The tragedy of energy efficiency. An interdisciplinary analysis of rebound effects

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Abstract
Energy efficiency improvements are generally seen as the most cost-efficient and effective strategies to achieve a rapid transition to a more sustainable society. However, so-called rebound effects arise when energy users or producers change their behaviour after an efficiency improvement has taken place so that they actually consume more energy related to services or commodities than expected. This may significantly reduce the expected benefits of efficiency improvements. The magnitude of rebound effects, particularly at the whole economy level, is however controversial.

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 some rebound mechanisms as they frame differently their objects of inquiry. In order to analyse the different rebound mechanisms, I consider four disciplinary framings: ecology, engineering, (neoclassical) economics and sociology (of practices). In each discipline I identify different kinds of rebounds. I show that in general they combine the improvement of energy and time efficiencies. Energy efficiency is linked to the minimisation of energy consumption (or entropy) and time efficiency amounts to mechanisms of maximisation (of power or profit) or multiplication (of machines or practices). I conclude that the combination of energy and time efficiency probably leads to backfire at long-term. The exploration through disciplines displays also the importance of infrastructure and system evolution in the shaping of rebound effects. I suggest that besides energy, power is an issue in itself that must be addressed if energy reduction is thought to be a premier objective.

Introduction: disciplinary framings of energy efficiency
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. In its last report, the IPCC (2014) recommends a series of energy efficiency measures 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 behavioural 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 analysed[1]. 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

1. Of 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.

cases consumption rebound can exceed 100 % of the theoretical energy savings and then completely erases the expected gains. This case is called 'backfire'.

There is no satisfactory classification of rebound effects, which have mostly been analysed 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 some rebound mechanisms as they frame differently their objects of inquiry. 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. Relationships between energy demand, economic activity and energy intensity are nonlinear. Rebounds appear stronger in developing economies, although more limited in developed ones where saturation effects might occur (Jenkins et al.2011). For example, when a village is electrified, light bulbs replace less efficient and more expansive lighting equipment. If income is low, the relative part of saved money may be high and reinvested in electrical appliances. In this case, economists say that demand for electricity services is far from saturated and is therefore very elastic. Furthermore, as we shall see, electricity use allows new activities to occur (e.g. by night), increases productivity and accelerates economic exchanges. This applies for instance to the development of electronics and smart technologies, which will probably result in new rebounds.

Energy efficiency is defined differently in each discipline, notably because energy and efficiency have different meanings. I glance first through the efficiency concept. 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 emphasise 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 (Nakicenovic et al. 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 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. 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 2010). 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 (Sorrell 2007). For example, a sense of comfort or cosiness is a service or output, but is hard to quantify.

The notion of energy consumption has also different meaning in disciplines. Contemporary energy consumption is a particularly complicated case as it embraces many diverse dimensions. Energy consumption refers in the first instance to two very different meanings. On the one hand, it is made possible by the production of energy from primary sources and the manufacture of standardized equipment. These products require complex socio-technical networks so that, for example, a washing machine can be produced, assembled and distributed, and also used through electricity supply. The technologies are intrinsic to the supply of energy services in modern society, and in addition they are constantly evolving as the new trend towards "smart grids" shows. On the other hand, energy consumption is a fantastic shortcut to describe the multiple uses of electricity or fuel. Consumers do not consume energy; they use a multitude of devices that render many valuable services. This idea is now well accepted. But who demands energy? Individuals, companies, societies or practices? Which consumes energy? Appliances or their users? Can we separate them so easily? What are the elements to be considered when explaining the observation that consumed energy is bigger than the theoretical value? Answers to these questions depend on the discipline in which the problem is framed.

I will show how rebound effects are defined and considered in four disciplinary framings: ecology, technology (or engineering), (neoclassical) economics and social practice theory. In each discipline, entities are endowed with specific properties and processes are organised along specific patterns. A discipline can be seen as a process of attributing properties to specific entities. A theory qualifies certain agents and at the same time disqualifies or neglects others (Wallenborn 2007). A theory is like a projector that sheds light on some actors in order to follow them and leave the others behind the scene. On stage, actors have some character that makes them interact with others in specific ways. Attributes and properties of the entities are designed through particular methodologies. For example, on the ecological scene, entities are organisms regulated by natural selection. Living beings in ecosystem reproduce themselves through the use of material and energy resources. In the technological setting, machines are powered by external source of energy and interconnected through infrastructures. Machine efficiencies are constantly improved and stabilised through standards that allow them to circulate. In the neoclassical economic framing, firms and individuals maximise their profit or utility. The mathematical formalism deals with factors of production and price elasticity. 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. Ontologies are not 'worldviews' because each discipline does not embrace the whole world, as they instead provide existence to special beings. Each disciplinary theory makes foundational assumptions about how the world is composed and through which causal processes occur.

Therefore each disciplinary framing selects the relevant entities and their relationships that fit with the rebound effect issue. Each framing receives a name by convenience but it should be clear that they draw on knowledge from different disciplines. For example, ecology includes elements from biology and thermodynamics; technology is closely related to economic concepts; economics is inspired by theoretical physics; practice theory inherits concepts from STS (science and technology studies). For this reason, each disciplinary framing is introduced with a short description of entities needed to describe rebound effects. Whilst exploring a disciplinary setting, I don't assess the validity of their axioms but I try to follow the reasoning in its own terms from primary assumptions to the conclusion.

Of course, interdisciplinarity is a challenging task since it switches from one mode of thinking to another, and multiplies specialised terms. However, in analysing an issue from different perspectives, one escapes from reductionism – at the risk of remaining superficial and of making oversimplifications. A bigger risk is, I think, to miss important elements which are relevant to rebound effect analysis. The definition of scientific disciplines is not very clear when they aim at studying sustainability and exploring alternative pathways from the present situation.[2] I don't pretend to grasp all the details, subtleties and variations of each discipline, but I aim at establishing contrasted viewpoints on the same question in selecting the relevant entities for the problem. This constitutes my research method that attempts to explore new ways of thinking of rebound effects. This might give the impression that, in clarifying differences between disciplinary framings, I somewhat "caricature" them, and I might frustrate monodisciplinary readers, but I think I gain new insights from the relationships between them. Other approaches could probably have been included in the analysis. I think, however, that the composition of these disciplinary framing is sufficient to comprehend and show the essential rebound mechanisms. Of course I am open to suggestions that would enlarge and specify the interdisciplinary approach of rebound effects.

Ecology: minimum entropy production and power maximisation

When entering in the ecological framing, 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 organised 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.

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. Fortuitous 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 favours 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 maximisation (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-organisation process of life consists in maintaining the conditions under which it can perpetuate itself. Energy efficiency is then a good strategy to preserve control on the relationships with the environment. Learning how to reduce 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. As entropy is an increasing function of any open system, which undergoes irreversible processes (Prigogine 1969), energy efficiency slows the rate of entropy

2. This lack of clarity is reflected in the discussions around "post-normal science" and "sustainability science".

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 that went unnoticed at the time, Alfred Lotka, theoretician of population dynamics, 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 favourable to the preservation of the species" (Lotka 1922). He shows that natural selection favours 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 favourable to its preservation. The result of energy efficiency is a relative preponderance in number or mass of theses organisms. Therefore, to the condition that untapped energy is 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 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, channelling and consumption are then comprehended as a rate of transformation, 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. 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. The application of the maximum principle to human societies supposes that social groups and organisations 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 organisations need energy to develop their activities and try to influence the behaviour of other organisations, power has here the double meaning of energy consumption rate and political strength.

In the ecological framing, 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 throughout the system: the efficiency improvement of energy-capturing devices changes the boundaries of the system. The maximum power 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 channelled 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 favoured 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 organisations 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 artefacts. 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 scrutinised 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 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 endeavour 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 industrialised.

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 hybridised 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 towards 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 framing, time efficiency is linked to the acquisition of energy. In contrast, the technological framing emphasises 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 channelled (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 analysed 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 harmonisation 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 realised 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 channelled energy. Infrastructures are never stabilised 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 fulfil 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 1993) 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.

Economics: maximisation of utility and profit

Economics stands here for the dominant and orthodox neoclassical economics, which mainly rests upon agent maximization problems. Two classes of agents are considered: firms and individuals – that should not be confused with producers and consumers since firms (an individuals) are both consumers and producers. Neoclassical economics rests upon three main hypotheses (Weintraub 2007).

First, individuals maximize utility and firms maximize profit. Utility is an abstract function usually interpreted as the satisfaction associated with the consumption of products (goods or services). It is a typical neoclassical concept that stands for subjective pleasure but is above all defined in mathematical terms (see below). Profit is the difference between revenue flows and expense flows. The equilibrium between demand and supply results from the maximization of utility by individuals under income constraint and from the maximization of profit by firms constrained by cost, including factors of production. Price occurs as the right balance between unlimited desires and wants, on the one hand, with unavailability and credit, on the other.

Second, firms and individuals have rational preferences among outcomes. They make decisions in accordance with the rational choice theory. This theory assumes that any 'agent' (be an individual or a firm) behaves with the logic and processing ability of a supercomputer and as if it was alone to make decisions.

Third, people act independently on the basis of full and relevant information. Other variables are qualified as exogenous and neglected, so that the theory is deterministic. Relations within the model are mathematical, namely inscribed in a writing that can handle fixed entities (out of time and space). The attribution of rational but narrow capabilities have been largely criticised by authors who are interested in real situations in which humans act, within institutions and with power. Nevertheless the model of the 'economic man' has a strong performative power both in the ways in which institutions and individuals behave as well as in shaping products that fit assumed interest. When neo-classical models frame policies (e.g. liberalisation of energy markets), firms compete in free markets (energy production is privatised) and individuals are invited to behave like rational agents (e.g. in choosing the best offer). In this case, actors are financially rewarded when they behave as predicted by the theory.

This simple model allows economists to mathematise 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 maximisation (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, labour, 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 optimised to yield maximum return of capital investment. For instance, capital and labour are monetarised so that their relative distribution can be optimised, and it is possible to calculate the best combination of workers and machines to maximise 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 organised into types. Economists do not agree on the classification of the mechanisms that may explain the rebounds (Gavankar and Geyer 2010, Turner 2013). 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 analysed 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 artefact 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 focusses 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 different households and companies. 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 areas.[3] They estimate the magnitude of 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 travelling 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.

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. 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 (Gavankar and Geyer 2010).

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 system.[4] First, the roots of the neoclassical theory lie in classical physics. Mirowski (1989) has shown how neoclassical mathematical formalism borrows line to line from the classical physics formalism and this imposed particular properties to utility, which I summarise here. 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 are outside the picture for the neoclassical framing cannot describe the dynamic evolution of the systems. "Neoclassical economics applied to economic development or economic history may account for the performance of an economy at a moment of time or, with comparative statistics, contrasts in the performance of an economy over time; but it does not and cannot explain the dynamics of change" (North, 1981, quoted in Chen 2005). Many attempts have been tried to integrate time and dynamics in economic formalism, but they remain marginal (Fisk 2011).

Second, 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, ecological and technological framings 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

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

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

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 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. This formalism can only deal with static rebounds, and cannot analyse how activities are transformed. The maximisation 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, labour 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.

Sociology: dispersive and integrative rebounds

Rebounds are explained within the ecological framing by the increased number of efficient living beings, which augment the total energy flow throughout the ecosystem. In the technological framing, rebounds are described with the escalating number of efficient machines and infrastructures. Economic rebounds arise when saved capital is used to perfomr 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 analysed through a social practice approach (Herring 2011, Wallenborn et al. 2013). 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.

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, Pantzar, and Watson 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 centred 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 compartmentalised 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. With colleagues, I have analysed the evolution of energy consumption in Belgium during the period 1960–2000 and how this is related to domestic appliance use and energy budget of different social groups (Wallenborn et al. 2013). 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.

Integrative and dispersive rebounds should not be considered as the 'practice equivalent' to direct and indirect rebounds. Their mechanisms are different because they are centred 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 framing, 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. 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.

Time is also gained by delegating tasks to machines. For example, the washing machine has helped liberate women from a painful task. 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 hours (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 labour 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 labour has led to an increase in the demand for labour – 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: towards backfire

In this section, I summarise what has been grasped about rebound effects through surveying disciplinary framings. The simplest model considers a system of humans and machines, which are interconnected through infrastructures and traversed by energy and material flows whose consumption is enacted in practices. This consumption produces both power (useful work by unit of time) and entropy (dissipation of energy). Machines are the main points of energy consumption and constitute therefore the targets of energy efficiency measures. Those actions aim at maximising useful work with a constant energy input. However, machine purposes can only be understood in relations to humans (e.g. households, companies or countries). Economic profit and utility capture mechanisms that can be considered as instantaneous adjustments to change of energy price. These mechanisms can be expressed in very restricted mathematical models. When energy efficiency improvements are accumulated through the use of appliances, it can be considered as an ingredient of practice evolution. Although energy efficiency is hardly quantified when dealing with situations in which machines and humans are actively linked, I have described how users are captured by infrastructures and lower prices.

In ecosystems, energy efficiency appears by chance and is selected because bearers get an advantage. In human societies, energy efficiency can be actively searched for creating new activities and energy can be efficiently distributed through infrastructures. The human species is characterized by the many tools and machines it produces, uses and organises through various networks. Systems of provision are wholly part of the extension of both energy efficiency and consumption. The delegation and the extension of human actions to objects continues to grow, and it mobilizes more and more materials (Wallenborn 2013). Energy efficiency promotes the consumption of resources, including energy. The development of infrastructures makes access to energy always easier. Efficiency of infrastructure includes energy consumption, but is mainly gauged through its capacity to carry energy or machines (which can be considered as embodied energy). Therefore, whereas energy efficiency of infrastructure is probably an important feature to be considered, it is overall through its time efficiency that infrastructure is crucial in the explanation of rebounds.

Throughout the previous sections, we have encountered several temporal dimensions of energy efficiency. First, the rate of energy consumption is increased when energy-capturing devices are more efficient. This is true for both living beings and machines. Second, energy use is increased when more energy efficient machines contribute to the building of both energy and technology supply. Third, machines can recruit users with the argument of saving time. We observe however that delegating practices to technology multiplies above all practices and probably increases global energy consumption. Fourth, energy efficiency is made irreversible through technological standards and social norms. In sum, time efficiency contributes to increase energy flows, to move faster energy and machines and to perform more tasks within the same duration.

Making energy efficiency improvement appears as a normal trend of individuals that are in competition to acquire energy sources or to save time. Entities are however distinguished by the rate of their evolution. Human bodies, machines, markets or practices do not evolve at the same pace. This makes obviously a huge difference for the system dynamics, namely the speed at which the system reconfigures itself following energy efficiency improvements. Self-organised systems arrange materials and products in order to increase outcomes by unit of time, and they can even move system boundaries framed by energy sources. However, the rate of transformation depends on the constituents of the system (i.e. relative number of humans and machines). If some consuming entities within the system improve their energy efficiency, we can observe rebounds at three distinct levels.

First, energy efficiency is improved locally, typically to a machine or an individual. We have seen that there are ecological, technological, economic and social advantages to improved energy efficiency, which are equivalent to enabling new possible activities. The energy flow then decreases for an equivalent power. But this opens up new possibilities since energy is now available for new activities. If saved energy is consumed after some delay, then the total energy consumption can decrease. But if there is no delay, energy is immediately consumed elsewhere, the flow of energy remains constant and power is increased. This case is similar to what is described in direct and indirect microeconomics rebounds. The boundaries of the system remain the same while new activities are enacted. The magnitude of the delay depends on the balance between the access to the freed energy and the possibility to store it. The configuration of infrastructures is therefore crucial to decide how to negotiate between diminished energy flow and increased power. In a free market, prices will be obviously adjusted to satisfy solvent demand and maximise power (as defined by infrastructure capacity).

At a second level, when energy efficiency of many machines (or social groups) is improved, the system configuration evolves and energy flows are accelerated and reconfigured. The efficiency mechanism applying to systems is no longer the optimisation of the ratio output/energy (as for individual machines) but the generation of an output, namely the rate of energy throughput in the system. At this level, practices evolve so that the system is adapted to its new energy flows. Adaptation happens in changing the identity of the system, in adding new entities and forging new relationships between them. And the status quo is not an option when social groups (e.g. companies or countries) are competing for energy resources. Improved energy efficiency will provide a competitive advantage to these groups either to reproduce themselves or to reconfigure their environment.

The third level concerns energy and time efficiency improvements applied to new energy sources. In that case boundaries of the system are extended and the whole dynamic of the system is amplified and accelerated. Of course, this last step depends crucially on the availability of energy sources. As long as the efficiency of extraction can improve, fossil fuels appear as an infinite stock, as the recent rush on shale fuel or tar sands demonstrates. Obviously this is a pure illusion supported by the idea of indefinite technological progress, notwithstanding climate change issue. And the question is to know whether renewable energy efficiency can be indefinitely improved so that systems can continue to grow.

Transformative rebounds can be understood only in the long-term – relative to the time of the evolution of the system. If the focus is on a machine, energy efficiency produces immediate effects once installed and power is redistributed quickly throughout the system. But if the focus is on innovation (i.e. the invention and diffusion) of more efficient machines, transformations take gradually place. If innovation is itself a source of improved efficiencies in other devices, it triggers a cascade of new machines and uses. Innovation creates new markets and reconfigures the relationship between machines, humans and products. Local efficiencies propagate across infrastructures while transforming them. When the cumulative increase in efficiency is large enough, it causes significant economic growth, stimulates new innovations, transforms social institutions and alters substantially practices. The general purpose technologies have the ability to operate in networks, based on infrastructures they help build. They can produce and circulate more objects, that is to say, increase embodied energy flow.

Conclusion: powerless policies?

If energy efficiency is the only considered way to fight climate change, I have argued that it will lead to counter-productive effects. Indeed, we have seen that energy efficiency improvements can lead to an increase of energy consumption, provided that 1) organised consumers are struggling to access to energy resources or to save time, 2) system evolution are nonlinear and fed with positive feedback loops of efficiency improvement, and 3) infrastructure development is considered in the description of energy capture and distribution.

1. The increase in energy productivity of a set of activities means that more energy is available for other practices and, if nothing tempers the creation of new practices, the net result will probably be an increase in energy flow, namely total power. Competition tends to select entities with bigger size for these increase their power to act on others and the ecosystems. 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. How to go from powerless policies towards policies without power, or rather with adjusted power for common aims?
2. 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.
3. In speaking the language of system dynamics, one can state that rebound effects create instabilities which can propagate and make emerging a new configuration. In topological terms, entities add up according to an arithmetic progression although relationships multiply according to a geometric ratio. The number of entity combination grows much faster than the number of entities. Still, energy efficiency enables the multiplication of relationships between machines and humans, in increasing either the number of machines and their circulation or the number of practices. It is then possible to distinguish between two kinds of systems – which could inspire computer modelling:
   a. Connections between entities are relatively rare. Energy channels are scarce and narrow, or do not function in permanence; they are specialised and selective (in contrast to general purpose technologies). This system evolves slowly and adapts itself to biospheric changes. Energy is renewable and relatively difficult to capture. If a new source of energy appears, it will be consumed with considerable delay. This system is clearly sustainable for it relies on what ecosystems can provide within given limits. However, the system complexity is rather poor and adaptation capabilities are limited.
   b. 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. Technological innovation is present and production accelerates through positive feedback loops, including energy and time efficiencies. The capacity to use resources is the only limiting factor. This system has a great complexity and good adaptation capabilities, but ecosystems are being destructed. It looks like our current unsustainable development.

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