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The Rebound Effect. From Classic Economic Theory to Behavioural Economics. An Experiment on Hyperbolic Discounting and Magnitude Effect.

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ABSTRACT

It is common opinion that improving the efficiency of an energy source will result in a proportional reduction of energy consumption. However this may not be the case, and efficiency gains could lead to a less than proportional decrease in consumption, or even to a net increase. This phenomenon is known as the 'rebound effect' (with the case of an increase in energy consumption called 'backfire' or 'boomerang'), and it was analysed for the first time by the English economists William Stanley Jevons, who showed how the passage from Newcomen's to Watt's engine augmented consumption of coal despite the efficiency improvement. This somewhat counterintuitive effect has, then, become known as the 'Jevons' Paradox'. In more recent years the argument has been further analysed by many other authors, especially Daniel J. Khazzoom and Leonard Brookes, from whom it took the name of 'Khazzoom-Brookes postulate'.

This study provides a review of the literature, presenting a theoretical analysis of the 'rebound' effect, based on price elasticity and energy demand elasticity, and some of the main empirical evidences. But also integrates it with the behavioural side, to see if some barriers there exist in terms of bounded rationality or behavioural fallacies of the consumers that limit the diffusion of energy conservation. More specifically it is be provided a deeper insight on the effect of hyperbolic discounting, 'magnitude effect' and relative thinking through two experiments focusing on consumption preferences and willingness to pay for LED bulbs.

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INTRODUCTION

Our society is characterized by a massive consumption, not just of good and services, but also of energy. We consume energy to light our houses, shops, and streets, to move our cars, trains and planes, to produce heating, electricity and consumption goods.

Over the last two and a half centuries the consumption of energy has increased tremendously, and the trend is not likely to detour in the next years. According to the International Energy Agency, the World's total final energy consumption has constantly augmented since 1971, and the U.S. Energy Information Administration forecasted a rise of 56% between 2010 and 2040 (as China and India enter the group of the developed economies). In the same time span (as the one considered by the IEA), the World Bank reports [1] that per capita energy use also has increased, from 1336.77 to 1897.95 kg of oil equivalent [2] (keep in mind that the population has almost doubled in such a period, hence the absolute rise is enormous).

Nations, governments and International Organizations are becoming more and more aware of the problem, and therefore are struggling to come up with measures to cope with it. In April 2009, the European Union issued the Directive 28/2009/EC of the European Parliament and of the Council (also known as the

[1] Data for energy use and population have been downloaded from the World Bank Group databank (here for the Energy Use indicator `http://data.worldbank.org/indicator/EG.USE.PCAP.KG.OE`, and here for the Total Population one `http://data.worldbank.org/indicator/SP.POP.TOTL`).

[2] The Ton of Oil Equivalent (TOE), of which the kg of oil equivalent is a submultiple, is a commercial unit of measure that allows to make comparisons between the various energy sources, and it corresponds to the quantity of heat obtained from the combustion of a ton of oil.

'Directive 20-20-20'), where it is state that Members of the Union have to reduce energy consumption through a 20% improvement of energy efficiency by 2020.

It is commonly thought that an increased efficiency will reduce energy consumption in a proportional way, so the 20% improvement in energy efficiency prescribed by the European Union should lead to a 20% reduction of energy and resources consumption. However this might not be the case, as "*these calculations overlook the fact that changes of efficiency have a price content*" (Khazzoom, 1980). As a matter of fact, an increased efficiency is likely to reduce effective prices, thus stimulating demand: the result could be that the reduction in energy consumption turn out to be less than proportional, or sometimes, the use of resources can even rise.

This is known as 'rebound effect', with the case in which demand increase more than make up for efficiency reduction called 'backfire'. Such a phenomenon was first analysed by the English economist William Stanley Jevons in 1865. In *The Coal Question*, the author states that efficiency improvements actually raised the consumption of coal, iron and other resources instead of reducing it. His study has been so widely accepted that the effect (especially the backfire case) has come to be labelled the 'Jevons' Paradox'.

As a consequence, the impact of energy and efficiency policies is not straightforward. Some claims they are counter-productive (Alcott, 2005); Khazzoom says that "*a program of indiscriminately accelerating efficiency improvement is likely to lead, at least in the case of some major end-uses, to a net increase in energy consumption greater than it would have been otherwise*"(Khazzoom, 1980). So, in defining these policies national administrations and international Organizations should pay a considerable attention to possible rebounds.

But why does this phenomenon arise? Why can efficiency improvement backfire? It has been said that increased efficiency causes a decrease in effective prices, which in turn stimulated demand, thus possibly rising energy and resources consumption more than it would have been otherwise. Hence, consumers and their behaviour play a central role in deciding what the effect will be, whether a proportional reduction, a less than proportional one, or even a net increase. With respect to the first case Binswanger says: "*this is not usually the case because technological improvements evoke behavioral responses*" (Binswanger, 2001).

This study aims to present a theoretical analysis of the 'rebound' effect, based on price elasticity and energy demand elasticity, as exposed in the literature. But also to integrate it with the behavioural side, to see if this phenomenon is due to some kind of bounded rationality or behavioural fallacies. In this field the literature usually connects the energy-efficiency paradox (a different name of the Jevons' paradox) to the influence of habits. In addition, there will also be conducted two experiments which try to link it to hyperbolic discounting, as well as a 'magnitude effect'.

CHAPTER 1

REBOUND

The rebound effect is the phenomenon that arises when an improvement in energy efficiency does not result in a proportional reduction of energy consumption, but, rather, in a less than proportional one, or even in a net increase (this last case being called 'backfire' or 'boomerang'). "*While the impact of improved energy efficiency may, on average, be expected to result in some reduction in energy consumption, there is neither an a priori reason, nor any empirical evidence, that would lead one to expect this result to apply uniformly to all end-uses*" (Khazzoom, 1980). The existence of such effect has been generally accepted by economists since the end of nineteenth century, however, Binswanger says, they disagree about its actual importance.

1.1 ENERGY EFFICIENCY

Before to dig into the analysis of the rebound effect it is needed to provide a clarification on the concept of 'energy efficiency'.

Common sense suggests that the term efficiency should represent the "ability" of an input to create a certain amount of output, namely how much input is needed to produce that output: the smaller the input requirement the higher the efficiency. The relationship can be expressed by the following ratio:

$$Efficiency = \frac{Useful\ Output}{Input}.$$

Since we are dealing with energy, the components will be 'Useful Energy Output' and 'Energy Input'.

Considering energy efficiency, the first definition that needs to be considered is the physical one, deriving from the laws of thermodynamic. According to this characterization, the numerator has to be expressed as either heat content or work potential, while the denominator is always the energy input requires to produce it. As a consequence, the ratio introduced before turns into:

$$Energy\ Efficiency = \frac{Useful\ Work\ or\ Energy\ Output}{Energy\ Input}.$$

However, the thermodynamic definition has problem in describing the cases when useful output is not given by heat or useful work. For this reason the literature on rebound effect has concentrated on output measured as a tangible physical unit rather then an energy content. This characterization is found in Khazzoom (1980), Saunders (1992, 2000), Schipper and Grubb (2000), Greening et al. (2000), Binswanger (2001), Alcott (2005). Examples of the useful output can be washing loads or cycles (for a washing machine or a dishwasher), or physical fuel per mile used or vehicle miles travelled (in the case of personal transportation). In this case the ration becomes:

$$Energy\ Efficiency = \frac{Useful\ Physical\ Output}{Energy\ Input}.$$

Both thermodynamic and typical researchers' definitions provide "*measures of energy efficiency that can be objectively measured, and can be compared in time-series analysis*" (Gavankar and Geyer, 2010).

Still, some are left, in the sense that such measures need to be defined individually: on the one hand if there exist different sub-systems in the same system which have different outputs; on the other hand they vary according to the objective of the study, such that different objectives require different (physical) measures of efficiency. Moreover, the objective, hence the efficiency measure, can be given by a combination of outputs, thus complicating things even further (for example, in the case of personal transportation the output for efficiency could be either one of the two previously presented, or a combination of them).

To overcome these difficulty it is possible to reason in terms of market prices, giving a monetary value to physical output allows to combine dissimilar quantities and aggregate at various levels. The resulting ratio looks like:

$$Energy\ Efficiency = \frac{Monetised\ Output}{Energy\ Input}.$$

At the highest level of aggregation, namely the national one, it turn into GDP per national energy consumption, or '(economy) productivity ratio'. However, market prices are influenced also by other factors others than efficiency. As a result, measures based on monetary values are not completely reliable to evaluate energy efficiency: there exist an asymmetry, which, as it will be said later in this chapter, is likely to lead to a biased estimation of the rebound effect.

1.2 AN HISTORIC PERSPECTIVE: THE JEVONS' PARADOX

Evidence of the effect was first provided by the English economists William Stanley Jevons (1835-1882), who, analysing coal resources and future progress possibilities for Britain in the book *The Coal Question*, claimed that efficiency gains did not lead to a reduction in the use of coal, but actually tended to increase consumption of coal and other resources (such as iron). "*It is very commonly urged, that the failing supply of coal will be met by new modes of using it efficiently and economically. The amount of useful work got out of coal may be made to increase manifold, while the amount of coal consumed is stationary of diminishing. ... [But] it is wholly a confusion of ideas to suppose that the economical use of fuel is equivalent to a diminished consumption. The very contrary is the truth*" (Jevons, 1865).

The core of his argument laid on the passage from Savery's and Newcomen's voracious and non-competitive engines, to the more efficient Watt's engine. The amount of coal needed to make the three engines work was progressively diminishing, however, the reduced rates of coal consumption made their installation more and more convenient, so that, in the end, the absolute consumption of coal in the economy increased. With respect to Savery's engine "*the cost of working kept it from coming into use; it consumed no coal, because its rate of consumption was too high*" (Jevons, 1865). Watt's one, on the other hand, granted a more 'economical use' of the resource (with a lower loss of heat), making it more competitive that the water-wheel (which had reached its maximum efficiency), thus being installed more and more often. The result was a net increase in coal consumption, despite the lower rate of consumption of each single engine. It is straightforward to see that, as Alcott says, "*his ... argument is unequivocally for backfire*" (Alcott, 2005).

Jevons' argument is based on the effect that an improved efficiency has on three components: profitability price and demand. He says: "*Economy multiplies the value and efficiency of our chief material ... , renders the employment of coal more profitable, and thus the present demand for coal is increased. ... [If] the quantity of coal in a blast furnace, for instance, be diminished in comparison with the yield, the profits of the trade will increase, new capital will be attracted, the price of pig iron will fall, but the demand for it increases and eventually the greater number of furnaces will more than make up for the diminished consumption of each*" (Jevons, 1865; Jevons, 1871).

Jevons' argument to link profitability with efficiency stems from trade and finance theory, and says that, since it is evident that new capital has been addressed to pig iron and coal sectors, their costs diminished thanks to increased efficiency. His motivation is really brief and quite inconclusive, and after he adds that the growth in demand derives also from new uses and different branches. More contemporary and exhaustive versions state that "*an improvement of energy* *efficiency of capital implies that [producers] can shift the production factor mix in the long run, and reduce the unit production costs, creating a margin for price setting. ... [In turn] lower sales price may generate additional demand*" (Berkout et al., 2000); and "*efficiency gains ... often work directly and indirectly against resource conservation. Any factors contribute to this counter-intuitive result, including the price and income effects of technological savings. Improved energy or material efficiency [therefore] may enable firms to rise wages, increase dividends or lower prices, which leads to increased net consumption [better, purchase power] by workers, shareholders or consumers respectively*" (Wackernagel and Rees, 1996).

The lack of a rigorous demonstration of the link between efficiency and profitability is integrated by the third, and most important component: demand, and especially 'new demand'. According to Jevons, in fact, increased efficiency augments profitability, which in turn stimulates demand, and this can more than make up for the lower input requirements. However, he realizes, it could be the case that such phenomenon does not take place within a single branch, but via more or less indirect interconnections of one branch with many others. This is nothing but today's income effect: as a product or a service become cheaper (thanks to efficiency gains), this makes consumers relatively richer, and allows them to deviate part of their increased purchasing power to other goods or services. With respect to this Khazzoom says that "*an improvement in the efficiency of one appliance influences not only the demand for own end-use, but also the demand for other end-uses. This follows from the fact that end-uses compete for the same overall budget, which simply reiterates the idea that the demand for electricity for any end-use depends on the efficiency of all appliances, not just on the appliance for that end-use*" (Khazzoom, 1980). As a matter of fact today the literature tends to distinguish between a micro or direct rebound effect, hence the increase (or less than proportional decrease) of energy and/or resources consumption following the increase in efficiency in that very appliance (to use Khazzoom's terminology); and a macro or economy-wide rebound, which is the increase in consumption of appliances other than the one which efficiency has improved, that in turn rises energy and/or resources consumption. These two concept will be further analysed later in this chapter.

However, "*Jevons has only shown that greater economy enables higher consumption; real rising consumption also requires consumers*" (Alcott, 2005). Income effect, substitution effect, consumers' surplus, price elasticity are just theoretical concepts, the rebound and backfire are evidences, thus an analysis of consumers' behaviour and responses is desirable, if not needed. For this reason later parts of this work will be addressed to investigate the problem from the perspective of behavioural economics.

At that time, though, there were some who claimed that efficiency gains (which were widely recognized) did not result in consumption growth. In his 1878 work, Anthony John Mundella, English manufacturer and statesman, claimed that "*although from 1869 to 1876 efficiency and pig iron production both went up, consumption of coal 'used in its Manufacture' went down*" (Mundella, 1878). His opinion was, hence, that "*there is no evidence showing that the economy of fuel in the making of pig iron, and the consequent reduction in price, has led to the manufacture of more iron, by which more coal would have been consumed, as Mr. Jevons argues*" (Mundella, 1878). The data he used leave open some questions, but, what it is more important, his argument fails to understand today's income and substitution effects, and the impact these have on the final equilibrium. Namely "*Mundella does concede the link between 'economy' and 'the consequent reduction in price', but not the rebound step to raised demand*" (Alcott, 2005).

1.3 ECONOMIC ANALYSIS OF THE REBOUND EFFECT

In the literature there is not a unique definition of the rebound effect. Binswanger says that it is based on the consideration that "*if technological progress makes equip-*

ment more energy efficient, less energy is needed to produce the same amount of product or service. However, the amount of product or service usually does not stay the same. Because the equipment becomes more energy efficient, the cost per unit of product or service ... falls, which, in turn, increases the demand for the product or the service" (Binswanger, 2001). Khazzoom would say that efficiency increases productivity, and "*with increased productivity comes a decline in the effective price of commodities, and ... in the face of lower effective prices, demand does not remain stagnant at its former level but tends to increase*" (Khazzoom, 1980).

Greening et al. (2000) claim that changes in energy efficiency lead to four different types of market responses. First of all the increase in energy efficiency puts a downward pressure on prices, that will make both consumers and firms (which will substitute energy services for other production factors[3]) to consume more of energy services, thus increasing energy consumption: this is the direct rebound. However, not only will increased real income for consumers and diminished costs of production for firms affect the size of the industry where efficiency gain took place, but also it will stimulate demand for other goods and services, which can result in a further increase in energy consumption as well as economic growth. The authors call this secondary rebound. On the side of consumers the size of such effect is determined by the share of total income spent on energy services, and, they say, "*since energy is a relatively minor share of an individual consumer's total expenditures, the secondary effects are probably insignificant*" (Greening et al., 2000). Whether such statement correspond to reality is at least debatable. On the firms' side, for a give sector the secondary effect arises from: "*(1) the increased demand for non fuel [non energy] inputs to their production process as a result of increased demand for output, and (2) the effect of the lower cost of one*

[3]However, they say, substitutability may be limited in the short-run (due to the design of production function), and the rebound could be zero. In the long-run, on the other hand, where a greater substitutability between factors is allows, the effect could emerge, leading to an increase in demand for energy as well as in the size of the industry.

sector's output on production costs of other sectors" (Greening et al., 2000). Again, they expect the effect to be small. All these arguments, however, focus on a static situation. Moving to a dynamic context, we face the economy-wide rebound. Analysing the behaviour of the economy as a whole (comprehending consumers, various sectors of production and government), the effect should be significant, even though, in the light of the fact that paths of technological change are mainly stochastic, uncertain in magnitude. Finally, since changes in technology can impact consumers' preferences and modify the organization of production, there is also a potential transformational rebound to be taken into consideration. For example technical advances seem to have affected preferences over time allocation, thus modifying labour participation rates and occupational structure. However, this is the most difficult type of rebound to analyse, and it is still not clear if it is likely to result in an increase or decrease of energy consumption. The difficulties are mainly due to a "*lack of time-series data on fuel [energy] and durable good consumption coupled with demographic detail, time use and expenditure diaries*" (Greening et al., 2000).

1.3.1 Micro Rebound

The analysis presents rebound for a single energy service (which can be room heating, mobility, lighting), given some preferences (utility function), in a neo-classical framework.

Energy efficiency, μ, is defined as the ratio between service output s, and the input of energy required to produce it, e:

$$\mu = \frac{s}{e}.$$

It follows that s could also be expressed as the product of technical efficiency times energy consumption: $s = \mu * e$. If the service was lighting, an household could light a room with a LED bulb with high energy efficiency (high μ, which requires only a small e to obtain the output s, thus involving a small expenditure), or with an halogen one with low energy efficiency (low μ, hence a greater e is needed to get s, and the cost turns out to be higher). The rebound effect implies that the use of more efficient technologies increases the demand of s since it reduces its cost, as explained in the example above.

As the analysis take place in a neoclassical framework the marginal cost of producing s equals its price, which then can be expressed as:

$$P_s = \frac{P_e}{\mu}.$$

So the price of the service is given by the ratio of the price of the energy input (needed to produce it) and the efficiency of the appliance: as the efficiency increases, for a given price of energy input, the price of the service goes down. If the service is a normal good its demand will go up. This effect has been illustrated by Khazzoom.

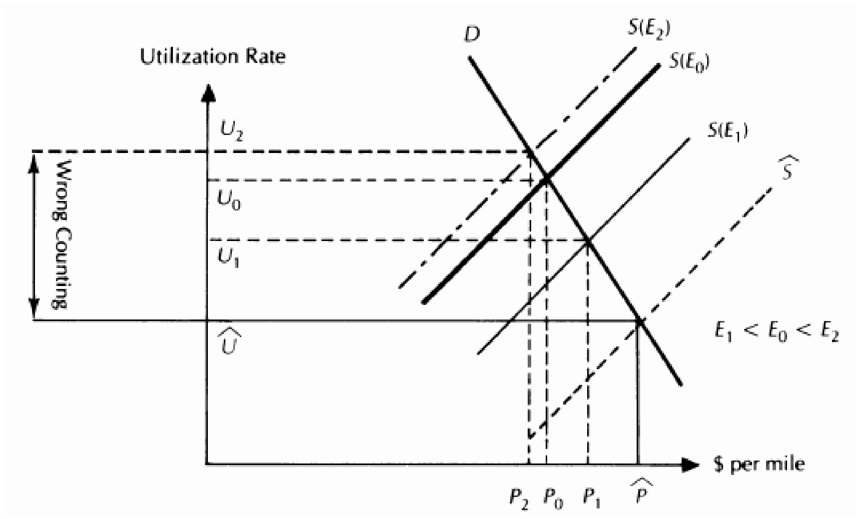

Figure 1.1: Relationship between Utilization Rate and Efficiency (Figure 1 in Khazzoom, 1980)

In the diagram 'Utilization Rate' stands for consumption, while 'dollar per mile' is a measure of efficiency (the service under investigation is supposed to be a car fleet). Along the demand curve efficiency/price-per-gallon can vary, hence demand does not shift as efficiency changes. On the other hand, along the supply curve efficiency is held constant, so a change in efficiency has the effect of moving it upward (increased efficiency/reduced price) and downward (diminished efficiency/increased price). As a consequence, the model moves along the demand curve, and to various level of efficiency correspond different prices per mile which lead to grater or lower consumption/utilization rate.

Being the starting point a level of efficiency E_0 - which leads to a price per mile P_0, the supply curve $S(E_0)$ and a utilization rate U_0 -, when it improves, to E_2, the price goes down to P_2, the supply shifts upwards reaching $S(E_2)$, and the economy moves along the demand curve, resulting in an augmented utilization rate U_2. As it is possible to see, efficiency gains result in a reduction of dollar per mile, which then, through movement of the supply curve along the demand curve, leads to an increase in consumption (measured by the utilization rate). This effect goes in the opposite direction from the one which assumes that augmented efficiency simply translate in diminished utilization rate, without taking into account the effect of reduced effective prices on demand. With reference to this Khazzoom says: "*if we were to put the available predictions of the impact of higher standards in the same analytical framework as above, they would indicate that when efficiency improves, the supply function shifts to the right as shown in the dashed curve $\hat{S}$, rather than to the left. (That is , the supply function will shift to the right in both cases, when efficiency drops and when it improves). The net effect is to predict a drop in the utilization rate to $\hat{U}$ when, in fact, the prediction should have been an increase to U_2*" (Khazzoom, 1980).

However, to come up with a definition of the rebound effect it is necessary to reason in terms of elasticities, more specifically the price elasticity of the demand for the service s, and the elasticity of energy demand with respect to energy efficiency (which is the rebound effect itself).

The first is defined as:

$$\begin{aligned}
\varepsilon_{P_s} &= \frac{\partial s}{\partial P_s} \cdot \frac{P_s}{s} \\
&= \frac{\partial(\mu e)}{\partial(P_e/\mu)} \cdot \frac{P_e/\mu}{\mu e} \\
&= \frac{\partial e}{\partial P_e} \cdot \mu^2 \cdot \frac{P_e}{\mu^2 e} \\
&= \frac{\partial e}{\partial P_e} \cdot \frac{P_e}{e} = \varepsilon_{P_e},
\end{aligned} \tag{1.1}$$

and implies that the price elasticity of the service s is equal to the price elasticity of the energy input *e*.

The second is given by:

$$\begin{aligned}
\varepsilon_\mu(e) &= \frac{\partial e}{\partial \mu} \cdot \frac{\mu}{e} \\
&= \frac{\partial(s/\mu)}{\partial \mu} \cdot \frac{\mu}{s/\mu} \\
&= \left[\frac{\partial s}{\partial \mu}\frac{1}{\mu} - \frac{s}{\mu^2}\right] \cdot \frac{\mu^2}{s} \\
&= \left(\frac{\partial s}{\partial \mu}\frac{\mu}{s}\right) - 1 \\
&= \left(\frac{\partial s}{\partial(P_e/P_s)} \cdot \frac{P_e/P_s}{s}\right) - 1 \\
&= \left(\frac{\partial s}{\partial(1/P_s)} \cdot \frac{1/P_s}{s}\right) - 1 = -\varepsilon_{P_s} - 1.
\end{aligned} \tag{1.2}$$

So the elasticity of energy demand with respect to energy efficiency equals the negative of the price elasticity of the demand for *s* minus 1. This equation "*defines the rebound effect in an exact way. It is the percentage of technical energy conservation potential that is offset by an increase in the service demand*" (Binswanger, 2001). There will be no rebound if ε_{P_s} is equal to zero, which is to say that the demand for the service is completely inelastic. In this case efficiency gains do not have any impact on effective prices, the elasticity of energy demand with respect to energy efficiency is minus one, so every improvement in energy efficiency is transferred to a reduction in demand for (consumption of) energy. With respect to this particular case Khazzoom says: "*in view of the unreasonableness of this requirement it* *should be clear that these estimates exaggerates the extent of savings achievable by improved appliance efficiency*" (Khazzoom, 1980). Hence, it could be said that it is common sense to imply the presence of a rebound effect. If ε_{P_s} is between zero and minus one the rebound is less than 100%, meaning that improved efficiency (by 1%) will reduce energy demand/consumption but less than proportionally (by (1 - $|\varepsilon_{P_s}|$)%). On the other hand, when $\varepsilon_{P_s} < -1$ energy demand rise will more than make up for the increase in efficiency.

Khazzoom also analyses what happens to the utilization rate as efficiency raises, for price held constant. He believes the elasticity of the utilization rate with respect to energy efficiency to be greater than one for low rates of utilization, and then it gradually decreases as the rate increases, till reaching a value of zero when the utilization rate approaches its asymptote (which could be to level different from 100%). To put it simple, for high levels of utilization, an improvement in efficiency will not lead to a significant increase in the utilization rate, while it is possible to appreciate such increase when an efficiency gain takes place in the case of a low level of utilization.

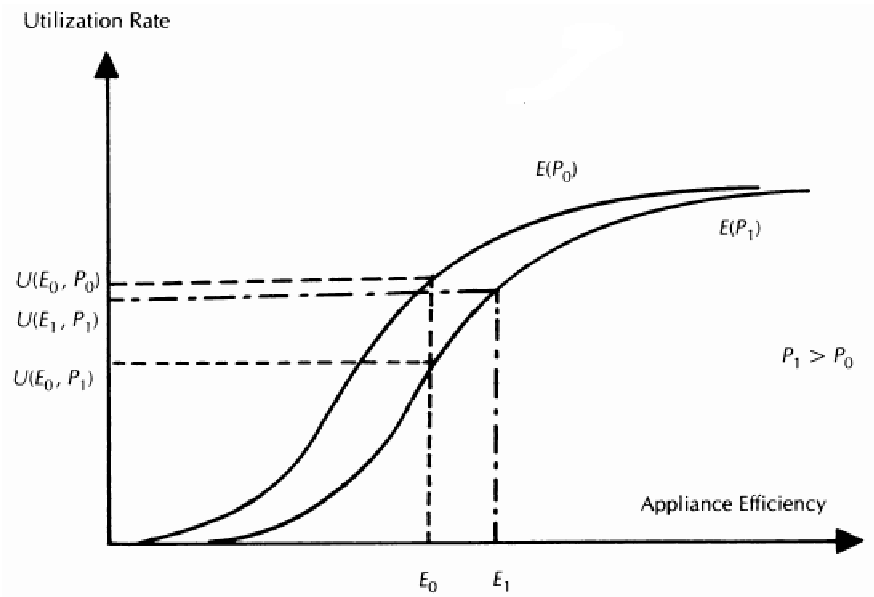

Figure 1.2: Relationship between Appliance Efficiency and Utilization Rate for fixed prices (Figure 2 in Khazzoom, 1980)

In the graph the curves $E(P)$ show how the utilization rate, $U(E,P)$, changes in response to a variation of efficiency for a given price P. In this representation a price change will shift the $E(P)$ curve to the left (when it declines) or to the right (when it raises). So, with price held constant, the utilization rate increases monotonically as efficiency increases, but its rise slows down as it approaches its asymptote for high level of efficiency, the elasticity having become very close to zero. It is also possible to see how, for a given level of efficiency, an increase or decrease in price will result in a lower or greater utilization rate.

The diagram is also useful to investigate the effect that an increase in efficiency of other appliances has on the utilization rate of the appliance in question. In fact efficiency improvements in other appliances can be considered to have the same effect as a reduction of price, thus moving the curve to the left and augmenting the utilization rate. This provides a first example of the indirect or macro rebound. However, considering a relationship in which efficiency changes for a fixed price level seems little realistic, as efficiency gains are supposed to reduce effective price of the very appliance which experienced said gains. Hence, this representation appears to be more useful to investigate some kind of indirect effect, rather than a direct one.

1.3.2 Evaluation and Estimation of Micro Rebound

Micro or direct rebound is by far the easiest to be investigated empirically, and, during the last decades, many studies have been conducted to assess this phenomenon.

Still, some difficulties remain. As it is pointed by Greening et al. (2000), in the case of residential fuel demand a primary issue is the exact identification of the appropriate activity measure. In addition, data collection and end-uses metering studies are lacking for a number of end uses. So, "*defining and estimating the energy usage that 'could have been' in the absence of rebound may be challenging in* *some rebound studies*" (Gavankar and Geyer, 2010).

But also at the stage of econometric evaluation, problems may arise. Often, the rebound effect is not directly observed, but rather elicited through elasticity estimates (as shown in the previous section). However, such energy-price elasticities are not constant and tend to be higher in periods with rising energy prices, providing an overestimation of the effect when this asymmetry is not accounted for.

Moreover, rebound estimations can fall prey of other biases. When variables like weather, demographics, capital requirements and capital costs for efficiency implementation, satiation or saturation effects, opportunity costs, and other factors are not included, the estimated effect is likely to be (upwardly) biased (Greening et al., 2000).

Again, several works concentrating on personal transportation and residential space heating, are based on household surveys, but these may give origin to some kind of selection bias, since data are gathered only from those who decided to participate to said surveys (so that the causal effect of interest is not randomly assigned). "*Consequently, these empirical studies cannot tell us the complete truth about the actual feedback between increases in energy efficiency and energy use*" (Binswanger, 2001).

However, as aforementioned, although the presence of a rebound effect is widely accepted, there is little agreement concerning its relevance, with the magnitude varying significantly according to how data has been gathered and which estimation methods have been adopted. Among those who believe in a little significance of the rebound it is worth mentioning Greening et al. (2000) and Schipper and Grubb (2000). On the other hand, the relevance of the effect is supported by Saunders (1992, 2000), Binswanger (2001), Wei (2007), and many others.

For what concerns households, personal transportation, residential space heating and residential space cooling are the main sources of fuel consumption.

In his work of 2001, Binswanger presents a table reporting a list of some of the main studies concerning personal transportation and residential space heating conducted in the last decades. Such table is displayed in the Appendix A.

From his review of the literature, Binswanger concludes that "*in general, empirical studies suggest that the rebound effect is indeed of empirical relevance*"; yet, he continues saying that, since the majority of the estimates are derived through price elasticities, which tend to soar in periods of rising energy prices (a potential source of bias that has already been mentioned), "*these empirical studies cannot tell us the complete truth about the actual feedback between increases in energy efficiency and energy use*" (Binswanger, 2001).

Other empirical analyses are reported in Greening et al. (2000). For what concerns residential space heating, the authors present the works of Klein (1985, 1987), Hsueh and Gerner (1993), Schwartz and Taylor (1995) and Cuijpers (1995, 1996). Klein analyses lifestyles and household energy uses, and his "*are the only studies that consider the trade-offs between capital and fuel consumption*" (Greening et al., 2000). He reports an estimated rebound of 40% (no control group has been used). Similar levels of the effect are shown also in Hsueh and Gerner (1993) and Cuijpers (1995, 1996), respectively 35% and 31%. In the works of Cuijpers, it is taken into consideration also the aspect of satiation of space heating. Less significant values are evidenced by Schwartz and Taylor (1995), with an estimate around 1-3%.

Regarding personal transportation, Greening et al. mention the findings of Wheaton (1982), Dahl (1986), Goodwin (1992) and Pickrell (1993), where the estimated effects varied from 20% to 50%. With respect to the first three studies, however, they say that, since these "*were performed with aggregate data, some of which is rather old, [their conclusion] should not be viewed as definitive*" (Greening et al., 2000). Moreover, in Goldberg (1996), who focused his analysis on new vehicles, the short-run effect was null.

Finally, for residential space cooling, Greening et al. state that the best measures of the rebound effect are provided by Hausman (1979) and Dubin et al. (1986), with estimates below 50%. However, these studies presents two main flaws: they were conducted during periods of high fuel prices and on small samples.

In general, despite the estimates being quite close to (when not exactly the same as) the ones presented in Binswanger (2001), the authors tend to be less enthusiastic, relegating the effect to be of little relevance.

In more recent years, Sorrell, Dimitropoulos and Sommerville (2009) presented an extensive review of empirical estimates of direct rebound, distinguishing in 'quasi - experimental' and econometric approaches, and, in line with what seen so far, dividing studies between personal transportation, space heating, space cooling, and other sources of residential energy consumption.

For what concerns estimates derived form econometric studies, they provide a summary of the analyses conducted in OECD countries. It emerges that, with respect to personal transportation, estimated effects range from 3% to 87%, with what they call the "best guess" (namely the interval which is more likely to resemble realistic results) being 10-30%. For space cooling, the estimates go from 0.6% to 60%, with again a best guess of 10-30%. In residential space cooling, where the number of studies is limited, the best guess and the total range of estimates coincide, and are given by the interval 1-26%. Finally, other sources of energy consumption seem to present rebound effects that go from null to 40%, with a best guess smaller than 20%. A list of all the studies they considered is reported in the Appendix A.

1.3.3 Macro Rebound

If Khazzoom was the main theorist of micro rebound, Leonard Brookes was his counterpart on the macro side. The two authors developed their arguments independently and almost in the same period (1979 and 1980), a fact, this, that led Saunders to coin the labelling 'Khazzom-Brookes postulate'. Later, Saunders himself will be one of the main exponent of the literature on economy-wide rebound, and advocate of 'backfire'.

The scene of macro rebound has seen some fierce debates, from that between Brookes and Grubb in the early 1990s on the existence of an economy-wide effect as such, to the one counterpoising Howarth and Saunders on the possibility of backfire in the end of the decade. And the macroeconomic side of the issue remains the most debated one also nowadays, even if, as claimed also by Dimitropoulos (2007), an empirical evidence hardly exists, and a widely accepted methodology to analyse the problem for higher level of aggregation has still to be found.

Brookes believe that energy plays a much more important role in terms of economic growth than what it is commonly thought, and, although maintaining that improving energy efficiency is indeed beneficial for the economy as a whole, he says that it does little to reduce energy consumption which, in fact, through some side effects, is likely to increase at a macroeconomic level. His argument is based on two major points. On the one hand the fact that energy efficiency, reducing the costs of production, and, in turn, effective prices of energy services, liberates purchasing power of the consumers, who will address their increased income to buy other goods and services that require energy to be produced. To use Saunders' words: "*energy efficiency gains look to the users a lot like price reductions, spurring increased demand either directly through price elasticities or indirectly through released purchasing power redirected to energy-using goods and services*" (Saunders, 1992). This income effect is likely to induce economic growth, which, in the end, will result in a augmented consumption that more than make up for the initial reduction in energy needs. On the other hand efficiency gains correspond to improvements in energy productivity which, by means of substitution of energy for other production factors , lead to increases in total factor productivity. "*The substitution of energy for capital and labour [has] such a beneficial effect on the productivity of those two inputs that their combined rate of productivity improvement [exceeds] the rate of improvement of energy productivity. [This makes the economy as a whole to grow, and in turn] results in a higher level of consumption than if there had been no such response*" (Brookes, 1990).

In his work of 1990, the author analyses the fallacies of energy efficiency solutions distinguishing two scenarios: a first scenario in which energy supply (or price) is a constraint to economic activity, and a second in which it is not. For what concerns the first case he concludes that never will improving energy efficiency help to reduce demand. Regarding the second, "more usual" case (to which the quotation above refers, even though with some arrangements), looking to historical data up to 1973, he observes that capital and labour productivity grew much faster than energy productivity, and, as a result, the new uses of energy that these growths contributed to create offset the efficiency gains. This view is summarized by Grubb: "*Brookes concludes that increasing energy efficiency has and will simply increase the attractiveness of energy for new uses: if it is more efficient, it is cheaper, so people do more with it. Consequently energy demand cannot be reduced by improving efficiency [even] when it is not a constraint on activity*" (Grubb, 1990). The Brookes-Grubb debate had officially begun.

After presenting a brief overview of Brookes' argument, despite conceding that with energy price being a constraint on economic activity improving energy efficiency indeed does not prove beneficial in reducing demand, Grubb claims that such argument presents at leas two weak points. The first, and less serious, is that Brookes in his analysis assumes that future economic reactions will closely resemble past ones (i.e. the historic trends he considered). However, this may (will probably) not be the case. "*The last two decades* [Grubb is writing in 1990] *have shown great changes in the pattern of energy and economic development. Few people* *believe that a long era of steadily declining fossil fuel prices will ever return*[4]*, and there is much evidence that some important end-uses of energy are approaching saturation, whilst the pattern of economic development is shifting towards less material and energy-intensive goods. General statements about the energy foundation of future economic growth, largely based on pre-1973 data, are therefore questionable*" (Grubb, 1990).

The second flaw arises from the fact that Brookes confuses "*the role of naturally-occurring efficiency improvements with the effects of deliberate attempts to minimize energy consumption*" (Grubb, 1990). To put it simple, if energy efficiency as such was the final goal, and not just a means, macroeconomic implications would be completely different. Hence, in a scenario where energy supply or price are not constraints, energy efficiency improvements could indeed induce a reduction in energy demand at an aggregated, economy-wide level.

For these reasons Grubb accuses Brookes to make "*a 'fallacy in aggregation' by neglecting large swathes of demand areas where improving efficiency can very effectively save energy*" (Grubb, 1990). His conclusion is that, being energy costs a generally limited share of GDP, in the order of a few percentage points of it, the extra consumption due to an increased purchasing power is likely to be of a comparable magnitude, thus not such to totally offset efficiency gains. And even when larger rebounds do occur, they are often due to some kind of substitutions, so that the final outcome in terms of energy demand is ambiguous, and could effectively result in net savings.

To support his thesis, the author reports the example of an analysis conducted by the U.S. Department of Energy, which, despite the attempt banish efficiency standards, showed that, in the end, macroeconomic effects of such standards (hence of a grater efficiency) would be beneficial for the system. In fact, several factors there exist that create an imbalance between what he calls investments

[4]As we know, this in fact proved to be the truth, and, after the two oil crises (especially the second one), fossil fuel prices, in particular that of oil, started a dramatic and constant rise, that stopped only in recent years.

in supply and in end-use efficiency, and measures to reduce or remove this imbalance are likely to result in energy savings, thus ameliorating economic and environmental conditions.

Brookes' reply came a couple of years later, in a 'Forum' on *Energy Policy* (where the entire debate took place). The British economist keeps on saying that increases in energy productivity are such to foster grater increases in other factors productivity. He mentions previous works by Schurr and Jorgenson, saying that "*Schurr pointed out that much of the reduction of output flowed not so much from improvements in the thermal efficiency of conversion of fuel into useful heat and work as from the increase in total output brought about by improvements in the productivity of non-energy inputs*"; and that "*the role of energy in raising the productivity of capital and labour [is] likely to be one in which... improvements in the productivity of the economy as whole would outstrip any improvement in energy productivity to produce an increase in total energy consumption at the macroeconomic level notwithstanding falls in energy consumption per unit of output*" (Brookes, 1992).

Moreover, he adds that energy efficiency must be seen as a means to achieve a goal, and not as the goal itself, as interpreting it in the opposite way is just nonsensical. Finally, he concludes that Grubb, in his 'Communication', did nothing but reiterate his point, with his representation of Brookes second scenario being only an exemplification of the first one "*with Grubb taking the place of OPEC (casting energy in the role of a scarce resource with his demand for blind subservience to the goal of maximizing energy efficiency per se)*" (Brookes, 1992).

To integrate the impact of improved energy productivity into an economic model various approaches have been followed, but none of them has found a universal acceptance, so further research in this field is required. The first and most common approach describes the effect that energy gains have on the economy in a Neoclassical fashion, where technological changes are assumed to be exogenously determined (namely they do not depend on the factors of the model), and resource availability does not constitute a limit to growth, thanks to unlimited substitution possibilities between production factors[5]. However, to prove rebound, or better backfire, in this scenario, some assumptions, which plausibility is questionable, seem to be required. For this reason, in more recent years the literature addressed its attention to a somewhat different approach, where technical advancements are generated within the system (and not given from outside) and the scarcity of resources does limit growth. This is the field of endogenous growth theory, and rebound effect has been simulated by some studies that apply computable general equilibrium (CGE) techniques.

For what concerns the Neoclassical growth context the literature has seen, in the late 1990s and early 2000s, a debate between Harry D. Saunders and Richard B. Howarth, the former claiming that with Neoclassical growth theory improvements in energy efficiency are always likely to backfire, the second contesting this conclusion and saying that Saunders' argument is based on not realistic assumptions.

In his paper published in 1992, Saunders examines the effect of energy efficiency improvements in a Neoclassical growth context, assuming a production function influenced by three factors (capital (K), labour (L), and energy (E)), taking fixed energy price and efficiency gains which are not damaging to the economy. Here, it is energy as such to be a factor of production, and not energy services: a point which will be criticized in Howarth (1997).

The author compares a baseline scenario without efficiency gains, with various cases where such gains occurred: first a simple case with a Cobb-Douglas production function, and then a number of different nesting strategies of a constant elasticity of substitution (CES) production function. The results are pre-

[5]So that, even if the amount of resources available in the system is limited, energy productivity improvements stimulate total factor productivity, so that even capital and labour becomes more efficient and can be substituted for other scarce resources. As this substitution ability is of an indefinite nature, namely can be done again and again without any constraint, it turn out that resource availability does not limit economic growth.

sented as forecasts of annual growth rates in the year 2100.

In the case where efficiency improvements do not take place the main hypothesis is that, under the assumption of fixed energy price, in the long-run energy is likely to grow "*in lock steps with economic growth*" (Saunders, 1992). This implies that: (a) energy, capital, labour and real output grow at the same rate, here supposed to be 3% a year; (b) energy intensity, namely the ratio of E/Y, is constant; (c) returns to all production factors are fixed (they do not grow nor shrink); (d) consumption per worker, given by the ratio C/L, is constant.

When efficiency gains are introduced, Saunders claims, energy consumption will be higher that it would have been otherwise ('Khazzoom-Brookes postulate'), and output and energy do not grow in lock steps anymore. The author describes efficiency gains a "*technical progress trends ... [which] can be capital - augmenting, labour - augmenting, energy - augmenting, or neutral*" (Saunders, 1992).

$$\tau_N = e^{\lambda_N t} = neutral\ technical\ progress$$

$$\tau_K = e^{\lambda_K t} = capital - augmenting\ technical\ progress$$

$$\tau_L = e^{\lambda_L t} = labour - augmenting\ technical\ progress$$

$$\tau_E = e^{\lambda_E t} = energy - augmenting\ technical\ progress$$

Since technologies that improve energy efficiency are likely to be a combination of all those technical progresses, τ_E is also called 'pure' energy efficiency gain. As a consequence, real economic output is expresses as:

$$Y = \tau_N F(\tau_K K, \tau_L L, \tau_E E).$$

The first step is to consider a Cobb-Douglas production function which, for fixed energy price, implies that: (a) E, K and Y grow at the same rate, and this is greater than the growth rate of L; (b) energy intensity, namely the ratio of E/Y, is constant; (c) real return to capital (*mpk*) and real energy price (P_e) are fixed, while real wage rate (w) increases, as labour becomes a more and more scarce resource; (d) real consumption per worker, C/L, increases; (e) consumption of energy soars, to a greater level than without efficiency gains; (f) real output grows faster than without technical progress.

Despite the increased energy consumption, Saunders, in accordance with the view expressed by Brookes, says that "*while it may be tempting to view increased energy use as an undesirable consequence of energy efficiency gains, it should be noted that economic welfare is improved by such gains, as revealed by the growth of consumption per worker*" (Saunders, 1992).

The results for the year 2100 are reported in below.

IN THE YEAR 2100:

	Annual Growth Rate (%/year)				Annual Growth Rate (%/year)				Fraction of No Tech. Progress Case	Fraction of No Tech. Progress Case
TECHNICAL PROGRESS	$\dot{Y}$	$\dot{K}$	$\dot{L}$	$\dot{E}$	$\dot{w}$	$\dot{Pe}$	$\dot{mpk}$	$\dot{(C/L)}$	E	C/L
None	3.0	3.0	3.0	3.0	0.0	0.0	0.0	0.0	1.0	1.0
Neutral	4.8	4.8	3.0	4.8	1.8	0.0	0.0	1.8	6.9	5.7
Capital-Augmenting	3.5	3.5	3.0	3.5	0.5	0.0	0.0	0.5	1.7	1.8
Labor-Augmenting	4.2	4.2	3.0	4.2	1.2	0.0	0.0	1.2	3.6	4.1
Energy-Augmenting	3.1	3.1	3.0	3.1	0.1	0.0	0.0	0.1	1.1	1.1

w = real wage rate
Pe = real price of energy
mpk = real marginal productivity of capital
C = aggregate consumption of goods and services
C/L = consumption per worker

Table 1.1: Factor Growth Rates with Cobb-Douglas Production Function (Table 2 in Saunders, 1992)

Though it might seem striking that an improvement that allows to produce the same amount of output for a smaller input requirement (in relative terms) in the end results in an augmented use of such input, this happens for two main reasons: first of all the input (energy in this case) becomes cheaper, so it is in fact substituted for the other factors (remember that labour is seen as a scarce resource); and second, the increased economic growth resulting from efficiency gains is likely to pull up input (energy) consumption in absolute terms.

However, the author realizes that Cobb-Douglas production function is too limiting, hence a complete analysis should move forward and consider more advanced models. These have been found in various forms of nesting models considering a constant elasticity of substitution (CES) production function.

The first nesting structure analysed is the 'Manne-Richels Nesting', which is a CES with a Cobb-Douglas nested within designed as $[(K, L), E]$, which takes the from:

$$Y = \tau_N\{\alpha[(\tau_K K)^{\beta}(\tau_L L)^{1-\beta}]^{\rho} + b(\tau_E E)^{p}\}^{1/\rho},$$

where

$$\rho = \frac{\sigma - 1}{\sigma},$$

and σ is the energy elasticity of substitution.

Results are reported for various level of σ.

It appears that capital - augmenting and labour - augmenting technical progresses are likely to increase the use of energy for all levels of energy elasticity of substitution (respectively by a 3.5% a year and 4.2% a year, which have to be compared with the 3.0% base rate in absence of technical progress). Again, the combination of the two effects seen before causes such increase.

On the other hand, for what concerns neutral and 'pure energy efficiency' gains, the impact on energy consumption depends on the levels taken by the energy elasticity of substitution. When σ is greater than unity energy intensity rises (as E grows at an annual rate of 5.3% as opposite to the 4.7% of Y), while

IN THE YEAR 2100:

Annual Growth Rate (%/year)

TECHNICAL PROGRESS	$\dot{Y}$	$\dot{K}$	$\dot{L}$	$\dot{E}$ $\sigma = 0.5$	$\dot{E}$ $\sigma = 1.0$	$\dot{E}$ $\sigma = 1.5$
None	3.0	3.0	3.0	3.0	3.0	3.0
Neutral	4.7	4.7	3.0	4.1	4.7	5.3
Capital-Augmenting	3.5	3.5	3.0	3.5	3.5	3.5
Labor-Augmenting	4.2	4.2	3.0	4.2	4.2	4.2
Energy-Augmenting	3.003	3.003	3.000	2.4	3.0	3.6

σ = energy elasticity of substitution

Table 1.2: Factor Growth Rates with Manne-Richels Nested CES Function (Table 3 in Saunders, 1992)

it shrinks for values smaller than unity (4.1%/year, which now is lower than the growth rate of real output). However, all values are greater than the one without technical progress (still 3.0% a year), hence the effective use of energy results augmented in absolute terms. This is consistent with the Khazzoom-Brookes postulate (and evidence of backfire). On the contrary, energy - augmenting technical progress leads to an annual growth rate of energy that is higher than the baseline scenario one only for values of elasticity of substitution greater than unity; while when this is below 1, efficiency gains result in an absolute decrease of energy consumption, thus contrasting with the postulate. It is worth noting, though, that "*this result is actually consistent with the stricter statement of the Khazzoom-Brookes* *postulate by Khazzoom, who added [the] requirement that the energy price elasticity be greater than unity*" (Saunders, 1992).

But the Manne-Richels nesting is just one of the three possible nesting structures, the other two being $[K, (L, E)]$ and $[L, (K, E)]$. For these two cases the author claims that energy - augmenting technical progress will always result in a increase in energy consumption, irrespective of the value of σ.

However, note that, as it has been said earlier, technology improvements are likely to be a combination of several of the technical progresses considered (rather than merely energy-specific), it could be completely possible that this combination will result in an absolute increase in the use of energy also for values of energy elasticity of substitution smaller than unity, thus, once more, proving consistent with the Khazzoom-Brookes postulate (even in its "lighter" version).

To prove these findings, Suanders mentions an empirical analysis by Hogan and Jorgenson (1991) for 35 sectors of the U.S. economy. He claims that the results "*describe the expected behaviour of energy - augmenting technical progress in the presence of an energy substitution elasticity greater than unity... [thus, suggesting] the presence in the U.S. economy of conditions that favour the Khazzoom-Brookes postulate*" (Saunders, 1992).

In 1997 Richard B. Howarth published a paper in which he reviews Saunders' work and presents a "simple" theoretical model, suggesting that macroeconomic impacts of energy efficiency gains could be less relevant than what argued by Saunders, with the possibility of backfire arising only in the presence some rigid assumptions that are not likely to verify in the real world.

Saunders' study presents two main fallacies. First of all it assumes energy and capital to be perfect substitutes, but empirical evidence on this topic is not coherent. In fact, analyses based on time series data present capital and energy as complement, while others using cross-sectional data indeed portray them as substitutes. Moreover, according to Lebel (1982), the elasticity of substitution between energy and non-energy inputs is likely to be between zero and one, suggesting "*that the degree of substitutability required for energy efficiency improvements to support increased energy use is unlikely to arise in real-world economic systems*" (Howarth, 1997), even if the possibility that this might happen is not completely excluded. (Remember that at an economy-wide level, despite a lower energy intensity, energy consumption was assumed to increase thanks to mechanisms of substitution of energy for capital, in combination with a general economic growth of the system). Because it is not clear what the reality is, assuming substitutability is limiting, and it tends to bias the results in the direction of an overestimation of the effect that technical progress has in increasing energy consumption.

Second, Saunders assumes energy as such to enter the production function, while, Howarth claims (and in this he seems to be right, even though, still, reality is more nuanced) it is energy services to be the input rather than raw energy. If this was not the case, it would correspond to assume that energy services are generated only with energy inputs, which is not the case, as they are the result of a combination of both energy and non-energy factors. In addition, given the fact that energy cost is just a small part of the wider cost component of energy services (in the production process), pure energy efficiency gains may generate a reduction in the cost of energy services which is relatively small, thus having a comparably small impact on energy consumption (namely limiting the possibility of backfire). Whether it is true that the cost of energy is only a small fraction of the cost of operating energy-using equipment it is at least debatable.

In the light of these clarifications, the conclusion is that backfire may arise only if the cost of energy constitutes a relevant part of the wider cost of energy services, and, at the same time, expenditures for energy services are a large share of the economic activity (namely the cost of energy services is a large fraction of the total cost of production).

For these reasons, Howarth develops a model which closely resembles that of

Saunders (he still uses a Cobb-Douglas production function), but that is characterized by unitary elasticity of substitution between energy and other production factors (thus presenting a Leontief-type structure). The main assumptions of the model are a continuous time, a competitive economy, and the production of a homogeneous consumption-investment good.

To produce this consumption-investment good the inputs of production are capital (K), labour (L) and energy services (X), and the production takes place according to the function:

$$Y = \alpha K^{\beta} X^{\gamma} L^{1-\beta-\gamma},$$

with α, β, and γ being positive constants, and $\beta + \gamma < 1$. Energy services are produced at a fixed cost per unit c (>0). The output, Y, is used for consumption and to invest in capital, so that $C = Y - cX$ (which also corresponds to net output).

It is then possible to derive everything in per capita terms

$$y = \alpha k^{\beta} x^{\gamma},$$

with $x = X/L$ and $k = K/L$; the growth rate of population being $g > 0$ $(= (dL/dt)/L)$.

The marginal productivity of per capita energy service ($\partial y/\partial x$) is equal to the unit cost c, so it results:

$$x = \frac{y\gamma}{c} = \left(\frac{\alpha\gamma}{c} k^{\beta}\right)^{\frac{1}{1-\gamma}},$$

form which γ may be interpreted as the share of output destined to the production of energy serviced ($= cx/y$). Substituting this formulation of x into the production function gives:

$$y = \left[\alpha \left(\frac{\gamma}{c}\right)^{\gamma} k^{\beta}\right]^{\frac{1}{1-\gamma}}.$$

Assuming a constant savings rate s[5] (so that $dK/dt = sY$), it is possible to

[5]"*A gross savings rate of s thus implies that the ratio of capital investment to net output is constant at* $s/(1-\gamma)$" (Howart, 1997).

derive the growth rate of capital per worker as:

$$\frac{dk}{dt} = \frac{d(K/L)}{dt} = sy - gk = s\left[\alpha\left(\frac{\gamma}{c}\right)^{\gamma} k^{\beta}\right]^{\frac{1}{1-\gamma}} - gk$$

Setting this equation equal to zero we can derive the steady state level of capital per worker. Then, substituting this value into the equations for x and y, also the steady states of energy services and output arise:

$$k^* = \left[\alpha\left(\frac{\gamma}{c}\right)^{\gamma}\left(\frac{s}{g}\right)^{1-\gamma}\right]^{\frac{1}{1-\beta-\gamma}}$$

$$x^* = \left[\alpha\left(\frac{\gamma}{c}\right)^{1-\beta}\left(\frac{s}{g}\right)^{\beta}\right]^{\frac{1}{1-\beta-\gamma}}$$

$$y^* = \left[\alpha\left(\frac{\gamma}{c}\right)^{\gamma}\left(\frac{s}{g}\right)^{\beta}\right]^{\frac{1}{1-\beta-\gamma}}.$$

The effect of efficiency gains is assumed to be a reduction in the effective cost of energy services; the impact of this reduction on capital, energy services and output can be analysed through elasticity measures, which capture the long-run responses of the economy:

$$\frac{\partial k^*/\partial c}{k^*/c} = -\frac{\gamma}{1-\beta-\gamma} < 0$$

$$\frac{\partial x^*/\partial c}{x^*/c} = -\frac{1-\beta}{1-\beta-\gamma} < -1$$

$$\frac{\partial y^*/\partial c}{y^*/c} = -\frac{\gamma}{1-\beta-\gamma} < 0$$

When the share of output that is destined to energy services is large (namely $\gamma > (1-\beta)/2$) a reduction in the unit cost of such services leads to more than proportional increase in capital and output. However, if energy services are just a small fraction of economic activity (γ tends to zero), the elasticities will approach zero, thus the effect of improvements in efficiency on macroeconomic performance is small. On the other hand, the impact on the demand for energy services turns out to be significantly large.

But to complete the analysis a further clarification is required, namely to describe the technology used to produce energy services. Here Howarth follows Howarth and Andersson (1993), and assumes that one unit of energy service is generated with ε units of (raw) energy and c_0 units of the consumption-investment good. The cost of production of energy services is given by:

$$c = c_0 + c_e\varepsilon,$$

where c_e is the cost of a unit of energy. Energy demand (E) is then defined by the quantity of energy service times the amount of raw energy that is needed to produce it: $E = \varepsilon X$ (or, in per capita terms, $e = \varepsilon x$).

Now focus on the impact of energy intensity (namely the value ε) on the demand for energy services, which, again, is measured by the elasticity:

$$\frac{\partial x^*/\partial\varepsilon}{x^*/\varepsilon} = \frac{\partial x^*/\partial c}{x^*/c} \cdot \left(\frac{\varepsilon}{c}\frac{\partial c}{\partial\varepsilon}\right) = -\left(\frac{1-\beta}{1-\beta-\gamma}\right) \cdot \left(\frac{\varepsilon c_e}{c}\right) < 0. \tag{1.3}$$

From this it is possible to appreciate how reducing energy intensity for the production of energy services is likely to augment their demand; however, the magnitude of the increase depends on the value taken by γ, and "*unless* $c_0 = 0$*, so that energy services are produced using energy inputs alone (the case examined by Saunders, 1992), improvements in energy efficiency ... would lead to less than proportional increases in the demand for energy services*" (Howarth, 1997).

To measure the rebound effect (which defines the impact of efficiency gains on the long-run use of raw energy) one last step is needed. Describing the steady state level of per capita use of energy as $e^* = \varepsilon x^*$, the long-run elasticity of energy demand with respect to energy use is:

$$\frac{\partial e^*/\partial\varepsilon}{e^*/\varepsilon} = 1 + \frac{\partial x^*/\partial\varepsilon}{x^*/\varepsilon}. \tag{1.4}$$

This is indeed a measure of the rebound effect. If the demand for energy services is very elastic with respect to energy intensity (with the value of elasticity being smaller than -1), then energy consumption will result increased as a consequence of an efficiency improvements, thus causing backfire as claimed by Saunders (1992). If, instead, the demand for energy services is relatively inelastic (with elasticity falling between zero and -1) "*the direct effect of changes in energy intensity will dominate the feedback effects that occur through increased demand for energy services*" (Howarth, 1997). This will lead to a rebound, as the augmented energy intensity causes a less than proportional reduction in energy use, but it will not backfire.

Then, Howarth concludes saying that "*empirical considerations suggest that the demand for energy services is most likely inelastic with respect to changes in energy intensity*" (Howarth, 1997). His idea, hence, is that improvements in energy efficiency will have a macroeconomic impact much smaller than that assumed by Saunders, which can in fact hamper energy conservation, by reducing energy consumption less than proportionally, but that is not likely to backfire, the increase in consumption verifying only under some rigid and little realistic assumptions.

Saunders' reply comes in 2000, when he publishes a couple of papers in which he further develops Howarth's model, proving that even in this case technical progress yields an increase in the economy-wide energy consumption.

Despite conceding to Howarth the merit of having made some important contributions in the analysis of efficiency gains' impact on energy use, in particular the distinction between raw energy and energy services, Saunders claims that "*his conclusion is flawed by the too-restrictive way he models energy services* [i.e. the Leontief structure of the production function], *... and he does not adhere to generally accepted conditions for balanced economic growth ... that would add restrictions to his derivation and affect his results*" (Saunders, 2000 - b). So, to demonstrate that energy efficiency improvements are always likely to backfire at a macroeconomic level, first he extends Howarth's model using a Cobb-Douglas technology; then, he does a step further and applies a balanced growth approach ("*that better honours the usual stipulations of neoclassical growth theory*" (Saunders, 2000 - b)). In both cases results are consistent with the backfire hypothesis.

To extend the Leontief-type representation provided by Howarth, Saunders replaces the cost function for energy services with one that presents a Cobb-Douglas structure, such that:

$$c = (c_e \varepsilon)^{\alpha} c_0^{1-\alpha};$$

to which correspond the energy service production function:

$$X = \left(\frac{E}{\varepsilon}\right)^{\alpha} \hat{O}^{1-\alpha},$$

where $\hat{O}$ is the consumption-investment good; or, in per capita terms:

$$x = \left(\frac{e}{\varepsilon}\right)^{\alpha} \hat{O}^{1-\alpha}.$$

It appears that the elasticity of c with respect to energy intensity ε is equal to α, which is smaller that 1 by definition. Substituting it into the expression of the elasticity of energy service demand with respect to energy intensity (1.3) yields:

$$\frac{\partial x^*/\partial \varepsilon}{x^*/\varepsilon} = \frac{\partial x^*/\partial c}{x^*/c} \cdot \left(\frac{\varepsilon}{c}\frac{\partial c}{\partial \varepsilon}\right) = -\left(\frac{1-\beta}{1-\beta-\gamma}\right)\alpha < 0. \tag{1.5}$$

Finally, note that:

$$e^* = \hat{O}^{*\frac{\alpha-1}{\alpha}} \varepsilon x^{*\frac{1}{\alpha}}.$$

Differentiating it with respect to ε, and rearranging terms a little bit (see Appendix B), the elasticity of energy use with respect to energy intensity is given by:

$$\frac{\partial e^*/\partial \varepsilon}{e^*/\varepsilon} = 1 - \frac{1-\beta}{1-\beta-\gamma} + \frac{\alpha-1}{\alpha}\left(\frac{\partial \hat{O}^*}{\partial \varepsilon}\frac{\varepsilon}{\hat{O}^*}\right) < 0. \tag{1.6}$$

This corresponds to a measure of the rebound effect, and it is negative[6], meaning that, even with Howarth's approach, energy efficiency improvements yield a

[6]This because the second term is smaller than -1 (remember that $\beta + \gamma < 1$). In the third term the partial derivative is positive, since an increase in energy intensity implies the increase in the cost of the energy component in the cost function for energy services, which, as a consequence, will be substituted with the (relatively cheaper) consumption-investment good $\hat{O}$. This partial derivative is preceded by the negative component $(\alpha - 1)/\alpha$, so that, being the ratio $\varepsilon/\hat{O}$ positive by definition, the third term results smaller than zero.

greater long-run energy consumption at the aggregate level. From this expression one can infer two things. First, that the negative sign of the third term suggests that substitution for fuel within the energy service sector is one of the sources causing energy consumption to rise. And second, that even ignoring this third component, the expression still evidences backfire, "*indicating that substitution within the energy services sector actually spurs increased use of energy services in the economy as a whole*" (Saunders, 2000 - b). This result is independent of the values of the parameters α, β and γ.

After demonstrating that even distinguishing between energy as such and energy services efficiency gains are always likely to backfire, Saunders extends the analysis to a balanced growth approach, showing that, also in this case, the results hold.

He considers a two-sector model with Cobb-Douglas production function, so that differences between energy services (E), and raw energy (that he calls physical fuel, F) are explicitly accounted for.

Economic output is generated via a combination of capital (K), labour (L) and energy services (E):

$$Y = \alpha K^{\alpha} L^{\beta} E^{1-\alpha-\beta},$$

while energy services are produced with the production function

$$E = \tau \hat{K}^{\gamma} \hat{L}^{\delta} F^{1-\gamma-\delta},$$

where $\tau = be^{\mu t}$ is an energy - augmenting technical change.

The time dynamic expansion of the economic output production function is:

$$\dot{Y} = \frac{1}{Y}\frac{dY}{dt} = \frac{\partial Y}{\partial K}\frac{K}{Y}\dot{K} + \frac{\partial Y}{\partial L}\frac{L}{Y}\dot{L} + \frac{\partial Y}{\partial \hat{K}}\frac{\hat{K}}{Y}\dot{\hat{K}} + \frac{\partial Y}{\partial \hat{L}}\frac{\hat{L}}{Y}\dot{\hat{L}} + \frac{\partial Y}{\partial F}\frac{F}{Y}\dot{F} + \frac{\partial Y}{\partial \tau}\frac{\tau}{Y}\dot{\tau},$$

where

$$\dot{Y} = \dot{K} = r, \qquad \dot{\hat{K}} = \hat{k}$$

$$\dot{F} = f, \qquad \dot{\hat{L}} = \hat{n}.$$

It is possible to demonstrate that for fixed energy (fuel) price, the growth rate of energy use is $f = r$. Knowing this, and calling the "natural" growth rate n, after some passages (see Appendix B), it is possible to rearrange the dynamic expansion to get:

$$f = n + \frac{1-\alpha-\beta}{\beta+\delta(1-\alpha-\beta)}\mu. \tag{1.7}$$

Since the second term is always positive, "*so long as there are energy efficiency gains (i.e., so long as $\mu > 0$), the rate of growth of fuel use, f, will exceed the rate of growth without efficiency gains n*" (Saunders, 2000 - b). So, even in a balanced growth context, energy efficiency improvements are always likely to backfire, and increase energy consumption.

This concluded the theoretical analysis of macro rebound. But theory is only one part of the story, and without sound empirical estimates it is destined to remain incomplete. However, as already said, empirical works concerning economy-wide rebound are few compared with those on direct rebound, and the significance of the effect they estimate varies considerably.

The literature agrees that the most reliable econometric evidence supporting economy-wide rebound coming from growth models is represented by a number of studies conducted by Jorgenson in collaboration with other authors. He developed an econometric model to investigate the behaviour of producers using a four-input production function (the inputs were capital, labour, energy and materials). The study was conducted for 35 sectors in the U.S.. What emerged is that "*technical change increases the share of energy in the value of output, in most of U.S. industries*" (Dimitropoulos, 2007), meaning that, after technical changes occurred, the output of the production contained a larger share of energy with respect to the situation without technical changes, so that said changes seem to increase the use of energy in the economy.

Another econometric analysis has been implemented by Gardner and Joutz (1996), in which the authors used a VAR (vector autoregressive) model and cointegration theory to test Saunders' theoretical results using real U.S. data. They recognize that that technical progress is likely to influence more that one input at a time, and the model accounts for both short- and long-run output responses to changes in technology and energy price. Their findings are somewhat different from Saunders' theoretical insights, mainly for what concerns the impact of a reduction in energy price, which does not seem to stimulate economic growth in the shot-run, and that of embodied technical progress, that does not appear statistically significant. "*Hence ... price or embodied technology effects, in the short-run, cannot increase in any case output or energy*" (Dimitropoulos, 2007). This is in contrast with what is expressed in Saunders (2000 - a,b) and Wei (2007)[7].

Moreover, in a study comparing energy intensities and energy uses in IEA countries, Schipper and Grubb (2000) says that they "*found no evidence of substantial macro-rebound within a sector, or of an economy-wide macro-effect*" (Schipper and Grubb, 2000). This, in conjunction with estimates of direct rebound in the order of 5-15%, led the authors to believe that in IEA countries rebound effect is only a second-order, minor effect. Still, in some cases significant indirect effects have been highlighted, and they concede that the rebound effect "*should not be neglected in appraisals of future energy demand or estimates of the impact of energy efficiency policies*" (Schipper and Grubb, 2000).

Neoclassical growth models, however, are somewhat limited to the extent to which they consider technical progress are exogenously determined, and they do not allow for resource availability to be a limit to economic growth. For these reasons computable general equilibrium (CGE) models have been implemented, allowing efficiency gains to be one of the determinants of the system and not given from outside. "*Doing so, endogenous growth theory enables new insights about*

[7] In Saunders (2000 - a) it is reported that a 20% improvement in energy efficiency implies an increase in economic output in the range of 1-2% in the short-run, and of 2.28% in the long-run. Wei (2007) states that Saunders' calculation was affected by a mistake, and the actual long-run increase is of a 3.6%. On the contrary, the study by Gardner and Joutz estimates a long-run increase in output of just 1.14%.

the relationship between resource scarcity, technical change, and economic growth, and hence constitutes a great leap forward compared with standard neo-classical growth theory" (Madlener and Alcott, 2009).

From the 1990s a number of studies have been conducted to simulate the impact of energy efficiency improvements on the consumption of energy and economic output using a general equilibrium approach. However, despite being based on similar methodologies, they "*exhibit significant differences in specification, parametrization, simulation procedure and other crucial assumptions that are likely to determine results*" (Dimitropoulos, 2007). Among the factors and specifications that might affect estimates it is possible to account the production function: first because different choices yield different results, and second since the concept of the production function itself presents some limitations as a blueprint for production at higher levels of aggregation. Also the role and substitutability of energy in such function are likely to influence the estimated effect, and the literature has not found a unique way to model it. Moreover, other inputs of production tend to behave differently from energy. Capital is relatively fixed in the short-run, while assumptions on depreciation and replacement rates need to be done when looking at the long-run. And even though labour is not a natural resource, it is considered a close substitute for energy, so that assumptions regarding labour supply and wages will have a considerable impact. Again, as already seen, technical progress can have different forms, so that various specifications or combinations can lead to different estimates. Also the structure of trade relations can affect results, and energy exporting countries are more likely to benefit from energy efficiency improvements than importing ones (which seem to be more prone to supply shocks). Finally, to develop a CGE model a full specification of public expenditures, saving rates and investments is required.

In Dimitropoulos (2007) it is presented a review (see Appendix A) of some of the main empirical works that simulate rebound effect in a computable general equilibrium environment. Some focus on developing countries, others on developed ones. They all differ for what concerns production function and the other specifications highlighted before, and they report estimates that range from 15% to 350%.

For all these reasons "*CGE models have been used more as policy informing tools and less as instruments for investigating how rebound works*" (Dimitropoulos, 2007).

Finally, economic models have been combined with engineering theory to give birth to some kinds of hybrid macroeconomic models. The so called E3 models (where the three Es are energy, economy and environment) combine economic and econometric theory with other forms to incorporate environmental impacts (like greenhouse gasses emissions).

An example of this kind od studies can be found in Barker et al. (2007). The authors develop a multi-sectoral, dynamic model, where many of the parameters have been estimated through econometric techniques, to assess the macroeconomic rebound effect in the UK. The results report a value for the rebound of 27%, and emissions are estimated to decline as a consequence of energy efficiency policies.

Another study was conducted for the Dutch economy by Koopmans (1997). Here the NEMO model was implemented, combining classic macroeconomic theory, using a CES production function, with 'putty-semi-putty' capital stock's responses to variations in prices[8], and allowing for asymmetric responses to energy prices. Surprisingly, the estimate for long-run macro rebound is extremely similar to that found in the UK case (again 27%). And analogous results have been achieved also in an analysis using the NEMS model run by Kydes (1997) for the U.S..

[8] In this way part of the adjustment to price change takes place instantaneously, and part in the mid/long term through capital replacement and investments. As a consequence, the model gives a justification for the finding that price elasticity of energy demand is typically lower in the short-run than in the long-run, thus suggesting similar magnitudes for the economy-wide rebound.

CHAPTER 2

BARRIERS TO ENERGY CONSERVATION

In Binswanger (2001) it is claimed that "*technological improvements evoke behavioral responses*". So, to fully understand the effects that efficiency gains will have on energy consumption, it is not sufficient to stop to a theoretical analysis of demand elasticities. For this reason in the years many studies have been conducted to further investigate the problem, aiming at individuating the barriers that can harm energy conservations.

One corpus of works tries to explain the reduced effect of energy conservation measures as a consequence of some kinds of market failures that arise when energy efficiency is involved. A different group of researches, on the other hand, seeks to link the energy paradox to a bounded rationality of the consumers, who, in real world, can prove to be quite distant from the idealized figure of the *homo economicus*.

2.1 THE ENERGY-EFFICIENCY GAP AND THE MAIN OBSTACLES TO ENERGY CONSERVATION

The 'energy-efficiency gap' can be broadly defined as the difference between the cost-minimizing level of energy-efficiency achievable at current prices and technology and the status quo level. When various frictions prevent energy-efficiency measures from being implemented or limit their effectiveness, such gap arises, and there are issues concerning the energy consumption and conservation.

In a 2007 work, Rohdin et al. analyse energy efficiency barriers and drivers for the foundry industry in Sweden. Here the authors provide a list of the main economic and behavioural barriers that are likely to affect energy conservation (Rohdin et al., 2007).

Among the economic explanations are hidden costs. They may affect agents' decision, and reduce both the ability and willingness to invest in energy-efficient solutions. Examples of such costs can be overhead costs, costs of collecting and analysing information, production disruption, inconvenience etc. (Rohdin et al., 2007).

A similar effect can be caused also by limitations in capital availability and accessibility, especially when it comes to low-income households (Hausman, 1979). With reference to this Yergin (1980) reports that more or less three quarters of households who perceive the possibility to enhance the energy efficiency of their home say they are not doing so simply because they cannot afford to invest in conservation measures. Dillman et al. (1983) argue that because of lack of financial opportunities energy conservation can be seen as an item that is foregone because too expensive to purchase.

Another major factor that can affect energy conservation is represented by imperfect information. Information can be related to market conditions, financing opportunities, as well as technical characteristics of energy-efficient solutions. Howarth and Andersson (1993) say that the diffusion of information generally comes to a costs: as acquiring the knowledge about equipments' performances that agents perceive necessary to process a rational decision is not straightforward, "*costs of improving consumer information may exceed the expected benefits to private agents*" (Howarth and Andersson, 1993).

Not only is this a relevant factor in terms of hidden costs, but, in turn, it also causes risk aversion and ambiguity aversion problems, since consumers typically tend to shy away from options they consider more risky and on which they feel they have limited knowledge. When taking decision involving a considerable degree on uncertainty, agents may act as they were using high implicit discount rates (Sutherland, 1991). Moreover, it can lead also to some kind of adverse selection, with consumers directing their investments to products they have more information about, or that appears to be dominant at the beginning but in fact turn out to be inferior in the future.

A considerable importance has also the so called 'principal-agent relationship'. If principal (or landlord) and agent (or tenant) are not able to find a solution that satisfies both parties, energy efficient measures can be prevented from being installed. Somewhat related to this feature is also the effect concerning incentives: when a party feels that he cannot gain from the implementation of efficiency improvements he or she will not be willing to direct money to said implementation, and when this perception affect both parties, due to some 'noise' which harms communication and limit agreement opportunities, there arises a case of principal-agent fallacy. Finally, it has to be considered that not all energy-efficient solutions are universally adoptable, and there exist an intrinsic heterogeneity that can prevent some products to be adopted by a specific agent (being this a company or a physical person).

Somewhat in between of economic and non-economic obstacles is heterogeneity. This may be due to technical and structural characteristics, implying that in some cases the adoption is simply not profitable or feasible (Jaffe and Stavins, 1994); or to physiological differences between agents, such that what is beneficial for someone it is not for someone else (Darley, 1977).

Behavioural explanations are found, first of all, in bounded rationality issues. Several studies have demonstrated that when it comes to take decisions that might be quite complicated agents are likely to rely on various simplifications and rules of thumb (Tversky and Kahneman, 1974).

Intrinsically related to this is the role of habits. Since relying on habits for what concerns everyday decisions is perceived as a more economical way of behaving, as it saves mental energies for other activities, people may tend to stick to their usual behaviours, thus preventing efficiency measures to spread.

In addition, an important factor is the source of information. In order for energy-conservation technologies to be adopted the relevant information regarding them should be vivid and simple, and most of all coming from a source that is felt reliable or representative. It appears that in this context friends' experiences and opinions are valued more than experts' evaluations (Stern, 1992).

Moreover, consumers may exhibit high implicit discount rates, so that hyperbolic discounting issues arise (Jaffe and Stavins, 1994).

2.2 MARKET FAILURES

Concerns related to the correct functioning of the market led Howarth and Andersson (1993) to argue that frictionless models are not reliable representations. As a consequence, they aimed at developing "*formal models that illustrate how competitive markets will fail to generate a socially efficient level of energy efficiency if their structural characteristics impede the effective transmission of information between market participants*" (Howarth and Andersson, 1993).

The authors begin with a simple one-period model, showing the difference between the equilibrium level of energy use (or energy intensity), e, achieved when consumers hold perfect information on the performance of an 'energy-using good' (intended as the quantity of energy e it needs to function), and when they take their decision based on on an *ex ante* expectation of such performance ($e^* = f(e)$). Since $f(\cdot)$ is differentiable, they show that the socially efficient level of energy use can be obtained even when agents hold imperfect information (as long as $f(e) = e + k$), thus meaning that what really matters in terms of market behaviours and equilibrium is not the level of expectation *per se*, but rather the relationship between expectations and actual characteristics (described by $f(e)$). However, note that even though a socially efficient level of energy intensity can be achieve for all values of k, every $k \neq 0$ implies a non-optimal level of ownership of the 'energy-using good'.

If information about the performance could be gathered at a cost C, depending on the values of the parameters of the model, agents could decide to rely on approximation rules of thumb. If C was sufficiently high, they may use *ex ante* expectations rather than punctual information for their consumption choices, and depending on the specific form taken by $f(\cdot)$ this could lead to inefficient levels of energy intensity (thus to an excessive use) and of good's purchasing.

Then, the authors extend the model to a dynamic formulation, introducing n identical firms which produce the energy-using device. Consumers take decision separately at each point in time, knowing only the past performances of the equipments and producers' reputation, so that they form an expectation based on the recursive relation $e^*_{it} = (1-\alpha)e^*_{it-1} + \alpha e_{it-1}$, where $\alpha \in (0;1)$ defines the updating speed of expectations.

The results claimed by Howarth and Andersson are that in competitive markets the socially efficient level is not achievable, and the steady state to which the economy tends implies an energy use that exceeds the efficient one. These findings seem not to be due to consumers' missperceptions *per se*, but are intrinsic in the market's mechanisms as households purchase equipments before they incur in the resulting energy costs, and do so according to expectations which are generated and updated on the basis of manufacturers' reputation and previous experience (Howarth and Andersson, 1993).

Another important contribution to the analysis of the influence that market failures have for the energy-efficiency paradox is represented by a study conducted by Jaffe and Stavins in 1994. The authors develop a model to investigate the use of energy-conserving technologies in the decision problem that is faced when a new building has to be constructed on the one hand, and on already existing structures on the other hand.

Among the main barriers considered are lack of information, principal/agent (builder /homeowner) problem and the fact that consumers typically face artificially low energy prices (which could lead them to lose interest in energy efficiency). Information regarding available technology and new solutions is said to have a central role in agents' decision process, to be costly to gather and to have public-good attributes (thus not provided by the market); moreover "*if others' use of the technology is an important source of information,... then adoption creates a positive externality because it generates information that is valuable to others*" (Jaffe and Stavins, 1994). However, it is evident how this way of reasoning can go also the other way around, so that if the technology has not already been adopted by someone else the information about it will not spread and so its diffusion will result severely harmed. In this context it should be responsibility of the public administration and the producers to provide the consumers all relevant information about the characteristics possessed and advantages generated by energy-efficient measures. In addition, information is likely to trigger other behavioural responses. The principal/agent issue occurs when decision regarding energy efficiency are taken by parties that are not the ones who pay the energy bills: in this case, as a consequence of the 'noise' aforementioned, it could be very difficult, if not impossible, for the investing agent to recover his/her investment from those who pay the bills, thus affecting the incentives connected to the implementation of energy-conservation measures, which, as a result, do not take place. The issue can have several forms, with the builder/landlord being the investor and the homeowner/tenant paying the bills, or the other way around.

In the case of new constructions, the problem is a maximization one, with the builders seeking to maximize their profits, given by the selling price of the house plus the discounted value of expected energy savings (deriving from the installation of an energy-efficient technology) minus construction and adoption (of said technology) costs. Hence, it takes the form of:

$$\begin{aligned} \max_I \pi_{ijT} = B + &\left[I \cdot \delta \cdot (1-w) \cdot \int_T^\infty g(k_{ijt}, \mu_{ijt}) \cdot e^{-rt} dt \right] \\ &- I \cdot \left[L(C_{iT}, S_{ijT}, \nu_{it}) - \gamma D_{iT} - X_{iT} \right], \end{aligned} \tag{2.1}$$

whit upper case letters being stocks or present values, lower case letters flows, and greek letters parameters (except for π and μ); j is an indicator of the house being constructed, i of the geographic area or political jurisdiction, and T is time. More specifically π_{ijT} represents the profit for house j in region i at time T. I is an indicator function that takes value 1 if the energy-efficient technology is adopted and zero otherwise. B is the selling price of the house if the technology is not installed. δ is the "*discount* ($0 \leq \delta < 1$) *or premium* ($\delta > 1$) *applied by the market to value of energy savings*" (Jaffe and Stavins, 1994), and it also allows to account for the principal/agent issue. w shows the ratio of energy consumption with and without the technology ($0 < w \leq 1$). The characteristics of the house (present and future) are expressed by k_{ijt}. μ_{ijt} comprehends the unobservable factors that affect energy consumption, and $g(\cdot)$ is a function that links house characteristics to energy use and expenditures. C_{iT} gives an engineering estimate of costs to purchase and install the energy-conservation technology (these costs are borne by the builders). S_{ijt} refers to the amount of houses which had already been built by the builder and that had the technology installed. This stock allows to account for experience, hence the diffusion of knowledge and information which should have a positive impact on the adoption I. ν_{iT} is the fraction of houses of new construction in jurisdiction i which have the technology installed. $L(\cdot)$ is the cost function, that incorporates both engineering costs and costs related to knowledge about the technology and diffusion of information. D_{iT} is a dummy variable for the presence in jurisdiction i of a regulation imposing the adoption of the technology in year T. X_{iT} indicates the subsidy or tax credit for the adoption in jurisdiction i, and γ is a "*parameter that captures the average perceived monetary equivalent cost of ignoring [the] regulation* (Jaffe and Stavins, 1994). The real interest rate of the market is given by r.

After defining the functional forms of $g(\cdot)$ and $L(\cdot)$, and proceeding with some arrangements, being P_{ijT} the energy price, $\alpha_1, \alpha_2, \alpha_3, \alpha_4$ parameters of the cost function $L(\cdot)$, and β_1 and β_m parameters to the $g(\cdot)$ function, the authors come up with a formulation illustrating how various factors affects the diffusion of energy-conservation technologies:

$$\begin{aligned} \ln(\delta) + \ln(1-w) + \beta_1 \ln\left(\int_T^{\infty} (P_{ijT}) e^{-rt} dt\right) + \sum_{m=2}^{m} \left[\beta_m \ln(k_{ijT}^m)\right] \\ - \ln\left((C_{iT})^{\alpha_1} \cdot (\nu_{iT})^{\alpha_2} \cdot \left(\frac{S_{ijT}}{\alpha_3}\right)^{\alpha_4} - \gamma D_{iT} - X_{iT}\right) + \ln(\mu_{ijT}) \geq 0. \end{aligned} \tag{2.2}$$

From this the impacts of the barriers previously illustrated can be investigated.

The principal/agent issue have a negative effect on the rate of adoption: in fact, if such issue exists δ will take values between 0 and 1, thus making the logarithm to be negative.

Second, when the energy prices are 'artificially low' (because of market factors or due to some kind of underestimation of the consumers as a consequence of imperfect information), namely when P_{ijT} is small, the rate of adoption is reduced (thus highlighting a negative impact also in this case).

On the other hand a reduction in adoption costs will stimulate the diffusion of energy-efficient technologies (both direct, C_{iT}, or indirect through learning, S_{ijT} and ν_{iT}). Moreover, "*depending on the magnitude of the parameter α_2, there may be a dynamic externality in which increased adoption today fosters adoption by increasing ν_{iT}*" (Jaffe and Stavins, 1994).

Finally, the presence of a regulation in the jurisdiction has a positive effect (note that it has a negative sign in a negative component, thus turning to be positive). This can happen in two ways: by reducing the expectations of adoption costs (via γ), or by directly reducing such costs with a subsidy or a tax credit (X_{iT}).

Somewhat similar results are shown also in the case of already existing buildings, although with some differences.

First of all, now the decision of investing in the energy-efficient technology is taken by the final user of such technology, who, hence, faces a cost minimization problem rather than a maximization one, which will tells the homeowner if and at what time to implement the installation. The overall cost he/she has to minimize is given by the present discounted vale (PV) of annual energy costs in the period in which the technology is not adopted (from the present to the time when the adoption takes place), plus the present discounted value of annual energy costs after the adoption, plus the present discounted value of the adoption costs. This is described by the following formulation:

$$\begin{aligned}\min_{T} PV(T) = &\int_0^T g(k_{ijt}, \mu_{ijt}) \cdot e^{-rt} dt + w \cdot \int_T^\infty g(k_{ijt}, \mu_{ijt}) \cdot e^{-rt} dt \\ &+ [L(C_{iT}, V_{iT}) - X_{iT}] \cdot e^{-rt} + \gamma \cdot \int_0^T D_{it} \cdot e^{-rt} dt,\end{aligned} \tag{2.3}$$

where T is the time of adoption, V_{iT} is the portion of homeowners who have already adopted the technology in jurisdiction i, and the other variables are as seen before. This is subject to the constraint $T \geq 0$.

First and second order conditions imply that installation should take place either at $T = 0$ or when $\partial PV(T)/\partial T \geq 0$. After having defined the functional forms of $g(\cdot)$ and $L(\cdot)$, and having computed the derivatives it results:

$$\begin{aligned}&\left[(1 - \delta \cdot w) \cdot P_{ijT} \cdot \sum_{m=2}^{M} \beta_m k_{ijT}^m\right] + \gamma D_{iT} - r \cdot [\alpha_3 + \alpha_1 C_{iT} + \alpha_2 V_{iT} - X_{iT}] \\ &+ \alpha_1 \left(\frac{\partial C_{iT}}{\partial T}\right) + \alpha_2 \left(\frac{\partial V_{iT}}{\partial T}\right) - \left(\frac{\partial X_{iT}}{\partial T}\right) + \mu_{ijT} \geq 0.\end{aligned} \tag{2.4}$$

As from (2.2), the presence of a regulation, governmental subsidies and lower adoption costs stimulate the diffusion of the technology. On the other hand high values of r discourage it.

Annual energy prices can slow down the adoption rate when 'artificially low', but no concern is given to future evolutions of such prices, with only their current value to be relevant.

However, future paths of adoption costs play an important role: if there are reasonable expectations for said costs to decrease in the future, it could turn out to be more convenient to postpone adoption despite of the existence of net benefits today. In fact, it could be that even if present net benefits deriving from adoption are positive, if costs for purchasing or installation are falling, it might be more profitable to wait. For the same reason, if rate of adoption is soaring, thus implying a rapid spread of information and learning, it could pay to wait (being $\alpha_2 < 0$). Again, increasing subsidies and tax credits might make homeowners to postpone the installation hoping (or waiting) for a higher financial support from the government.

On a more empirical ground lays the study from Schleich and Gruber (2008), who analyse the impacts of various barriers on energy-efficiency investments on several organizations belonging to 19 sub-sectors in the German commercial and service sectors. They focus on enterprises which are typically small, and whose production is little energy-intensive (namely the cost of energy is a small share of the overall cost). An organization is defined 'active' if it "*adopted at least 50% of the set of energy-efficiency measures which... where deemed feasible [for said organization]*" (Schleich and Gruber, 2008), and 'inactive' otherwise.

The authors conduct an econometric analysis developing a separate Logit model for each sub-sector considered. The dependent variable is dichotomous, taking value 1 for 'active' and 0 for 'inactive'. This is regressed on a vector of 9 independent variables. EKNOWN is a dummy representing whether the organization is aware of the split of final energy consumption into thermal and electric energy, and it is used as a proxy for lack of information about energy consumption. Since poor information on energy consumption is expected to discourage the adoption of technologies for energy conservation, EKNOWN is expected to have a negative impact. INFO is a dummy variable expressing the lack of information regarding energy-efficiency measures. TIME is a dummy defining if there is a lack of time to fully assess the consequences of the implementation of an energy-efficiency measure. These two variables are proxies for information costs, transaction costs and possibly bounded rationality (Schleich and Gruber, 2008), thus, again, negative coefficients are expected. PRIORITY is a dummy saying whether the organization have other investments opportunities which have the priority on the energy-conservation one(s). Given the fact that the presence of different investment priorities is likely to postpone the adoption of efficiency measures, this PRIORITY should affect negatively the dependent variable. This may also stand as a proxy for a credit constraint if money has already been devoted to alternative projects, or for accessibility to credit in the case various loans for other investments have been taken out. Again, the effect is supposed to be negative. UNCERT is a dummy highlighting the fact that energy costs may change in the future; its expected sign is negative. RENTED is a dummy saying if the building(s) where the enterprise works have been rented. This stands for the principal/agent (landlord/tenant) issue, so again the effect ought to be negative. PURCH is a dummy to express if efficiency measures are automatically considered in organizational procedures. ENERGY gives the share of costs for energy of the overall costs, so it is expected to have a positive coefficient. Finally, SIZE is simply the size of the organization, and its effect should be positive since "*larger organizations are more able than smaller ones to deal with information and other transaction costs, bounded rationality, credit constraint, or uncertainty*" (Schleich and Gruber, 2008). Note that the first six dummies broadly represent the main barriers and market failures introduced before.

The estimations highlight that the effects of the various barriers tend to vary in different sub-sectors, with typically two or three being statistically significant and no clear combination emerging (with the only exception of the pair EKNOWN-RENTED, where organizations which rent their spaces seems to be less informed about energy consumption paths and composition). "*Sub-sectors with fewest statistically significant barriers tend to be quite energy intensive, such as hospitals, the hotel industry, laundries and dry cleaners, or horticulture*"[9] (Schleich and Gruber, 2008).

EKNOWN is significant with the expected negative coefficient for seven sub-sectors. These typically have low absolute energy costs, thus making the implementation of measures to monitor energy consumption relatively more expensive: if no measure to increase the knowledge about energy consumption is undertaken, such knowledge cannot be improved, in turn discouraging the installation of technologies for energy conservation as it might appear to be of little importance.

INFO turns out to be statistically different from zero and to negatively affect the dependent variable of interest in about a third of the sub-sectors, mainly in private or public services organizations as banks, insurance companies, schools and public administrations.

Rather surprising is the fact that TIME results significant only in two cases (hotel industries and non-commercial organizations). A similar evidence is found for UNCERT (with banks and insurance companies replacing hotels).

RENTED appears statistically significant in more than a half of the cases, and it occurred typically for those sub-sectors where renting buildings or spaces is not common.

Also the goodness of fit measures, given by the 'Pseudo R^2', vary considerably across sub-sectors, ranging from an explanatory power of 13% in the case of agriculture, to a 39% for laundries and dry cleaners.

More detailed results can be seen in the Appendix A. In any case it seems,

[9] The authors argued that more energy intensive enterprises should suffer less from these barriers, as there are more incentives to enhance energy efficiency

again, that the lack of information (both in terms of energy consumption patterns and concerning energy-efficiency measures), credit constraints and accessibility, and the principal/agent problem are some of the main limiting forces than can prevent energy-conservation technologies to diffuse and be implemented.

A study by Dillman et al. (1983) focuses more specifically on the relationship between financial means and energy-conservation actions in contexts of high energy prices[10]. Since high prices increase households' expenditures, people are expected to react by either cutting back and adjusting their lifestyles, or implementing some conservation measures. The authors argue that poor households resign themselves with reducing their energy and other goods consumption to cope with increased prices, while more wealthy households opt for the adoption of more enduring and expensive solutions for energy conservation. With the definition of two measures for financial wealth, one given by family income in the year previous of the analysis, and the other by financial resources accumulated by the family in past years, it could be possible to read the paper in terms of the impact of capital availability and accessibility, as the latter measure is a proxy of means of obtaining financial resources.

Respondents to the survey were asked whether and to what extend did higher energy prices made them cut back in a number of activities, not necessarily directly relate with energy consumption (as education, heath care, vacation, savings and so on). Answers show that a considerable portion of households undertook significant cutbacks, and that those who took cutbacks in one activity typically did so also for other ones. It is also highlighted a negative relationship between cutbacks in each activity and education and family income, meaning that the higher the income the less "sacrifices" a household is likely to take. In addition, the authors derive a 'cutback index' dividing lifestyle cutbacks into four

[10]Note that this is a different effect of energy prices from the one seen in Jaffe and Stavins (1994), where 'artificially low' prices could put a downward pressure on the incentive of undertaking efficiency measures

categories from 'Low' to 'High'[11].

Then, energy-saving activities are divided in 'home adjustments' and 'conservation actions'. The former are "non binding" activities, that can be taken almost immediately, without requiring retrofitting measures or (considerable) money expenditures. The latter, on the contrary, are more enduring solution, which implies the implementation of retrofitting measures to enhance the energy efficiency of the house, which come to a cost, and that are not simply applicable nor reversible (both in terms of time and money)[12].

It is shown that people who have taken greater cutbacks, namely with higher values of the 'cutback index', are more likely to take 'home adjustments'. Also the mean percent of responses is increasing as the value of the index increases. A 'home adjustment index' is calculated, again evidencing a positive relationship with the 'cutback index'. On the contrary there is no clear relationship between 'conservation actions' (and the 'energy action index') and the 'cutback index', meaning that "*being forced to cut back one's lifestyle because of energy prices appears to have little influence on the number of energy conservation actions taken*" (Dillman et al., 1983).

Finally, the three indices are compared with measures of family income (and, in turn, of capital accessibility). The findings highlight that there is a striking negative relationship between the lifestyle index and the income measures, so that households who have made lifestyle cutbacks are likely be those with smaller income availability and a reduced access to financing opportunities. Similarly, the 'energy action index' is positively related with income, and mainly with the proxy for financing opportunities, while no clear relationship emerges with the

[11] This index wants to show whether an household is likely to undertake little or considerable cutbacks in his lifestyle as a consequence of increased energy expenditures.

[12] Examples of 'home adjustments' could be closing off rooms to avoid having to heat or cool the entire house, setting a lower temperature on the thermostat, turning off bulbs and electrical devices when not in use. While 'conservation actions' might comprehend floor, ceiling and perimetral walls insulation, or installation of storm doors and windows

'home adjustment index'.

These evidences make the authors to claim that "*lifestyle adjustments are being taken by people whose financial situation probably leaves them no alternative but to cut back. Conservation actions, on the other hand, are being taken by people who have money to invest*" (Dillman et al., 1983). As a consequence, income availability and the possibility to access to financial means can represent a sever obstacle to the diffusion of energy-efficiency measures, thus hampering the reduction of energy conservation.

However, the final point expressed in the paper may look a little counter-intuitive. Having defined 'home adjustments' as actions that are almost immediate and do not require the investment of money, although they are in fact a different thing from lifestyle cutback, it seems strange that no correlation is found with income measures. As they do not imply any expenditure, they should be somewhat *comparable* with reductions in lifestyle habits, so we should observe also in this case a negative relation with income. If households who do not have the financial means to afford the implementation of conservation measures are willing to change their habits and undertake some cutbacks in the various activities, they should also be willing to undertake costless actions to reduce their energy expenditures. So, if the analysis shows that the 'haves' are more likely to adopt conservations solutions to cope with increased expenditure, it somewhat falls short in demonstrating what is the behaviour of the 'have-nots', as a negative correlation of income should be expected not only with lifestyle cutbacks but also with 'home adjustments'. A possible justification for the absence of the latter relationship could be based on households'preferences, meaning that, say, setting a lower temperature on the thermostat is perceived worse than reducing vacation, so that people are more likely to undertake the second rather than the first. Moreover, changing of energy-related habits may be thought to have (possibly) severe effects on health and life conditions, which other activities (as vacation, for instance) do not have. However, since among such activities there is also health care, this should not be the case, or, at least, the effect of such perception should be limited.

2.3 BEHAVIOURAL BARRIERS

Choices concerning energy use and energy efficiency are closely related to consumers' behaviour, and consumers may not always act as economic theory assumes.

People are intrinsically different from each others: they have different preferences, they live in difference places and come from different backgrounds, they have different needs and they have different energy consumptions. This implies that what is good for someone might not be for someone else, hence "*even if a technology is profitable* on average*, there will be* some *individuals or firms for whom it is* not *profitable*" (Jaffe and Stavins, 1993). This has been experimented also by Darley (1977) in a study conducted on the installation of an innovative, potentially energy-saving thermostat (which the author labels 'psychostat') in a group of households in Twin Rivers, N.J. He found that one family, despite the absence of technical problems of the technology and a 20% reduction in the energy bill, had a bad experience and was not satisfied. Hence, differences in lifestyles, backgrounds, living conditions and preferences have to be taken into account, as they could severely affect the diffusion of efficiency measure, in turn limiting the reduction of energy use.

In light of the fact of this multidimensional heterogeneity, classic economic theory is not sufficient by itself. In this field, psychology and theories that strive to provide a more realistic representation of consumers' behaviour can have a great deal to say.

Behavioural economic theory suggests that people purchase goods and/or services for maintenance, accumulation, pleasure and accomplishment or establishment (Faiers et al., 2007). Hence, understanding why and how agents consume can provide a significant help in the diffusion of energy-conservation technologies. With reference to this Stern says: "*energy use is not a behaviour, but an outcome of behaviour*" (Stern, 1992).

People consume to satisfy their 'needs' or 'wants', which are strongly linked with values and attitudes, and these in turn can affect pro-environmental behaviours. Also moral and ethic can be seen as relevant determinants in this sense. When a person is strongly convinced that his actions are right (in the context of his ethical values and attitudes), he or she will stick to such behaviour, and a habit arises. Relying on habits for everyday-life decisions "*frees up resources than can be devoted to solving non routine-like problems and, as such, it can be said to be a highly rational way of allocating our limited cognitive abilities*" (Maréchal, 2009).

During the years many models have been developed to incorporate the effect of habits on intertemporal choices, implying that the utility from current consumption depends on the level (and composition) of past consumption (Frederick et al., 2002). Among the others, it is worth mentioning Pollack (1970) and Ryder and Heal (1973). In such models, instantaneous utility is assumed to be a function of present consumption (c_t) and a state variable z_t which usually takes the form of the exponentially weighted sum of past consumption.

It is obvious that habits can have either a beneficial or detrimental impact on energy conservation and consumption. If his system of values brings an individual to be 'environmentally-friendly', relying on his habits to take decisions that involve energy implies a positive effect in terms of consumption reduction. This positive effect can be enhanced if the individual perceives to be part of a society that strives to achieve the same goal and shares the same values. In this case, it could be possible to characterize it as a collective habit, in the sense of a behaviour undertaken by the majority of the persons. On the other hand, if the set of values goes in the opposite direction, this can fosters 'non-environmentally-friendly' behaviours, thus hampering energy conservation, independently of the diffusion of energy-efficient technologies (thus leading to the 'energy-efficiency paradox'). An interesting analysis on the values that characterize an 'energy-saver' can be found in Barr et al. (2005).

Furthermore, since a considerable part of domestic energy consumption is not visible (Jackson, 2005), people rely on habits even more than in other circumstances, implying that they may not correctly take into consideration (remote) environmental impacts caused by their decisions in such a context (Maréchal, 2009). Again, this can facilitate the perpetuation of 'non-environmentally-friendly' behaviours.

In addition to this, it is the fact that habits are both influenced by and influencing what Maréchal (2009) calls Socio-Technical System, STS (namely the set of social, technical, energetic, infrastructural, demographic and cultural features that characterize a society in a give time)[13]. Hence, the formation of a collective set of habits is such to reinforce the perpetuation of a given STS, thus preventing changes and further discouraging energy conservation.

To prevent this from happening, it could be desirable to have policies that, on the one hand, aim at shifting the STS to a more sustainable one, and, on the other hand, try to dismantle habits that such STS has generated and promote new ones, more incline to foster energy conservation. However, none of these goals are easily achievable, in part because habits are "sticky", and people tend not to act in such a way to contradict them. This is known as 'dissonance'. "*Where individuals experience inconsistency [with their habits], this creates a state of dissonance, which in turn drives a desire to return to consistency*" (Faiers et al., 2007). In this sense habits can act as change-resisting factors, and lead to a situation in which, despite awareness of a need to change behaviour, such change does not take place

[13]The author claims that our society is now in a STS characterized by oil, plastics and mass electrification (Maréchal, 2009).

as too in contrast with the habitual behaviour. When the context is that of a STS based on hydrocarbons and massive consumption, this self-reinforcing attitude of habits may prevent energy efficiency to lead to reductions in energy consumption.

Moreover, in an attempt to limit dissonance individuals tend to adopt measures to convince themselves that their actions are indeed the best ones, creating a sort of 'confirmation bias'. This is done by exaggerating the attractiveness of the chosen action and the unattractiveness of the rejected one. Again, it appears that this mechanism can work in such a way to prevent a reduction in energy use, even if efficient measures are available and a latent sentiment of the need to undertake a change toward more sustainable solutions is present. Said bias can act at an individual level, as just explained, or at an aggregate one, facilitating the perpetuation of the current STS.

Another fundamental driver of human behaviour when it comes to energy-related decisions is information. As already said in the previous section, and as claimed also by Stern (1992), information is multidimensional, namely can be related to characteristics of the efficient technology as well as of market conditions. It has been shown that "*individuals with either more knowledge or concern about particular environmental issue state a willingness to pay higher prices for alternative products*", and that greater knowledge is an important predictor of pro-environmental behaviours (Faiers et al., 2007). For this reason, both producers of new, more efficient technologies, and public administrations interested in enhancing energy conservation, should strive to make information available.

Still, gathering information is not a costless effort, and typically agents would require to analyse and try the product in order to form the adequate knowledge. Also in this case, habits can play an important role. If an individual has already formed a habit, he or she is typically well accustomed with a particular product, possessing a deep understanding of it, so that learning about a new technology can appear as a greater effort than it really is; but it may also cause problems in terms of dissonance, thus further discouraging the diffusion of energy efficiency and reinforcing the (unsustainable) status quo. As a consequence, learning turns out to be a 'context specific' issue.

But it is necessary to remember that people are fundamentally different, and they differ also in their ability to acquire and evaluate new information and process them to come up with a coherent decision. In two words, they differ in 'cognitive complexity'. This fact confirms the idea that what is adequate in one case may not be in another, and this heterogeneity has to be taken into account when implementing a policy as well as when providing information.

Since acquisition of relevant information is costly, many energy-related decisions take place under uncertainty, leading to problems of risk and ambiguity aversion. Howarth and Andersoon (1993) try to incorporate uncertainty in their model. They concede that agents are different, and their beliefs depend on cognitive abilities and specific contexts, and they assume that such beliefs vary across individuals according to some probability distribution. Differently from the case analysed in the previous section, the authors now consider two devices ($i = 1, 2$) offering equivalent energy services, and n consumers purchasing only one of the two. Consumers do not know the actual levels of energy intensity of each device (e_i), but form 'unbiased estimates drawn from the distributions': $e_i^* = e_i + u_i$, where u_i is independently and normally distributed with mean 0 and variance σ_i^2. As before, consumers expectations are based on imperfect, incomplete observations of the devices. Technology 1 is assumed to be inferior, having greater energy intensity and higher adoption costs. The authors demonstrate that both when agents are naive, believing their estimates e_i^* represent the true intensity, and when they indeed recognize that estimates are stochastic, the inferior device does not disappears from the market. Assuming device 1 was already present in the market, and it is the one agents are accustomed to, while device 2 is the new, energy-efficient technology, uncertainty plays an important role in purchasing decisions. If $\sigma_1^2 = 0$, uncertainty only affects the more efficient product[14], and "*consumers will purchase [it] only if its expected cost savings relative to technology 1 exceed a threshold that increases with their degree of uncertainty*" (Howarth and Andersson, 1993). Even if the degree of uncertainty could be reduced to zero for a certain cost, if the difference between cost savings granted by the more efficient device and the cost to acquire the relevant knowledge about its performance is small, individuals could nevertheless decide to stick to a context with uncertainty.

As a result, not only is it sufficient to make information available, but it is also necessary to do it in the most efficient way.

"*Information is more likely to change behaviour when it is specific, vivid and personalized*" (Stern, 1992). It has been shown that informing about energy-saving techniques with a closed-circuit video program was 20% more effective then providing the same information in written form (Winett et al., 1982). Hence, relevant information about energy conservation should be framed in such a way to increase its accessibility and effectiveness. For example, in a study by Pitcher and Katsikopoulos (2008), it is demonstrated that people are more keen to choose green electricity solutions when these are presented as the default option instead of the carbon-based one. Measures aimed at making information more salient can help in limiting 'confirmation biases' and in deconstructing unsustainable habits.

But framing can act also in other ways. For example, it has been proven that households think to their energy bills more in monetary terms rather than in physical units (which would be more suited unit measures to deal with energy conservation). As a result, "*when energy prices are rising, people sometimes perceive their conservation efforts as ineffective because their bills do not fall*" (Stern, 1992). This can discourage the diffusion of energy-efficiency solutions even when they are

[14]"*Generally speaking, the most energy-efficient technologies are new to the market, and it is reasonable to suppose that consumers will lack familiarity with such products and thus attach a high degree of uncertainty to their performance*" (Howarth and Andersson, 1993).

available and households do feel the need to undertake greater environmental commitments. In Chapter 1.3 it was said that, in periods with rising energy prices, estimates of the rebound effect could be overstated if not accounting for such issue.

Also, the trustworthiness of the source of information plays a crucial role. The more the 'provider' is felt as reliable and trustworthy, the greater the likelihood that the information he is giving will be assimilated and exploited to improve the knowledge about a new product. However, reliability and trustworthiness are not synonyms of expertise, and it appears that individuals are more prone to follow advices of relatives and friends, rather than technical inputs of experts. As a consequence, agents may be induced [or discouraged] in investing in energy efficiency not because they have rational expectations this will allow them to save [waste] money, or because engineering reports praise [denigrate] the characteristics of a device and its ability in reducing energy consumption, but rather because they have heard from people they know and they trust that the investment will [will not] pay, or because those who have already made such investment are satisfied [dissatisfied] (Stern, 1992). In the study by Darley (1977), many people were induced to install the thermostat because they had got positive feedbacks from their friends or colleagues who were original participants to the experiment. Those who were satisfied by the energy-efficient technology brought, on average, five other 'second-stage innovators', while the family who experienced problems with the device and was not satisfied proved not to be a source of 'second-stage innovators'.

So, even though energy-efficiency measures are indeed available in the system, their diffusion can be severely limited by the effects of the 'confirmation bias' and negative judgements within a society. These effects can be further reinforced by the fact that, in an attempt to contrast dissonance, agents tend, on the one hand, to aggregate in groups that share common views, and, on the other hand, to filter advices, discarding those in contrast with their ideas and keeping those in accordance so as to find justification. The creation of social networks sharing common views, in conjunction with the fact that the more "distant" are the opinions and background of the advisor from those of the one seeking advice (irrespective of the fact that the former may or may not possess a high degree of expertise, and that his advices may or may not be correct), might further reinforce 'confirmation bias', thus contrasting energy conservation.

Finally, the uncertainty connected to decisions involving energy (in terms of future energy prices and consumption, or paybacks of energy-saving technologies) may induce agents to adopt high implicit discount rates. Moreover, people might fall prey of hyperbolic or quasi hyperbolic discounting. Even if an individual is sensitive to environmental concerns, and he plans to adopt more efficient technologies in the future, it could be that, when the time to make the investment eventually comes, his implicit discount rate gets bigger, thus making the investment less attractive. Hyperbolic discounting can also be enhanced by all the problems concerning the lack of knowledge and 'confirmation biases' aforementioned, creating a vicious cycle that slows down the diffusion of energy-saving measures and limits the reduction of energy consumption.

Not only is hyperbolic discounting generated by this time inconsistency, but it can also arise from the fact that the more selling prices of energy-using devices are reduced as a result of increased productivity in the production process (due energy efficiency[15]), the greater becomes the implicit discount rate of consumers, and the less they are willing to pay for more efficient devices. This 'size effect' implies that energy efficiency acts in such a way to prevent energy-use reduction, hence sustaining the hypothesis of a rebound effect. Both these last two aspects will be further investigated in the following Chapter.

[15] Remember that Saunders (1992) argued that energy efficiency is not likely to improve only the productivity of the energy component, but rather to have positive spillovers also on productivities of other factors.

CHAPTER 3

INTERTEMPORAL CHOICES AND ENERGY EFFICIENCY

Decisions concerning energy efficiency are strongly influenced by time and time preferences, as they involve tradeoffs between costs and benefits (in the form of energy savings and energy-bill reductions for households, but also more socio-environmental ones, like a healthier environment, or a society which is less dependent on fossil fuels) occurring at various periods. Hence, differences in time preferences may significantly affect the adoption of measures for energy conservation.

In 1937 Paul Samuelson presented the 'Discounted Utility (DU) Model' to deal with intertemporal choices. Despite DU still represents the most accepted way to cope with time preferences, other models have been developed to provide a more realistic representation of individuals' decisions mechanisms. Especially, 'Hyperbolic Discounting' (HD) and 'Quasi-hyperbolic Discounting' imply that agents attach a greater importance to the present with respect to the future: namely, they have a discount rate that declines over time.

When applied to energy efficiency, this might mean that, while when they have to make plans for the future people are more willing to pay and to adopt conservation measures, when the time to actually implement the investment does come, their discount rate increases, they become more reluctant to spend higher amounts, and do not proceed with the installation. In this sense HD may affect energy consumption.

3.1 TIME DISCOUNTING

The interest for intertemporal choices was first explicitly manifested in 1834 by John Rae with his work *The Sociological Theory of Capital*. As Adam Smith, his purpose was to explain what drives the wealth of a Nation. He felt that Smith's argument was incomplete, as it lacked in introducing a fundamental element, namely the 'effective desire of accumulation'.

He believed that preferences over choices occurring at different times are determined by the interactions of four factors, two playing in favour of the desire of accumulation (i.e. the bequest motive and the propensity to exercise self restraint), and two limiting it (namely uncertainty about the future and the excitement generated by immediate consumption)[16]. Hence, Rae makes intertemporal tradeoffs depending in psychological factors: on the one hand the desire to create a capital for heirs, on the other hand pleasure of immediate consumption and the discomfort associated to self-restrictions.

The argument was then further investigated by Eugen von Böhm-Bawerk, who believed that humans systematically tend to underestimate future wants and needs. This bounded rationality implies that, since future appears less important, present consumption is increased, possibly to levels which are not optimal. Such view is shared also by Arthur Cecil Pigou, who, in his *The Economics of Welfare* claims: "*our telescopic faculty is defective, and we, therefore, see future pleasure, as it were, on a diminished scale*" (Pigou, 1920). The fact that people perceive future as less important may be due to various reasons (some of which had already been

[16]These arguments are analysed also by William S. Jevons and his son. The two believe that individuals care solely about immediate utility, and that the only reason to postpone consumption is if this generates some kind of 'anticipal' utility: namely, agents experience utility by virtue of having deferred part of their consumption to the future, thus allowing them to consume more at that time.

introduced by Rae). First of all there exist a 'pure time discounting', namely an intrinsic tendency to care more about the present. Second, some exogenous factors could act in such a way to increase uncertainty and risk related to the future (for example the possibility of death may be a strong deterrent in postponing consumption)[17]. Finally, it is often difficult to wait for a delayed pleasure when an immediate gratification is available, hence there is an opportunity cost connected with the delaying of present consumption.

Later on, the topic was analysed also by the American economist Irving Fisher, who presented a suggestive representation plotting current consumption with consumption in the following year. From this it seems that the rate of time preference depends on time preferences and diminishing marginal utility (Frederick et al., 2002). Moreover, in addition to the determinants exposed by Rae and Böhm-Bawerk, Fisher includes 'foresight' (that, in contrast with what said the Austrian author, represents the ability to imagine future needs), and 'fashion' (which could be interpreted as self-establishment, stimulating individuals to desire to become rich, and the rich to live in an ostentatious manner).

"*Hence, [at the end of the nineteenth and] in the early part of the twentieth century, 'time preference' was viewed as an amalgamation of various intertemporal motives*" (Frederick et al., 2002).

The "revolution" comes in 1937, when Paul Samuelson, in his paper *A Note on Measurement of Utility*, presents the Discounted Utility Model. The model represents a significant step forward with respect to previous theories, and, despite Samuelson's manifest reservations about its validity, it is immediately and almost universally accepted, becoming the reference method to deal with intertemporal choices.

[17]However, note that there are factors which might have an opposite effect, stimulating the propensity to defer a part of present consumption. For instance, the uncertainty related to future health conditions may induce households to increase their savings, hence postponing consumption, so as to be prepared to face possible future expenditures for healthcare.

The main advantages are its simplicity and the fact that it is highly tractable and applicable to a great variety of situations, condensing all motives underlying time preferences in a single parameter given by the discount rate ρ.

The DU model specifies an individual's preferences over intertemporal consumption profiles $(c_t, ..., c_T)$ (where t are time periods), which, under usual assumption of completeness, continuity and transitivity, can be represented with an intertemporal utility function:

$$U_t = \sum_{k=0}^{T-t} D(k) \cdot u(c_{t+k}),$$

where

$$D(k) = \left(\frac{1}{1+\rho}\right)^k$$

is called discount function, and gives the relative weight an individual attaches in period t to his well-being in period $t+k$. If, instead of looking at a discrete-time case, one turns to the continuous one, the formulation becomes:

$$U_t(\{c_\tau\}_{\tau\in[t,T]}) = \int_{\tau=t}^{T} e^{-\rho(\tau-t)} \cdot u(c_{t+k}).$$

Being ρ a positive parameter, it implies that the discount function is decreasing in k, namely $D(k)$ decreases over time. Such 'impatience' means that agents value more the present than the future, and the "near future" than the "distant future". However, the discount rate is constant and refers only to adjacent periods, thus allowing to summarize a person's time preferences with a 'single discount factor' $\delta = 1/(1+\rho)$. The consequence of this is that intertemporal preferences are 'time consistent', hence "*delaying or accelerating two dated outcomes by a common amount should not change preferences between [them]*: if in period t an agent prefers outcome X at t to Y at $t+d$, this must be true for all t[18] (Frederick et al., 2002).

As a matter of facts, DU condenses all the psychological motives highlighted by Rae, Böhm-Bawerk, Fisher and the other predecessors, into a single parameter

[18]If $U_t(X_t) > U_t(Y_{t+d})$, then it must be $U_t(X_{t+c}) > U_t(Y_{t+c+d})$.

given by the discount rate. Even if this represents an easier and more automated way to deal with the issue of intertemporal choices, it might be too simplistic[19]. For this reason during the years other models have been developed to better portray the relationship between time preferences and the underlying psychological determinants.

The fact that people value less the future than the present led a part of the literature to strive to model theoretical frameworks which effectively represent such issue. The idea that agents have a declining rate of time preference originated models where the discount rate is no longer constant, but tends to decrease in time. Several studies seem to corroborate such issue. For example, Thaler (1981) asked people what amount of money they would require in one month, one year and ten years, to make them indifferent from receiving 15$ today. The average answers were respectively 20$, 50$ and 100$, implying an implicit annual discount rate of 345%, 120% and 19%[20]. Other examples of time inconsistency arise when people prefer 1000$ now to 1010$ tomorrow, but 1010$ in 31 days to 1000$ in thirty days[21].

To cope with such fallacies 'Hyperbolic Discounting (HD)' and 'Quasi Hyperbolic Discounting' models have been developed. Now the discount rate is ρ_n, and it is decreasing over time (hence it decreases in n). It has been claimed that "*a hyperbolic functional form, which imposes declining discount rates, fits the data better than the exponential functional form, which imposes constant discount rates*" (Frederick et al., 2002). This is further confirmed by a comparison across studies, in which

[19]Samuelson himself recognizes this problem, claiming that "*any connection between utility as discussed [in the DU model] and any welfare concept is disavowed*"; moreover he adds that "*it is completely arbitrary to assume that the individual behaves so as to maximize an integral in the form envisaged [here]*" (Samuelson, 1937).

[20]The annual discount rates, x, where computed by equating $15 = 20 \cdot e^{-x\cdot(1/12)}$, $15 = 50 \cdot e^{-x\cdot(12/12)}$ and $15 = 100 \cdot e^{-x\cdot(10)}$.

[21]In this case the second prospect simply delays everything by 30 days, so if $u_t(1000) > \delta u_t(1010)$, it should also be $\delta^{30} u_t(1000) > \delta^{31} u_t(1010)$, as $\frac{\delta^{30} u_t(1000)}{\delta^{30}} = u_t(1000)$ and $\frac{\delta^{31} u_t(1000)}{\delta^{30}} = \delta u_t(1000)$. If, as it appears from the experiment, it is $\delta^{30} u_t(1000) < \delta^{31} u_t(1010)$, it implies $u_t(1000) < \delta u_t(1010)$, which is a clear violation of time consistency.

the average estimated discount factor, δ, of each study is plotted against the time horizon of such study. The regression line displayed in Figure 3.1 has a positive slope, meaning that δ increases as time horizon increases, which in turn reflects a decline in the discount rate ρ. However, it is worth noting that, when the Frederick et al. removed the studies with time horizons smaller than one year the effect disappeared.

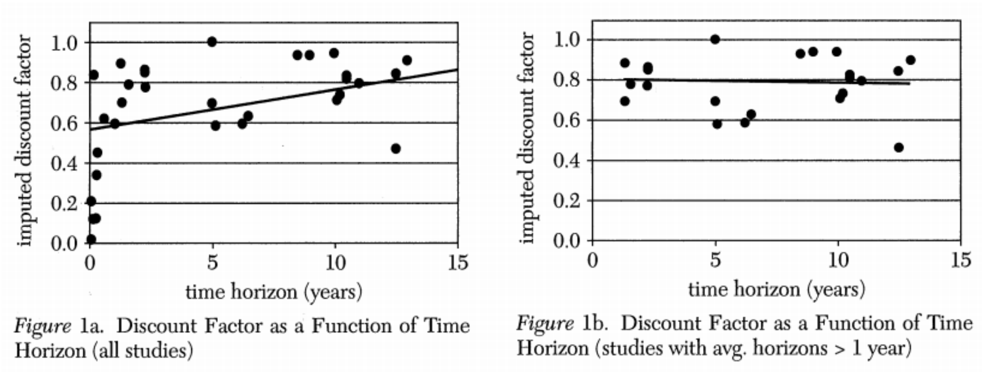

Figure 3.1: Relationship between Discount Factor and Time Horizon (Figure 1a and 1b in Frederick et al., 2002)

The first author who explicitly attempted to model decreasing time preferences was Robert Henry Strotz (1955-56), who claimed that "*for any discount function other than exponential, a person would have time-inconsistent preferences*" (Frederick et al., 2002), and that there is "*no reason why an individual should have such a special discount function*" (Strotz, 1955-56). However, he only proposed strategies that persons who foresee their preferences might chance over time could implement, but he did not come up with any theoretical formulation of a coherent model.

Such formulation, which is still one of the mostly recognized and adopted, has been provided by David Laibson (1997). His is a simple, highly tractable model, which captures many of the qualitative implication of HD (Frederick et al., 2002), characterized by a discount function that takes the form:

$$D(k) = \begin{cases} 1 & \text{if } k = 0 \\ \beta\delta^k & \text{if } k > 0. \end{cases}$$

where, again, $\delta = 1/(1+\rho)$. Here, ρ is a long-run time-consistent discount rate, while $\beta \leq 1$ highlights a bias for the present (with the case in which $\beta = 1$ representing classic exponential discounting).

Since the per-period discount rate between two adjacent periods is $\rho = (1 - \beta\delta)/\beta\delta$, while that between *any* two periods is $\rho = (1-\delta)/\delta$ (which is smaller than, or at least equal to, the former, as $\beta \leq 1$), the "(β, δ) *formulation assumes a declining discount rate between [the present] period and the next, but a constant discount rate thereafter*"[22] (Frederick et al., 2002).

Several analyses evidence that for consumption-savings decisions, HD provides a better representation than exponential discounting.

Moreover, HD seems to fit well consumers' behaviour also in the context of purchase choices of electrical appliances. In this case there is a tradeoff between the immediate expenditure for the purchase of the appliance (which is greater for more efficient items), and the future energy savings. If consumers behave following a hyperbolic discounting model, when they evaluate different prospects, they may plan to buy a more efficient but more expensive appliance, as the savings in terms of energy-bills this could generate are likely to more than compensate the higher purchasing price. But, if, when the time buy such appliance comes, the discount function becomes steeper, and their discount rate increases, then they are less willing to pay the extra amount for the greater efficiency, and end up purchasing the less efficient but cheaper appliance. Being this the case, hyperbolic discounting can represent a serious limitation to the diffusion of measures

[22] This particular functional form of the discount function was introduced the first time by Phelps and Pollak (1968) in a study on intergenerational altruism, while it was Elster (1979) to apply it to decision making.

for energy conservation and the reduction of energy consumption. This idea is corroborated by the findings of various studies, where "*discount rates implied by consumers' choices vastly exceed market interest rates*" (Frederick et al., 2002).

However, these results may be influenced by many of the factors analysed in Chapter 2, as capital or liquidity constraints, the ignorance of possible intertemporal arbitrage[23], a lack of information, uncertainty, hidden costs, so that "*high discount rates implied by the widespread use of inefficient electrical appliances might not result from the discounting of future cost savings per se*" (Frederick et al., 2002).

3.2 MAGNITUDE EFFECT

It has been said that high discount rates, in line with hyperbolic discounting, may not be entirely due to time discounting *per se*, but rather they are the results of (possible interactions between) other factors.

In a 1992 paper, Loewenstein and Prelec analyse the so called 'Intertemporal choices anomalies'[24] in an hyperbolic discounting framework. For the scopes of this work, the interest will focus specifically on one of these.

The 'size effect', or 'magnitude effect' as the authors label it, implies that consumers tend to discount more smaller outcomes (or prospects) than greater ones. This translates, in their model, in the fact that "*the value function*[25] *[$v(\cdot)$] is more elastic for outcomes that are larger in absolute magnitude*":

$$\varepsilon_v(x) < \varepsilon_v(y),$$

for $0 < x < y$ or $y < x < 0$ (Loewenstein and Prelec, 1992).

[23]So that capital constraints are further reinforced by the fact that agents are not aware of capital markets or are not able to exploit them in order to acquire the funds needed to adopt energy-efficient measures.

[24]These, which are widely investigated also in Frederick et al. (2002), are, equivalently to 'Expected Utility (EU) anomalies', "*preference patterns that create difficulty for the [DU] model*" (Loewenstein and Prelec, 1992).

[25]For their analysis Lowenstein and Prelec develop a model that follows 'Prospect Theory' (see Kahneman and Tversky, 1979), where the utility function that characterizes EU models is replaced by a value function, which, despite being a sort of utility, is such to put the accent more on gains and losses with respect to a reference point, rather than on final wealth as in EU.

This is shown by the greater convexity (in the loss domain, i.e. the third quarter) and concavity (in the gain domain, i.e. the first quarter) of the value function in the case of smaller outcomes (right chart in Figure 3.2). The result is that, when facing small amounts, the impact of a gain or a loss (with respect to the reference point) on the value function is contained, thus translating in a high implicit discount rate.

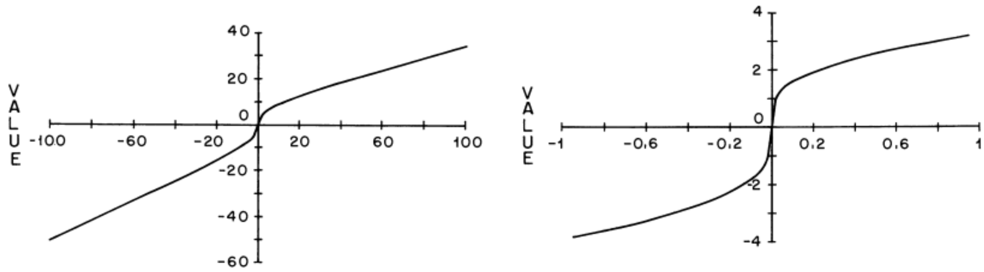

Figure 3.2: Magnitude Effect
(Figure II and III in Loewenstein and Prelec, 1992)

The magnitude effect can have severe consequences on energy conservation and the purchase of more energy-efficient electric devices.

As already mentioned, these are products or services that imply a tradeoff between an immediate expenditure and future savings in the energy bills, which might be relatively small if considered independently (i.e. one at a time). The result is that "*the small delayed electricity [savings] associated with the consumer durables will be substantially devalued due to the dependence of discounting on outcome magnitude. Thus, consumer durable purchases will be insensitive to electricity charges, and discount will appear to be high*" (Loewenstein and Prelec, 1992).

So, since the savings in energy bill granted by, say, a LED bulb with respect to a halogen one, are small in absolute terms, agents might apply higher discount rates on them, with the consequence that the greater initial expenditure of the more efficient device may loom larger than the future cost reductions, thus discouraging its purchase, hampering energy conservation.

In addition, as augmented energy efficiency increases productivity, reducing costs of production, thus allowing to sell, *ceteris paribus*, to a lower price, the magnitude effect could, again, act in such a way to put an upward pressure on implicit discount rates, making consumers less willing to pay the extra amount for more efficient devices. In this sense, the magnitude effect could provide a possible explanation for the rebound effect: as energy efficiency (in production) increases, prices go down, the discount rate goes up, and the more efficient products (which still cost more than the less efficient ones, despite the reduction in price) are less likely to be purchased (than had the increase in efficiency not happened), as the price difference looms larger. This effect is further investigated in the experiments that will be presented in the next chapter.

3.3 RELATIVE THINKING

This phenomenon is, in fact, not closely related to intertemporal choices and discounted utility theories, but it is one of the main effects investigated in the experiments that will be presented in Chapter 4. For this reason, it seems appropriate to provide a brief explanation about it, as already done for hyperbolic discounting and magnitude effect.

The theory of rational choice implies that consumers should think in absolute terms and not in relative ones. For example, an individual who is willing to drive a certain distance in order to save 5€ on a 20€ good, should also be willing to drive the same distance to save 5€ on a 2000€ good, despite the fact that the relative saving is greater in the first case.

In fact, focusing on the relative part of a good's price that is being saved may lead to non-optimal decisions: "*a consumer who spends 20 minutes to save $3 on a $10 good and later refuses to spend 20 minutes to save $50 on a $30,000 good (because the relative savings are high in the first case and low in the second case) could have the same amount of free time an be richer by $47 by making the opposite choice*" (Azar, 2011).

Nevertheless, in the literature it is possible to find several examples demonstrating that people often behave according to relative thinking. For example, Thaler (1980) applies Prospect Theory to investigate why individuals put more effort to save 5$ on a 25$ radio than on a 500$ TV. Again, Tversky and Kahneman (1981) conduct a study showing that, assuming consumers have to buy a calculator and a jacket, they are more willing to drive 20 minutes to save 5$ on the calculator when the prices are 15$ for the calculator and 125$ for the jacket then when they are vice versa. This because the relative savings loom larger in the first circumstance, while the amount of money people actually save is the same in both cases. The authors claim that "*[respondents] evaluate potential savings in a more inclusive account [with respect ot the minimal account that involves only the 5$ benefit], which includes the purchase of the calculator but not of the jacket. By the curvature of v [the value function], a discount of 5$ has a greater impact when the price of the calculator is low then when it is high*" (Tversky and Kahneman, 1981).

This finding is confirmed also by later studies, which constructed similar experiments varying the population, the price of the second (not discounted) good, and even the presence of a second good.

In Azar (2011), respondents were asked to express their willingness to pay (or willingness to accept, in the light of the particular design of the problem), instead of just answering yes or no. Moreover, the experiment takes into consideration several goods and various price alternatives. This allows the author to suggest that "*people exhibit relative thinking when trading off time and money; they behave as if the value of their time is increasing with the price of the good they want to purchase*" (Azar, 2011). Therefore, the lower the price of the good, the more the effort they are willing to exert in order to purchase the cheaper item, thus contradicting what the theory of rational choice prescribes. In addition, the experiment collects also information about gender, undergraduate majors, and years in the undergraduate program, allowing to show that, if studying economics does not help to mitigate the effect *per se*, the more economics courses one took the less he or she is likely to express relative thinking. Notably, this evidence is somewhat confirmed also in the experiments presented in the next Chapter.

CHAPTER 4

THE EXPERIMENTS

To test the actual validity of what said so far on the interactions between behavioural barriers and the rebound effect two experiments have been conducted.

They consider particular energy-using devices, namely lighting bulbs, and focus on consumers' purchasing decisions and willingness to pay between LED bulbs and less efficient but cheaper options.

In order to clarify a little the context, LED bulbs represent the new frontier of lighting. They exploit diodes[26] that emit light in a very narrow band of wavelengths, allowing to have a high performance and a duration of life which is considerably greater than that of common incandescent or halogen bulbs, and to consume little amounts of energy, thus having a small environmental impact and granting considerable savings in the energy bill. Yet, all these advantages come to a cost, and the purchasing price is still significantly higher than that of halogen or CFL[27] bulbs.

The first experiment is a paper questionnaire distributed to a class of students enrolled in the first year of bachelor's degree in Economics and Management at Ca' Foscari University. The second is an online survey, in which respondents are paid 1$ for correctly completing the assignment. To control for the accuracy of the responses, in the online experiment, an attention check has been implemented,

[26]In fact LED stands for 'light-emitting diode'.

[27]CFLs, or 'compact fluorescent lamps', are another kind of energy-efficient bulbs, which, however, have lower performances, both in terms of consumption of energy and of enlightenment.

and only those who successfully passed it were accepted and paid.

The two experiments have slightly different designs, but they control for the same effects, and the results can be effectively compared.

4.1 DESIGN

Both experiments consider two models of LED bulbs, two models of CFL bulbs and two of halogen bulbs. The energy efficiency, represented by how much less energy a bulb consumes with respect to a halogen one, has been normalized to 80% in the case of the two LED models, and 40% for the CFLs, so that the only thing in which the models differ from one another is their wattage[28], hence their price. Namely, a LED bulb which has a wattage x and one with a wattage $x + c$ are both 80% more efficient than halogen bulbs with equivalent wattages, but the first one is sold at a price p, while the more powerful one at a price $p + k$. This will allow to analyse the magnitude effect.

The experiments aim at controlling if and how the purchase of LED bulbs is affected by hyperbolic discounting, magnitude effect and absolute/relative thinking. If people exhibit hyperbolic discounting they could plan to buy a more efficient but more expensive LED bulb in the future; however, when the time to make the investment comes, the fact that their discounting becomes steeper induces them to opt for the cheaper solution. In this way devices granting greater energy savings do not spread, and the consumption of energy is not reduced by energy efficiency improvements.

Second, the magnitude effect might make individuals to have an implicit discount rate that increases as price decreases. The consequence is that, as energy efficiency gains allow to produce devices for a lower price, agents discount them more than had the efficiency gains not taken place. As a result, the lower the

[28] The wattage is a measure of electric power.

price, the less consumers are willing to pay for energy-saving items, so that energy efficiency is, again, ineffective in reducing energy use.

Finally, it may seem reasonable to assume that agents are likely to pay more attention to the absolute value of energy consumption and savings of an electrical device. If this is the case, they might be more willing to pay an extra amount for energy efficiency for big appliances (as refrigerators, washing machines, air conditioners and so on), which have greater consumption and savings per use in absolute terms than bulbs, irrespective of the fact that their efficiency is relatively smaller than that of LED bulbs. So, absolute thinking could induce consumers to direct their efficiency investments towards 'big' appliances, which consume more in absolute terms, as their savings loom larger, even though they are relatively less efficient than 'smaller' ones (LED bulbs).

To analyse the first two effects, individuals are presented with a purchasing decision between a LED bulb and a less efficient bulb for a central lighting spot (namely one which is often in use) of their house.

In the experiment conducted among students, the problem provided the average use of the bulb for such spot in hours per day and per year, the expected duration of life of each typology of bulb (LED, CFL, halogen), the cost of electricity (taken from the Italian Authority for electric energy, gas and the water system[29], updated at the second trimester of 2016), and the respective expenditure for energy consumption. More specifically it was phrased as follows:

> Consider the bulb of a central lighting spot of your house (for example one in the kitchen). The average use is of 5.5 hours per day (corresponding to 2000 hours a year, more or less). The cost of electricity is 0.1547 €/kWh. For such lighting spot the annual expenditure for electricity consumption is: 1.7€ with a LED bulb, 2.8€ with a CFL (energy saving) bulb, and 12.4€ with

[29] Autorità per l'energia elettrica il gas e il sistema idrico, http://www.autorita.energia.it/it/elettricita/prezzirif.htm.

a halogen bulb. The expected duration of life is 15000 hours for the LED bulb, 10000 hours for the CFL bulb and 2000 hours for the halogen bulb (corresponding respectively to 7.5 years, 5 years and 1 years at the considered use rate).

However, although students were told they did not have to process calculations in order to answer the questions, but just to provide their intuition, the presence of all these figures regarding electricity prices and consumption induced them to think they had to solve a maximization problem. As a consequence, they perceived the experiment a more complicated task than it really was, discouraging them, so that not all the students succeeded in understanding and completing the questionnaire.

In light of these difficulties, the online version has been simplified, eliminating the information on the cost of electricity and annual expenditures for electricity consumption, and providing only the average use for the lighting spot and the expected duration of life. This new design seems to better represent the situation consumers typically face when they have to make purchase decisions for the specific devices considered.

Also, since the online experiment was U.S.-centric, all prices have been displayed in dollars instead of euros. However, as this is nothing but a mere rescaling, the goodness and comparability of results is not affected. From now on references to experiments' question will always be reported in dollars.

For what concerns absolute/relative thinking, the experiments presented the comparison between bulbs and another device which has a greater absolute consumption of electric energy: washing machines. Here two frameworks have been designed, that are identical in both experiments: one in which energy use is expressed in physical terms (kilowatt-hour, kWh), so that efficiency can be elicited from the differences of the two consumptions, and one in which it is displayed in percentage terms. Individuals are asked for which of the two devices they would be willing to spend an extra amount for energy efficiency, provided that at least one of the two must be the energy-efficient option.

Hyperbolic Discounting

To investigate hyperbolic discounting, respondents are asked to say what amount of money they would be willing to pay for a LED bulb which is respectively 80% and 40% more efficient than a halogen or CFL one which has a certain cost (the actual formulation of the experiments is reported in Appendix C). The demand is repeated for two different time periods in the experiment conducted with students, namely today and in one year from now. In the online experiment, on the other hand, the periods are three: today, in six months from now, and in one year from now. In both settings individuals are told that they will have to change the bulb in a certain period, and are asked to state the amount of money they will be willing to pay *more* for the LED bulb at that specific time. An example of question is:

> **In one year from now** you will have to change the bulb of such lighting spot.
> What extra amount "X" will you be willing to pay **next year** for a LED bulb
> that consumes 80% less energy than a halogen bulb which costs 1.39$?

The experiments are divided in two treatments. One presents the demands moving from the present to the future (from now on referred to as the 'Now-Future (NF) treatment'), the other one in the opposite way (the 'Future-Now (FN) treatment'). Respondents were randomly assigned to the first or the second. This was done to see whether the order in which intertemporal choices are presented influences the answers (for example, if the average "Xs" are greater or smaller in the 'Now-Future treatment' than in the 'Future-Now' one).

The idea is that if, for a given cost of the comparison bulb (1.39$ in this case), the average amount "X" increases as the periods of time move from the present toward the future, meaning that agents are more willing to pay when the installation has to be done later in time, or, alternatively, that they are less willing to pay as the installation time approaches, this is testimony of a discount rate that decreases over time, hence of hyperbolic discounting.

If this is the case, consumers may be rational and patient today, making plans to purchase more efficient LED bulbs to substitute the less efficient (reference) ones when these do not function anymore; but then, when the time to actually undertake the investment and substitute them comes, their discount rate increases and they are no longer willing to pay the extra price for the more efficient solution, so that measures for energy conservation do not spread. As a consequence, efficiency gains might result ineffective in reducing energy consumption, thus validating the hypothesis of rebound.

The presence of high implicit rates of discount for electric appliances has been revealed by many studies during the years: around 20% for air conditioners (Hausman, 1979), 102% for gas water heaters and 243% for electric ones (Ruderman et al., 1897), from 45% to 300% for refrigerators and 138% for freezers (Gately, 1980, and Ruderman et al., 1897).

The elicitation of specific discount rates for bulbs, however, is beyond the scope of this work. Here the aim is to verify whether consumers as less willing to pay as the purchasing date approaches, which, in turn, limits the effectiveness of energy efficiency in reducing consumption of energy. For this reason, it seems sufficient to look at the differences between the averages of responses at different times: if such averages are increasing, this is testimony of the presence of hyperbolic discounting. Moreover, to derive an exact discount rate the problem should consider also all future savings in the energy bill and fluctuation in the cost of electricity, but these are assumptions we did not make.

Magnitude Effect

Magnitude effect is elicited via the same set of questions as for hyperbolic discounting, but the rationale is different. If before the comparison was between answers for different periods, for a given reference cost of comparison bulbs (i.e. how "X" varies moving from today, to six months from now, to one year form now, being the cost of the less efficient bulb fixed at C), now it is between different costs of the comparison bulb in a certain period. For example:

> *Q1.* **In one year from now** you will have to change the bulb of such lighting spot. What extra amount "X" will you be willing to pay **next year** for a LED bulb that consumes 80% less energy than a halogen bulb which costs 1.39$?
>
> *Q2.* **In one year from now** you will have to change the bulb of such lighting spot. What extra amount "X" will you be willing to pay **next year** for a LED bulb that consumes 80% less energy than a halogen bulb which costs 2.95$?

Also in this case, the fact that the experiments present two treatments allows to control for possible influences of the order in which questions are presented on the magnitude effect.

It was said that the experiments consider two models of LED, CFL and halogen bulbs respectively, and that the only difference between one model and the other is represented by their costs (or purchasing prices). Since no information is given regarding the actual wattage of each model, and the energy savings of LED bulbs with respect to the less efficient ones are normalized to 80% and 40% for halogen and CFL respectively, one could interpret the reduction in price that occurs moving from *Q2.* to *Q1.* as due to an enhanced productivity in the manufacture of bulbs, allowing to produce the same item for a lower production cost, that, in turn, translates into a lower price.

It follows that, if the average amount "X" decreases as the price of the comparison bulb falls, this evidences the presence of a magnitude effect. As a consequence, as energy efficiency enables production costs to decrease, putting a downward pressure on prices, this has an opposite impact on consumers' implicit discount rates, which tend to raise, thus making people less willing to pay the extra amount for energy efficiency, inducing them to purchase the less efficient option.

This fact that energy efficiency improvements (in the production side) hamper the diffusion of energy-saving devices is, again, coherent with the hypothesis of rebound, and, notably, possibly backfire. The case of backfire could take place when there is a conjunction of high discount rates and an increasing demand for energy-using devices (which is quite common in developed and developing societies, that are ever more famished of energy and electricity to sustain their standards of living). The consequence is that the more energy efficiency increases the more do the implicit discount rates, and the less consumers are willing buy more efficient items to satisfy their needs. It follows that the devices that are purchased are the ones which consume more energy, so that, in the end, energy efficiency is likely to increase, not reduce, energy use.

Absolute vs. Relative Thinking

It has been said in Chapter 3.3 that, according to the theory of rational choice, consumers should think in absolute terms, and not in relative ones, as doing so will allow them to make optimal decisions.

However, when considering energy-using devices the issue is not that straightforward, as these involve tradeoffs between an immediate expenditure and several delayed savings. Hence, in this particular case, relative thinking could actually lead to a better solution.

Big appliances (like refrigerators, washing machines, dish-washers, etc.) have a greater per use consumption than smaller devices (like bulbs), and also energy savings generated by a more efficient solution are greater in absolute terms. However, they could be smaller in relative terms. If an agent rationally follows absolute thinking, he will always be more willing to pay the extra amount for augmented energy efficiency for the bigger appliance which allows to save E per use, rather than for the smaller one which implies savings of e (with $e \ll E$), despite the fact that the former is also more expensive. Yet, it could be that the smaller device is used more during the year than the big one, so that, if e is a relatively greater saving, addressing the expenditure for energy efficiency to the small appliance may result in more significant reduction in energy bills, thus turning out to be beneficial, especially in the long run.

For the experiments, it has been considered the comparison between bulbs (a LED one and a CFL one) and washing machines (a class A+++ one and a class A+ one). Washing machines have higher prices, higher absolute consumption and energy savings per use, while bulbs have a lower consumption per use but imply greater savings in relative terms (40% moving from the CFL bulb to the LED one, with respect to just 20% between the class A+ and A+++).

A report of the Institute for Energy and Transport of the European Commission evidenced that lighting represents a greater share (almost 13%) of final households energy consumptions than washing machines (8.6%). So, addressing the investment for energy efficiency toward the washing machine rather than the bulb, just because the former presents greater savings per use in absolute terms, could not be an optimal solution.

Respondents are asked for which of the two devices (bulbs or washing machines) they would be willing to pay an extra amount in order to have a greater energy efficiency. The question is presented in two different ways (common to both experiments): one displaying consumptions in absolute terms (kWh), the other in percentage terms (via the degree of energy efficiency). The two frameworks (*F1.* and *F2.*) are actually identical, they only differ in the way in which consumption/efficiency is expressed.

> *F1.* Consider two bulbs: a LED bulb that consume 3.63 kWh a year (calculated for a use rate of 2 hours a day every day, or 11 kWh a year for a use rate of 5.5 hours/day) and costs 7.90$, and a CFL (energy saving) bulb that consume 5.94 kWh a year (or 18 kWh a year) and costs 4.40$.
> Consider two washing machines: one in energy class A+++ that consumes 153 kWh a year (calculated on 220 standard washes, corresponding to 660 hours) and costs 450$, and one in energy class A+ that consumes 196 kWh a year and costs 270$.
> Both bulbs and washing machines have at least a 2-years warranty.
>
> *F2.* Consider two bulbs: a LED bulb that costs 7.90$, and a CFL (energy saving) bulb that costs 4.40$. The LED bulb consumes 40% less energy with respect to the CFL one.
> Consider two washing machines: one in energy class A+++ that costs 450$, and one in energy class A+ that costs 270$. The A+++ washing machine consumes 20% less energy than the A+ one.
> Both bulbs and washing machines have at least a 2-years warranty.

Since lighting impacts more on energy expenditures than washing machines, it could be better to decide to spend more for the bulb rather than for the washing machine. Note that in the experiments it was also provided the option to purchase the more efficient solution in both cases.

Individuals who reason according to absolute thinking should be more likely to choose the washing machine when consumptions are expressed in kWh.

Hence, if the bulbs is selected more often in the relative framework than in the absolute one, it shows that agents actually have the absolute thinking behaviour, as their choice for the washing machine is influenced by the way in which consumption/efficiency is displayed. This also implies that there is a framing effect, so that the way in which information is presented matters for consumption decisions, and to improve the diffusion of LED bulbs it would be better to report not only the wattage but also energy savings relative to the less efficient options. Note that, since frameworks did not specify neither the fractions of lighting and washing machine consumptions in terms of annual household electricity bill, nor the flows of future savings granted by the more efficient devices, it is not possible to assess whether reasoning in terms of relative rather than absolute thinking is beneficial. The purpose here is solely to see if indeed agents do so, with all implications in terms of optimal ways of displaying information.

However, this part of the experiments presents various flaws.

First of all, differently from bulbs, washing machines do not have a unique indicator of consumption per unit of time, but this is expressed in terms of the number of washes per year (220) based on the 'standard cycle', which differs from model to model[30]. For this reason, two "ideal washing machines" have been created in order to proceed with the comparison.

In addition, the number of hours (660) a washing machine is assumed to be working for the derivation of annual consumption corresponds to a very little use of the bulb (significantly smaller than that assumed to test for hyperbolic discounting and magnitude effect). This could induce respondents to believe that the utilization rate of the bulb is actually smaller than that of the washing machine, thus inducing them to opt for the latter in their choice.

Moreover, there might be other factors, which are specific for each individual (such as tastes, or the composition of household energy consumption) influenc-

[30] A standard cycle for a certain washing machine could take x hours, while for another it could take x' hours, so that calculating the consumption in kWh per year and compare it with that of a bulb is not easy. For simplicity it has been assumed that the standard cycle takes 3 hours to be completed, so that in a year the washing machine is in function for 660 hours.

ing the decision.

For these reasons, the results (if any) emerging from this analysis should be taken carefully, and by no means considered definitive.

4.2 DATA

The first experiment has been conducted in a class of students enrolled in the first year of bachelor's degree in Economics and Management. The sample, hence, is quite homogeneous, made of individuals with more or less the same age, resident in the same area, with similar background and knowledge of economic theories and household energy expenditures.

The total number of questionnaires distributed was 70: 35 for the 'Now-Future treatment' and 35 for the 'Future-Now treatment'. As already said, the huge amount of information provided in this first formulation discouraged some respondents to complete the experiment in all its part, so that the number of valid results may vary from question to question.

The online experiment aimed at collecting two hundred observations. However, since some respondents failed the control question, the final number of valid surveys was 194. Participants were randomly assigned to one treatment or the other, and in the end the distribution was 98 to 'Now-Future treatment', and 96 to the 'Future-Now' one. The survey has been designed as to force people to answer to all questions, so that, differently for the students' experiment, the sample sizes are always the same.

At the end of the questionnaire, some demographic questions have been added, so as to provide a better representation of the sample. Of the 194 participants 110 were male and 84 were female.

The average age was 37.23 years, with a minimum of 19 years, a maximum of 70 years, and quartiles being respectively 28 years (first quartile), 34 years (median), and 45 years (third quartile). Almost everyone was older than the students from the first experiment, and the majority had between 25 and 50 years old. This is not surprising in light of the particular medium that has been used to submit the survey. The information regarding the age of respondents might also suggest that, on average, this second sample should posses a greater knowledge regarding energy expenditures and energy bills, and should have faced the kind of decision problems presented in the experiment more often during their lives.

For what concerns education level, 13 subjects were high school graduated, 52 attended college but did not complete it, 22 possed a 2-years college degree and 74 a 4-years college degree, 26 had a master degree, 6 a doctoral degree and 1 a professional (J.D. or M.D.) one. No one had a level lower than high school. If in the first experiments all respondents had a certain background in economic theory, in this case it is not possible to assess what is the knowledge of participants on this topic, but the number of those who posses some kind of degree (129 out of 194) suggests that, on average, they are well instructed, hence the results should be sufficiently reliable.

It is important to keep in mind that the greater heterogeneity of the second sample might lead to significant variability of responses.

4.3 RESULTS

4.3.1 *Students' Experiment*

As already mentioned, the questionnaire distributed among students reported only two time periods for each treatment: today and in one year from now. Moreover, not all students answered to all questions, so that the sample sizes differ in various cases.

For what concerns the investigation of hyperbolic discounting and magnitude effect, the average responses are displayed in Table 4.1.

As it is possible to see, in none of the two treatments the number of students

	Today	1 Year From Now
Treatment Now-Future (N=28)		
Halogen 1.39€	2.0851 (1.5373)	2.3527 (1.8062)
Halogen 2.95€	2.6698 (1.59)	2.7866 (1.8877)
CFL 4.40€	2.2221 (1.8736)	2.1968 (1.9645)
CFL 6.40€	2.4771 (2.5953)	2.2325 (2.3519)
Treatment Future-Now (N=31)		
Halogen 1.39€	2.6271 (2.3407)	2.3611 (2.3595)
Halogen 2.95€	3.5906 (2.6837)	3.6797 (2.8174)
CFL 4.40€	2.8894 (2.2144)	3.1438 (2.6419)
CFL 6.40€	3.7188 (2.7689)	4.0438 (3.6265)

Standard errors in parenthesis

Remember that the students' experiment was designed in euros terms

Table 4.1: Average willingness to pay in the experiment with students

who answered to all questions is equal to thirty-five, nor the two sample sizes (which, unfortunately are quite small) are the same. Still, this does not represent a severe limitation for the analysis.

In addition, note that the average amounts in the 'Future-Now' treatment are almost always greater than the corresponding one in the 'Now-Future treatment'. This evidences the fact that there is some kind of anchoring of the second answer to the first answer which had been provided.

In order to assess the presence and magnitude of hyperbolic discounting we look at the differences between the amounts in each row: if the number to the right, i.e. the (average) amount "X" respondents would be willing to spend in addition to the cost of the comparison bulb in one year from now to purchase the LED one, is greater than the one to the left, i.e. what they would be willing to spend today, this is testimony of the presence of hyperbolic discounting. The effect that emerges is a little fuzzy, with the differences going in the right direction in the cases of 'halogen 1.39€ (NF)', 'halogen 2.95€ (NF and FN)', 'CFL 4.40€ (FN)' and 'CFL 6.40€ (FN)', but in the opposite direction otherwise.

This kind of comparison may be tainted by the anchoring effect that has been observed. However, since students were randomly assigned to one treatment or the other, to overcome this problem it is possible to focus on a comparison *between* treatments rather than *within*, thus subtracting the elements in the first column of the upper part and those in the second column of the lower part, which are the first choices individual faced in the respective treatment (for example 'halogen 1.39€ today (NF)' minus 'halogen 1.39€ 1 year (FN)'). With the respondents randomly assigned to one of the two treatments, and the first answer not being anchored to any previous judgement, it is possible to claim that these averages correspond to the actual willingness to pay for that specific time period, hence it seems reasonable to compare them.

At this point, the effects always go in the expected direction, with the amounts to the right being greater than those to the left. This means that, as the time of undertaking the investment approaches, individuals are less willing to pay the extra amount for energy efficiency. As a consequence, the diffusion of measures for the conservations of energy is limited, and energy consumption is not reduced.

After having verified the presence of the desired effect, it is necessary to test whether the differences are statistically significant or not. Since all the "variables" are non-normally distributed[31], in order to verify the statistical significance of the differences a 'one-tailed' Wilcoxon Signed Rank test has been conducted, imposing the first amount (the one representing the willingness to pay today in the NF treatment) to be smaller than the second one (the willingness to pay in one year in the FN treatment). The Null Hypothesis of equivalence of the means is rejected for p-values <0.05.

[31] The p-values of the Shapiro-Wilk test are all <0.05, thus allowing to reject the Null Hypothesis of normality at a 5% significance level.

The test is statistically significant only in the case of the comparison with the 6.40€ CFL bulb (p-value=0.02196, which allows to reject H_0 at a 5% significance level). In the other cases it is not possible to reject H_0.

As a matter of fact, even if the direction it is the desired one, it is possible to claim that the amount agents are willing to pay today is statistically smaller than the one they will be willing to spend in one year from now only when the decision is between a LED bulb and a CFL bulb that costs 6.40€.

To assess the presence of the magnitude effect, on the contrary, the comparison has to be made between amounts in adjacent rows for the same time period and typology of the comparison bulb: so, for example, between 'halogen 1.39€ today (NF)' and 'halogen 2.95€ today (NF)'. In this case comparisons are always made *within* treatments, as there is no possible way of anchoring. If the average amount agents are willing to spend when the comparison is made with the more expensive bulb is greater than the average amount when the comparison is with the less expensive one, this implies that the more the price decreases the more does the willingness to pay.

From the figures reported in Table 4.1, it appears that the effect indeed goes in the expected direction, thus supporting the hypothesis of a magnitude effect, with differences that range from 0.04€ to 1.32€ . The percentage reductions in willingness to pay are significantly greater when the comparison is with halogen bulbs than when it is with CFL ones, varying from -15.57% to -35.83% in the case of halogen bulbs (where the reduction in price is of 52.88%), and from -1.6% to -22.30% for CFLs (with price decreasing by 31.25%). Moreover, it appears that in the 'Now-Future' treatment the effect strengthens moving from the future to the present, thus in a sense reinforcing hypothesis of hyperbolic discounting, while in the 'Future-Now' treatment it goes in the opposite directions, meaning that anchoring still plays a certain role.

Again, it is necessary to verify if this effect is statistically significant. This is done with a paired, 'one-tailed' Wilcoxon test. The p-values confirm that the difference between averages is statistically different from zero at a 5% significance level in most of the cases, and sometimes also at a 1% level. Only in two cases the means are not statistically different: when it is considered the comparison with CFL bulbs in the 'Now-Future' treatment in both time periods, with a p-value of 0.183 when the comparison takes place today, and a p-value of 0.3033 when it is considered in one year from now. In all other cases it is confirmed that, as the purchase price falls, agents express a lower willingness to pay an extra amount to buy the more efficient device.

If this decline in price is due to efficiency gains in the production process, that enhance total productivity, energy efficiency may prove inefficient in reducing energy consumption, thus validating hypotheses of rebound. However, if the trends evidenced here seem sufficient to support the rebound effect, they are still not big enough to corroborate the presence of backfire.

The part on relative thinking is, as expected, the one where results are more nuanced, and it is not evidenced a uniform effect.

The hypothesis was that, if individuals reason in absolute terms, as proscribed by economic theory, they will be more inclined to choose the washing machine when consumption and savings are expressed in kilowatt-hours then when they are percentages. As a result, seeing a greater number of respondents deciding to address their expenditure for energy efficiency to the bulb in the relative framework highlights that they indeed have this absolute thinking. This leads them to select the washing machine because, being consumption per use greater, savings loom larger when they are expressed in physical units energy, although the class A+++ washing machine provides a relatively smaller efficiency improvement than the LED bulb.

In the 'Now-Future' treatment it is possible to appreciate an increase in the preferences for the bulb moving from the absolute framework to the relative one:

the bulb is selected 37.5% of the times when energy efficiency is displayed in relative terms, with respect to 30% when it was expressed in physical units. However, also the preferences for the washing machine raise, and they do more than those for the bulb: from 20% to 43.75%.

On the other hand, in the 'Future-Now' treatment both 'Bulb' and 'Washing Machine' are selected more times in the absolute framework than in the relative one.

Combining the results from the two treatments, it appears a very little increase in the preference for the bulb moving from the absolute framework to the relative one, a more consistent increase in the preference for the washing machine, and a reduction for the option of purchasing the most efficient model for both devices.

	Relative	Absolute
Bulb	19	18
Washing Machine	28	22
Both	18	23

Table 4.2: Aggregate Absolute vs. Relative thinking in the experiment with students

These particular results may be due to the fact that students have not often faced this kind of purchase decisions, nor are they very familiar with energy bills. In addition, being them students of economics, they might be more prone to reason according to what economic theory prescribes, so that they tend to stick to the option that appears more efficient in absolute terms. This would also confirm what was evidenced in Azar (2011), namely that taking courses of economics leads to express absolute thinking more often. Such effect could have possibly been reinforced by the fact that the two frameworks were presented in the same page in the questionnaire, so that they tended to apply a sort of absolute thinking also in the relative framework.

Note also that the sample sizes are different: the relative framework had 65 valid observations, while the absolute one only 63.

For these reasons and the ones mentioned in the part dedicated to relative thinking, the results are not representative of a coherent effect, and should by no means be taken as definitive.

4.3.2 *Online Experiment*

The greater heterogeneity of the sample is shown by the standard errors in Table 4.3, which are systematically higher than those reported for the students' experiment.

	Today	6 Months From Now	1 Year From Now
Treatment Now-Future (N=98)			
Halogen 1.39$	5.8058 (7.2476)	5.3151 (5.4183)	5.3842 (4.96)
Halogen 2.95$	5.7873 (5.7018)	6.0312 (6.3113)	5.9613 (5.9278)
CFL 4.40$	3.6072 (3.7244)	4.2048 (5.0298)	4.3189 (4.5252)
CFL 6.40$	4.0656 (4.6699)	4.3682 (5.4188)	4.1811 (4.6937)
Treatment Future-Now (N=96)			
Halogen 1.39$	4.5713 (3.1879)	5.1415 (5.7187)	5.7416 (10.2995)
Halogen 2.95$	4.7877 (4.1592)	5.3539 (5.068)	5.9216 (9.584)
CFL 4.40$	3.6651 (2.9039)	3.7419 (3.428)	4.2616 (8.3526)
CFL 6.40$	3.8856 (3.8802)	3.8772 (3.9017)	4.3979 (6.2169)

Standard errors in parenthesis

Table 4.3: Average willingness to pay in the online experiment

Again, the presence of hyperbolic discounting can be highlighted by the fact that the average amounts respondents are willing to pay *more* for the LED bulb increase moving from 'today', to '6 months from now', to '1 year from now'. If this is generally the case in the 'Future-Now' treatment, on the other hand, in the

'Now-Future' one, the effect is more confused. For example, in the case of the comparison with the 6.40$ CFL bulb, the amount increases moving from 'today' to '6 months from now', but then decreases when the decision is postponed to '1 year from now'. Or, even more in contradiction with the desired effect, in the 1.39$ halogen bulb case, the amount today is considerably greater than those of future periods.

Moreover, differently from what was observed in the first experiment, average amounts in the 'Future-Now' treatment are systematically smaller than the corresponding ones in the 'Now-Future' treatment, showing a different kind of anchoring. As a consequence, the comparisons *between* treatments, although presented in Appendix C, are less meaningful and likely to be, in the majority of the cases, insignificant since the direction of the effect is opposite to the desired (and tested) one.

Also in this case, the Shapiro-Wilk test highlights that variables are highly non-normal. So, to verify if the averages are statistically different from one another, it is again adopted a 'one-tailed' Wilcoxon Signed Rank test.

The test has been conducted for all possible comparisons *within* treatments, i.e. 'today-1 year', 'today-6 months' and '6 months-1 year'; and for the same comparisons *between* treatments, putting the amounts from the 'Future-Now' treatments always as the option more distant in time (i.e. in the comparison 'today-1 year' of the 4.40$ CFL bulb, it is tested the willingness to pay today expressed in the 'Now-Future' treatment against the willingness to pay in one year from now expressed in the 'Future-Now' one). However, note that, since the decision in six months is never displayed as the first question, it is likely that the amounts provided for such time period suffer from some kind of anchoring bias in both treatments, so that the *in between* comparisons involving these observations are of little relevance. And, in fact, they are never significant, even when the effect does go in the desired direction.

For the 1.39$ halogen bulb (for all possible permutations of time periods in the 'Now-Future' treatment and between treatments), for the 2.95$ halogen bulb (for the comparison '6 months-1 year' in the 'Now-Future' treatments and *in between*, and for the 'today-6 month' comparison *in between*), and for the 6.40$ CFL bulb (for the comparison 'today-6 months' in the 'Future-Now' treatment and *in between*), the effect goes in the direction opposite to the expected one, with the amount more distant in time being smaller than the closer one. Clearly, in none of these cases is the Wilcoxon test significant.

For all other comparisons, it is possible to appreciate an average willingness to pay that increases as the purchasing decision is delayed to a future time period. However, in the majority of the cases the differences between averages are found to be not statistically significant at a 5% significance level (the detailed results are displayed in the dedicated table in Appendix C).

Also in the case of magnitude effect, the anomalies in the results taint some comparisons in the 'Now-Future' treatment (for halogen bulbs 'today', and CFL bulbs in '1 year from now'). However, as seen in the students' experiment, in the majority of the cases the effect goes in the expected direction, with the willingness to pay being smaller when the decision is made against the cheaper option for each typology. However, differently from the first experiment, the differences in willingness to pay are generally smaller for future periods than for the present. This is, in a certain sense, in contrast with the hypothesis of hyperbolic discounting, and could once more be explained in the light of the anomalies aforementioned.

Again, the Wilcoxoc tests are not always significant, even when the effects go in the desired direction (see Appendix C). Still, statistical significance occur with a relative greater frequency than in he case of hyperbolic discounting (one third of the times), thus confirming the evidence, already seen in the experiment distributed among students, that the magnitude effect seems to play a more important role than hyperbolic discounting in consumers' preferences on energy efficiency. This also provides a stronger support to theories of rebound, being the magnitude effect more suited to explain evidences of rebound and even backfire. Note, however, that never are the effects revealed in this work sufficient to claim backfire. In fact, the percentage reductions in willingness to pay (when the differences are statistically significant) vary, more or less, form -12% to -3%, while, as already stated, prices decline respectively of 31.25% and 52.88% for CFL bulbs and halogen bulbs.

Nevertheless, even though the effect does not always prove to be significant, the differences in average amounts consumers would be willing to pay *more* for energy efficiency do go in the expected direction. Moreover, issues related to the particular design of the experiments, or to the way in which these have been distributed, may have played an important role in the analysis conducted. As a consequence, the results presented in this work, if not definitive, show that the themes which have been investigated could be of interest in the field of energy efficiency and energy economics. This should act as a stimulus to further expand the research into the link between intertemporal preferences, behavioural flaws, and theories of rebound.

In particular, it would seem useful to try to develope a model that incorporate the magnitude effect in a coherent theory of rebound. This could be done by designing a consumers' demand function for energy-using devices ($Q_D(E)$) which depends on their preferences ($u(\cdot)$), positively on their income (Y), negatively on the price of such device (p_E), and negatively on a discount rate (δ) that, however, is itself negatively affected by the price of the device (i.e. $\delta = f(p_E)$). So that, a reduction in price (caused by a greater energy efficiency in the production, which allows to produce the device for a lower cost, but which does not change the energy efficiency of the energy-using device) has an ambiguous impact on the demand of the good, increasing it via the direct effect on the demand function

($Q_D(E)$), but reducing it through the indirect effect on the discount rate (being δ a negative function of p_E, as price falls, δ increases, but this makes the demand to decline). Moreover, since a price reduction also causes an income effect, making consumers richer, thus augmenting their purchasing power and inducing them to buy more of the good, it would be interesting to analyse in what cases (i.e. for what values of the parameters of the discount function, utility function and demand function, if any) such reduction, generated by a greater energy efficiency in the production side, leads to an indirect effect that more than makes up for the increase in purchasing power.

Finally, for what concerns the part on absolute/relative thinking, the results are perfectly in line with the original hypothesis. In fact, in both treatments, it is possible to appreciate a significant increase in the individuals who would be more willing to address their investments for energy efficiency to the purchasing of the LED bulb when information regarding consumption and savings are expressed in relative terms with respect to when they are reported in physical units.

	Relative	Absolute
Bulb	70	53
Washing Machine	40	39
Both	84	102

Table 4.4: Aggregate Absolute vs. Relative thinking in the online experiment

It is possible to observe that, moving from the absolute framework to the relative one, the preferences for 'Washing Machine' remain more ore less the same, while those for 'Both' are significantly reduced, thus meaning that the difference is almost entirely captured by 'Bulb', which, in fact, presents a sharp increase.

These results show how changing the way in which information is provided, displaying energy savings with respect to the less efficient reference option in relative terms, can be highly beneficial for those devices which have small per use consumptions. To foster the diffusion of energy-saving appliances, producers and public administrations should pay particular attention not only to provide all relevant information pertaining energy use and efficiency, but also to the way in which this information is conveyed. So, in the particular case of LED bulbs, it would seem appropriate to display in the product labels[32] not only the energy class to which the device belongs to and its wattage, but also a specific reference of its energy efficiency compared with the baseline option (represented by halogen bulbs). Doing so, consumers would be more willing to pay for the more efficient, but also more expensive, LED bulb, thus allowing to reduce energy consumptions.

It is worth noting, however, that also in the absolute framework 'Bulb' was selected more times than 'Washing-Machine', meaning that the shift of preferences may not be entirely do to the absolute or relative thinking.

The difference with respect to what seen in the experiment conducted among students, where the effect was almost insignificant, is (probably) due to the fact that the online sample was, on the one hand, considerably greater than the classroom where the first questionnaire was distributed, and, on the other hand, that it was more heterogeneous and made of individuals who, in theory, possess a greater experience in terms of energy bills and purchasing decisions involving these particular energy-using appliances.

These experiments concentrate on issues of hyperbolic discounting and framing of information, but the decision problems with which consumers have been presented could be influenced also by other barriers, such as household income, limited capital availability, heterogeneity of tastes and preferences for the design

[32] In the European Union, energy-using goods must have an EU Energy Label, that reports the energy class of the particular good, its average consumption, and other pieces of information which are specific for each kind of appliance. The EU Energy Label was first introduced with the Directive 92/75/EEC of the European Council, which has been replaced by the Directive 2010/307EU of the European Parliament and Council.

of bulbs or washing machines, which have not been accounted for here. Hence, future researches may extend the design, including also other behavioural and market barriers, and see how these affect the diffusion of energy-efficient measures. But also if and how their presence modifies the effects observed here for hyperbolic discounting and information.

Recapitulating, the effect of hyperbolic discounting is a little confused, in the students' experiment, when looking at a comparison *within* treatments, while it goes is the expected direction focusing on a comparison *in between*. On the other hand, due to a strange anchoring in the data, it does not go in a clear direction in the online experiment. In both cases, when the directions are the desired ones, the statistical tests not always prove to be significant. The magnitude effect always goes in the expected direction in the experiment conducted among students, and the Wilcoxon test is significant in the majority of the cases. The direction remains the desired one also in the online experiment, but now the tests are not always significant. Finally, the impact of relative thinking appears to be weak in the students' experiment, while it emerges more vigorously in the online one, with the bulb selected more often when information is provided in relative rather than absolute terms.

	Effect *within*	Effect *in between*	Significance
Students' experiment			
Hyperbolic Discounting	Confused	Expected one	Differences not always statically significant
Magnitude effect	Expected one	-	Differences mostly statistically significant
Relative thinking	Expected one but weak	-	-
Online experiment			
Hyperbolic Discounting	Confused	Confused	Differences not always statically significant
Magnitude effect	Expected one	-	Differences not always statistically significant
Relative thinking	Expected one	-	-

Table 4.5: Overview of the phenomena under investigation and results

CONCLUSION

Energy efficiency is undoubtedly a fundamental determinant for human development, and plays a central role in reducing polluting emissions and contrasting global warming.

However, during the last two centuries, economic literature has started to question the idea that indiscriminately augmenting energy efficiency will lead to a proportional decrease in energy consumption. In fact, data on energy trends shows that, although energy efficiency has increased from the First Industrial Revolution to present days, so has energy consumptions. This evidence is particularly accentuated in the period after the Second World War: with the technological and cybernetic revolution, an ever increasing number of ever more efficient energy-using goods has been produced, and energy consumption has soared to unprecedented levels in human history.

The explanation economists advanced is that, not only do efficiency gains have a technological content, allowing to produce the same amount of output for a lower input requirement, but they also have a price content: a greater energy efficiency is likely to increase overall productivity, allowing to lower production costs and thus to sell for a lower price. The consequence is that economic agents have greater purchasing power, which leads them to consume more: in economics this is called 'income effect'. If this consumption is devoted to energy-using devices, then improvements in energy efficiency could result in a less than proportional decrease, or even a net increase, in energy consumption.

This phenomenon is known as rebound effect, with the case in which efficiency gains cause a greater energy use called backfire. The issue was first analysed in 1865 by the English economist William Stanley Jevons, who, in his book *The Coal Question*, demonstrated how the passage from Savery's, to Newcomen's, to Watt's engine in fact increased the consumption of coal and pig iron. Savery's engine was so inefficient that its operating costs were simply too high for making it coming into use, so that, despite its extreme fuel voracity, the actual consumption of coal was little. On the other hand, the greater efficiency of Watt's engine enabled it to extend production, and absolute national consumption of coal boomed. His argument has been so widely accepted by the economic literature that the phenomenon is also known as 'Jevons' paradox'.

The debate has been revived in the last two decades of the twentieth century, when the works of Daniel J. Khazzoom and Leonard Brookes stimulated further investigation into the link between energy efficiency and energy use. Their contribution has been so fundamental that Harry D. Saunders coined the expression 'Khazzoom-Brookes postulate'. This led to the development of a better understanding of the rebound effect, which has been divided into three (four) "sub-effects". First the 'direct' or 'micro rebound', meaning that an increase in energy efficiency in the production of a certain energy-using good puts a downward pressure on its price, which leads consumers and firms to consume more of such good. Second the 'indirect rebound', deriving from the fact that the increase in real income is likely to stimulate not only the industry where the efficiency gain took place, but also other ones, leading to a further raise in energy consumption and economic growth. Finally, looking at a dynamic perspective, there is an 'economy-wide rebound'.

Still, even though the existence of a rebound effect is not questioned, there is not a unique opinion concerning its magnitude, and economists have long been divided between spokesmen of backfire, and those who claimed than, in reality, the effect is small and of little significance.

But, apart from the consequences of energy efficiency improvements in terms of income and substitution effects, it is possible that market flaws and behavioural biases hamper the diffusion of more efficient technologies, thus limiting the ability of energy efficiency to reduce energy consumption.

Market failures such as hidden costs, difficulties in capital accessibility, imperfect information, and the 'principal-agent relationship', and behavioural fallacies like bounded rationality, habits formation, risk aversion, consumers' heterogeneity and high implicit discount rates, may prevent efficient technologies from being adopted, thus generating the so called 'energy-efficiency gap'.

Many studies have been conducted, focusing on both sides of the issue, evidencing than indeed these factors play a relevant role in the formation and perpetuation of such gap.

In this work, the attention has been put primarily on the effect that high implicit discount rates can have on consumers' choices on energy efficient devices. These particular choices are likely to present tradeoffs between an immediate expenditure, represented by the purchasing price of the item (which is greater in the case of more efficient products), and many delayed savings (the reductions in energy consumption and, in turn, in energy bills). More specifically, the aim was to see whether problems of hyperbolic discounting and magnitude effect affect individuals' willingness to pay for bulbs. In additions, we wanted to see if consumers' absolute or relative way of thinking influences their purchase decision between big (washing machines) and small (bulbs) appliances.

Two experiments have been conducted to investigate these effects. Respondents were asked to state their willingness to pay *more* for a LED bulb with respect to less efficient but cheaper bulbs. This was repeated for various time periods and prices of the comparison bulbs. Moreover, they were also presented with the purchasing choice between bulbs and washing machines. They were given two alternatives for each appliance, of which one was more efficient than the other (in particular, the efficient option for bulbs was relatively more efficient than that for washing machines), and were asked to state whether they would address their investments for energy efficiency toward the bulb, the washing machine or both. The problem was formulated in two ways, one where consumption and efficiency were expressed in absolute terms, the other in relative ones.

If it is evidenced an increasing willingness to pay as time periods in which the investment for energy efficiency should be undertaken moves toward the future, and as the price of the comparison bulb increases, and, if the bulb is selected more times in the relative framework than in the absolute one, this proves that agents indeed are likely to show hyperbolic discounting, magnitude effect and absolute thinking.

The results from the experiments highlighted that, in the majority of the cases, effects go in the expected directions. Individuals seem, on average, more willing to pay when the comparison between LED bulbs and less efficient ones takes place in the future, thus validating the hypothesis of hyperbolic discounting. As a consequence, when planning to make investments for energy efficiency they are patient and willing to undertake said investments. But when the time comes to actually invest, their implicit discount rate increases, they are no longer willing to pay the extra amount for the more efficient option (or not willing to pay an amount as big as the one they were willing to pay at the beginning), and they opt for the less efficient one, so that technologies for energy conservation are not adopted, the 'gap' is perpetuated, and energy efficiency proves ineffective in reducing energy consumption, in line with theories of rebound.

Again, respondents show a lower willingness to pay as the price of the comparison bulb declines. The implications are that, as energy efficiency allows for the production of goods at a lower cost, in turn reducing purchasing prices, consumers are less willing to pay the extra amount for the more efficient devices (since this extra price looms relatively larger), so these are purchased less frequently than had the efficiency gain not taken place. Also in this case, such evidence corroborates hypotheses of rebound, and, notably, also of backfire when the demand of energy-using items is increasing (which happens very frequently in developed and developing economies).

However, despite going in the expected directions, the effects were not always proven to be statistically significant, so the conclusions we can derive from the experiments are not definitive. Still, the findings suggest that the phenomena investigated indeed play a certain role in the relationship between energy efficiency and energy consumption, thus evidencing that further developments of the issue might be of considerable interest. Moreover, it would be advisable to try to develop a model that explicitly integrates the magnitude effect in a coherent theory of rebound, designing consumers' demand for the energy-using device as a negative function of the price of such devices and of the discount rate, which, in turn, is itself a negative function of the price. In the light of the hypothesis that the magnitude effect could make efficiency gains to actually backfire, future research could also concentrate in defining for which values of the parameters of such a model (if any) improvements in energy efficiency lead to a net increase in energy consumption. Then, it could be beneficial to move from Saunders' and Howarth's works, and to exploit CGE techniques to design a general equilibrium model, suitable for providing useful advice in terms of policy implications.

Finally, the findings evidence a greater preference to address expenditures for energy efficiency towards the bulb when information regarding consumption and savings is expressed in relative terms rather than in absolute ones. This seems to demonstrate that people chose the washing machine in the absolute framework because, being its per use consumption greater, the savings that the more efficient option granted loomed larger, while in reality they were not. If this is the case, producers and public administrations should display, at least for small appliances, all the relevant information concerning energy consumption, energy savings and duration of life, not only in absolute terms (e.g. kilowatt per year), but also relative to the less efficient baseline option. Conveying information in a more salient way could stimulate consumers to undertake investments for energy efficiency more frequently, thus allowing for the reduction the energy-efficiency gap and, in turn, energy consumption.

In addition to what said above, future research could try to implement the design of these experiments, formulating assumptions on the set of delayed energy savings generated by the more efficient LED bulbs and on possible fluctuation of the cost of electricity, so as to derive an exact measure of the discount rate, which, to the knowledge of who writes, has still not be done in the specific case of bulbs. Or, on the other hand, it should try to further expand it, introducing other barriers such as income and capital availability, heterogeneity in people's preferences and tastes for the shape and design of bulbs and washing machines, or the 'landlord-tenant relationship', to assess their impact on the adoption of energy-efficient technologies, and the way (if any) in which their presence modifies the results highlighted by this work in terms of the effect of hyperbolic discounting and information.

In any case, in the light of the many previous empirical findings on the magnitude of the rebound, and since observed effects from these experiments are not sufficiently big to justify hypotheses of backfire, measures for the improvement of energy efficiency do not have to be discarded and labelled as useless or counterproductive. Until humanity will not be able to find alternatives to fossil fuels to sustain its energy needs, efforts directed at augmenting energy efficiency of the present socio-economic system are one of the best opportunities to tackle problems of pollution and climate change. However, such measures have to be (re)designed more carefully, conveying information in the most salient way, overcoming market and behavioural barriers that hamper their efficacy, so as to reduce rebound effects as much as possible.

APPENDIX A

TABLES

In this Appendix are reported some of the Tables of various authors mentioned in the main corpus of this work.

Econometric estimates of the direct rebound effect for personal automotive transport using aggregate panel data.

Author/year	Short-run rebound effect	Long-run rebound effect	Country	Data	Model structure	Functional form	Estimation technique	Comments
Wirl, 1997	10–20%	27–30%	UK, France, Italy	Aggregate Panel (X-country)	Single equation (S) Dynamic	Double log	OLS	
Johansson and Schipper (1997)		5–55% Best guess: 30%	12 OECD	Aggregate Panel (X-country) 1973–1992	Recursive (S, ε, NO)	Double log	Various	S is the total distance travelled. Using distance travelled per vehicle gives a best guess of 20%. Careful attention to data quality. Equivalence of $\eta_\varepsilon(S)$ and $\eta_{P_E}(S)$ not tested.
Haughton and Sarkar (1996)	9–16%	22%	US	Aggregate Panel (US states) 1972–1991	Simultaneous (S, ε)	Double log	2SLS	S is the distance travelled per driver. P_E found to influence ε with hysteresis effect.
Small and Van Dender (2005)	4.5%	22%	US	Aggregate Panel (US states) 1961–2001	Simultaneous (S, ε, NO)	Double log	3SLS	S is the distance travelled per-capita. RE estimated to decline with income. Tests suggest that $\eta_\varepsilon(S) \neq \eta_{P_E}(S)$. Estimate based on $\eta_{P_S}(S)$ on preferred.

Table A.2: Estimated rebound effect for personal transportation using panel data (Table A3 in Sorrell et al., 2009)

For reasons of space this table is reported in the fist page, separated from the other ones from the same reference, and the one from Binswanger (2001), which is mentioned before in the text, is displayed at the following page.

Study	Sample	Results
The impact of improved mileage on gasoline consumption (Blair et al., 1984)	Vehicle miles traveled in Florida (monthly data) from 1967 to 1976	RE-effect of 21%
An econometric model integrating conservation in the estimation of the residential demand for electricity (Khazzoom, 1986)	Study of electrically heated homes in Sacramento, CA	Long-run RE-effect of 65%
Price effect of energy efficient technologies (Dubin et al., 1986)	Study of 214 households participating in a program of improving the efficiency of home heating	RE-effect between 8 and 13%
An analysis of the impact of residential retrofit on indoor temperature choice (Dinan, 1987)	Study of a sample of 252 households whose dwellings were weatherized	RE-effect small but statistically significant
Changes in indoor temperatures after retrofit based on electricity billing and weather data (Hirst, 1987)	Study based on an evaluation of Residential Weatherization Program throughout the Pacific Northwest, which compared the behavior of the homes that participated in the program with nonparticipants	RE-effect between 5 and 25%
Forecasting a state-specific demand for highway fuels: the case for Hawaii (Leung and Vesenka, 1987)	Vehicle miles traveled in Hawaii (annual data) from 1967 to 1980	RE-effect of 25%
The effectiveness of mandatory fuel efficiency standards in reducing the demand for gasoline (Mayo and Mathis, 1988)	Vehicle miles traveled in the US (annual data) from 1958 to 1984	Short-run RE-effect of 22% and long-run RE-effect of 26%, however, statistically not significant
The FHWA/Faucett VMT forecasting model (Weinblatt, 1989)	Vehicle miles traveled in the US (annual data) from 1966 to 1985	RE-effect below 10%
The US demand for highway travel and motor fuel (Gately, 1990)	Vehicle miles traveled in the US (annual data) from 1966 to 1988	RE-effect of 9%
Vehicle use and fuel economy: how big is the 'rebound effect'? (Greene, 1992)	Vehicle miles traveled in the US (annual data) from 1966 to 1989	RE-effect between 5 and 19% depending on model
Another look at US passenger vehicle use and the rebound effect from improved fuel efficiency (Jones, 1993)	Vehicle miles traveled in the US (annual data) from 1966 to 1990	Short-run RE-effect of 13% and long run RE-effect of ~30%
Asymmetric energy demand due to endogenous efficiencies: an empirical investigation of the transport sector (Walker and Wirl, 1993)	Road transport in France, Germany and Italy from 1961 to 1985. The demand for transport services is derived from an annual technological fuel efficiency series (km/l of gasoline) that multiplied with the energy demand of a year yields the demand for transport services	Long-run RE-effects between 32 (Germany) and 51% (Italy)
Gasoline tax as a corrective tax: estimates for the US (Haughton and Sarker, 1996)	Vehicle miles traveled in 50 US States (annual data) from 1970 to 1991	Long-run RE-effect of 22%
Fuel economy rebound effect for US household vehicles (Greene et al., 1999)	Analysis of household survey data at 3-year intervals over a 15-year period in the US from 1979 to 1994	Long-run RE-effect of ~20%

Table A.1: Empirical studies on direct rebound effect for households (Table 1 in Binswanger, 2001)

Econometric estimates of the direct rebound effect for personal automotive transport using household survey data.

Author/year	Short-run rebound effect	Long-run rebound effect	Country	Data	Model structure	Functional form	Estimation technique	Comments
Goldberg (1996)	0%		US	Rotating panel 1984–1990 (CES)	Discrete/ continuous	Double log (utilisation equation)	Nested logit (discrete) and instrumental variables (utilisation)	Very detailed model, but estimates utilisation of new cars only. If endogeneity bias ignored, RE estimated to be 22%.
Puller and Greening (1999)	49%		US	Rotating panel 1980–1990 (CES)	Simultaneous equation (dynamic—single year)	Double log	2SLS	Confined to non-business travel. Find $\eta_{P_E}(\varepsilon)<0$ reflecting only short-term changes in driving habits. Partly explains high estimate of RE. Omission of vehicle age may lead to bias.
Greene et al. (1999)		23%	US	Pooled cross-section (travel survey)	Simultaneous equation	Double log	3SLS	RE estimated from $\eta_{\varepsilon}(S)$ for households owning 1 to 5 vehicles—quoted figure is weighted average and relates solely to utilisation. Find
West (2004)	87%		US	Cross-section (CES-1997)	Discrete/ continuous	Double Log (utilisation equation)	Nested logit (discrete) ad instrumental variables (utilisation)	S is the distance travelled by household. RE estimated from $\eta_{P_G}(S)$—represents an upper bound since $P_S \leqslant P_G$.
Frondel et al. (2008)		56–66%	Germany	Panel	Single equation	Double log	Fixed/between/ random effects	RE estimated from $\eta_{P_E}(S)$, $\eta_{\varepsilon}(S)$ and $\eta_{P_E}(E)$. Results insensitive to elasticity measure and estimation method.

Table A.3: Estimated rebound effect for personal transportation using time-series and cross-section data (Table A2 in Sorrell et al., 2009)

Econometric estimates of the direct rebound effect for personal automotive transport using aggregate panel data.

Author/year	Short-run rebound effect	Long-run rebound effect	Country	Data	Model structure	Functional form	Estimation technique	Comments
Wirl, 1997	10–20%	27–30%	UK, France, Italy	Aggregate Panel (X-country)	Single equation (S) Dynamic	Double log	OLS	
Johansson and Schipper (1997)		5–55% Best guess: 30%	12 OECD	Aggregate Panel (X-country) 1973–1992	Recursive (S, ε, NO)	Double log	Various	S is the total distance travelled. Using distance travelled per vehicle gives a best guess of 20%. Careful attention to data quality. Equivalence of $\eta_{\varepsilon}(S)$ and $\eta_{P_E}(S)$ not tested.
Haughton and Sarkar (1996)	9–16%	22%	US	Aggregate Panel (US states) 1972–1991	Simultaneous (S, ε)	Double log	2SLS	S is the distance travelled per driver. P_E found to influence ε with hysteresis effect.
Small and Van Dender (2005)	4.5%	22%	US	Aggregate Panel (US states) 1961–2001	Simultaneous (S, ε, NO)	Double log	3SLS	S is the distance travelled per-capita. RE estimated to decline with income. Tests suggest that $\eta_{\varepsilon}(S) \neq \eta_{P_E}(S)$. Estimate based on $\eta_{P_S}(S)$ on preferred.

Table A.4: Estimated rebound effect for personal transportation using household survey data (Table A4 in Sorrell et al., 2009)

Econometric estimates of the direct rebound effect for household heating using single equation models.

Author/year	Short-run rebound effect	Long-run rebound effect	Country	Data	Functional form	Estimation technique	Comments
Douthitt (1986)	10–17%	35–60%	Canada	Cross-section 1980–1981 SS: 370	Double log	OLS	RE estimated from $\eta_{P_E}(E_{heat})\|_{\varepsilon_h}$. Elasticities vary with price level.
Hsueh and Gerner (1993)	35% (electric)	–	US	Cross-section 1980–1981 SS: 1028 gas, 253 Electricity	Double log	OLS	Equation for E_{total} incorporating engineering variables determining cost of S_{heat}. RE estimated from $\eta_{P_E}(E_{total})\|_{\varepsilon_h}$
	58% (gas)						
Schwarz and Taylor (1995)	–	1.4–3.4%	US	Cross-section 1984–1985 SS: 1188	Double log	OLS	Measure of thermostat setting (T_i) and level of thermal insulation allows estimates of $\eta_{\varepsilon_h}(T_i)$ and $\eta_{\varepsilon_h}(S_{heat})$.
Haas et al. (1998)	–	15–48%	Austria	Cross-section SS: ~400	Double log	OLS	RE estimated from a number of sources, including $\eta_{P_E}(E_{heat})$, $\eta_{\varepsilon_c}(E_{heat})$ and $\eta_{\varepsilon_h}(E_{heat})$.
Guertin et al. (2003)	–	29–47%	Canada	Cross-section 1993 SS: 440 (188 gas; 252 elec.)	Double log	OLS	Use of frontier analysis to estimate ε_c. RE estimated from $\eta_{P_S}(S_{heat})$ where $P_S = P_E/\varepsilon_c$.

Table A.5: Estimated rebound effect for residential space heating using simple equation models (Table A5 in Sorrell et al., 2009)

Econometric estimates of the direct rebound effect for household heating using multi-equation models.

Author/year	Short-run rebound effect	Long-run rebound effect	Country	Data	Functional form	Estimation technique	Comments
Dubin and McFadden (1984)	25–31%		US	Cross-section 1975 SS: 313	Discrete-continuous	Logit (discrete) and instrumental variables (utilisation)	Electrically heated households. RE estimated from $\eta_{P_E}(E_{heat})$. No control for ε.
Nesbakken (2001)	15–55% (average 21%)		Norway	Cross-section 1990 SS: 551	Discrete-continuous	Logit (discrete) and instrumental variables (utilisation)	Various fuel combinations. RE estimated from $\eta_{P_E}(E_{heat})$. No control for ε.
Klein (1987, 1988)	25–29%		US	Pooled cross-section: 1973–81 SS: 2157	Household production	3SLS	Simultaneous estimation of a cost function for S, a demand function for S and an equation for the relative share of capital and fuel. RE estimated from $\eta_{P_S}(S_{heat})$, which in turn is estimated from $\eta_{P_G}(S_{heat})$.

Table A.6: Estimated rebound effect for residential space heating using multi-equation models (Table A6 in Sorrell et al., 2009)

Estimates of the direct rebound effect from quasi-experimental studies of household heating.

Authors	Location	Approach	Shortfall	Temperature take-back	Comments
Hirst et al. (1985)	USA	Before–after study of 79 households who received subsidies for efficiency improvements. Internal temperature changes estimated through analysis of billing data and external temperatures.		Mean 0.4 °C, but higher 1.3 °C for low-income households. Mean loss of 11% of potential savings.	No control group and risk of selection bias. Take-back estimates not statistically significant (high variance between households). Acknowledged inaccuracies in method of estimating internal temperatures.
Hirst (1987)	USA	Before–after study of 210 households who received subsidies for efficiency improvements. Compared to control group of 38 eligible non-participants. Internal temperature changes estimated through analysis of billing data and external temperatures.		Mean 0.2 °C for first year participants and 0.7 °C for second year participants. Mean loss of 5% and 25%, respectively of potential savings.	Selection bias. Take-back estimates not statistically significant (high variance between households). Acknowledged inaccuracies in method of estimating internal temperatures.
Hirst et al. (1989)	USA	Multiple regressions of before–after electricity bills and cross-sectional comparisons with household explanatory variables.	50% of potential savings.	20% of potential savings.	Illustrates influence of age of house on achieved savings. Unclear how savings estimates were obtained.
Dinan and Trumble (1989)	USA	Before–after monitoring of average internal temperatures of 310 households receiving subsidises for energy-efficiency improvements. Extensive collection of socio-economic and demographic data.		Mean 0.3 °C; but higher (0.4 °C) in low-income households. Mean loss of 5% of potential savings.	Monitored full heating year before and after efficiency improvement. Direct monitoring of internal temperature, but only in central living area. No control group. Results suggest both physical and behavioural factors contribute to take-back.
Megdal et al. (1993)	Southern USA	Estimates take-back for three household efficiency programmes using a combination of engineering evaluations and econometric techniques.		Mean 0.6–1.1 °C. Mean loss of 18–40% depending upon programme (higher for low-income groups).	Novel techniques and triangulation of results. But poorly described, so unclear how estimates obtained. Calibrating engineering models reduced the gap between actual and predicted savings by 10%.
Nadel (1993)	USA	Review of 9 utility evaluations of space heating-efficiency measures.		Median 0.14 °C. All < 0.5 °C.	Original studies not accessible. Little analysis of methodologies used. Few studies used a control group.
Milne and Boardman (2000)	UK and USA	Empirical analysis of before–after temperature measurements from 13 UK efficiency projects in mostly low-income households from the 1970s and 1980s.		Loss of potential energy savings depends upon initial whole-house average temperature: 50% for 14 °C, 30% for 16.5 °C, 20% for 19 °C and zero for 20 °C.	Small-scale studies covering short time periods and various types of energy-efficiency improvement. No control groups and data and methodologies not transparent. Results suggest that take-back varies with nature of energy efficiency improvement and that comfort depends on factors other than temperature.

Table A.7: Estimated rebound effect for residential space heating using quasi-experimental approaches (Table A9 in Sorrell et al., 2009)

Table A.7 (continued)

Henderson et al. (2003)	UK	Two before–after studies of participants in energy-efficiency programmes for electrically heated dwellings. First confined to statistical analysis of weather-corrected energy consumption in 8000 dwellings (two thirds low income). Second included internal temperature monitoring of 350 dwellings over short time period, together with supporting surveys.	Mean shortfall: First study 68%. Second study 60%.	0.4 °C take-back in second study, corresponding to ∼18% of potential savings (∼30% of shortfall).	No control groups and evidence of selection bias. First study found negative relationship between shortfall and energy use prior to installation, but no significant difference between income groups. Shortfall found to depend on factors other than behavioural response.
Energy Savings Trust (2004)	UK	Before–after comparison of gas consumption data from 499 low-income, gas-heated households for one year before and one year after space heating improvements.	Mean shortfall 55%.		No control group shortfall declines and savings rise in proportion to pre-installation fuel consumption. Results very sensitive to method chosen for weather correcting consumption data.
Oreszczyn et al. (2006)	UK	Monitoring of living room, bedroom and external temperatures in 1604 low-income households over 2–4 week periods over two winters. Includes 274 pre-intervention dwellings and 633 post-intervention (189 insulation improvements, 156 heating system improvements and 288 both).		1.6 °C rise in living room; 2.8 °C rise in bedrooms.	Cross-sectional study, but methodologically robust with large sample size. Wide variation in initial temperatures and larger take-back in dwellings with lower initial temperatures.
Hong et al. (2006)		Monitoring of living room and bedroom temperatures in 1372 low-income households over 2–4 week periods over two winters (692 pre and 568 post improvement and 112 pre- and post-). Monitoring of fuel consumption in 2659 households over same periods (1255 pre- and 1162 post-improvement and 242 pre- and post-).	Insulation resulted in 10% savings, but upgrade of boiler had no effect.	65–100% of potential savings as temperature take-back.	Cross-sectional study, but methodologically robust with large sample size. Larger take-back in dwellings with lower initial temperatures. Large shortfall due in part to poor installation of insulation and behavioural responses such as increased window in warmer properties.
Martin and Watson (2006)	UK	Measurement of fuel consumption and whole house internal temperatures in 59 low-income households for 12 weeks before and after insulation improvements.	Mean shortfall 55%.	Mean 0.57 °C (0.49 °C for low-income groups, but not significant) 10% of potential savings as temperature take-back	Small sample size and no control group.

Econometric estimates of the direct rebound effect for space cooling.

Author/year	Short-run rebound effect	Long-run rebound effect	Country	Data	Functional form	Estimation technique	Comments
Hausman (1979)	4%	26.5%	US	Cross-section 1978 SS: 46	Discrete-continuous	Nested logit (discrete) and instrumental variables (utilisation)	Room air-conditioners individually metered. RE estimated from $\eta_{\varepsilon_c}(E_{cool})$. Use of instrumental variables avoids endogeneity bias.
Dubin et al. (1986)	1–26%		US (Florida)	Cross-section 1981 SS: 214–396	Discrete-continuous	Nested logit (discrete) and instrumental variables (utilisation)	RE estimated from $\eta_\varepsilon(E)$. ε is a composite of ε_c and ε_h. Quasi-experimental design ensures ε_c is exogenous. Comprehensive data on structural characteristics allows ε_h to be estimated with an engineering model.

Table A.8: Estimated rebound effect for residential space heating using multi-equation models (Table A7 in Sorrell et al., 2009)

Econometric estimates of the direct rebound effect for other household energy services.

Author/year	Short-run rebound effect	Long-run rebound effect	Country	Data	Functional form	Estimation technique	Comments
Guertin et al. (2003)		34–38% (water) 32–49% (appliances/ lighting)	Canada	Cross-section 1993 SS: 440	Double log	OLS	ε_c estimated using frontier analysis. RE estimated from $\eta_{P_S}(S)$ where $P_S = P_E/\varepsilon_c$
Davis (2007)	<5.6 clothes washing		US	Panel 1997 SS: 98	Double log	Fixed effects	RE estimated from $\eta_{P_c}(S)$. Quasi-experimental study, so ε_c is exogenous.

Table A.9: Estimated rebound effect for other sources of residential energy consumption (Table A8 in Sorrell et al., 2009)

Author/year	Country	Production	ESUB	Efficiency %	Rebound %	Comments
Semboja (1994)	Kenya	CD–L	1 or 0	1	170–350	Simulations for energy production and use
Dufournaud et al. (1994)	Sudan	CES	0.2–0.4	100–200	54–59	Households only, well structured, extensive sensitivity analysis
Van Es et al. (1998)	Holland	CES	$0<\sigma<1$	100	15	Bottom-up feed database, explicit representation of efficiency improvements
Vikström (2004)	Sweden	CES	0.07–0.87	12–15	60	Dynamic simulations with counterfactual efficiency changes
Grepperud and Rasmussen (2004)	Norway	CES	$0<\sigma<1$	100 AAGR electricity or oil	<100	Dynamic simulations with counterfactual scenarios
Washida (2004)	Japan	CES	0.3–0.7	1	35–70	Sensitivity analysis reveals positive relation of rebound with ESUB
Glomsrod and Wei (2005)	China	CD, L, CES	1	NA	>100	Focused on limiting emissions with a tax on coal use
Hanley et al. (2005)	Scotland	CES	0.3	5	120	Open region approach with major energy exports
Allan et al. (2007)	UK	CES	0.3	5	30–50	Extensive sensitivity analysis

Abbreviations: CD: Cobb–Douglas, L: Leontief, ESUB: elasticity of substitution (σ), CES: constant ESUB, AAGR: average annual growth rates of energy productivity (per sector), NA: not available.

Table A.10: Studies adopting a CGE approach (Table 1 in Dimitropoulos, 2007)

Logit estimation results

	EKNOWN	INFO	TIME	PRIORITIY	UNCERT	RENTED	PURCH	ENERGY	SIZE	CONSTANT	N	'Pseudo' R^2
Small commercial businesses and trade												
Agriculture	−0.52 (0.38)	0.23 (0.42)	−0.16 (0.39)	−0.66 (0.43)	0.56 (0.40)	−0.97 (1.21)	1.34 (0.97)	0.37[a] (0.22)	0.03 (0.02)	−4.73[a] (2.59)	148	0.13
Bakeries	−0.37 (0.56)	−0.58 (0.55)	−0.86 (0.57)	0.34 (0.55)	−0.40 (0.55)	−1.07[a] (0.68)	−1.16 (1.06)	0.11 (0.31)	0.11[a] (0.05)	−0.18 (3.39)	88	0.22
Butchers	−0.13 (0.63)	−0.62 (0.69)	−0.31 (0.81)	−1.50[a] (0.76)	1.04 (0.76)	−1.09[a] (0.67)	0.18 (1.08)	−0.01 (0.47)	0.07 (0.08)	1.12 (5.09)	76	0.22
Car repair industry	−0.80 (0.54)	0.73 (0.61)	0.37 (0.59)	0.42 (0.56)	−0.66 (0.57)	−0.86 (0.66)	−0.53 (1.06)	−0.03 (0.31)	0.14[a] (0.06)	−0.65 (3.28)	78	0.28
Construction	−0.98[a] (0.48)	−0.16 (0.58)	−0.70 (0.49)	−0.27 (0.47)	0.25 (0.47)	−1.24[a] (0.75)		−0.03 (0.24)	0.02 (0.02)	−0.37 (2.20)	98	0.18
Horticulture	−2.21[a] (0.90)	−1.65[a] (0.85)	−0.71 (0.72)	−0.34 (0.77)	1.24 (0.83)	0.13 (1.49)		0.05 (0.41)	0.00 (0.00)	−2.16 (2.76)	57	0.38
Laundries and dry cleaners	−0.51 (0.68)	−0.65 (0.77)	−1.34[a] (0.73)	−0.51 (0.69)	−0.26 (0.71)	−0.59 (0.87)		−0.03 (0.41)	0.06[a] (0.03)	−0.09 (4.53)	66	0.39
Metal industry	−0.93[a] (0.51)	0.69 (0.56)	0.09 (0.56)	−0.33 (0.49)	0.29 (0.49)	−1.58[b] (0.57)	0.36 (0.77)	0.20 (0.26)	0.03 (0.04)	−3.64 (2.68)	116	0.21
Retail trade	−0.69[a] (0.29)	0.37 (0.34)	−0.23 (0.34)	−0.27 (0.31)	−0.18 (0.30)	−1.91[b] (0.33)	0.79 (0.58)	0.27[a] (0.17)	0.00[a] (0.00)	−3.61[a] (1.72)	291	0.29
Wholesale trade	−0.91[a] (0.40)	1.08[a] (0.50)	−0.76 (0.49)	0.41 (0.45)	−0.55 (0.43)	−2.54[b] (0.61)	0.65 (0.81)	0.18 (0.19)	0.00 (0.00)	−2.90[a] (2.05)	164	0.31
Wood working and processing	−0.07 (0.49)	−0.03 (0.57)	−0.69 (0.50)	−1.05[a] (0.51)	0.75 (0.49)	−0.13 (0.66)	0.39 (0.78)	0.06 (0.25)	0.05 (0.05)	−1.00 (2.68)	94	0.18
Public and private services organisations												
Banks and insurance companies	−0.48 (0.44)	−1.02[a] (0.48)	−0.47 (0.44)	−0.03 (0.50)	0.88[a] (0.42)	−1.49[b] (0.50)	−0.48 (0.61)	−0.02 (0.23)	0.00 (0.00)	1.15 (2.13)	126	0.26
Gastronomy	−1.16[a] (0.54)	−1.16[a] (0.65)	0.49 (0.59)	−0.29 (0.51)	−0.05 (0.51)	−1.29[a] (0.54)	0.11 (1.27)	−0.17 (0.32)	0.03 (0.02)	0.59 (3.36)	102	0.27
Hospitals	−0.31 (0.57)	−1.17 (0.85)	−0.05 (0.55)	−1.51[a] (0.66)	−0.03 (0.54)	−0.41 (1.44)	−0.14 (0.93)	0.41 (0.45)	0.00 (0.00)	−1.77 (4.81)	79	0.26
Hotel industry	0.27 (0.40)	0.05 (0.47)	−0.51 (0.44)	0.10 (0.43)	0.61 (0.44)	−1.13[a] (0.57)	0.80 (0.74)	0.09 (0.29)	0.01 (0.01)	−1.45 (3.02)	128	0.14
Non-commercial organisations	−0.53 (0.41)	0.01 (0.56)	−0.87[a] (0.49)	−0.22 (0.42)	−0.73[a] (0.42)	−1.15 (0.76)		0.14 (0.25)	0.02[b] (0.01)	−1.62 (2.46)	126	0.36
Public administration	−0.70 (0.52)	−2.09[a] (0.92)	−0.00 (0.63)	−1.11[a] (0.51)	0.29 (0.51)	−1.76[a] (0.86)	0.27 (0.88)	0.00 (0.29)	0.00 (0.00)	−0.25 (2.84)	93	0.32
Schools	−1.11[a] (0.54)	−1.76[b] (0.66)	0.54 (0.57)	−0.49 (0.52)	−0.23 (0.51)	1.36 (0.96)	2.51[b] (0.98)	0.49[a] (0.29)	0.00[a] (0.00)	−4.99[a] (2.46)	92	0.33
Services	−0.78 (0.65)	−0.56 (0.72)	−0.45 (0.62)	0.38 (0.60)	0.08 (0.61)	−2.06[b] (0.66)	0.42 (0.81)	−0.20 (0.44)	0.03 (0.03)	0.72 (4.04)	76	0.31

'Pseudo' R^2 is the Nagelkerke coefficient of determination.

[a] Individually statistically significant at least at 10% level.

[b] Individually statistically significant at least at 1% level.

Table A.11: Logit estimations of barriers to energy efficiency for 19 sub-sectors in the German economy (Table 3 in Schleich and Gruber, 2008)

Appendix B

Demonstrations

In this Appendix are shown some of the derivations of the formulas reported in the main corpus of this work.

Derivation 1.

In Saunders (2000 - b) replacing the steady state levels of per capita energy services (x) and consumption-investment goods ($\hat{O}$), yields:

$$e^* = \hat{O}^{*\frac{\alpha-1}{\alpha}} \varepsilon x^{*\frac{1}{\alpha}}.$$

To get the elasticity of energy use with respect to energy intensity, which corresponds to a measure of the rebound effect, it is necessary to differentiate e^* with respect to ε. Remembering that both x and $\hat{O}$ are functions of ε, it is:

$$\begin{aligned}
\frac{\partial e^*}{\partial \varepsilon} &= \hat{O}^{*\frac{\alpha-1}{\alpha}} x^{*\frac{1}{\alpha}} + \frac{\alpha-1}{\alpha}\hat{O}^{*\frac{\alpha-1}{\alpha}-1} \varepsilon x^{*\frac{1}{\alpha}} \cdot \frac{\partial \hat{O}^*}{\partial \varepsilon} + \frac{1}{\alpha}\hat{O}^{*\frac{\alpha-1}{\alpha}} \varepsilon x^{*\frac{1}{\alpha}-1} \cdot \frac{\partial x^*}{\partial \varepsilon} \\
&= \frac{e^*}{\varepsilon} + \frac{\alpha-1}{\alpha}\hat{O}^{*\frac{\alpha-1}{\alpha}} x^{*\frac{1}{\alpha}} \cdot \frac{\varepsilon}{\hat{O}^*}\frac{\partial \hat{O}^*}{\partial \varepsilon} + \frac{1}{\alpha}\hat{O}^{*\frac{\alpha-1}{\alpha}} x^{*\frac{1}{\alpha}} \cdot \frac{\varepsilon}{x^*}\frac{\partial x^*}{\partial \varepsilon} \\
&= \frac{e^*}{\varepsilon} + \frac{\alpha-1}{\alpha}\frac{e^*}{\varepsilon} \cdot \frac{\varepsilon}{\hat{O}^*}\frac{\partial \hat{O}^*}{\partial \varepsilon} + \frac{1}{\alpha}\frac{e^*}{\varepsilon} \cdot \frac{\varepsilon}{x^*}\frac{\partial x^*}{\partial \varepsilon}.
\end{aligned}$$

Then, dividing both sides by e^*/ε, and substituting (1.5), gives:

$$\begin{aligned}
\frac{\partial e^*}{\partial \varepsilon}\frac{\varepsilon}{e^*} &= 1 + \frac{\alpha-1}{\alpha}\frac{\varepsilon}{\hat{O}^*}\frac{\partial \hat{O}^*}{\partial \varepsilon} + \frac{1}{\alpha}\left(-\frac{1-\beta}{1-\beta-\gamma}\right)\alpha \\
&= 1 - \frac{1-\beta}{1-\beta-\gamma} + \frac{\alpha-1}{\alpha}\frac{\varepsilon}{\hat{O}^*}\frac{\partial \hat{O}^*}{\partial \varepsilon}.
\end{aligned}$$

Derivation 2.

In Saunders (2000 - b) the time dynamic expansion of Y is defined as:

$$\dot{Y} = \frac{1}{Y}\frac{dY}{dt} = \frac{\partial Y}{\partial K}\frac{K}{Y}\dot{K} + \frac{\partial Y}{\partial L}\frac{L}{Y}\dot{L} + \frac{\partial Y}{\partial \hat{K}}\frac{\hat{K}}{Y}\dot{\hat{K}} + \frac{\partial Y}{\partial \hat{L}}\frac{\hat{L}}{Y}\dot{\hat{L}} + \frac{\partial Y}{\partial F}\frac{F}{Y}\dot{F} + \frac{\partial Y}{\partial \tau}\frac{\tau}{Y}\dot{\tau};$$

by taking all the partial derivatives it gives:

$$\begin{aligned}
\dot{Y} = {} & \alpha\alpha K^{\alpha-1}L^{\beta}E^{1-\alpha-\beta}\cdot\frac{K}{Y}\cdot\dot{K} + \alpha\beta K^{\alpha}L^{\beta-1}E^{1-\alpha-\beta}\cdot\frac{L}{Y}\cdot\dot{L} \\
& + \alpha(1-\alpha-\beta)K^{\alpha}L^{\beta}E^{-\alpha-\beta}\cdot\tau\gamma\hat{K}^{\gamma-1}\hat{L}^{\delta}F^{1-\gamma-\delta}\cdot\frac{\hat{K}}{Y}\cdot\dot{\hat{K}} \\
& + \alpha(1-\alpha-\beta)K^{\alpha}L^{\beta}E^{-\alpha-\beta}\cdot\tau\delta\hat{K}^{\gamma}\hat{L}^{\delta-1}F^{1-\gamma-\delta}\cdot\frac{\hat{L}}{Y}\cdot\dot{\hat{L}} \\
& + \alpha(1-\alpha-\beta)K^{\alpha}L^{\beta}E^{-\alpha-\beta}\cdot\tau(1-\gamma-\delta)\hat{K}^{\gamma}\hat{L}^{\delta}F^{-\gamma-\delta}\cdot\frac{F}{Y}\cdot\dot{F} \\
& + \alpha(1-\alpha-\beta)K^{\alpha}L^{\beta}E^{-\alpha-\beta}(1-\gamma-\delta)\hat{K}^{\gamma}\hat{L}^{\delta}F^{1-\gamma-\delta}\cdot\frac{\tau}{Y}\cdot\dot{\tau}.
\end{aligned}$$

Now rearrange terms a little bit:

$$\begin{aligned}
\dot{Y} = {} & \alpha\frac{\alpha K^{\alpha}L^{\beta}E^{1-\alpha-\beta}}{Y}\cdot\dot{K} + \beta\frac{\alpha K^{\alpha}L^{\beta}E^{1-\alpha-\beta}}{Y}\cdot\dot{L} \\
& + (1-\alpha-\beta)\frac{\alpha K^{\alpha}L^{\beta}E^{-\alpha-\beta}\cdot\gamma\tau\hat{K}^{\gamma}\hat{L}^{\delta}F^{1-\gamma-\delta}}{Y}\cdot\dot{\hat{K}} \\
& + (1-\alpha-\beta)\frac{\alpha K^{\alpha}L^{\beta}E^{-\alpha-\beta}\cdot\delta\tau\hat{K}^{\gamma}\hat{L}^{\delta}F^{1-\gamma-\delta}}{Y}\cdot\dot{\hat{L}} \\
& + (1-\alpha-\beta)\frac{\alpha K^{\alpha}L^{\beta}E^{-\alpha-\beta}\cdot(1-\gamma-\delta)\tau\hat{K}^{\gamma}\hat{L}^{\delta}F^{1-\gamma-\delta}}{Y}\cdot\dot{F} \\
& + (1-\alpha-\beta)\frac{\alpha K^{\alpha}L^{\beta}E^{-\alpha-\beta}\cdot\tau\hat{K}^{\gamma}\hat{L}^{\delta}F^{1-\gamma-\delta}}{Y}\cdot\dot{\tau}
\end{aligned}$$

Remembering that $Y = \alpha K^{\alpha}L^{\beta}E^{1-\alpha-\beta}$, and $E = \tau\hat{K}^{\gamma}\hat{L}^{\delta}F^{1-\gamma-\delta}$, it is:

$$\begin{aligned}
\dot{Y} = {} & \alpha\dot{K} + \beta\dot{L} + (1-\alpha-\beta)\frac{\alpha K^{\alpha}L^{\beta}E^{-\alpha-\beta}\cdot\gamma\cdot E}{Y}\cdot\dot{\hat{K}} \\
& + (1-\alpha-\beta)\frac{\alpha K^{\alpha}L^{\beta}E^{-\alpha-\beta}\cdot\delta\cdot E}{Y}\cdot\dot{\hat{L}} \\
& + (1-\alpha-\beta)\frac{\alpha K^{\alpha}L^{\beta}E^{-\alpha-\beta}\cdot(1-\gamma-\delta)\cdot E}{Y}\cdot\dot{F} \\
& + (1-\alpha-\beta)\frac{\alpha K^{\alpha}L^{\beta}E^{1-\alpha-\beta}}{Y}\cdot\dot{\tau} \\
= {} & \alpha\dot{K} + \beta\dot{L} + (1-\alpha-\beta)\gamma\dot{\hat{K}} + (1-\alpha-\beta)\delta\dot{\hat{L}} \\
& + (1-\alpha-\beta)(1-\gamma-\delta)\dot{F} + (1-\alpha-\beta)\dot{\tau}.
\end{aligned}$$

Recall that $\dot{Y} = \dot{K} = r$, $\dot{\hat{K}} = \hat{k}$, $\dot{F} = f$ and $\dot{\hat{L}} = \hat{n}$; and given that Saunders shows that $\dot{Y} = \dot{\hat{K}} = \hat{k} = r$ as well as $\hat{n} = n$, and $\dot{\tau} = \mu$, the expression becomes:

$$f = \alpha f + \beta n + (1-\alpha-\beta)\gamma f + (1-\alpha-\beta)\delta n +$$
$$(1-\alpha-\beta)(1-\gamma-\delta)f + (1-\alpha-\beta)\mu;$$
$$f(1-\alpha-(1-\alpha-\beta)\gamma-(1-\alpha-\beta)(1-\gamma-\delta))$$
$$= n(\beta+(1-\alpha-\beta)\delta) + (1-\alpha-\beta)\mu;$$
$$f(\delta(1-\alpha-\beta)+\beta) = n(\delta(1-\alpha-\beta)+\beta) + (1-\alpha-\beta)\mu;$$
$$f = n + \frac{1-\alpha-\beta}{\delta(1-\alpha-\beta)+\beta}\mu.$$

Derivation 3.

In Jaffe and Stavins (1994) the first problem considered is that of the maximization of profits by the builder who has to decide whether to adopt energy-efficiency measures, and it is given by (2.1).

The first-order conditions imply the benefits deriving from the installation (in terms of increased selling price of the house) equal (exceed) the overall cost of adoption, and are represented by the expression:

$$\delta \cdot (1-w) \cdot G(k_{iJT}, \mu_{ijT}) + \gamma D_{iT} \geq L(C_{iT}, S_{ijT}, \nu_{iT}) - X_{iT},$$

where $G(\cdot)$ is the expected discounted present value of $g(\cdot)$, and it is assumed to have a Cobb-Douglas form for simplicity.

Defining k_{jt}^m the m-th element of the vector k_{ijt}, in particular it is $k_{ijt}^1 = P_{ijt}$ the price of energy. Moreover, the other elements in k_{ijt} are assumed to be constant or to be such that agents have static expectations on them (so that $k_{jt}^m = k_{JT}^m, \forall t > T$, for $m = 2, ..., M$).

Now it is possible to express $G(\cdot)$ as:

$$G(\cdot) = \left[\int_T^\infty (P_{ijt})e^{-rt}dt\right]^{\beta_1} \cdot \left[\prod_{m=2}^{M} (k_{JT}^m)^{\beta_m}\right] \cdot \mu_{ijT}.$$

The vector k_{ijt} is technology-specific, but typically it would include variables as number of rooms, number of heating degree-days in the area, income and education of homeowner, etc.

The cost-of-installation function $L(\cdot)$ is assumed to present a decrease as either builder's knowledge or diffusion of the technology in the jurisdiction increase. This is obtained with the following form:

$$L(\cdot) = (C_{iT})^{\alpha_1} \cdot (\nu_{iT})^{\alpha_2} \cdot \left(\frac{S_{ijT}}{\alpha \quad 3}\right)^{\alpha_4}.$$

Here α_2 is the cost sensitivity to installation diffusion, α_3 is the 'average' experience, while α_4 is the sensitivity to the builder's experience with respect to the typical one.

Now, dividing the F.O.C. by the right-hand side, it is possible to rewrite them as a benefit/cost ratio:

$$\left[\frac{\delta \cdot (1-w) \cdot G(k_{iJT}, \mu_{ijT}) + \gamma D_{iT}}{L(C_{iT}, S_{ijT}, \nu_{iT}) - X_{iT}}\right] \geq 1.$$

Substituting the functional forms previously introduced, and taking the natural logarithm for simplicity yields (2.2).

Derivation 4.

The second problem analysed by Jaffe and Stavins (1994), is a cost minimization by the homeowner expressed in (2.3). First- and second-order conditions implied that $\partial PV(T)/\partial T \geq 0$, so taking the derivative with respect to T of (2.3), remembering that the derivative of an integral corresponds to the function inside the integral, dividing everything by e_{-rt}, and rearranging terms gives:

$$\begin{aligned}(1 - \delta \cdot w) g(k_{ijT}, \mu_{ijT}) + \gamma D_{iT} \geq r\left[L(C_{iT}, V_{iT}) - X_{iT}\right] \\ - \left(\frac{\partial L}{\partial C_{iT}} \frac{\partial C_{iT}}{\partial T}\right) - \left(\frac{\partial L}{\partial V_{iT}} \frac{\partial V_{iT}}{\partial T}\right) + \left(\frac{\partial X_{iT}}{\partial T}\right),\end{aligned}$$

where $-\delta w$ is used to discount annual energy costs that will take place after the adoption.

Then, define $g(\cdot)$ and $L(\cdot)$ as:

$$g(\cdot) = P_{ijT} \cdot \sum_{m=2}^{M} \beta_m k_{ijT}^{m} + \mu_{ijT};$$

$$L(\cdot) = \alpha_3 + \alpha_1 C_{iT} + \alpha_2 V_{iT}.$$

Substituting these into the equation previously derived and taking the partial derivatives of L with respect to C_{iT} and V_{iT}, yields equation (2.4).

APPENDIX C

EXPERIMENTS

C.1 STUDENTS' EXPERIMENT

The experiment was divided in two treatments, one presenting the question before assuming the decision has to be taken today and then in one year (the 'Now-Future' treatment), and the other where first is presented the problem in one year and then today (the 'Future-Now' treatment). Questionnaires were randomly distributed, meaning that students were assigned to one treatment or the other at random.

The introduction providing all the relevant information concerning the bulbs, the lighting spot and the cost of electricity was displayed on a screen for the entire duration of the experiment. It says:

> Consider the bulb of a central lighting spot of your house (for example one in the kitchen). The average use is of 5.5 hours per day (corresponding to 2000 hours a year, more or less). The cost of electricity is 0.1547 €/kWh. For such lighting spot the annual expenditure for electricity consumption is: 1.7€with a LED bulb, 2.8€with a CFL (energy saving) bulb, and 12.4€with a halogen bulb. The expected duration of life is 15000 hours for the LED bulb, 10000 hours for the CFL bulb and 2000 hours for the halogen bulb (corresponding respectively to 7.5 years, 5 years and 1 years at the considered use rate).

Then, the two treatments were designed as follows.

'Now-Future' Treatment

First are presented the questions assuming the substitution of the bulb and the purchase decision occur immediately. Then, to give a little brake, the questions presenting the decision between bulbs and washing machines to investigate relative - absolute thinking are inserted. Finally, the attention is brought back to intertemporal choices, assuming substitution and purchase occur in one year from now.

> Q1. You have to change the bulb of such lighting spot **today**. What extra amount "X" are you willing to pay **now** for a LED bulb that consumes 80% less energy than a halogen bulb which costs 1.39€?
>
> Q2. You have to change the bulb of such lighting spot **today**. What extra amount "X" are you willing to pay **now** for a LED bulb that consumes 40% less energy than a CFL (energy saving) bulb which costs 4.40€?
>
> Q3. You have to change the bulb of such lighting spot **today**. What extra amount "X" are you willing to pay **now** for a LED bulb that consumes 80% less energy than a halogen bulb which costs 2.95€?
>
> Q4. You have to change the bulb of such lighting spot **today**. What extra amount "X" are you willing to pay **now** for a LED bulb that consumes 40% less energy than a CFL (energy saving) bulb which costs 6.40€?
>
> Q5. Consider two bulbs: a LED bulb that costs 7.90€, and a CFL (energy saving) bulb that costs 4.40€. The LED bulb consumes 40% less energy with respect to the CFL one.
> Consider two washing machines: one in energy class A+++ that costs 450€, and one in energy class A+ that costs 270€. The A+++ washing machine consumes 20% less energy than the A+ one.
> Both bulbs and washing machines have at least a 2-years warranty.
>
> Assume you have to by a bulb (for a central lighting spot of your house, for example the kitchen) and a washing machine, of which at least one with a greater energy efficiency. For which product would you be willing to pay a higher cost to get a greater energy efficiency?
>
> 1) Bulb
> 2) Washing Machine
> 3) Both

Q6. Consider two bulbs: a LED bulb that consume 3.63 kWh a year (calculated for a use rate of 2 hours a day every day, or 11 kWh a year for a use rate of 5.5 hours/day) and costs 7.90€, and a CFL (energy saving) bulb that consume 5.94 kWh a year (or 18 kWh a year) and costs 4.40€.
Consider two washing machines: one in energy class A+++ that consumes 153 kWh a year (calculated on 220 standard washes, corresponding to 660 hours) and costs 450€, and one in energy class A+ that consumes 196 kWh a year and costs 270€.
Both bulbs and washing machines have at least a 2-years warranty.

Assume you have to by a bulb (for a central lighting spot of your house, for example the kitchen) and a washing machine, of which at least one with a greater energy efficiency. For which product would you be willing to pay a higher cost to get a greater energy efficiency?

1) Bulb
2) Washing Machine
3) Both

Q7. **In one year from now** you will have to change the bulb of such lighting spot. What extra amount "X" will you be willing to pay **next year** for a LED bulb that consumes 80% less energy than a halogen bulb which costs 1.39€?

Q8. **In one year from now** you will have to change the bulb of such lighting spot. What extra amount "X" will you be willing to pay **next year** for a LED bulb that consumes 40% less energy than a CFL (energy saving) bulb which costs 4.40€?

Q9. **In one year from now** you will have to change the bulb of such lighting spot. What extra amount "X" will you be willing to pay **next year** for a LED bulb that consumes 80% less energy than a halogen bulb which costs 2.95€?

Q10. **In one year from now** you will have to change the bulb of such lighting spot. What extra amount "X" will you be willing to pay **next year** for a LED bulb that consumes 40% less energy than a CFL (energy saving) bulb which costs 6.40€?

'Future-Now' Treatment

In this case the other in which intertemporal choices are presented is inverted, putting first the decisions in one year from now, and then today. Again, the relative-absolute thinking part is inserted in the middle of the two.

Q1. **In one year from now** you will have to change the bulb of such lighting spot. What extra amount "X" will you be willing to pay **next year** for a LED bulb that consumes 80% less energy than a halogen bulb which costs 1.39€?

Q2. **In one year from now** you will have to change the bulb of such lighting spot. What extra amount "X" will you be willing to pay **next year** for a LED bulb that consumes 40% less energy than a CFL (energy saving) bulb which costs 4.40€?

Q3. **In one year from now** you will have to change the bulb of such lighting spot. What extra amount "X" will you be willing to pay **next year** for a LED bulb that consumes 80% less energy than a halogen bulb which costs 2.95€?

Q4. **In one year from now** you will have to change the bulb of such lighting spot. What extra amount "X" will you be willing to pay **next year** for a LED bulb that consumes 40% less energy than a CFL (energy saving) bulb which costs 6.40€?

Q5. Consider two bulbs: a LED bulb that costs 7.90€, and a CFL (energy saving) bulb that costs 4.40€. The LED bulb consumes 40% less energy with respect to the CFL one.
Consider two washing machines: one in energy class A+++ that costs 450€, and one in energy class A+ that costs 270€. The A+++ washing machine consumes 20% less energy than the A+ one.
Both bulbs and washing machines have at least a 2-years warranty.

Assume you have to by a bulb (for a central lighting spot of your house, for example the kitchen) and a washing machine, of which at least one with a greater energy efficiency. For which product would you be willing to pay a higher cost to get a greater energy efficiency?

1) Bulb
2) Washing Machine
3) Both

Q6. Consider two bulbs: a LED bulb that consume 3.63 kWh a year (calculated for a use rate of 2 hours a day every day, or 11 kWh a year for a use rate of 5.5 hours/day) and costs 7.90€, and a CFL (energy saving) bulb that consume 5.94 kWh a year (or 18 kWh a year) and costs 4.40€.
Consider two washing machines: one in energy class A+++ that consumes 153 kWh a year (calculated on 220 standard washes, corresponding to 660 hours) and costs 450€, and one in energy class A+ that consumes 196 kWh a year and costs 270€.
Both bulbs and washing machines have at least a 2-years warranty.

Assume you have to by a bulb (for a central lighting spot of your house, for example the kitchen) and a washing machine, of which at least one with a greater energy efficiency. For which product would you be willing to pay a higher cost to get a greater energy efficiency?

1) Bulb
2) Washing Machine
3) Both

Q7. You have to change the bulb of such lighting spot **today**. What extra amount "X" are you willing to pay **now** for a LED bulb that consumes 80% less energy than a halogen bulb which costs 1.39€?

Q8. You have to change the bulb of such lighting spot **today**. What extra amount "X" are you willing to pay **now** for a LED bulb that consumes 40% less energy than a CFL (energy saving) bulb which costs 4.40€?

Q9. You have to change the bulb of such lighting spot **today**. What extra amount "X" are you willing to pay **now** for a LED bulb that consumes 80% less energy than a halogen bulb which costs 2.95€?

Q10. You have to change the bulb of such lighting spot **today**. What extra amount "X" are you willing to pay **now** for a LED bulb that consumes 40% less energy than a CFL (energy saving) bulb which costs 6.40€?

Tables and Results

Here are presented the tables reporting all the results of the tests conducted in order to investigate statistical significance of hyperbolic discounting and magnitude effects analysed in the main corpus of this work.

The values displayed in the tables are the one reported in Table 4.1. In addition, are shown the p-values from the Wilcoxon Signed Ranks test, and a brief description of what we can conclude from such p-values in terms of the significance of the effects under investigation.

	1 Year (FN)	Today (NF)	p-value	Conclusions
Halogen 1.39€	2.361	2.0851	0.5912	It is not possible to reject H_0 at the 5% significance level. The averages are not statistically different.
Halogen 2.95€	3.6797	2.6698	0.1217	It is not possible to reject H_0 at the 5% significance level. The averages are not statistically different.
CFL 4.40€	3.1438	2.2221	0.1687	It is not possible to reject H_0 at the 5% significance level. The averages are not statistically different.
CFL 6.40€	4.0438	2.4771	0.02196	It is possible to reject H_0 at the 5% significance level. The average today is statistically smaller than the average in one year.

Treatment to which the values belong to in parenthesis

Table C.1: Hyperbolic discounting in the students' experiment.

Halo 2.95€	Halo 1.39€	p-value	Conclusions
When the comparison takes place today			
2.6698 (NF)	2.0851 (NF)	0.01969	It is possible to reject H_0 at the 5% significance level. The average willingness to pay is statistically lower when the comparison is with the bulb that costs 1.39€ than when it is with the 2.95€ one. For a reduction in price of -52.88% agents are willing to spend 22% less
3.5906 (FN)	2.6271 (FN)	0.0047	It is possible to reject H_0 at the 1% significance level. The average willingness to pay is statistically lower when the comparison is with the bulb that costs 1.39€ than when it is with the 2.95€ one. For a reduction in price of -52.88% agents are willing to spend 26.83% less
When the comparison takes place in one year from now			
2.7866 (NF)	2.3527 (NF)	0.016	It is possible to reject H_0 at the 5% significance level. The average willingness to pay is statistically lower when the comparison is with the bulb that costs 1.39€ than when it is with the 2.95€ one. For a reduction in price of -52.88% agents are willing to spend 15.57% less
3.6797 (FN)	2.3611 (FN)	0.0003154	It is possible to reject H_0 at the 1% significance level. The average willingness to pay is statistically lower when the comparison is with the bulb that costs 1.39€ than when it is with the 2.95€ one. For a reduction in price of -52.88% agents are willing to spend 35.83% less

Treatment to which the values belong to in parenthesis

Table C.2: Magnitude effect for the comparison with halogen bulbs in the students' experiment.

CFL 6.40€	CFL 4.40€	p-value	Conclusions
When the comparison takes place today			
2.4771 (NF)	2.2221 (NF)	0.183	It is not possible to reject H_0 at the 5% significance level. The average willingness to pay is not statistically different.
3.7188 (FN)	2.8894 (FN)	0.00074	It is possible to reject H_0 at the 1% significance level. The average willingness to pay is statistically lower when the comparison is with the bulb that costs 4.40€ than when it is with the 6.40€ one. For a reduction in price of -31.25% agents are willing to spend 22.30% less
When the comparison takes place in one year from now			
2.2325 (NF)	2.1968 (NF)	0.3033	It is not possible to reject H_0 at the 5% significance level. The average willingness to pay is not statistically different.
4.0438 (FN)	3.1438 (FN)	0.0016	It is possible to reject H_0 at the 1% significance level. The average willingness to pay is statistically lower when the comparison is with the bulb that costs 4.40€ than when it is with the 6.40€ one. For a reduction in price of -31.25% agents are willing to spend 22.26% less

Treatment to which the values belong to in parenthesis

Table C.3: Magnitude effect for the comparison with CFL bulbs in the students' experiment.

	Relative (NF)	Absolute (NF)	Relative (FN)	Absolute (FN)
Bulb	12	9	7	9
Washing Machine	14	6	14	16
Both	6	15	12	8

Table C.4: Absolute vs. Relative thinking in the experiment with students

C.2 ONLINE EXPERIMENT

The experiment has been distributed through a famous online platform for surveys and questionnaire. Participants were told the assignment consisted in a brief experiment on energy efficiency, which would take ten minutes to be completed. The reward was set at 1$ for the correct completion. They were also informed that some control checks were present, and that their failure meant the rejection of the assignment and the consequent not awarding of the reward.

Also the online experiment is divided in the 'Now-Future' and 'Future-Now' treatments, and again respondents were randomly assigned to one or the other. At the beginning of both treatments a short introduction was displayed, reminding participants that in completing the questionnaire they were not required to process exact calculations:

> This is a brief experiment to see consumers' choices when it comes to decide how much they are willing to pay for energy efficiency. It is made of 15 questions, and should take no more than 10 minutes to be completed. As this is not a mathematical problem to be solved, you can give your intuition to answer the questions, you are not required to process exact calculations.

Differently from the experiment conducted with students, here the paragraph with all relevant information regarding bulbs and the lighting spot is repeated at the beginning of all the pages displaying intertemporal problems. Again, the relative-absolute thinking questions are inserted as a break between such problems, but, since the time periods are now two and not just two (as there is also the option in six months), the two formulation in relative and absolute terms have been separated. In addition, the tree options which are proposed ('Bulb', 'Washing Machine' and 'Both') have been randomized, so that they were not always displayed in the same order. This was done to avoid participants to choose an answer only in reason if its position.

A control question has been introduced in order to see whether a respondent put enough attention in taking the experiment. If a participant failed the control he was not paid, and his/her answers not taken into consideration for the analysis.

At the end of the survey, those who passed the attention check were presented with some demographic questions to gather some pieces of information regarding their gender, age, country of origin and residence, and level of education.

'Now-Future' Treatment

Consider the bulb of a central lighting spot of your house (for example one in the kitchen). The average use is of 5.5 hours per day (corresponding to 2000 hours a year, more or less). The expected duration of life is 15000 hours for a LED bulb, 10000 hours for a CFL bulb and 2000 hours for a halogen bulb (corresponding respectively to 7.5 years, 5 years and 1 year at the considered use rate).

Q1. You have to change the bulb of such lighting spot **today**. What extra amount "X" are you willing to pay **now** for a LED bulb that consumes 80% less energy than a halogen bulb which costs 1.39$?

Q2. You have to change the bulb of such lighting spot **today**. What extra amount "X" are you willing to pay **now** for a LED bulb that consumes 40% less energy than a CFL (energy saving) bulb which costs 4.40$?

Q3. You have to change the bulb of such lighting spot **today**. What extra amount "X" are you willing to pay **now** for a LED bulb that consumes 80% less energy than a halogen bulb which costs 2.95$?

Q4. You have to change the bulb of such lighting spot **today**. What extra amount "X" are you willing to pay **now** for a LED bulb that consumes 40% less energy than a CFL (energy saving) bulb which costs 6.40$?

Q5. Consider two bulbs: a LED bulb that costs 7.90$, and a CFL (energy saving) bulb that costs 4.40$. The LED bulb consumes 40% less energy with respect to the CFL one.
Consider two washing machines: one in energy class A+++ that costs 450$, and one in energy class A+ that costs 270$. The A+++ washing machine consumes 20% less energy than the A+ one.
Both bulbs and washing machines have at least a 2-years warranty.

Assume you have to by a bulb (for a central lighting spot of your house, for example the kitchen) and a washing machine, of which at least one with a greater energy efficiency. For which product would you be willing to pay a higher cost to get a greater energy efficiency?

1) Bulb

2) Washing Machine
3) Both

Consider the bulb of a central lighting spot of your house (for example one in the kitchen). The average use is of 5.5 hours per day (corresponding to 2000 hours a year, more or less). The expected duration of life is 15000 hours for a LED bulb, 10000 hours for a CFL bulb and 2000 hours for a halogen bulb (corresponding respectively to 7.5 years, 5 years and 1 year at the considered use rate).

Q6. **In six months from now** you will have to change the bulb of such lighting spot. What extra amount "X" will you be willing to pay **in six months** for a LED bulb that consumes 80% less energy than a halogen bulb which costs 1.39$?

Q7. **In six months from now** you will have to change the bulb of such lighting spot. What extra amount "X" will you be willing to pay **in six months** for a LED bulb that consumes 40% less energy than a CFL (energy saving) bulb which costs 4.40$?

Q8. **In six months from now** you will have to change the bulb of such lighting spot. What extra amount "X" will you be willing to pay **in six months** for a LED bulb that consumes 80% less energy than a halogen bulb which costs 2.95$?

Q9. **In six months from now** you will have to change the bulb of such lighting spot. What extra amount "X" will you be willing to pay **in six months** for a LED bulb that consumes 40% less energy than a CFL (energy saving) bulb which costs 6.40$?

Q10. Consider two bulbs: a LED bulb that consume 3.63 kWh a year (calculated for a use rate of 2 hours a day every day, or 11 kWh a year for a use rate of 5.5 hours/day) and costs 7.90$, and a CFL (energy saving) bulb that consume 5.94 kWh a year (or 18 kWh a year) and costs 4.40$.
Consider two washing machines: one in energy class A+++ that consumes 153 kWh a year (calculated on 220 standard washes, corresponding to 660 hours) and costs 450$, and one in energy class A+ that consumes 196 kWh a year and costs 270$.
Both bulbs and washing machines have at least a 2-years warranty.

Assume you have to by a bulb (for a central lighting spot of your house, for example the kitchen) and a washing machine, of which at least one with a greater energy efficiency. For which product would you be willing to pay a higher cost to get a greater energy efficiency?

1) Bulb
2) Washing Machine
3) Both

Consider the bulb of a central lighting spot of your house (for example one in the kitchen). The average use is of 5.5 hours per day (corresponding to 2000 hours a year, more or less). The expected duration of life is 15000 hours for a LED bulb, 10000 hours for a CFL bulb and 2000 hours for a halogen bulb (corresponding respectively to 7.5 years, 5 years and 1 year at the considered use rate).

Q11. **In one year from now** you will have to change the bulb of such lighting spot. What extra amount "X" will you be willing to pay **next year** for a LED bulb that consumes 80% less energy than a halogen bulb which costs 1.39$?

Q12. **In one year from now** you will have to change the bulb of such lighting spot. What extra amount "X" will you be willing to pay **next year** for a LED bulb that consumes 40% less energy than a CFL (energy saving) bulb which costs 4.40$?

Q13. **In one year from now** you will have to change the bulb of such lighting spot. What extra amount "X" will you be willing to pay **next year** for a LED bulb that consumes 80% less energy than a halogen bulb which costs 2.95$?

Q14. **In one year from now** you will have to change the bulb of such lighting spot. What extra amount "X" will you be willing to pay **next year** for a LED bulb that consumes 40% less energy than a CFL (energy saving) bulb which costs 6.40$?

Q15. Which typology of bulbs has the greater energy efficiency between LED, CFL and halogen?

1) LED
2) CFL
3) Halogen

Q16. What is your gender?

1) Male
2) Female
3) Other

Q17. What is your country of origin?

Q18. In which country do you reside?

Q19. What is your age?

Q20. What is the highest level of education you have completed?

1) Less than High School
2) High School / GED
3) Some College
4) 2-year College Degree

5) 4-year College Degree
6) Masters Degree
7) Doctoral Degree
8) Professional Degree (JD, MD)

'Future-Now' Treatment

Consider the bulb of a central lighting spot of your house (for example one in the kitchen). The average use is of 5.5 hours per day (corresponding to 2000 hours a year, more or less). The expected duration of life is 15000 hours for a LED bulb, 10000 hours for a CFL bulb and 2000 hours for a halogen bulb (corresponding respectively to 7.5 years, 5 years and 1 year at the considered use rate).

Q1. **In one year from now** you will have to change the bulb of such lighting spot. What extra amount "X" will you be willing to pay **next year** for a LED bulb that consumes 80% less energy than a halogen bulb which costs 1.39$?

Q2. **In one year from now** you will have to change the bulb of such lighting spot. What extra amount "X" will you be willing to pay **next year** for a LED bulb that consumes 40% less energy than a CFL (energy saving) bulb which costs 4.40$?

Q3. **In one year from now** you will have to change the bulb of such lighting spot. What extra amount "X" will you be willing to pay **next year** for a LED bulb that consumes 80% less energy than a halogen bulb which costs 2.95$?

Q4. **In one year from now** you will have to change the bulb of such lighting spot. What extra amount "X" will you be willing to pay **next year** for a LED bulb that consumes 40% less energy than a CFL (energy saving) bulb which costs 6.40$?

Q5. Consider two bulbs: a LED bulb that consume 3.63 kWh a year (calculated for a use rate of 2 hours a day every day, or 11 kWh a year for a use rate of 5.5 hours/day) and costs 7.90$, and a CFL (energy saving) bulb that consume 5.94 kWh a year (or 18 kWh a year) and costs 4.40$.
Consider two washing machines: one in energy class A+++ that consumes 153 kWh a year (calculated on 220 standard washes, corresponding to 660 hours) and costs 450$, and one in energy class A+ that consumes 196 kWh a year and costs 270$.
Both bulbs and washing machines have at least a 2-years warranty.

Assume you have to by a bulb (for a central lighting spot of your house, for example the kitchen) and a washing machine, of which at least one with a greater energy efficiency. For which product would you be willing to pay a higher cost to get a greater energy efficiency?

1) Bulb
2) Washing Machine
3) Both

Consider the bulb of a central lighting spot of your house (for example one in the kitchen). The average use is of 5.5 hours per day (corresponding to 2000 hours a year, more or less). The expected duration of life is 15000 hours for a LED bulb, 10000 hours for a CFL bulb and 2000 hours for a halogen bulb (corresponding respectively to 7.5 years, 5 years and 1 year at the considered use rate).

Q6. **In six months from now** you will have to change the bulb of such lighting spot. What extra amount "X" will you be willing to pay **in six months** for a LED bulb that consumes 80% less energy than a halogen bulb which costs 1.39$?

Q7. **In six months from now** you will have to change the bulb of such lighting spot. What extra amount "X" will you be willing to pay **in six months** for a LED bulb that consumes 40% less energy than a CFL (energy saving) bulb which costs 4.40$?

Q8. **In six months from now** you will have to change the bulb of such lighting spot. What extra amount "X" will you be willing to pay **in six months** for a LED bulb that consumes 80% less energy than a halogen bulb which costs 2.95$?

Q9. **In six months from now** you will have to change the bulb of such lighting spot. What extra amount "X" will you be willing to pay **in six months** for a LED bulb that consumes 40% less energy than a CFL (energy saving) bulb which costs 6.40$?

Q10. Consider two bulbs: a LED bulb that costs 7.90$, and a CFL (energy saving) bulb that costs 4.40$. The LED bulb consumes 40% less energy with respect to the CFL one.
Consider two washing machines: one in energy class A+++ that costs 450$, and one in energy class A+ that costs 270$. The A+++ washing machine consumes 20% less energy than the A+ one.
Both bulbs and washing machines have at least a 2-years warranty.

Assume you have to by a bulb (for a central lighting spot of your house, for example the kitchen) and a washing machine, of which at least one with a greater energy efficiency. For which product would you be willing to pay a higher cost to get a greater energy efficiency?

1) Bulb
2) Washing Machine
3) Both

Consider the bulb of a central lighting spot of your house (for example one in the kitchen). The average use is of 5.5 hours per day (corresponding to 2000 hours a year, more or less). The expected duration of life is 15000 hours for a LED bulb, 10000 hours for a CFL bulb and 2000 hours for a halogen bulb (corresponding respectively to 7.5 years, 5 years and 1 year at the considered use rate).

Q11. You have to change the bulb of such lighting spot **today**. What extra amount "X" are you willing to pay **now** for a LED bulb that consumes 80% less energy than a halogen bulb which costs 1.39$?

Q12. You have to change the bulb of such lighting spot **today**. What extra amount "X" are you willing to pay **now** for a LED bulb that consumes 40% less energy than a CFL (energy saving) bulb which costs 4.40$?

Q13. You have to change the bulb of such lighting spot **today**. What extra amount "X" are you willing to pay **now** for a LED bulb that consumes 80% less energy than a halogen bulb which costs 2.95$?

Q14. You have to change the bulb of such lighting spot **today**. What extra amount "X" are you willing to pay **now** for a LED bulb that consumes 40% less energy than a CFL (energy saving) bulb which costs 6.40$?

Q15. Which typology of bulbs has the greater energy efficiency between LED, CFL and halogen?

1) LED
2) CFL
3) Halogen

Q16. What is your gender?

1) Male
2) Female
3) Other

Q17. What is your country of origin?

Q18. In which country do you reside?

Q19. What is your age?

Q20. What is the highest level of education you have completed?

1) Less than High School
2) High School / GED
3) Some College
4) 2-year College Degree
5) 4-year College Degree
6) Masters Degree
7) Doctoral Degree
8) Professional Degree (JD, MD)

Tables and Results

The tables reported here are equivalent to the ones displayed in the previous section of this Appendix for the experiment conducted among students.

For reasons of space, in this case are presented first the table concerning the magnitude effect, and then those on hyperbolic discounting.

Halo 2.95$	Halo 1.39$	p-value	Conclusions
When the comparison takes place today			
5.7873 (NF)	5.8058 (NF)	0.2179	It is not possible to reject H_0 at the 5% significance level. The average willingness to pay is not statistically different.
4.7877 (FN)	4.5713 (FN)	0.7035	It is not possible to reject H_0 at the 5% significance level. The average willingness to pay is not statistically different.
When the comparison takes place in six months from now			
6.0312 (NF)	5.3151 (NF)	0.0484	It is possible to reject H_0 at the 5% significance level. The average willingness to pay is statistically lower when the comparison is with the bulb that costs 1.39$ than when it is with the 2.95$ one. For a reduction in price of -52.88% agents are willing to spend 11.87% less.
5.3539 (FN)	5.1415 (FN)	0.356	It is not possible to reject H_0 at the 5% significance level. The average willingness to pay is not statistically different.
When the comparison takes place in one year from now			
5.9613 (NF)	5.2842 (NF)	0.19	It is not possible to reject H_0 at the 5% significance level. The average willingness to pay is not statistically different.
5.9216 (FN)	5.7416 (FN)	0.506	It is not possible to reject H_0 at the 5% significance level. The average willingness to pay is not statistically different.

Treatment to which the values belong to in parenthesis

Table C.5: Magnitude effect for the comparison with halogen bulbs in the online experiment.

CFL 6.40$	CFL 4.40$	p-value	Conclusions
When the comparison takes place today			
4.0656 (NF)	3.6072 (NF)	0.0033	It is possible to reject H_0 at the 1% significance level. The average willingness to pay is statistically lower when the comparison is with the bulb that costs 4.40$ than when it is with the 6.40$ one. For a reduction in price of -31.25% agents are willing to spend 22.30% less
3.8865 (FN)	3.6651 (FN)	0.1058	It is not possible to reject H_0 at the 5% significance level. The average willingness to pay is not statistically different.
When the comparison takes place in six months from now			
4.3682 (NF)	4.2048 (NF)	0.02025	It is possible to reject H_0 at the 5% significance level. The average willingness to pay is statistically lower when the comparison is with the bulb that costs 4.40$ than when it is with the 6.40$ one. For a reduction in price of -31.25% agents are willing to spend 3.8% less
3.8772 (FN)	3.7419 (FN)	0.2217	It is not possible to reject H_0 at the 5% significance level. The average willingness to pay is not statistically different.
When the comparison takes place in one year from now			
4.1811 (NF)	4.3189 (NF)	0.1085	It is not possible to reject H_0 at the 5% significance level. The average willingness to pay is not statistically different.
4.3978 (FN)	4.2616 (FN)	0.0494	It is possible to reject H_0 at the 5% significance level. The average willingness to pay is statistically lower when the comparison is with the bulb that costs 4.40$ than when it is with the 6.40$ one. For a reduction in price of -31.25% agents are willing to spend 3.1% less

Treatment to which the values belong to in parenthesis

Table C.6: Magnitude effect for the comparison with CFL bulbs in the online experiment.

	1 Year	6 Months	Today	p-value	Conclusions
Halogen 1.39$					
'Now-Future' within					
	5.3842	-	5.8058	0.1382	It is not possible to reject H_0 at the 5% significance level. The averages are not statistically different.
	-	5.3151	5.8058	0.7	It is not possible to reject H_0 at the 5% significance level. The averages are not statistically different.
	5.3842	5.3151	-	0.0122	It is possible to reject H_0 at the 5% significance level. The average in six months is statistically smaller than that in one year.
'Future-Now' within					
	5.7416	-	4.5713	0.27	It is not possible to reject H_0 at the 5% significance level. The averages are not statistically different.
	-	5.1415	4.5713	0.36	It is not possible to reject H_0 at the 5% significance level. The averages are not statistically different.
	5.7416	5.1415	-	0.3	It is not possible to reject H_0 at the 5% significance level. The averages are not statistically different.
Between treatments					
	5.7416	-	5.8058	0.4	It is not possible to reject H_0 at the 5% significance level. The averages are not statistically different.
	-	5.1415	5.8058	0.372	It is not possible to reject H_0 at the 5% significance level. The averages are not statistically different.
	5.7416	5.3151	-	0.49	It is not possible to reject H_0 at the 5% significance level. The averages are not statistically different.

Table C.7: Hyperbolic discounting in the online experiment for the comparison with the 1.39$ halogen bulb

	1 Year	6 Months	Today	p-value	Conclusions
Halogen 2.95$					
'Now-Future' within					
	5.9613	-	5.7873	0.041	It is possible to reject H_0 at the 5% significance level. The average today is statistically smaller than that in one year.
	-	6.0312	5.7873	0.087	It is possible to reject H_0 at the 10% significance level. The average today is statistically smaller than that in six months.
	5.9613	6.0312	-	0.294	It is not possible to reject H_0 at the 5% significance level. The averages are not statistically different.
'Future-Now' within					
	5.9216	-	4.7877	0.133	It is not possible to reject H_0 at the 5% significance level. The averages are not statistically different.
	-	5.3539	4.7877	0.034	It is possible to reject H_0 at the 5% significance level. The average today is statistically smaller than that in six months.
	5.9216	5.3539	-	0.578	It is not possible to reject H_0 at the 5% significance level. The averages are not statistically different.
Between treatments					
	5.9216	-	5.7873	0.47	It is not possible to reject H_0 at the 5% significance level. The averages are not statistically different.
	-	5.3539	5.7873	0.487	It is not possible to reject H_0 at the 5% significance level. The averages are not statistically different.
	5.9216	6.0312	-	0.597	It is not possible to reject H_0 at the 5% significance level. The averages are not statistically different.

Table C.8: Hyperbolic discounting in the online experiment for the comparison with the 2.95$ halogen bulb

	1 Year	6 Months	Today	p-value	Conclusions
CFL 4.40$					
'Now-Future' within					
	4.3189	-	3.6072	0.0015	It is possible to reject H_0 at the 1% significance level. The average today is statistically smaller than that in one year.
	-	4.2048	3.6072	0.0023	It is possible to reject H_0 at the 1% significance level. The average today is statistically smaller than that in six months.
	4.3189	4.2048	-	0.32	It is not possible to reject H_0 at the 5% significance level. The averages are not statistically different.
'Future-Now' within					
	4.2616	-	3.6651	0.8	It is not possible to reject H_0 at the 5% significance level. The averages are not statistically different.
	-	3.7419	3.6651	0.81	It is not possible to reject H_0 at the 5% significance level. The averages are not statistically different.
	4.2616	3.7419	-	0.712	It is not possible to reject H_0 at the 5% significance level. The averages are not statistically different.
Between treatments					
	4.2616	-	3.6072	0.348	It is not possible to reject H_0 at the 5% significance level. The averages are not statistically different.
	-	3.7419	3.6072	0.29	It is not possible to reject H_0 at the 5% significance level. The averages are not statistically different.
	4.2616	4.2048	-	0.5419	It is not possible to reject H_0 at the 5% significance level. The averages are not statistically different.

Table C.9: Hyperbolic discounting in the online experiment for the comparison with the 4.40$ CFL bulb

	1 Year	6 Months	Today	p-value	Conclusions
CFL 6.40$					
'Now-Future' within					
	4.1811	-	4.0656	0.1002	It is not possible to reject H_0 at the 5% significance level. The averages are not statistically different.
	-	4.3682	4.0656	0.079	It is possible to reject H_0 at the 10% significance level. The average today is statistically smaller than that in six months.
	4.1811	4.3682	-	0.4672	It is not possible to reject H_0 at the 5% significance level. The averages are not statistically different.
'Future-Now' within					
	4.3979	-	3.8856	0.8	It is not possible to reject H_0 at the 5% significance level. The averages are not statistically different.
	-	3.8772	3.8856	0.686	It is not possible to reject H_0 at the 5% significance level. The averages are not statistically different.
	4.3979	3.8772	-	0.4115	It is not possible to reject H_0 at the 5% significance level. The averages are not statistically different.
Between treatments					
	4.3979	-	4.0656	0.4	It is not possible to reject H_0 at the 5% significance level. The averages are not statistically different.
	-	3.8772	4.0656	0.4171	It is not possible to reject H_0 at the 5% significance level. The averages are not statistically different.
	4.3979	4.3682	-	0.453	It is not possible to reject H_0 at the 5% significance level. The averages are not statistically different.

Table C.10: Hyperbolic discounting in the online experiment for the comparison with the 6.40$ CFL bulb

	Relative (NF)	Absolute (NF)	Relative (FN)	Absolute (FN)
Bulb	35	26	35	27
Washing Machine	22	19	18	20
Both	41	53	43	49

Table C.11: Absolute vs. Relative thinking in the online experiment

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