dynamics. However, we can assume that the notion of productivity is central to the macroeconomic rebound. If more energy is available, productivity can increase, such as substituting machines for humans. A more efficient innovation is likely to quickly attract capital whose materialization will consume energy. The introduction of energy efficiency changes the relationship between energy, equipment, labor and capital, and thus the production function. It is obviously impossible to model these substitutions in sufficient detail to account for the multitude of practices. But it is very likely that the various econometric studies greatly underestimate the magnitude of rebound effects.

ECOLOGY: MINIMUM ENTROPY PRODUCTION AND POWER MAXIMIZATION

When entering in the ecological ontology, we are invited to think in terms of relationships between living beings and of long-term evolution. It is then important to understand first how this special mode of thinking works and on which concepts it relies to describe complex adaptive systems. Ecology is helpful in apprehending the idea of (inter)relationship, but also in showing that creative processes must be part of the description of phenomena. Ecology convenes two key concepts: interaction and adaptation. Thermodynamics and the Darwinian evolution of ecosystems frame the questions of ecology. Thermodynamics analyses energetic processes of systems whatever their composition is. Based on two general principles (conservation of energy and production of entropy), this science can deal with systems that exchange matter and energy with the external world. Ecosystems are systems in dynamic equilibrium: they exchange energy and matter with the exterior, but what is important from an ecology point of view is how material flows are organized so that life is sustained and reproduced.

Energy flows throughout the ecosystems along trophic chains that relate producers, consumers and decomposers. Producers are autotroph plants, which are able to feed (trophê) themselves

(auto) from minerals in using energy from solar radiation and, as a result, to synthesize organic matter. Heterotroph plants and animals appropriate (and consume) a part of the potential energy accumulated in the producers. All organisms are fated to die and to be consumed by decomposers: bacteria, fungus and invertebrates. Organic matter is decomposed into minerals; the trophic cycle is closed. Flows of matter and energy go through ecosystems and these flows are transformed by all the living beings. Actually, the flows are the ties between beings. In ecological systems, energy flows unidirectionally from potential energy sources (namely dilute sunlight) through its collection and storage in living beings, while some of the available potential energy is dissipated into heat at each stage of the chains (Odum, 2007).

The Darwinian theory of evolution is another pillar of ecology because it concerns how life is reproduced through the transmission of the genome from one generation to the next. Random variations in a species can be accumulated over generations if they provide a comparative advantage to reproduction in a given environment. So, small differences can gradually become a bifurcation in the species evolution. A new species is then conceived as an emergent property of the ecosystem. Ecosystem evolution is described as co-evolution between living beings (e.g., symbiosis or predation) that favors each species to reproduce itself over time. As we shall see, machines also co-evolve with other entities but according to a non-Darwinian, faster evolution.

The analysis of ecological systems provides interesting clues for explaining rebound effects. Their dynamic results indeed from the tension between two mechanisms: minimum entropy production and power maximization (Polimeni et al., 2008). They correspond to two types of efficiency: (1) a ratio between output and input, which is relevant on a smaller scale, like individual organisms; (2) the rate of generation of an output, which is relevant at a higher level. The first mechanism applies to energy efficiency and can be transposed to living beings as the following. An individual living being is an open system exchanging matter and energy with its environment. It sustains itself in regulating these exchanges. This open system is in a steady non-equilibrium state and operates within stable boundary conditions. The self-organization process of life consists in maintaining the conditions under which it can perpetuate itself. The random improvement of energy efficiency can then lead to a better control on the relationships with the environment. The reduction of energy losses is clearly advantaged by evolution at the individual level. For example, an animal that has thick fur and can keep warm through the winter increases its chance of survival in case of cold weather. As entropy is an increasing function of any open system, which undergoes irreversible processes (Prigogine, 1968), energy efficiency slows the rate of entropy production and can then be termed as the minimum entropy production principle.

At the level of a species, however, another mechanism is operating, based on the efficiency of flows running through an ecosystem. In a short article, Alfred Lotka remarks that the fundamental resource for the evolution and reproduction of organic world is available energy through trophic chains. He states that “the advantage must go to the organisms whose

energy-capturing devices are most efficient in directing available energy into channels favorable to the preservation of the species” (Lotka, 1922). He shows that natural selection favors the organisms which are most efficient to use untapped energy so that they affect paths of energy flows through the ecosystem. If a more energy efficient species appears, it will channel the energy into arrangements favorable to its preservation. The result of energy efficiency is a relative preponderance in number or mass of these organisms. Therefore, to the condition that untapped energy sources are available, more energy will be captured into the ecosystem functioning, interactions between species will be reconfigured and the energy flow throughout the system will increase.

Lotka suggests two possible and exhaustive cases on the availability of material resources required for the species reproduction. If the environment contains enough varied material resources, a species that becomes fortuitously capable of using more energy for its own purposes (including feeding) is more likely to reproduce itself. This species then operates as the agent of the increase of the total mass of the system and in the flow of energy throughout the ecosystem. If, conversely, the environment presents limitations in the material supply, the species will develop a strategy of intensification of material flows. Lotka gives the example of farmers who, in a limited area, will operate two crops a year instead of one. This species is then the agent of an increase in material and energy flows that run through the ecosystem. In each case, a more energy efficient organism increases energy flows, provided there is untapped available energy. “Natural selection tends to make the energy flux through the system a maximum, so far as compatible with the constraints to which the system is subject” (Lotka, 1922). As energy is not just flowing throughout the system but used and transformed at a certain pace, energy flow is equivalent to power (energy consumption by unit of time). Energy capture, channeling and consumption are then comprehended as a rate of transformation (and dissipation), and each organism activity within the ecosystem can be described by a quantity of power.

Although Lotka had clearly also humans in mind, he did not explicitly link his conclusion to human development. However, Lotka's idea was taken up by the ecologist Odum, who applied it to human societies and coined the maximum power principle (or the maximum exergy rate principle). This “principle can be stated: during self-organization, system designs develop and prevail that maximize power intake, energy transformation, and those uses that reinforce production and efficiency” (Odum, 2007). As long as untapped available energy is present, a species that invents new ways to use this energy will develop faster than others and will enhance energy flows. Although this evolution is based on learning (and not on randomness), the application of the maximum principle to human societies supposes that social groups and organizations are struggling against each other to access to resources. For example, this can be observed at the level of countries or companies. The competition between human groups leads to increasing resource use and consumption, which can be expressed as power growth. To the extent that organizations need energy to develop their activities and try to influence the behavior of other organizations, power has here

the double meaning of energy consumption rate and political strength.

In the ecological ontology, both minimum entropy production and maximum power principles result from natural selection, although they operate at different level of complex adaptive systems. Whilst energy efficiency applies to individual points of consumption, maximum power relates to flows and relationships between consumption points. At the lower level, energy efficiency is a way to create either more resilience or more available energy. At the higher level, energy capture efficiency indicates at which rate energy flows and dissipates throughout the system: the efficiency improvement of energy-capturing devices changes the boundaries of the system. The maximum power principle has the immense advantage to bring temporal and dynamical dimensions to the issue of energy consumption. When we consider energy efficiency alone, we seem to face a real alternative: either consuming less or consuming for another purpose. And we can then envisage political and ethical ways to limit new energy consumption activities to benefit fully from energy efficiency measures. However, when energy efficiency is related to the way energy is captured and channeled in systems, it appears as a mean to satisfy the maximum power principle: energy which is not consumed by an individual can be used by another and make the group or the species growing.

There are good arguments that minimum entropy production and maximum power are favored by natural selection. However, to which extent can this apply to human societies? To reach their conclusions, Lotka and Odum need to consider organisms that obey to the natural selection, use material and energy resources to reproduce themselves and modify the system boundaries with energy-capturing devices. The application of Darwinian evolution to human groups is a highly contentious topic, but we can guess that as long as organizations are struggling to access to energy they will give greater place to energy capture strategies over energy conservation ones. Furthermore, the maximum power principle rests upon the increased efficiency of energy capture, which has been tremendously developed by humans, especially since the industrial revolution. In the case of natural selection, the change of system boundaries is slow whilst it is much faster for machines when oriented selection operates. We have then to turn to machines and their development to understand how rebounds emerge in modern societies.

TECHNOLOGY: MACHINES, INFRASTRUCTURES AND STANDARDS

With technology, we step away from natural and living beings to artificial entities: machines and infrastructures. I understand here technology as the branch of knowledge dealing with engineering and sciences applied to artifacts. Energy efficiency deals with machines (and systems of machines), which by definition require an external energy source. On another hand, we shall see that the temporal dimension of efficiency appertains to the way machines are interconnected through infrastructures, which are obviously necessary to channel energy with the order and determined quantity that is required by machines, but also to circulate

technological objects. This section is then devoted to the analysis of rebound effects when the scrutinized entities are machines and their interconnections are through infrastructures.

In the engineer's world, efficiency is broadly defined as the ratio between an output and an input. In the case of energy efficiency, input is energy and output is useful work (or other forms of energy like heat or light). Engineers use thermodynamics, which studies conversions between different forms of energy, to improve the efficiency of machines or their elements. The way in which technology has captured "useful work" has resulted in the strange notion of energy. At the same time stock and transformation, the meaning of energy has been fixed in two principles more contradictory than reconcilable. While the first principle does not limit the transformation of heat into work, the second principle sets a limit to this transformation. In his *Reflections on the Motive Power of Fire*, Carnot (1824), imagines an abstract machine whose functioning depends only on two sources, hot and cold. The course of an ideal cycle, infinitely slow, indicates the maximum efficiency of the machine which depends only on the difference in temperature between the two sources. A minimal amount of energy is needed to produce a useful work. Even when operating infinitely slowly, a thermal machine necessarily degrades a certain amount of energy into heat. A real machine, whose useful work is produced in a finite time consumes more energy than this minimum (Ruzzenenti and Basosi, 2010). During an infinitely slow transformation, no power is produced. Therefore, the operation of a machine is always a compromise between efficiency and power. For example, a car has maximum efficiency for a certain power. Therefore, the key distinction is between energy in general and heat in particular. While energy is conserved as a sum of quantities, it is degraded irreversibly to heat (i.e., entropy increases). Engineers continuously endeavor to improve the efficiency in getting the most of the useful work while minimizing losses. Engineering relies on multiple sets of figures, obtained from measures read on instruments. Indeed, in the engineering sciences, processes must be measurable and they can be industrialized.

Energy efficiency of machines is constantly improved through trials and measurements. Each new generation of machine includes new features, whose energy efficiency improvement is not the last one because energy usually constitutes the biggest part of running costs. The historian of technology can show how machines are descendents of other machines, and how they evolve. However, this evolution does not proceed from Darwinian natural selection, but rather from a Lamarckian process in which a generation can transmit what has been learned during its life to the next generation. Chance can occur in the development of a machine, but what is learned during the life of a machine can be directly passed to its descendants thanks to the engineer's language. Furthermore, machines are hybridized together and innovation creates always more devices that substitute only partially for the old ones. Machine evolution is therefore much faster than living beings, and can be steered toward greater energy efficiency.

Rebound effects in technological systems have first been identified by Jevons (1865). Although this economist did not use the term "rebound," he displayed a case that is today described

as “backfire”—when rebound is greater than the expected energy savings. Jevons states that Watt’s steam engine, which resulted from efficiency improvements, engaged the economy in a process of positive feedback loops between energy efficiency, coal consumption, coal mining, coal circulation, and steel production. In saving coal, Watt’s machine makes it profitable to remove more coal than it consumes: a coal flow is created. The cheaper coal allows multiplication of steam engines, in factories, on rails or on the water. The faster and farther coal is transported, the more it is available for new uses. Added to this are new processes to produce better steel with less energy and therefore more cost-effectively. Jevons shows how alliances of coal, steam and steel are strengthened when engineers improve the efficiency of the machines. Coal and steel create the condition of their expansion, like an autocatalytic process. Energy efficiency gains have reduced energy costs and thus helped to extend the use of steam engines and consume more coal than before. Three mechanisms can be identified in this rebound effect: (1) more useful work is available per machine and can then produce more output; (2) within a competitive economy, the number of machines increases and deliver more benefits and economic growth; (3) gains are so important that energy prices decrease and this results in new consumption of energy-intensive goods.

Jevons’ paradox is today classified among “transformational effects,” whose “changes in technology have the potential to change consumers’ preferences, alter social institutions, and rearrange the organization of production” (Greening et al., 2000). Production, consumption and life patterns have changed considerably following the multifaceted alliances of coal, steam and steel. Steam engines belong to the class of “general purpose technologies,” along with electricity, steam turbines, lighting, motor vehicles, electronics, computers, and some others (Sorrell, 2007). The composition of electronics, electricity grid and Internet is today the equivalent of the alliance between coal, steam and steel two centuries ago. Electronics is often considered as a way to reduce energy consumption, while at the same time it multiplies in a series of new objects and transforms the way we communicate. As a whole, general-purpose technologies contribute to connect machines together. These technologies are continuously improved and applied to new uses. In addition, these technologies substitute only partially for the old ones. They allow producing more and faster. They all undergo the phenomenon of maturation—the rate of energy efficiency improvement decreases as the improvement opportunities are dwindling—but at the same time also their price reduces and they are affordable for new users.

We have seen that, within the ecological ontology, time efficiency is linked to the acquisition of energy. In contrast, the technological ontology emphasizes efficiency that eases the distribution of energy and machines. Since the 19th century and the exploitation of fossil sources, machines are networked in a systematic way (e.g., train, telegraph, electricity, cars, ICT). Not only are machines always more energy efficient, but infrastructure efficiency is also constantly improved. For rebound analysis, infrastructures are important for two main reasons. First, energy networks are necessary to supply machines. Machines can only work with channeled (or commercial) energy,

be it coal, oil, gas, or electricity. And this energy is distributed via different material networks whose energy efficiency is constantly improved. Energy supply networks extend because both new energy sources can be efficiently exploited and supply efficiency can itself be improved. Second, machines circulate through systems of provision, from factories to users. This circulation allows new, more efficient machines to replace older ones. Some machines are mobile and can carry other machines. Energy efficiency embedded in machines is disseminated thanks to distribution networks whose energy efficiency is continuously improved. Infrastructure efficiencies can be compared (e.g., road vs. train vs. air, or gas vs. electricity) but are generally neither linked to the intensification of technology use nor to the circulation of machines. To sum up, rebounds in infrastructures are understood as a positive feedback loop: energy efficiency improvements circulate thanks to energy efficiency improvement. Therefore, infrastructures increase embodied energy both by their material structures and the objects they help to circulate. This embodied energy is rarely analyzed in rebound studies.

Although systemic effects of infrastructures play a chief role in rebound effects, they are generally not studied as such. This is explained by the fact that infrastructures are usually made invisible through technological agreement and harmonization of standards. As engineers attempt to capture regular phenomena and to extend them into material networks, standards and patents frame their questions. Standards are issued to settle purified phenomena that displayed physical laws and to create objects that can travel outside laboratories. The extension of the laboratory is realized through a large network of coordinated instruments of measure (Latour, 1987). Technological objects are reliable because a whole invisible arrangement of instruments continually controls what circulates within the network and allows various machines to use channeled energy. Infrastructures are never stabilized yet. They stop working if they are not regularly controlled and maintained. Standards has but the goal to become invisible so that objects and information can circulate with minimal friction. They are designed “to fulfill coordination functions through production (by giving producers information useful in designing new products) and exchange (by making explicit the specified properties of a product)” (Borraz, 2007). Standards are intrinsically linked to the development of markets. A standard creates a space of circulation and allows competition within selected agents (those that do not acknowledge the standard are excluded from this space). Standards create irreversibility and orient choices: material networks acquire inertia or “momentum” (Hughes, 1983) and provide new possible activities.

Economists debate whether energy efficiency is the cause of economic growth or whether it is the capital that can provide more efficient means. Jevons, who helped initiate this question, clearly places the technology as the source of wealth. “Civilization is the economy of power, and our power is coal. It is the very economy of the use of coal [i.e., energy efficiency] that makes our industry what it is; and the more we render it efficient and economical, the more our industry will thrive, and grow our works of civilization” (Jevons, 1865). For Jevons, the depletion

of Britain's coal resources is inevitable but mostly occurs at an accelerated rate as long as there is a way to improve the overall efficiency of the coal use. In this perspective, energy efficiency is also a temporal efficiency since energy efficiency accelerates the use of (efficient) technology.

In conclusion, backfire is more plausible if machines, infrastructure and their relationships are included in the rebound description. In complex adaptive systems, events happen at different time- and space-scales and require adopting simultaneously several points of view that capture independent and incommensurable causalities (Polimeni et al., 2008). Neoclassical economists highly simplify the relationships between energy and a given service (or a product) and do not do justice to how humans and machines are arranged. If the energy is considered only as a price, then it accounts for only a small proportion of economic production. But if energy is seen as a flow that feeds machines embedded in arrangements with humans, and if it varies (in prices or input), then it can be considered as the cause of various cascading effects. In addition, if the ratio of outputs to energy consumption (i.e., energy efficiency) changes, the configurations of these effects are doubly affected: the input (energy) and outputs adapt to the new environment.

SOCIOLOGY: DISPERSIVE AND INTEGRATIVE REBOUNDS

Rebounds are explained within the ecological ontology by the increased number of efficient living beings, which augment the total energy flow throughout the ecosystem. In the technological ontology, rebounds are described with the escalating number of efficient machines and infrastructures. Economic rebounds arise when saved capital is used to perform new or more activities. Rebounds in the sociological framework are also elucidated in considering the increasing number of relevant entities: practices. I reduce here sociology to practice theory, for several reasons. First, this theory is helpful to understand how energy demand evolves because it makes sense of the use of new machines. Second, it links explicitly daily routines to machines and infrastructures and accounts for material objects and their ability to guide practice in new directions. Third, transformational rebounds can be analyzed through a social practice approach (Herring, 2011). One of the explicit goals of the theories of practice is to escape from the sterile duality between the individual and the social structure. These theories take as their unit of analysis social practices, that is to say, the actions to which the "practitioners" (e.g., householders) give meaning. A practice can be identified as the unit of social activity across space and time (e.g., eating, cooking, traveling, laundry, sleeping). Obviously, energy consumption is not the aim of performing practices, but rather the result of daily activities. It should be noted that the sociological studies using a practice approach have analyzed much more households than professionals. Examples will therefore be provided for households, but all human activities are virtually concerned by this approach.

The performance of a practice actively integrates heterogeneous elements: a human body, material objects, skills, rules, infrastructure, etc. (Reckwitz, 2002). For example, when I am cooking a cake, I am creating links between flour, eggs, sugar, butter, the oven, a plate and other tools, in following a recipe and drawing on some skills. The evolution of practices can be described as the establishment or the disappearance of relations between elements (Shove et al., 2012). If I get a new oven, with new functionalities, I might be tempted to try new recipes and captured in new practices. When adopting the perspective of practice, issues are no longer centered on a free and rational individual, but on the evolution of daily activities. What are the material and immaterial resources necessary for the performance of a practice? How does a practice emerge, how is it transformed, and how does it disappear? How are individuals recruited by a practice? According to this approach, ways of life are greatly "scripted" by objects and infrastructure. It is not the individual who possesses objects, but the human is "possessed" by practices. Understanding trends and changes in energy demand implies then understanding the dynamic of social practices. The evolution of practices explains why, during the last decades, household have increased their absolute level of energy consumption while they were equipping themselves with more efficient machines and appliances.

In this sociological framework, we can distinguish two kinds of rebounds: dispersive and integrative. Dispersive rebounds are exemplified by the socio-technical transition of domestic heating from coal stoves to central systems. The gas boiler (or electric radiator) has deeply disrupted the configurations of domestic space and time. Cooking, dining, bathing, dishwashing, all these practices once integrated around the same stove, are now compartmentalized and dispersed around different appliances and in diverse rooms. Skills and competences have evolved, and the meanings of heating and other practices have developed alongside this. Time devoted to heating has been reduced meanwhile comfort has increased. Even if energy efficiency of the services individually delivered by the appliances has increased, the overall energy consumption has generally increased also. As regards heating, the dynamic of rebound effects is largely the consequence of a shift in the material and conventional system of practices. For example, heating has been extended to new rooms and these rooms have been furnished with various appliances.

The use of electrical appliances serves our comfort by helping to simplify daily household duties but, at the same time, the number of electrical appliances is continuously increasing. Shove (2003) challenges the idea that comfort we have always dreamt of is the one we have today; comfort is an evolving norm that is not predetermined since it results from a socio-technical history that might have been otherwise. However, when a norm is established and practiced, it becomes somewhat irreversible. For example, in 1970 the average indoor temperature was estimated to 17°C but it has risen to 21°C in 2002. Air conditioners and heated floors are today bringing new expectations of comfort and create spaces and times for new practices. The energy efficient equipment that disrupts practices fosters the indirect rebound effects. The evolution of energy consumption in OECD countries during the period 1965-1995 shows that the budget share devoted

to fuels and heat has generally decreased (from 2.5 to 1.5%) whereas the budget share for electricity has increased from 1.5 to 2.5% (Schipper and Grubb, 2000). Therefore we observe that although households increase the use of appliances and energy consumption, the energy share of their budget is kept at a constant relative level. This would not have been possible without concomitant energy efficiency improvements. Energy efficiency is therefore an ingredient in the transformation of domestic practices.

The case of individual motor vehicles shows another reconfiguration of practices. The acquisition of a car to commute between home and work contributes generally to transform the temporal and spatial dimensions of practices. In this case, the result is not a disruption of practices but an integration of practices that were disconnected: commuting, shopping, driving children to the school, leisure trips, etc. are now coordinated through a single machine. Driving a car can indeed save a considerable amount of time and constitutes a convenience in everyday life. The energy efficiency improvements of cars enable people to multiply practices while keeping their budget under control.

The same reflection can apply to professional spaces where, for instance, the introduction of efficient electrical lighting has allowed to disperse activities throughout day and night. The trend in dispersion of professional activities is also related to the efficiency improvement of means of transport (more kilometer/hours for the same budget share). Conversely, the introduction of computers can be seen as an integrative rebound because it concentrates many practices that used to be dispersed.

Integrative and dispersive rebounds should not be considered as the “practice equivalent” to direct and indirect rebounds. Their mechanisms are different because they are centered on the number of practices that can be performed in a given time. Rebounds happen either when each practice consumes more energy than the previous ones, or when energy efficiency does not compensate for the multiplication of practices (even though some practices are abandoned). Furthermore, the comparison between practices with and without central heating (or car) is difficult since it is hard to allocate the resulting consumption to specific practices.

The development of infrastructures (pipes or wires for heating, roads for car) plays a decisive role in the evolution of practices and calls for an understanding of how agency is distributed between machines and humans (Wilhite, 2012). In the sociological ontology, efficiency is not based on energy but on time. Output can be comfort or any expected outcome of a practice: convenience, cleanliness, entertainment, communication, etc. Time is here the relevant input, as it is a limited resource for humans from whom it is possible to derive an efficiency estimate: the number of activities per hour (Binswanger, 2001; Jalas, 2002). Delegation of tasks to efficient appliances gains time and comfort. If instead of looking at the traditional equivalence of time and money, we analyse conversions between time and energy, interesting rebound effects are observed which help to understand the transformation of practices.

Time is gained by delegating tasks to machines. For example, the washing machine has helped liberate women from a painful task. The adoption of new domestic appliances in the 20th century along with the spread of time-saving technology in private houses did not lead to any decrease in the time spent on housework but instead created new chores and new social norms, raising the benchmark standards by which cleanliness is evaluated: vacuum cleaners shifted the acceptable level of tolerance toward the presence of dust and grime on floors, carpets and furniture fixtures (McGaw, 1982; Cowan, 1983). Along with the evolution of social norms, domestic duties expanded sufficiently to absorb all of the time saved by technological commodities. Contemporary examples of timesaving apparatuses are cars, supermarkets, Internet and other information and communication technologies. It is remarkable that these arrangements change not only time, but also the space and the dynamic of practices. And timesaving devices generally use energy. Integrative rebounds occur when the use of machine speeds up access to services. The owner of a car will tend to use it if he thinks it saves him time. For example, the chain of frozen products (factory-supermarket-car- freezer-microwave) replaces the practice of cooking at home, which is less energy intensive. Computers, another example, certainly save time, but also help to increase activities and increase energy uses.

With technology, many activities can be performed simultaneously. I can cook, listening to the radio, while machines are washing my clothes and my dishes. Multitasking can extend the “duration” of a day up to 43 h (Shove, 2009). Practices follow each other but they also pile up. This applies both to paid and domestic work. Wages have grown because of increased labor productivity, which is partially the result of improved energy efficiency at workplaces. In return, income allows consumers to buy energy using equipment and to pay their running costs. Increasing energy efficiency means then more work, more income, more activity and more energy consumption. The historical productivity growth of labor has led to an increase in the demand for labor—and not a decrease as many analysts had forecasted it (Jenkins et al., 2011). In the case of energy, the self-reinforcement dynamic is the following: substitution of energy for human and animal work increases productivity and entails a bigger economic growth, which in return increase energy consumption.

SYNTHESIS OF THE REBOUND MECHANISMS

The sequence of the route we have achieved through the four disciplinary ontologies is not a coincidence. The construction of a coherent narrative of the rebound effects makes it necessary to go through various stages. First of all, the neoclassical economics, which provides by far the most abundant literature on “rebound effects,” posed the problem while noting that quantifications are problematic (even when the representations of energy consumption are static) and that energy production also needs to be addressed. Then, the issue of rebound effects was addressed by questioning what is energy and

its consumption in ecosystems. New effects arise when the ontology includes relationships and processes, and that they can be seen in the light of a Darwinian theory of evolution. Next, technological ontology has shown how rebound effects occur in a world of machines and infrastructure. Finally, the ontology of social practices needed to describe rebound effects can be summarized as a set of bodies, machines and infrastructures through which energy and materials are flowing. The basic ontology of rebound effects is complete if we add the way in which capital is actualized in entities (bodies, machines, infrastructures) and their relations (flows of energy and materials) and sometimes imposes the principle of profit maximization.

To describe the process of materialization of efficiency, one can like Shove (2018) use the Latour's concept of *purification* (Latour, 1993). Energy efficiency is developed through precision (Wise, 1997) and purification strategies that only occur in laboratories. Modern societies have flourished by separating nature from culture, but at the cost of a proliferation of hybrids. The purification of materials allows an almost infinite set of combinations. Machines, appliances and infrastructure evolve from new materials. In the big realm of innovation, most of the work goes unnoticed. Installation, maintenance and repair take much more economic resources than research and development, but these "basic and boring" activities have been neglected in our understanding of the modern world (Graham and Thrift, 2007). Engineers are actively seeking more efficiency, chasing and tracking losses, leaks, friction and other dissipation, while tirelessly pursuing their ideas. This echoes with Edison's famous quote that inventions come from one per cent inspiration and 99% perspiration. All inventions flow from laboratories to industries and to new situations, with users who do not understand the black-boxed objects, and in an infinite variety of configurations, which are not tested in the laboratory. Blackboxing devices with coordinated standards allows them to circulate and be ready for use. In this large set of entities and relationships, embedded efficiency creates multiple effects, which can be described but are very difficult to quantify.

The difficulty of quantifying the effects, however, cannot be an obstacle to the understanding of a class of phenomena: an improvement in energy efficiency can have important and uncontrollable effects when they arrive in large numbers, and modify infrastructures, market exchanges and practices. These purification and composition effects can certainly be described as efficient transformations to the extent that they reduce local energy consumption. The energy flows are real, even if we do not know what is measured by the equivalences created in the laboratory and observed each time a measurement is made. The composition of devices in new situations and the reconfiguration of practices create effects in which energy plays a specific role but that it is not relevant to try to measure because there is always a share of the efficiency that is actually productivity. The situations before and after the improvement of efficiency are often difficult to compare, especially considering that infrastructures and markets distribute energy savings very quickly. In competitive situations, it is difficult to conceive of a limitation of access to resources.

After having gone through the four disciplinary ontologies, one can identify at least four types of effects. First, the constant improvement of devices (of production, distribution or consumption) accelerates activities at all levels of the infrastructures and machines. However, this acceleration is mainly felt at the level of individual lives, in households and at work in particular. In this case, efficiency is translated into productivity, which allows more activities to be performed in the same period of time, especially because the share of the budget devoted to energy does not explode. Where efficiency is translated into economic gains, it is desirable from the economic point of view to invest capital. This first effect can be stated as follows: the improvement of energy efficiency increases the number of activities per unit of time, including through the delegation of actions to always more devices. The delegation and the extension of human actions to objects continues to grow, and it mobilizes more and more materials (Wallenborn, 2013). Improving efficiency therefore contributes to economic growth.

Ecosystems exhibit two other types of effects, as we saw in the section on ecology. On the one hand, improving energy efficiency can lead to increased resilience to a shortage of energy or food. In this case, living beings are more likely to reproduce when energy or food are scarce. For businesses and households, activities and practices are the units of analysis, and the improvement of an activity or practice efficiency increases its chances of reproduction, even in a changing environment. This second effect can be expressed as follows: the reproduction of a family of activities increases when they minimize their production of entropy.

On the other hand, when the improvement in efficiency is applied to energy capture, it increases the power of the entities involved. These entities are living species, businesses or human societies. When evolution is Darwinian, which is counted in millions of years, the change in efficiency allows different species to adapt. All living beings have strategies for capturing energy, but only humans have developed an extended ability to shape their environment that can be used to thrive. Modern societies have the opportunity to use energy to replicate configurations that are easy, comfortable and even luxurious. In a Lamarckian evolution, the increase in power can notably be used to build new energy capture devices, and to increase the power of the entity in return. At this stage, energy efficiency is an end in itself because it no longer questions the use of energy other than in terms of increased energy consumption. The maximization of power, the third effect, takes place in a context of competition that transforms the environment for the benefit of the entity that manipulates its power to increase it. Purification of energy consumption processes is then done by excluding humans and other living considerations from this process.

The fourth effect summarizes the three others by amplifying them: the effects are all the more uncontrolled, producing unexpected hybrids, that they take place in systems where infrastructures and markets are likely to circulate the "non-consumption" for make energy available elsewhere, in another activity. In this perspective, human societies are entities that organize production and consumption systems. Complex societies add distribution and assembly links: complexity

comes from the construction of distribution networks, which are materialized in supply infrastructures. The energies that feed the machines are part of a production-distribution-consumption system in which many activities take place: extraction, maintenance, marketing, multiple uses,... This system has developed thanks to a constant increase of efficiency of “resources,” that is, useful materials considered to be outside human activities. Efficiency concerns all resources, but energy and time are special resources because they are necessary for movement and transformation. Energy is necessary for the development of power, which is here political as well as energetic. It is in this context that it is necessary to think how efficiency circulates more efficient machines, builds more efficient (but also more complex and fragile) infrastructures.

CONCLUSION: LIMITING REBOUNDS IMPLIES LIMITING COMPETITION, INFRASTRUCTURE AND MARKET

Rebound effects arise from the improvement of energy efficiency. But they can be amplified through various factors, which need then to be identified if we hope to master them and limit energy consumption. To conclude, I will discuss briefly what these factors are in our contemporary society and how to counter them. I will then only consider Lamarckian evolution, and will leave out the evolution of ecological systems from the final analysis. First, the competition between entities leads either to more activities or aggregated power. Entities can be here: human groups, territories, machines, practices... Human activities, equipped with technologies, are not only at the end of the energy flows, but constitute the very reproduction and extension of energy capture, transformation and distribution. Human practices are plural and highly diverse, but some can be identified as able to aggregate and form *societies* (in the broad sense of the term).

Power takes a double meaning (energy rate and political capacity to act on other entities) when we climb the scale of aggregation: at some point, the issue of a fair distribution of resources is raised. We have however to follow defined networks, infrastructures and corporations, for instance. In this case, energy efficiency contributes to the aggregation of power, and this aggregation in turn increases power. Competition tends to select entities with bigger size for these increase their power to act on others and on their environment (including the ability to find new resources). Therefore, when both energetic and political powers coalesce, they give place to bigger entities that can shape the environment to their advantage. In other words, power actualises through various materializations that increase

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power. A direct fight against rebounds is then the limitation of power, their even distribution and thus the simplification of institutions and societies. This is realized through local cooperation and solidarity, in contrast to long networks in which tight relationships are not possible.

Second, infrastructures that distribute energy (and efficient machines) enable rebounds to occur fast: the saved energy in a place can be used in another place if adequate infrastructures are present. When connections between entities are numerous, energy flows continuously in large channels, which are growing due to energy efficiency improvements. Many machines are present and related through developed infrastructures. Energy sources are not renewable and appear like an infinite stock. In contrast, to limit rebounds, it seems necessary to decrease the number of connections between entities, so that energy channels are scarce and narrow, or do not function in permanence; they are specialized and selective (in contrast to general purpose technologies). This kind of system evolves slowly and adapts itself to biospheric changes, and is more fit to renewables whose production is variable.

Third, the equivalence between energy and money makes possible to link energy to all markets. Therefore what is saved as energy is immediately translated into available money or capital, which can be used in any activity, be it high- or low-carbon intensive. As a factor of production, energy is often considered as negligible. However, nothing would happen without it. Non-regulated markets select the most powerful entities—for which resources seem unlimited—and the fastest entities that can augment the pace of their exchanges. Capitalism is an incredibly efficient economic system because it acts in a world without ecosystems and with high-rate capital exchanges at short term. No political institution is today able to take long-term measures. Therefore, the limitation of rebounds could happen if energy won't be fungible anymore, namely exchangeable with money, but would belong to an independent system of exchange. All theories pointing to the idea of energy as a common good are going in this direction.

AUTHOR CONTRIBUTIONS

The author confirms being the sole contributor of this work and has approved it for publication.

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