Micro-economic approach to the energy rebound effects for households

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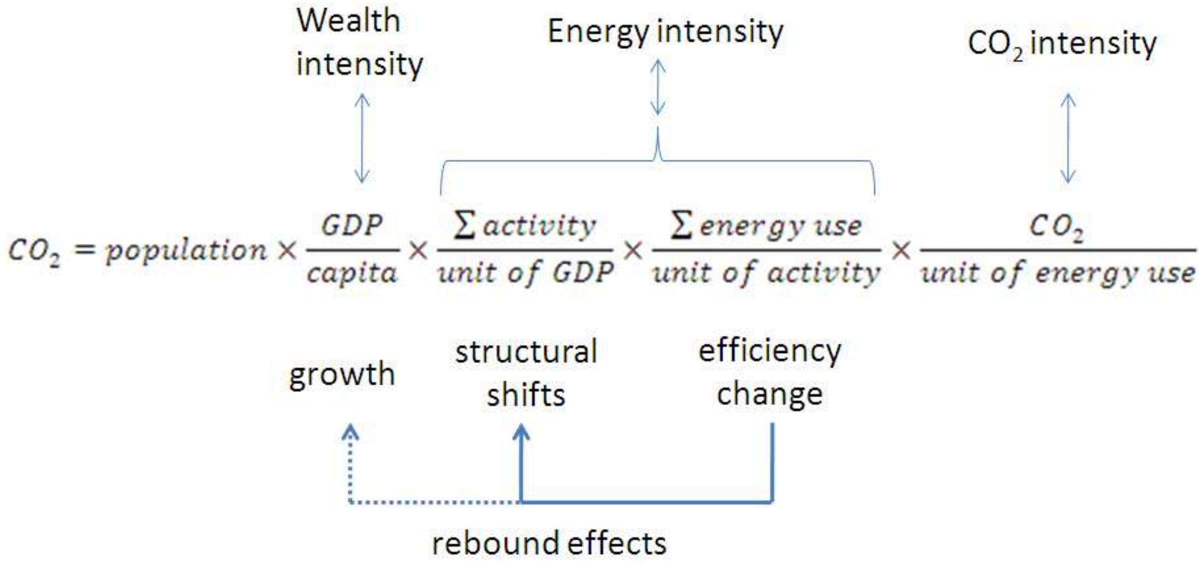
1. Background to energy rebound effects in economic literature

1.1. Relevance of the energy rebound effect for energy and climate change policies

"*Many concepts of sustainable development emphasize the importance of efficiency improvements by technological progress*" [Binswanger, 2001, p. 120]. As early as the 1970s, energy analysts like Lovins [1976] promoted a "soft energy path", not only based on a diversity of energy production methods (matched in scale and energy quality to end-use needs) and "soft technologies" (renewable energy, biofuels, cogeneration), but also on a prompt and firm commitment to efficient use of energy. Nowadays, regional and national governments, international development agencies and NGOs focus on energy efficiency gains to reduce energy use and related (greenhouse gas and other pollutant) emissions [e.g. IPCC, 2007; Stern, 2007; Doris et al., 2009; McKinsey, 2009; IEA, 2010; European Commission, 2011]. Contemporary policymaking relies on a straightforward link between increased energy efficiency and reduced energy consumption *at the economy-wide level* [Koerth-Baker et al., 2011, p. 2], or on a linear, direct, and one to one relationship between energy efficiency improvements and carbon emission reductions [Jenkins et al., 2011, p. 52]. Energy efficiency policies rest on the notion that an increase in energy efficiency by 1% will also lead to a decrease in energy use by approximately 1%. However, (cost-effective) technological efficiency improvements induce or evoke behavioural responses by the economic agents (households, firms) that may partially or completely offset the expected energy savings and subsequent environmental gains [Berkhout, 2000, p. 425]. An increase in efficiency by 1% may thus cause a reduction in energy use that is far below 1% [Binswanger, 2001, p. 120]. This phenomenon is variably known to energy economists as 'offsetting behaviour' or as the 'snap-back', 'take-back' or 'rebound' effect. Sometimes, an increase in energy efficiency may even cause a net increase in energy use at the macro level, which is also known as the 'backfire' effect. The latter was first put forward by Stanley Jevons, in his classic work 'The Coal Question', published in 1865. Jevons observed that the introduction of the new efficient steam engine initially decreased coal consumption which led to a drop in the price of coal. This meant not only that more people could afford coal, but also that coal was now economically viable for new uses, which ultimately greatly increased coal consumption [Gottron, 2001, p. 1-2]. For this reason, the backfire effect is sometimes labelled "Jevons' paradox" [e.g. Polimeni & Polimeni, 2006].

In broad terms (figure 1), we can distinguish two kinds of behavioural responses leading to the so-called economy-wide rebound effects: a structural shift in activities (a.k.a. 'composition effect') and an economic growth effect. As stated by Dimitripoulos and Sorrell [2006]: "*A fall in the real price of energy services may reduce the price of intermediate and final goods throughout the economy, leading to a series of price and quantity adjustments, with energy-intensive goods and sectors gaining at the expense of less energy intensive ones. Energy efficiency improvements may also reduce energy prices and increase economic growth, which could further increase energy consumption*" [Dimitropoulos & Sorrell, 2006, p. 3] Vikström [2003, p. 8] puts it this way: "*Due to the fall in real prices of energy services, products that use energy will become relatively cheaper. The more energy intensive, the cheaper it will be. This leads to readjustments between sectors, with energy intensive sectors gaining at the expense of less energy intensive ones. (..)There is also an additional effect due to the fact that the economic growth created by an energy efficiency improvement will in itself increase energy consumption by some second-order fraction*" [Vikström, 2003, p. 8]. Or finally, in the words of Saunders [1992]: "*…energy efficiency gains can increase energy consumption by two means: by making energy appear effectively cheaper than other inputs; and by increasing economic growth, which pulls up energy use.*" [Saunders, 1992, p. x]

Figure 1: Two behavioural responses leading to the economy-wide rebound effect



$$CO_2 = population \times \frac{GDP}{capita} \times \frac{\sum activity}{unit\ of\ GDP} \times \frac{\sum energy\ use}{unit\ of\ activity} \times \frac{CO_2}{unit\ of\ energy\ use}$$

Source: Based on Verbruggen [2009]

In interpreting figure 1, a few cautionary remarks concerning terminology are in order. The term 'energy efficiency' can have different meanings. Most economy-wide studies of energy efficiency are based on the measurement of total energy use per unit of gross domestic product (GDP), which should be defined as the *energy intensity* of an economy [Pears, 2004, p. 3]. However, many studies by energy experts look at what Pears [2004] calls 'functional energy intensity', i.e. "*the energy used per unit of delivery of a useful service*" [Pears, 2004, p. 3]. Functional energy intensity more or less coincides with the reciprocal of the macro-economic notion of 'energy productivity', where average energy productivity is defined as average (useful) output per unit of energy input (see e.g. Berndt [1978, p. 48]). "*For most macro-economic models, energy efficiency is usually assumed to be equivalent to energy productivity, which encompasses changes in thermodynamic efficiency and disembodied technical progress*" [Dimitropoulos, 2007, p. 6359]. We base figure 1 on Verbruggen [2009], who decomposes energy intensity as the sum of many products of two factors: the technical energy efficiency[1] in performing a societal activity, and the weight of that activity in the GDP of the country. The latter factors depend on the sector structure of the economy (relative importance of the different sectors), and of the detailed composition of the various sectors, technologies, goods and services, etc. [Verbruggen, 2009, p. 2932]. It thus becomes clear how an increase in 'energy efficiency' (i.e. a decrease in total energy use per unit of a *particular* activity), through a structural shift (increase in energy intensive activities at the expense of less energy intensive ones), may actually reduce, cancel out or even negate the potential impact of these technical improvements on

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[1] Strictly speaking, since 'energy efficiency' in engineering terms refers to the ratio of useful output over total energy inputs (more or less analogous to 'energy productivity' in economics), and intensity is considered as the reciprocal of efficiency (or productivity), 'technical energy intensity' as opposed to '(economic) energy intensity' would have been a more consistent term.

the ‘energy intensity’ (total energy use per unit of GDP) of an economy [Verbruggen, 2009, p. 2932; Pears, 2004, p. 3; Birol & Kepler, 2000, p. 458].

For a number of reasons the economy-wide rebound effect remains “*a controversial subject that has generated great debates among energy economists*” [Dimitripoulos, 2007, p. 6360][2].

Firstly, it is very difficult to estimate the economy-wide rebound effect, because this effect “*represents the net effect of a number of different mechanisms that are individually complex, mutually interdependent and likely to vary in importance from one type of energy efficiency improvement to another*” [Sorrell, 2007, p. 3]. It is particularly hard to trace or prove the exact causality underlying certain mechanisms [van den Bergh, 2011, p. 52]. As stated by Sorrell [2010], the key question is “*whether economic growth is the cause of increased energy consumption and/or improved energy efficiency, or whether increased energy consumption and/or improved energy efficiency is a cause of the growth in economic output*” [id., ibid., p. 1887].

Secondly, in evaluating the empirical evidence of the rebound effect, it is important to realize that results vary considerably depending not only on the accepted definition of energy efficiency but also on the spatial and temporal dimensions used in the analysis.

> Rebound effects need to be defined in relation to particular measures of energy efficiency (e.g., thermodynamic, physical, economic), to relevant system boundaries for both the measure of energy efficiency and the change in energy consumption (e.g., device, firm, sector, economy) and to a particular time frame [Sorrell, 2010, p. 1786].

A third observation is that while accelerating the adoption of energy efficiency improvements may not make for particularly efficacious climate policy, it does probably make for very good economic policy, as it “*is likely to result in greater economic productivity and growth*” [Jenkins et al., 2011, p. 53], increasing real income and generally improving welfare [Sorrell, 2010, p. 1786]. Even if rebound effects are real, “*energy efficiency would be a most effective policy for economic development and improvement of the quality of life for the poorest of people in the poorest countries*” [Goldstein et al., 2011, p. 20-21]. Furthermore, given the actual activity levels, energy consumption would almost certainly be significantly higher than it would have been without the energy efficiency improvements [IEA, 2004] (figure 2). The existence of rebound effects is not an argument for abandoning energy efficiency [Linares & Labendeira, 2009, p. 10].

Finally, a lot of the controversy seems to arise from the fact that economic growth and structural shifts in activities, *as invoked by energy efficiency improvements*, are neither anticipated nor intended in most energy or climate change policies. The view that improvement in energy efficiency (or energy productivity) certainly takes back some of the expected energy savings is now widely accepted in literature [e.g. Laitner, 2000; Dimitripoulos, 2007, p. 6360; van den Berg, 2011, p. 51; EC, 2011, p. 32, EMF, 2011, p. 8]. Point of contention remains the exact magnitude of the economy-wide rebound effect. But even so, “*Rebound effects tend to be almost universally ignored in official analyses of the potential energy savings from energy efficiency improvements*” [Sorrell, 2009, p.

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[2] To illustrate how controversial the subject (still) is, one of the news items in the 17 February 2011 Nature issue reads “Experts tangle over energy-efficiency 'rebound' effect”.

2001], a sentiment echoed by Jenkins et al. [2011] stating that "*it is remarkable that rebound mechanisms remain almost entirely ignored in projections of energy efficiency's ability to drive lasting reductions in energy use or greenhouse gas emissions*" [id., ibid., p. 50]. The truthfulness of the rebound phenomenon "*directly undermines the effectiveness of energy efficiency measures that are used as policy instruments for meeting* CO_2 *emissions targets*" [Dimitripoulos, 2007, p. 6360]. This was recognized by the European Environment Agency, conceding that "*Rebound effects might also jeopardize environmental and resource-efficiency achievements*" [EEA, 2010, p. 141]. Huge uncertainties regarding the magnitude notwithstanding, policy makers and energy analysts should take probable economy-wide rebound effects into consideration when designing energy or climate change policies [IEA, 2005, p. 36].

1.2. On the confusion regarding 'energy efficiency gap' and 'economy-wide energy rebound'

Before proceeding to a more formal definition of "energy rebound effects", we have to say a few words about the so-called "energy efficiency gap" and the way this notion sometimes gets confused with economy-wide rebound effects in energy or climate change policy scenarios [see e.g. Koerth-Baker, 2011, p 6].

The term "energy efficiency gap" was first coined by Hirst and Brown [1990], and refers to the gap between the current and "optimal"[3] level of energy efficiency, as society fails to take full advantage of cost-effective, energy-saving opportunities. We will not attempt to epitomize the vast literature on the energy efficiency gap [e.g. Jaffe & Stavins, 1994; Golove & Eto, 1996; Brown, 2001; Thollander, Palm & Rohdin, 2010], but limit ourselves to information problems. Information problems concerning the available technologies and potential (energy) cost savings among consumers are considered one of the more important market imperfections[4] hampering the diffusion of energy efficient technologies [Jaffe & Stavins, 1994, p. 805; Verbruggen, 2003, p. 1438; Gillingham et al., 2009, p. 2; Lima de Azevedo, 2007, p. 1230; Linares & Labendeira, 2009, p. 6]. Information problems include imperfect (insufficient and / or incorrect) information, asymmetric information and split incentives:

- Consumers often lack sufficient information about technology characteristics. The (transaction) costs of collecting information about the energy performance of an energy efficient technology can be substantial. Furthermore, the information provided may not always be accurate. Consumers may also be poorly informed about their own energy use. For example, most automobile buyers do not know the exact fuel economy of their vehicles or their fuel expenditures over time [Turrentine & Kurani, 2007, p. 1120-1221]. In the home, most households have no idea of the *implicit* price of energy services, as "*The costs of energy consumption of many equipment disappear from the sight of the consumer as a part of the monthly bill*" [Berkhout et al., 2000, p. 426]. In future, this obstacle may partly be overcome as "more intelligent" household appliances include feedback and sensor devices;

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[3] "Optimal" as based on engineering-economic analysis.

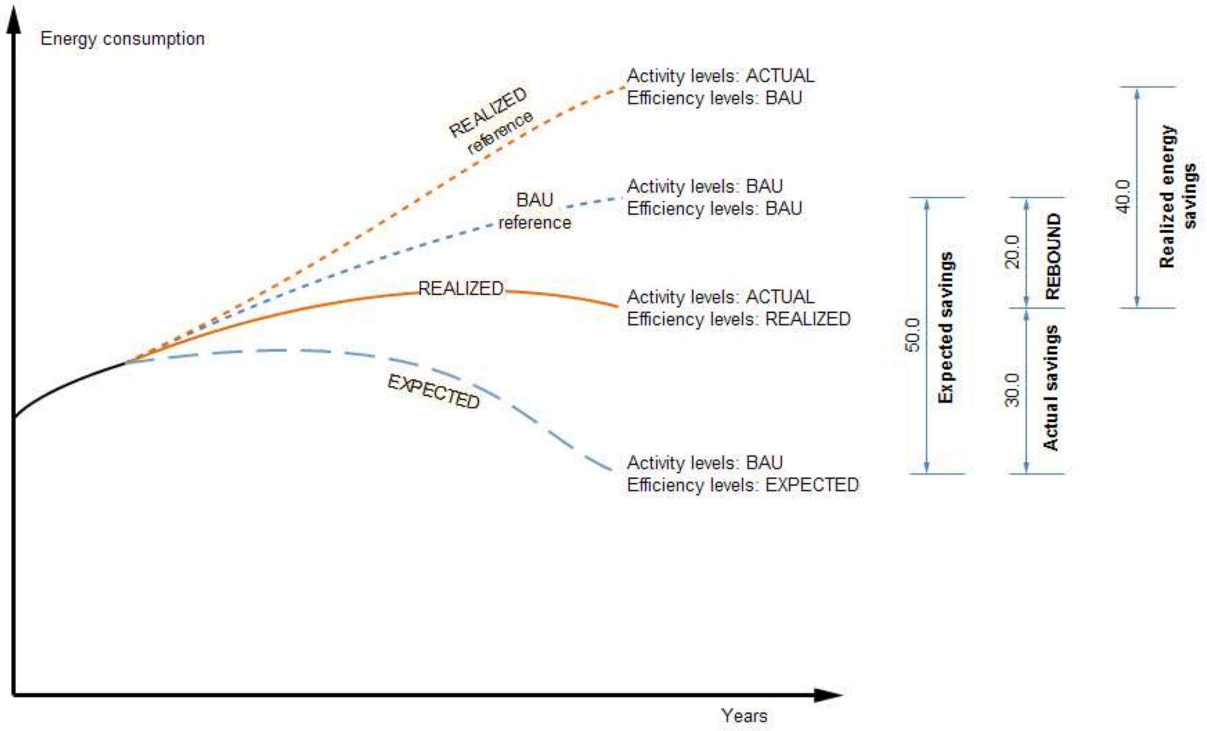
[4] Literature often makes a distinction between market "failures" (flaws in the way markets operate) and "barriers" (other obstacles that contribute to the slow adoption and diffusion of energy efficient innovations). Information problems are usually considered "failures" [e.g. Brown, 2001, p. 1199]. One should be aware that '*The distinction between market ''barriers'' and ''failures'' is precarious…*' [Verbruggen et al., 2010, p. 859].

- Asymmetric information in this context implies that sellers of energy-efficient technologies are unable to transfer information on the ex-post benefits of those technologies to buyers since the energy efficiency is unobserved;
- A split incentive (or landlord-tenant relationship) occurs when the party (e.g. landlord) that decides the level of energy efficiency, is not the party (e.g. tenant) that pays the energy bills. The landlord may not be able to recover the additional capital costs from the party that enjoys the energy savings (e.g. by increasing the rent) and thus decide to under-invest in energy efficiency.

Market failures like asymmetric information and split incentives are directly related to the Principal-Agent (PA) problems in economics. The principal-agent problem arises when two parties engaged in a contract have different goals and different levels of information (IEA, 2007). Information problems are sometimes considered "behavioural anomalies", e.g. when consumers cannot process the information effectively (bounded rationality). Other imperfections include, amongst others, constrained access to capital and limited availability (market supply) of energy efficient technologies [see e.g. McKinsey, 2009, pp. 24-27].

In figure 2 we illustrate the difference between energy efficiency gap and the economy-wide rebound effects.

Figure 2: energy efficiency gap versus economy-wide rebound effect



In our example (figure 2), assuming no change in activity levels *as a direct result of efficiency improvements*, engineers project or "expect" energy savings of 50 units relative to what energy use would have been in the business-as-usual (BAU) reference scenario if there had been no improvements in energy efficiency. We call these savings "expected energy savings". They are sometimes also called "engineering savings".

However, it is claimed by many economists that as a result of efficiency improvements, activity levels *do* change, i.e. over and above the levels they would have reached in the BAU scenario. The difference between the energy use in a "realized reference scenario" where on the one hand we assume that activity levels have increased to the levels they supposedly would reach when introducing efficiency improvements but where on the other hand we assume no real change in energy efficiencies; and energy use in a "realized scenario" (i.e. as a result of both realized efficiency improvements and increased activity levels as a result of those improvements), results in what we prefer to call the "realized energy savings"[5] of 40 units. The fact that the "realized energy savings" (40 units) are but 80% of the projected or expected (engineering) energy savings (50 units) has nothing to do with the rebound effect, but may be attributed to the so-called "energy efficiency gap" due to market imperfections and in particular "behavioural failures" (see inter alia).

In estimating the rebound effect however one defines the "actual energy savings" as the difference between energy consumption in the "realized scenario" (defined as above) and the "expected scenario" (efficiency levels improve as expected by the engineers, but activity levels do not increase as a result of those efficiency improvements). It is very unfortunate that this difference (30 units in our example) is commonly called "actual" energy savings. It should be clear from our example that the "real amount" of energy savings "realized" is 40 units and not 30 units.

Figure 2 makes very clear that the definition of economy wide energy rebound effect crucially depends on the comparison of two very different kinds of scenarios: a "realized scenario" (where activity levels do change as a result of efficiency improvements) and a "BAU scenario" (where activity levels do not change as a result of efficiency improvements) The economy wide rebound effect is measured using the difference between the "expected (or engineering) energy savings" (50 units) and the (poorly defined) "actual" energy savings (30 units), and expressed as a percentage of the "expected energy savings". Thus in our example the rebound effect would be calculated as (50-30)/50 x 100 = 40%. In other words, following the rebound definition, it would appear than only 60% of the expected (engineering) energy savings were actually "realized" (whereas in reality, 80% were realized). Then again, in absolute terms, energy consumption "in reality" would be 30 units higher than "expected" by engineers, since they did not take into account increased activity levels as a direct result of efficiency improvements.

It would thus seem that many heated discussions[6] originate from a mutual misunderstanding, where the "engineering side" accuses economists of underestimating the "realized energy savings" (in our example by a quarter), and where the "economists side" blames the engineers of downplaying the relevance of possible changes in actual activity levels as a result of improved energy efficiencies.

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[5] Our definition of "realized" savings is not a generally accepted one, but we have to introduce this new terminology to distinguish "realized" savings from "actual" savings (see following).

[6] For instance, an article "The Efficiency Dilemma" by David Owen in The New Yorker (December 20, 2010, p. 78) claiming that "*The problem with efficiency gains is that we inevitably reinvest them in additional consumption",* sparked a lively debate about the effectiveness of energy efficiency. His critique was further developed by energy economist Charles Komanoff ("If efficiency hasn't cut energy use, then what?"), in the online journal Grist (December 16, 2010), stating that "*Through engineering brilliance and concerted political and regulatory advocacy, we have increased energy-efficiency in the small while the society around us has grown monstrously energy-inefficient and cancelled out those gains*." To this Amory Lovins responded that "'*…reduced US primary energy intensity has offset 78% of the aggregate energy consequences of economic growth 1975-2009*."

On a final note, figure 2 was drawn from an "omniscient" perspective. Measuring energy savings and evaluating energy efficiency policies is notoriously difficult. In an ex post analysis, the energy consumption in the "realized scenario" is the only real figure. The energy consumption levels in the three other scenarios are "*predicated on a host of assumptions, some buried in computer software*" [Inhaber, 1997, p. 105].

1.3.Formal definition of energy rebound effects

Discussions of the rebound effects, particularly in empirical studies, would greatly benefit "*from a clear-cut definition, as it is often unclear what exactly is included, and how the numerator and the denominator are defined*" [Berkhout, 2000, p. 431]. A general (theoretical) definition of rebound effects, however, is straightforward.

Most formal definitions try to describe the rebound effect as somehow measuring the discrepancy between the expected (engineering) energy savings (assuming that production or consumption levels do not change as a result of efficiency changes) and the "actual" energy savings (where production or consumption levels *do* change as a result of efficiency changes). The name 'engineering savings' or 'calculated savings' refers to "*a theoretical quantity of energy that could be saved after an increase in energy efficiency, if the quantity of goods and services demanded or consumed were held constant*" [Madlener & Alcott, 2009, p. 370-371]. So, for example, as light bulbs use less and less kWh energy input per useful output of lumens/m², society could choose to produce and consume no more of these things, or indeed other things, yielding real energy savings in any given time period[7] [Madlener & Alcott, 2009]. The aforementioned discrepancy stems from behavioural reactions of economic agents (changes in production and/or consumption levels) in contrast to keeping the status quo, particularly where the efficiency gains bring reduced costs. The rebound effect due to energy efficiency improvements[8] may therefore be understood in terms of technical-engineering versus behavioural-economic phenomena [van den Bergh, 2011, p. 46].

Or for those who prefer a more graphical definition:

Figure 3: Energy rebound as the discrepancy between 'expected' and 'actual' energy savings

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[7] Technically speaking, the ratio energy input to useful output [e.g., kWh per lumen/m²], is called 'energy intensity', the inverse of energy efficiency.

[8] In psychology, adoption of a specific technology that reduces overall energy consumption *without changing relevant behaviour* is labelled 'efficiency behaviour', whereas merely a change in consumer's behaviour is known as 'curtailment behaviour'. [Gardner & Stern, 2009; Gardner & Stern, 2002] Analysts like Oikonomou et al. [2009, p. 4787] link efficiency behaviour with 'energy efficiency' and curtailment behaviour with 'energy conservation'. In theory, energy conservation resulting from changes in behaviour (e.g. lowering the thermostat, driving fewer kilometres) can also stimulate behavioural-economic changes that may partly or wholly undo the initial gains [van den Bergh, 2011, p. 45-46]. In this report, we will not concern ourselves with this type of rebound effects, because they do not reduce the marginal costs (costs per additional unit) of an energy service.

Source: based on Gavankar & Geyer [2010, p. 17]

This rebound effect is typically expressed as a percentage of the expected energy savings, as predicted by the engineer [Berkhout, 2000, p. 426].

In general, rebound effects are defined as non realized savings in the use of resources relative to expected savings in the use of these resources.

$$RE = \frac{ESR - ASR}{ESR} \times 100 = \left(1 - \frac{ASR}{ESR}\right) \times 100$$

Where *RE* = rebound effects, *ASR* = actual saved resources and *ESR* = expected saved resources.

Within literature there are four expected outcomes (no rebound, typical rebound, negative rebound and backfire):

- If the actual saved resources (*ASR*) are equal to the expected saved resources (*ESR*), or *ASR* = *ESR*, than the rebound effects (*RE*) equal 0 %.
- In most cases, the actual saved resources (*ASR*) are smaller than the expected saved resources (*ESR*), but still positive, or *ASR* < *ESR* and *ASR* > 0. In these instances the rebound effect are situated between 0% (not included) and 100%. A rebound effect of 30% means that only 70% of the expected resource savings or “engineering savings” are realized. If the actual saved resources (ASR) are zero, than the rebound effects (RE) equal 100%. All the expected resource savings are exactly cancelled out by the rebound effect. Every rebound effect within the interval (0%, 100%] is also identified as “take-back” or “snap-back” effect.
- In some relatively unusual but not impossible cases the actual saved resources (ASR) might actually be higher than the expected saved resources (ESR), or ASR > ESR. This is called “negative rebound”, since RE < 0. A negative rebound at the household level might occur when a family that installs a new energy-efficient hot water heater is motivated to find other ways to save energy (e.g. by taking shorter showers, washing clothes in cold water, or by limiting dishwasher use to full loads) [Ehrhardt-Martinez & Laitner, 2010, p. 7-77].
- At the macro-level, it has been postulated that actual saved resources (ASR) may be negative (ASR < 0), i.e. more resources are consumed after the efficiency improvements than before, resulting in rebound effects (RE) greater than 100%. These rebound effects are usually referred to as ‘backfire’, so named because Brookes [1978] and Khazzoom [1980] first[9] raised the question whether newly enacted government policies to save energy through efficiency improvements caused real energy savings, or – because of a rebound effect greater than 100% - might actually ‘backfire’. The assertion that increased energy efficiency will lead to higher energy consumption, is known as the Khazzoom-Brookes Postulate or KB Postulate. Saunders [1992] formally stated the KB Postulate as follows: “*With fixed real price, fuel efficiency gains will increase fuel consumption above where it would be without those gains* “

van Den Bergh [2011, p. 51] categorizes the possible magnitude of the economy-wide rebound effect as *small* (0-20%), *significant* (20-50%), *worrisome large* (more than 50%) or *counterproductive* (more than 100%).

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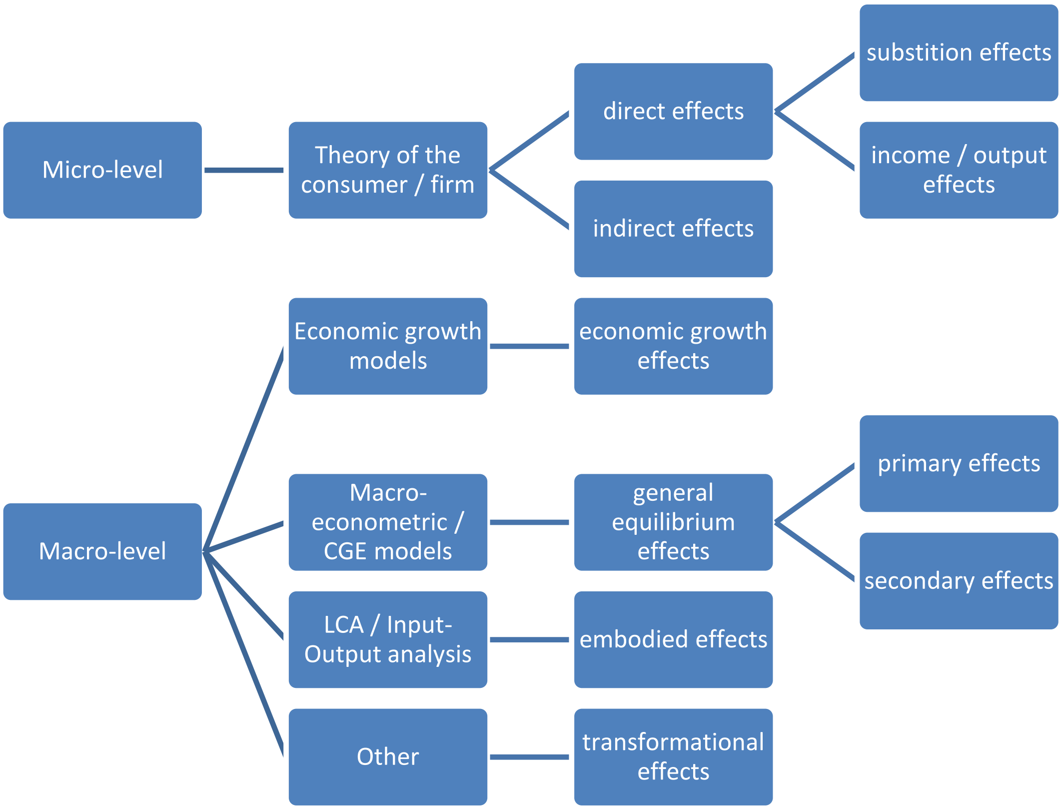
[9] Although both authors credit Jevons [1865] being the first to discuss the backfire effect.

1.4.A novel classification of rebound effects

"*There is no standardized classification, terminology or even definition of rebound effect in the literature*" [Gavankar & Geyer, 2010, p. 18]. Madlener and Alcott [2006] "*have counted approximately 28 different terms for rebound effects in the literature*" [id., ibid. p. 3]. In addition, those definitions are overlapping. Hence, "…*achieving consistency across the literature is ultimately impossible*" [Jenkins et al. 2011, p. 12].

Rather than presenting a conventional 'taxonomy', figure 4 uses models in economic theory as a guide to classify rebound effects. For more traditional typologies we refer to Greening et al. [2000, p. 390-392], Sorrell [2006, p. 4], Jenkins et al. [2011, p. 13] and van den Bergh [2011, p. 47-48]. The main reason for choosing this classification is that our analysis is limited to rebound effects at the micro-level. This chapter epitomizes the main results of the macro-level literature, and draws heavily on Jenkins et al. [2011], Sorrell [2009] and Dimitropoulos [2007].

Figure 4: Categories of rebound effects



1.4.1. Micro- versus macro-level effects

The rebound effects studied at the level of individual economic agents (households, firms) include the micro-economic effects that consist of the *direct* and *indirect* rebound effects. Direct rebound effects are so called because they refer to a change (increase) in demand for the energy service directly affected by the (energy) efficiency improvement. A classic example would be a homeowner who replaces a conventional boiler with a condensing boiler to increase the heating efficiency of his home, only to take advantage of the resulting decrease in home heating costs to increase the average room temperature, the amount of time the home is heated, and / or the number of rooms heated. Another example of direct rebound effects are increases in trips made and/or distances travelled because of improved fuel and/or vehicle efficiency. We will study direct effects for households in greater detail in the following chapters[10]. The *indirect* rebound effects at the micro-level refer to a change in demand for other goods or services (households) or for other factor inputs (firms), which themselves require energy to provide[11] For example, savings made through the more efficient heating of the home may be directed to extra overseas holidays.

The rebound effects studied at the macro-level are what we previously called *economy-wide* rebound effects. They are "*macro effects that result from the interaction between different actors, both producers and consumers, in the economy*" [Hertwich, 2005, p. 86], and as such they encompass all effects studied at the micro-level. The debate on the nature and magnitude of the rebound effect "*seems to concentrate especially on the macro-economic side of the issue*" [Dimitripoulos, 2007, p. 6354], as it would appear that "*increased energy-efficiency at the micro-economic level, while leading to a reduction of energy use at this level, leads not to a reduction, but instead to an increase in energy use, at the national, or macroeconomic level"* [Herring, 1999, p. 214]. However, at the macro-level, "*…empirical evidence is almost non-existent and there is no single widely accepted methodology that can depict rebound in higher levels of aggregation*" [Dimitripoulos, 2007, p. 6354].

1.4.2. Economic growth effects

Based on the established Solow–Swan (neoclassical) model for economic growth, Saunders [1992] developed a formal model of economic growth where output is dependent on the inputs of capital, labour and energy. Saunders used a Cobb–Douglas and a nested Constant Elasticity Substitution (CES) function to simulate what would happen to output and energy consumption following continuous improvements in energy productivity. He showed that the effect of energy efficiency on energy use depends on the elasticity of substitution between energy and the non-energy inputs. If this elasticity is greater than 1, energy use will be increased. Howarth [1997] has criticized the theoretical assumption of this approach, arguing that energy services, rather than energy itself, enter the production function as a factor input. By means of a modified growth model, Howarth has shown that a backfire effect will only occur if energy costs dominate the total cost of energy services and expenditures on energy services constitute a large share of economic activity. Empirical research suggests that both are implausible [id., ibid, p. 7]. Saunders [2000, 2008] in reply demonstrated that neoclassical theory still predicts backfire, but that the magnitude of rebound depends almost entirely on the choice of the underlying aggregate production (or cost) function. For instance, the Leontief production function is always "fuel conserving" (efficiency improvements have a *positive* net effect on energy savings), while Cobb-Douglas and Generalised Leontief functions are always "fuel using" (backfire). The commonly used CES and Translog functions are only sensitive to rebound as the case

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[10] In particular, as we will show later, the direct rebound effects consist of the substitution effect and the income (households) or output (firms) effects.

[11] The micro-level indirect effects are sometimes said to result in so-called *secondary* effects at the macro-level [e.g. Greening et al., 2000, p. 391], although Sorrell [2009] explicitly distinguishes secondary effects from embodied effects [Sorrell, 2009, p. 202] and rather confusingly calls the ensemble of secondary and embodied effects 'indirect effects' (thus mixing up terms at the micro- and macro-level). In summary, one might say that secondary effects relate to all macro-level rebound effects *not directly* associated with the energy service whose energy efficiency has improved. Adding to the confusion, Jenkins et al. [2011, p. 13] decided to call the indirect effects at the micro-level "substitution effects", again showing little respect for the established terminology in elementary micro-economic theory of demand. To make matters worse, later on Jenkins et al. [2011, p. 20-21] use "re-spending effect" to refer to the indirect effect at the household level.

may be in particular forms (CES) or under specific circumstances (Translog). Hence, many studies based on these production functions are likely incapable of simulating rebound effects. In the 1990s the standard neo-classical growth model has been extended to account for endogenous technological progress. A further development of these so-called endogenous growth models to also account for rebound effects "*renders hope that in the future the relationship between economic growth, technical change and resource use (and eventually the size of various rebound effects on the macroeconomic level) can be better modelled and understood*" [Madlener & Alcott, 2006, p. 7]. However, this 'new' growth theory "*has generally neglected energy-related issues, and to the best of our knowledge, no author has approached the rebound question with an endogenous growth model*" [Dimitropoulos, 2007, p. 6356].

1.4.3. General equilibrium effects

General equilibrium theory can be supplemental to economic growth theory, since it '*offers insights to how energy productivity gains diffuse within an economy*" [Dimitripoulos, 2007, p. 6357]. We refer to the rebound effects analyzed in general equilibrium models as 'general equilibrium effects' [e.g. Herring, 2006], but they are also known as rebound effects resulting from 'market-clearing price and quantity (re)adjustments' [e.g. Hertwich, 2005, p. 86; Greening et al., 2000, p. 390].

Computational general equilibrium models (CGE models) are inspired by neoclassical macro-economic theory, but they allow dealing with circumstances that are too complex for analytical solutions. CGE models are calibrated to reflect the structural and behavioural characteristics of particular economies. CGE models thus require assumptions about production structures, functional forms and values of the relevant parameters - including those that determine elasticities of substitution [Sorrell, 2008, p. 3]. As opposed to econometric methods, the rebound effects are evaluated rather than estimated and tested [Guerra & Sancho, 2010, p. 4]. Their main advantage over econometric techniques is that they permit to isolate the effects of energy productivity gains from the influence of other possibly confounding variables (simply by running the model with and without changes in energy efficiency), and to decompose the economy-wide rebound effect into 'primary' and 'secondary' rebound effects from specific energy efficiency improvements. CGE models also provide scope for sensitivity analysis, "*although in practice this appears to be rare*" [Sorrell, 2009, p. 221]. Several CGE studies have simulated improvements in the productivity of energy[12], and although "*these studies follow a similar modelling philosophy, they exhibit significant differences in specification, parameterisation, simulation procedure and other crucial assumptions that are likely to determine results*" [Dimitripoulos, 2007, p. 6357]. The results are very inconclusive: estimates range from 15% to 350% on a wide variety of research objectives, methodologies and assumptions [Dimitripoulos, 2007, p. 6358-9]. "*…the assumptions of CGE models with regard to production structures and elasticities of substitution appear to be only tenuously linked to the empirical literature on this subject; while the empirical literature itself appears to be confused, contradictory and inconclusive. This suggests that the numerical results of CGE models - including the estimates of rebound effects - should be treated with great caution*' [Sorrell, 2008, p. 5].

Another approach to estimate economy-wide rebound effects is the use of dynamic general equilibrium models of national economies, combining principles of general equilibrium theory with

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[12] The large majority of these studies examine energy productivity improvements in the production sectors of the economy and thus yield little insight into the impact of end-use efficiency improvements in consumer sectors. [Jenkins et al., 2011, p. 33]

advanced econometric techniques [Dimitripoulos, 2007, p. 6359-60]. "*In contrast to their CGE counterparts, macro-econometric models do not rely upon restrictive assumptions such as constant returns to scale and perfect competition and replace the somewhat ad hoc use of parameter estimates with econometric equations estimated for individual sectors. However, this greater realism is achieved at the expense of greater complexity and more onerous data requirements*" [Sorrell, 2009, p. 224]. Over time, these top-down macro-econometric simulation models have been linked to bottom-up systems engineering models of the energy sector. Still, even the most sophisticated models linking the micro- and macro-scales (e.g. Barker & Foxon, 2008; Barker, Dagoumas & Rubin, 2009[13]) are "*restricted by exogenous assumptions about the scale of direct rebound and other key factors and are limited to modeling 'pure' energy productivity improvements without considering the potential for multi-factor productivity improvements from energy-saving technologies to trigger even greater rebound or even backfire*" [Jenkins et al., 2011, p. 50]. Jenkins et al. [2011] note that at the scope of an interconnected, global economy the scale of the economy-wide rebound effect appears to be on the order of 50% or greater. This compares to 25-40% for the developed nations [id., ibid., p. 40]. This empirical evidence needs to be interpreted with plenty of caution, also keeping in mind that studies based on 'integrative models' to explore the macro-level rebound effects are scarce to date.

1.4.4. Embodied effects

Many improvements in energy efficiency can be understood as the 'substitution' of capital for energy within a particular system boundary. For example, thermal insulation (capital) may be substituted for natural gas or heating fuel oil (energy) to maintain the internal temperature of a building at a particular level. But estimates of energy savings typically neglect the 'embodied energy', i.e. the energy required to produce, install and maintain the measures that improve energy efficiency, such as thermal insulation. Substituting capital for energy therefore shifts energy use from the sector in which it is used to sectors of the economy that produce that capital [Sorrell, 2009, p. 215].

Estimates of the embodied energy of different categories of goods and services can be obtained from life-cycle analysis (LCA), input–output analysis, or a combination of the two. Relatively few empirical studies have estimated the embodied energy associated with specific energy efficiency improvements, and those that have appear to focus disproportionately upon domestic buildings [Sorrell, 2009, p. 215]. These studies indicate that rebound effects due to the embodied energy effect are likely to be small (<15%), but "*can be more significant for efficiency improvements with long economic payback periods, a short lifespan and / or energy intensive production and installation requirements*" [Jenkins et al., 2011, p. 20]. Sorrell [2009] concludes that "*…while techniques based upon embodied energy estimates provide a promising approach to quantifying indirect and economy-wide rebound effects, the application of these approaches remains in its infancy*" [id., ibid, p. 221].

1.4.5. Transformational effects

For the sake of completeness, we add 'transformational' or 'enabling' effects as a further category of rebound effects to the list. Some authors (e.g. Greening et al. [2000], Sorrell [2010]) mention that technological progress in the long term may have the potential to induce changes in the preferences of consumers and to introduce new production techniques that transform the organization of production. Changes in technology might even alter social institutions. EUPOPP [2009] gives as an example of transformational effects the introduction of the microwave oven, which is more energy-

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[13] For example, in their MDM-E3 model, direct rebound is not modelled but fixed exogenously based on surveys of prior empirical studies.

efficient for heating small amounts of food than a conventional oven. "*Microwave ovens, however, have not replaced conventional ovens, but have rather engendered a totally new category of products (ready-to-heat microwave meals)*" [Heiskanen & Schönherr, 2009, p. 80-81].

The notion of transformational effects remains vague. Allan et al. [2006] presume that by transformational effects is "*meant either that technical change itself and/or household utility functions are themselves endogenous in the very long-run*" [id., ibid, p. 21]. As Lorentz & Woersdorfer [2009, p. 6] or Allan et al. [2006, p. 21] observe, these types of rebound effects are not pursued further in (economic) literature.

2. The mainstream micro-economic approach to rebound effects for households

2.1. Preliminaries – delimitations and definitions

Our analysis focuses entirely on energy services in the household sector. For a discussion of rebound effects in other sectors (firms) we refer to Saunders [2011]. A brief overview of economy-wide rebound effects was presented in chapter 1.

Furthermore, it is important to distinguish price induced efficiency gains from non-priced induced efficiency gains. The former are caused by factor substitution, e.g. thermal insulation (capital) replacing natural gas (energy). The latter are due to technological improvements. Our main concern is with the micro-economic rebound effects associated with energy efficiency improvements of technologies[14]. Energy rebound effects resulting from pure behavioural changes (so-called "energy conservation" measures like lowering the thermostat or eco-driving) will not be discussed in detail.

The estimated direction and magnitude of the rebound effects will partly depend upon how energy service, energy efficiency and (implicit) costs of the energy service are defined.

2.1.1. Energy services

Consumers admittedly[15] do not need (marketable) commodities[16] such as a boiler, a light fixture, a car, a washing machine or a TV, but rather they need thermal comfort, visibility (illumination), mobility, clean clothes or entertainment. Energy demand by households is thus a *derived* demand – energy is combined with other commodities to produce (or derive) the services households desire.

"*Taking a service-based approach helps to clarify the nature of the essential services that require energy inputs …*" and "*The correct definition of a service requirement is an important step toward identification of the potential for energy efficiency improvement, …*" [Pears, 2004, p. 8]. In particular, using the concept of energy services offers the following distinct advantages:

- It reveals the importance of clearly defining the system boundaries. For example, in the case of space heating, the energy system could be the boiler or the entire house;
- It highlights the range of available choices. For example, Pears [2004, p. 9] uses the energy service 'cleaning clothes' as an example to demonstrate the range of available choices to provide a particular energy service (see figure 5);
- It draws attention to the close connection between energy demand and capital goods. This has at least three implications. Firstly, as technology improves households can enjoy the same amount of services but with a lower energy input. Secondly, there is a markedly dynamic component of energy demand, separating the short run (capital stock is fixed) from the long run (capital stock is adjusted). And thirdly, as decisions to buy capital goods are affected not only by current and / or expected future (energy) prices but also by income, changes in energy demand may well reflect changes in wealth [Kriström, 2008, p. 96-97].

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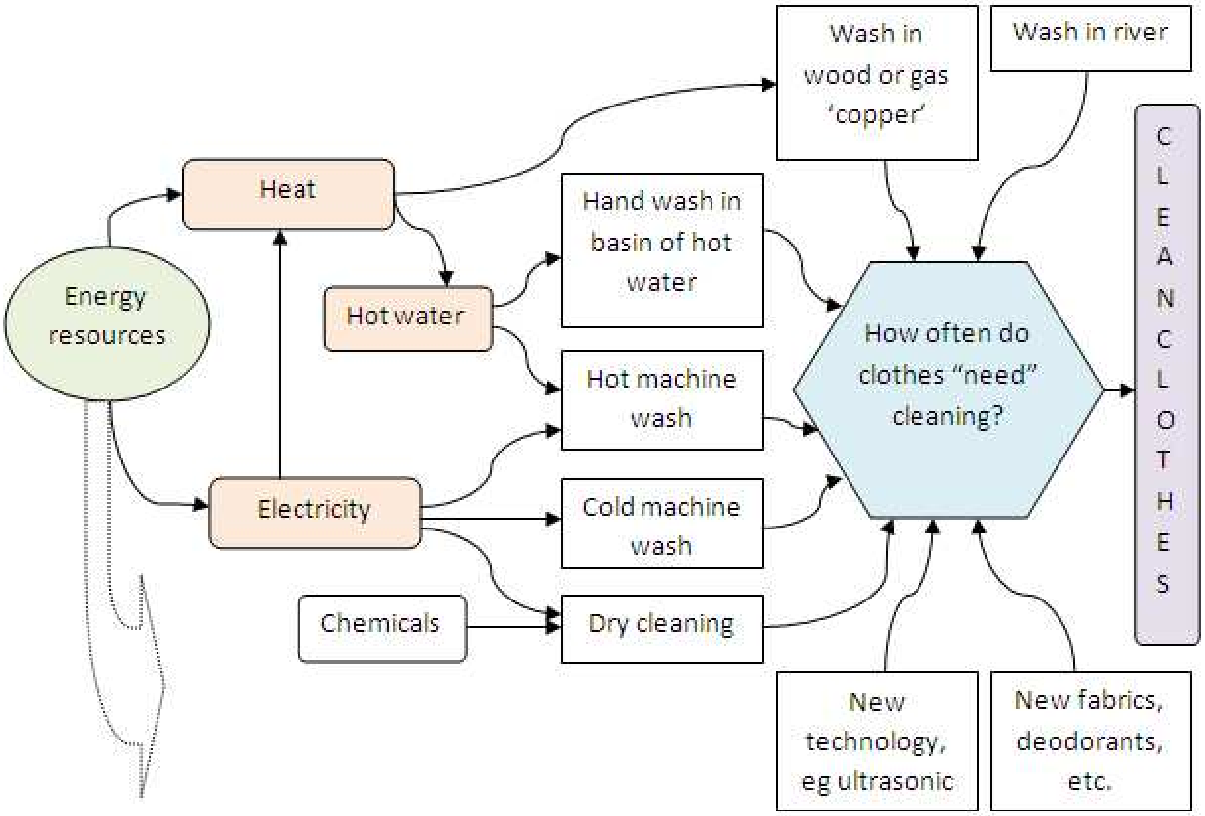
[14] Technological innovation may itself be price induced, but this will not be discussed here.

[15] But consumers may need the freedom and flexibility that brings about a washing machine compared to a laundrette, of a TV set compared to a movie at the theatre, etc. In general, consumption is multifunctional. See also the § on attributes of energy services [Boulanger P.-M., personal communication 2011].

[16] A commodity is defined as a particular good or service delivered at a specific time and at a specific location.

Figure 5: Example of the supply of an energy service, the provision of clean clothes, showing the range of choices* available.



(*) The scheme does not show additional energy services such as drying and ironing clothes. Also not shown are laundrettes or laundry services, who provide the same cleaning service by other means (e.g. shared machines), and may also provide other services such as collection, 'service washes' (the labour element is provided by staff) and delivery [Cooper & Evans, 2002].
Source: adapted from Pears [2004, p. 9]

The KLEM approach to energy services

Energy services such as heating, lighting, mobility, clean clothes or entertainment are provided through energy systems that involve particular combinations of capital (K), labour (L), energy carriers (E) and materials (M). For example, the energy system providing the energy service 'space heating' may include primary conversion equipment (e.g. boilers), secondary conversion equipment (e.g. radiators), equipment for distributing energy, manual or electronic controls, but also building fabric, thermal insulation, ventilation systems and glazing [Sorrell, Dimitropoulos & Sommerville, 2009, p. 1357]. Or, the energy system providing the energy service 'lighting' is made up of lamps, luminaries and supporting systems such as power supplies and ballasts [Lima de Azevedo, 2007, p. 1228], but also of passive daylighting sources such as conventional windows, clerestory windows, skylights, glass block walls, light shelves, tubular daylight guidance systems (TDGS), etc.

Nevertheless, as noted by Madlener & Alcott [2007], "*…the common concept in the rebound literature of 'energy services' should be reconsidered, because every good and service requires energy inputs (just as, perhaps, they require capital, labour and non-energy material inputs as in Q = f(K,L,E,M)*" (id, ibid, p. 8]. Later on, we will define the useful outputs of energy services as inputs to meet the “ needs and wants” of households. In other words, the demand for (useful outputs of) energy services is in itself a kind of derived demand.

Attributes of energy services

“*Energy services may also have broader attributes that may be combined with useful energy outputs in a variety of ways. For example, all cars deliver passenger kilometres, but they may vary widely in terms of speed, comfort, acceleration and prestige*” [Sorrell, Dimitropoulos & Sommerville, 2009, p. 1357]. When consumers buy a car, they are concerned with a variety of characteristics including performance, reliability, safety, styling, status, resale value and fuel-efficiency, but the primary emphasis may be on any one of these factors” [Ehrhardt-Martinez, 2009, p. 3]. Advertising plays an important role in shaping the relation between product offering and tastes, de-emphasizing the technical aspects of automobiles and enhancing the social dimensions of prestige, distinction and personal freedom [Laird, 1999]. Hence, consumers may make trade-offs between useful output and other attributes of an energy service [Sorrell, Dimitropoulos & Sommerville, 2009, p. 1357]. For example, a MIT study estimates that in the U.S. for the period 1980 to 2006 75% of the expected energy savings due to improvements in on-road vehicle fuel economy (engine efficiency) were “taken back” to accommodate consumer preferences for heavier vehicles and more powerful engines (horsepower / torque / acceleration), and another 2.5 to 7.5% by increases in distances travelled [Knittel, 2012].

2.1.2. Energy efficiency

“*Energy efficiency is a generic term, and there is no one unequivocal quantitative measure of 'energy efficiency'*” [Patterson, 1996, p. 377]. “*In practice, one very rarely encounters an explicitly stated definition of energy efficiency*” [NAS, 2010]. In principle, end-use energy efficiency concerns the technical relationship between on the one hand the maximum quantity of useful outputs of services (for instance, space heating, lighting, cooling, mobility, etc.) obtainable from a chosen and appropriately used technology, and on the other hand the (total) quantity of primary or final energy[17] consumed by that technology [Oikonomou et al., 2009].

The energy efficiency of an energy system is more formally defined as the ratio of useful output(s) to total energy input(s) converted to provide the useful output(s).

$$\eta = \frac{S}{E}$$

Where η is energy efficiency, S is useful output(s) and E is (converted) energy input(s) [18]. For example, the energy efficiency of an air conditioner may be defined as the amount of heat removed from air per kilowatt-hour of electricity input.

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[17] “Primary energy consumption refers to the direct use at the source, or supply to users without transformation, of crude energy, that is, energy that has not been subjected to any conversion or transformation process.” [OECD, glossary of statistical terms] “Final energy is the energy supplied to the consumer in each end-use sector, which is ultimately converted into heat, light, motion and other energy services. It does not include transformation and distribution losses.” [IEA, 2008, p. 86] The ‘primary energy equivalent’ (of final energy) is an energy measure that accounts for losses in the production, transportation and distribution of final energy carriers (e.g. losses in electricity generation, transmission and distribution).

[18] This definition of energy efficiency assumes proportionality between level of energy service and energy input, regardless of the level. This may not be true in general, but provides for a convenient first-order approximation of the relationship of S with respect to ε.

The denominator E is always measured as energy (e.g. in kWh or MJ). The one exception is the (pure) economic indicator of energy efficiency, where both useful output(s) and energy input(s) are enumerated in monetary terms (market values).

A key element in any definition of energy efficiency remains the meaning of 'useful'. Value judgements are required to define what is considered to be a useful output. In that respect even the thermodynamic definition "*…combines engineering metrics with human preference*" [Lovins, 2004, p. 386]. Or as Boulding [1981] puts it: "*The significance of the efficiency concept, however, depends on the significance of the outputs and inputs in terms of human valuations*".

The thermodynamic definition

In the *thermodynamic* definition of energy efficiency, the numerator S is measured as useful *energy* outputs. For example, for an electric motor, the useful output can be measured as torque (in Nm), ignoring undesired outputs such as heat, noise, vibration and stray electromagnetic fields. End-use energy efficiency is thus defined as the ratio of useful energy outputs over energy inputs. It is a *dimensionless* number with a value between 0 and 1. Were it not for the word 'useful', the above definition would be trivial, as the First Law of Thermodynamics tells us that energy is conserved in all transformations (i.e. the ratio of energy outputs to energy inputs is always unity, or 100%) [Radovic, 2001]. Table 1 summarizes useful outputs and energy inputs for some common energy conversion devices.

Table 1: Typical efficiencies for some common energy conversion devices

Device	Useful energy output	Energy input	Typical efficiency
Electric heater	Thermal energy	Electricity	100 %
Electric motor (large)	Mechanical energy	Electricity	90 %
Electric motor (small)	Mechanical energy	Electricity	65 %
Fluorescent lamp	Light	Electricity	20%
Incandescent lamp	Light	Electricity	5%
Battery	Electricity	Chemical	90%
Steam boiler (power plant)	Thermal energy	Chemical	85%
Gas turbine (industrial)	Mechanical energy	Chemical	30%
Automobile engine	Mechanical energy	Chemical	25%
Steam turbine	Mechanical energy	Thermal energy	45%
Electric generator	Electricity	Mechanical energy	95%
Silicon solar cell	Electricity	Solar	15%

Source: Radovic, 2001.

The thermodynamic definition of energy efficiency is not a *qualitatively* unitless number. The units in the numerator and denominator must also be of the *same energy form*, thus reflecting the quantitative equality and the qualitative difference of the various energy forms. For example, because power is the rate of energy utilization, efficiency can also be expressed as a power ratio. The efficiency of an electric motor consuming 100 watts (W) of power to obtain 90 watts of mechanical power is therefore 90%. If an energy system consists of two or more sub-systems then the efficiency of the system is the product of efficiencies of the individual sub-systems. For example, if in a power plant the boiler converts the chemical energy in a fossil fuel to thermal energy with an efficiency of 88%, the turbine converts the thermal energy to mechanical energy with an efficiency of 40%, and the generator converts the mechanical energy to electricity with an efficiency of 98%, then the efficiency of the power plant is (0.88) (0.40) (0.98) = 0.35 or 35%.

The thermodynamic energy efficiency as defined above is also known as first-law efficiency. In thermodynamics one also defines *exergy* efficiency or second-law efficiency as the ratio of the 'theoretical minimum amount of work required to produce the desired flow' over the 'maximum amount of work that could be produced from the sources flow'.

The physical-thermodynamic definition

Thermodynamic definitions fall short of adequately capturing the situation where the useful output is not expressed as an energy form. The (hybrid) physical-thermodynamic definition of energy efficiency measures the useful output as a "tangible" (physical) unit rather than an energy conversion output [Gavankar & Geyer, 2010, p. 12]. For example, the useful output of a washing machine could be the kilograms of clothes washed rather than the thermodynamic thermal or mechanical energy. For residential heating, the physical output could be the volume (in m^3) [or floor area (in m^2)] of space heated within a certain time period. For freight transport, the useful output can be measured by tonne kilometres, considering that the desired output of freight transport is to move a given mass of freight (measured by tonnes) over a given distance (measured by kilometres). Like thermodynamic efficiency indicators physical-thermodynamic indicators[19] can be objectively measured, but they have the added advantage that they refer to what consumers are actually requiring in terms of an end-use service [Patterson, 1996, p. 380].

Depending on how useful energy output is defined, its measurement can be more or less problematic for many types of energy services [Sorrell & Dimitropoulos, 2008]. For example, "*…the energy service delivered by passenger cars may be measured in terms of vehicle kilometres, passenger kilometres or (rather unconventionally) tonne kilometres*" [Sorrell, Dimitropoulos & Sommerville, 2009, p. 1357]. The useful output of a domestic heating system could be defined "*as the average internal temperature of the house and measured directly using field thermometers or indirectly from thermostat settings. But the latter are notoriously inaccurate …*" [Sorrell & Dimitropoulos, 2008, p. 639]. Moreover, useful energy output measured as the average internal temperature can be a poor proxy for the thermal comfort of the occupants, which depends upon a number of different variables such as "*… (1) attitudes toward thermal comfort, (2) individual activity levels, (3) air temperature, (4) mean radiant temperature (heat exchange between the human body and the surrounding temperature), (5) air velocity or draft, and (6) humidity..*" [Greening et al., 2000, p.393]. Therefore, the physical unit in which the useful output is measured may depend on the objectives and scope of the study [Gavankar & Geyer, 2010, p. 13].

The economic-thermodynamic definition

Another problem is that of "joint production", where an energy system produces multiple useful outputs. For example, a wood or coal stove may be used to heat the room, to produce domestic hot water and even for cooking. The problem of allocating one energy input to several outputs is known as the "partitioning problem". In macro-economics, the problem of comparing different physical outputs is 'solved' by measuring the monetary (market) values of those outputs. This not only allows aggregating the different outputs of one energy system, but also the outputs of different energy

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[19] It is customary, however, to express physical indicators as "energy intensity", i.e. energy per unit of useful output (e.g. kWh/m^2, MJ/tonne-km, etc.)

systems.[20] The main problem with the (hybrid) economic-thermodynamic definition of energy efficiency is the inability of this indicator to separate the changes in energy consumption over time due to technical improvements of the energy system from other factors like changes in energy prices or (structural) changes in the useful output mix.

The lifestyle definition

The ultimate end of an energy system is welfare, to be interpreted as *"…well-being, quality of life, or whatever terms have been applied to express the ultimate end of satisfying people's real needs and wants*" [Nørgård, 2000, p. 105]. Since welfare in general cannot be quantified, the efficiency by which an energy system converts energy into welfare cannot be expressed by numbers either. For this reason, energy models usually do not explicitly include non-quantifiable elements such as welfare.

The boundaries of the energy system

The definition and measurement of energy efficiency depends on how the system boundary is defined. The borders of the considered system can be widened both in space and time[21].

Lovins (2004, p. 387) decomposes (technical) energy efficiency as the product of at least five different kinds of energy efficiency along the chain of energy conversions:

- The *extractive efficiency* of converting energy resources such as fossil fuels (coal, oil, natural gas), uranium ore or renewables to primary[22] energy;
- The *conversion efficiency* of primary into secondary energy. Examples of secondary energy are refined petroleum products (e.g. gasoline), dry natural gas, grid electricity or district heat;
- The *distribution efficiency* of delivering secondary energy from the point of conversion to the point of end-use;
- The *end-use efficiency* of converting the delivered secondary energy into desired energy services;
- The *hedonic efficiency* of converting delivered energy services into human welfare. For example, delivering useful heat to a room may still not achieve 100% thermal comfort for the occupants of that room.

Or another example, in time, the energy consumption by the occupants during the usage phase of a building can be supplemented by the so-called 'grey energy' consumption. Grey energy is the energy which is consumed before or after the usage phase of the house or building, including construction energy (both direct and energy embodied in the construction materials) and demolition energy.

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[20] At the national level, the ratio becomes GDP per national energy consumption. This is also called the (economy) energy productivity ratio. In macro-level policy analysis, the use of the energy productivity ratio in combination with the well established labour and capital productivity ratios can provide useful insights into whether energy inputs acts as complements or substitutes to these other factor inputs [Patterson, 1996, p. 382].

[21] One a more philosophical note, one could in principle trace (most) energy inputs back to flows of solar energy inputs.

[22] The energy forecasting community has adopted at least two conventions for measuring *non-fossil fuel* primary energy (such as renewables or nuclear): the output of the conversion technology is assumed to be the primary energy, which implicitly assumes an energy conversion efficiency of 100%; or an average fossil fuel conversion factor is assumed and used to back calculate an equivalent fossil energy primary equivalent [Kydes & Cleveland, 2007].

And last but not least, non-commercial energy inputs are often ignored in energy accounting. These are energy inputs not acquired through the market exchange process, such as locally collected and often unprocessed biomass-based fuels (e.g. firewood, crop residues or cattle dung)[23], which are used especially in rural households for cooking and heating. Renewables such as solar, wind or geothermal energy are also sometimes excluded, as they are considered to be free sources of energy. For instance, IEA (2007) does not take into account *passive* solar energy for direct heating, cooling and lighting of dwellings. BP [2010] does not include renewable energy in its published BP Statistical Review, because of problems with the completeness, timeliness and quality of the data.

2.1.3. Costs of energy services

Since rebound effects refer to an increase in demand (behavioural response) when the real per unit costs of an energy service decline as a result of technical improvements in the energy efficiency of that service, it is worthwhile to investigate the nature of these costs.

Implicit or effective prices of energy services versus market energy prices

The scope of our research pertains only to the potential for rebound in response to so-called *below-cost* efficiency improvements, i.e. improvements that have the effect of decreasing the overall marginal costs of energy services. The marginal cost of an energy service is the change in total costs of producing (or delivering) one more unit of useful output of the energy service. For example, marginal costs could be the costs per additional unit of heating degrees provided in case of home heating; or the costs per additional lumen output for lighting. These marginal costs are also known as the *implicit* or *effective* price of an energy service. Furthermore, a clear distinction must be made between the implicit or effective price of an energy service (as defined above) and the market price of an energy carrier (e.g. cost per unit of heating fuel oil or per unit of electricity). The micro-level rebound effects are mainly driven by reductions in the implicit / effective price (or marginal costs) of energy services. Changes in the *implicit* prices of *energy services* can occur even if there are no changes in the *market* prices of *energy carriers* [Jenkins et al., 2011, p. 8; Koerth-Baker et al., 2011, p. 3].

At the macro-level, efficiency improvements may reduce *aggregate* demand for a particular energy carrier, leading to a possible reduction in market prices for that energy carrier, and this ‘market price effect’ may in turn drive a rebound effect in energy demand as consumers respond to now lower energy prices [Jenkins et al., 2011, p. 8]. We will not concern ourselves with these macro-level effects.

Capital costs and other expenses other than energy costs

Energy costs are only one component of providing an energy service at the household level. Overall (private) costs must also include annualised capital, maintenance, labour, material and time costs [Sorrell, Dimitropoulos & Sommerville, 2009, p. 1357].

Possible substitution effects between the inputs (capital, labour, energy, materials) of an energy service will affect energy use [Binswanger, 2001, p. 122]. Energy-efficiency improvements reduce the energy costs of the energy service, but the direct rebound effect will also depend in part upon how these improvements affect the (real) costs of the other inputs (capital, labour, materials).

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[23] These are also known as ‘traditional’ fuels or biomass.

In particular, the (initial) capital costs of durable goods have to be taken into account as well, especially when the more energy efficient technology is more expensive than alternatives with comparable characteristics but a lower efficiency level [Sorrell and Dimitropoulos, 2008; Mizobuchi, 2008; Madlener and Alcott, 2009]. The resulting reduction in the relative *overall* marginal costs of the energy service would be lower with than without taking into account the (discounted and annualized) capital costs. Estimates of the direct rebound effect neglecting capital costs might thus be biased in terms of overestimating the effect [Woersdorfer, 2010, p. 6]. Finally, one cannot exclude the possibility that the more energy efficient technology may (also) be more expensive in terms of maintenance, repair and operations (MRO).

If energy efficient equipment is more expensive than similar but less energy efficient equipment, and given the high implicit discount rates consumers typically have[24], the life cycle cost (LCC)[25] of the energy efficient technology would be significantly higher. On the one hand, the relatively high LCC of energy efficient durables (as compared to less efficient ones) may not encourage an increase in the number of units purchased, or their average size. On the other hand, once purchased, energy efficient equipment may be expected to have a higher utilisation rate, owing to their lower *short-run* marginal costs [Sorrell, 2009, p. 207].

Perhaps one should not overemphasize the importance of capital costs, since "*In practice, many types of equipment appear to have both improved in energy efficiency over time and fallen in overall cost relative to income*" [Sorrell, Dimitropoulos & Sommerville, 2009, p. 1358]. And capital costs are of course irrelevant for rebound effects resulting from pure behavioural changes (e.g. walking or cycling instead of using the car).

Opportunity costs of time and space

The overall costs of an energy service also include the time spent and / or the space required by the consumer. The opportunity costs of time and space – in the sense of Becker [1965][26] – may thus affect certain types of rebound effect. "*This has not been included in the traditional rebound theories, in spite of the fact that the substitution between time and money is a central concern of consumer economics*" [Hertwich, 2005, p. 88].

An example of the opportunity costs of space is an increase in refrigerator size, which may not be the best use of available space. "*However, space constraints may become less important over time if technological improvements reduce the average size of conversion devices per unit of output or if*

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[24] Several studies indicate that implicit discount rates for energy efficient investments in end-use technologies vastly exceed market interest rates. They also vary substantially across end-use technologies, and may or may not vary with income [Lima de Azevedo, 2007, p. 1230].

[25] Life-cycle cost (LCC) is the sum of all *discounted* one-time and recurring relevant costs over the full life span of a product, taking into account first costs (including capital investment, purchase and installation costs) and future costs and benefits (including energy, operating, maintenance, repair, upgrade and capital replacement costs, and salvage costs or benefits at the end of the lifetime). The *conventional* (and incorrect) engineering-economic approach to calculate the 'average' cost of expected energy savings is to divide the levelized annual cost of an energy efficiency improvement by the (constant) annual energy savings from the improvement. Formally, $CSE = \frac{\Delta I.q + \Delta M}{\Delta E}$ with CSE is the (levelized) cost of saved energy [€/kWh], ΔI is the additional capital cost [€], $q = \frac{d}{1-(1+d)^{-n}}$ is the capital recovery factor [$year^{-1}$], ΔE is annual energy savings [kWh/year], ΔM is the annual change in labour, material and other non-energy costs and monetized benefits [€/year]; n is number of years of energy savings [years] and d is annual real discount rate [Meier, 1982; Worrell et al., 2004].

[26] Becker sees time as an input into consumption activities. (see also x)

rising incomes lead to an increase in average living space…" [Sorrell, Dimitropoulos & Sommerville, 2009, p. 1358].

An example of the opportunity cost of time is the time necessary for driving longer distances, which may not be the best use of available time.

The impact of time constraints on the direct rebound effect is ambivalent. Time can be a constraint for consumption, but might also induce the usage of time-saving equipment [Schettkat, 2009, p. 9-10]. Hence, changes in energy use are frequently just 'side-effects' of households' time-saving efforts [Binswanger, 2001, p. 122].

On the one hand, a time constraint could be a reason for demand saturation, limiting the scope of the rebound effect [Lorentz & Woersdorfer, 2009, p 10]. Mobility research seems to indicate that faster transport implies that people travel larger distances but keep total travel time constant [Hertwich, 2005, p. 88]. It would seem that in industrialized countries demand for car travel is time-constrained [the so-called *fixed travel time budget* hypothesis], not cost-constrained. Hence, savings in time (e.g. through new road capacity) potentially have much higher rebound potential [de Haan et al., 2009, p.1093] than decreasing marginal costs of car use as a result of improvements in fuel efficiency. It has long been known to transportation researchers that any changes in the transportation system that reduces congestion without otherwise making driving more expensive, will cause travel on the congested facility to increase, thus partly offsetting the policy's effect on congestion. This feedback effect is known as the "induced demand effect". The induced demand effect interacts with the rebound effect. The rebound effect will be slightly dampened by the additional congestion[27] it creates. "*If fuel-efficiency improvements increase travel demand at locations and times where congestion is present, they will tend to worsen congestion, which will itself tend to deter travel by exactly the reverse of the mechanism that produces induced demand*" [Hymel et al., 2010, p. 1].

On the other hand, time-saving technological progress frequently exerts a large influence on energy use. Many time-saving devices require an increase in energy consumption. For example, using a time-saving electric clothes dryer uses more energy than hanging clothes to dry. But even if the time-saving activity uses less energy than the substituted one, time saving innovations are likely to increase energy consumption (time rebound effect)[Binswanger, 2001, p. 122]. The time rebound effect describes "*changes in total resource use due to increased efficiency in time use, which in turn influences the use of resources in general* [Spielmann et al., 2008, p. 1389]. For example, a microwave oven uses more energy per minute of operation than a conventional oven. But the use of a microwave oven saves a substantial amount of time over the use of other technologies such as conventional ovens, stove tops or slow cookers. In general, the reduced amount of time will generally lead to lower energy costs per meal cooked. Technological innovations of a time-saving nature like convenience food or automated washing machines thus imply reductions in relative utilization costs that might trigger behavioural reactions [Lorentz & Woersdorfer, 2009, p 10]. But time saved from microwave cooking will also be reallocated to additional activities. For example, some of the time saved may be used to increase the number of hot meals prepared at home (direct

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[27] Congestion costs are measured by the extra time it takes to drive under congested conditions, multiplied by the value of travel time (usually taken to be about half the market wage).

time rebound effect), and some may be used for additional energy-intensive leisure activities (indirect time rebound effect)[Brenčič and Young, 2008 ,p. 3].

The opportunity cost of time should increase with rising incomes [Sorrell, Dimitropoulos, Sommerville, 2009]. Also, (additional) leisure time (resulting from shorter household working hours) may be spent on resource intensive activities (jet-skis) or less resource intensive activities (e.g. surfing). Preferences may differ between individuals and may change over time [Wuppertal, 2009]. This illustrates once more that the rebound effects (direct + indirect) may vary between households and over time, and may be influenced by a large number of variables [Sorrell, Dimitropoulos, Sommerville, 2009, p. 1358].

2.2.Micro-economic analysis of rebound effects in the household sector

2.2.1. Rational choice theory

The most commonly used theoretical framework for micro-level analysis of the rebound effects in the household sector is the neoclassical model of consumer behaviour or 'rational choice theory'.[28] This theory considers four basic elements: the consumer's available *income*, the *prices* of goods or services on the market, the consumer's *preferences* and the behavioural assumption of '*utility maximisation*'. Given a limited income, a specific range of commodities to choose from, and a potentially infinite set of preferences, the consumer chooses commodities from those available in such a way as to maximise his or her subjective utility within the constraints of his or her available income [Jackson, 2005, p. 30]. The rational choice theory of consumer behaviour is based on a number of axioms regarding consumer preferences. These axioms are described in detail in annex 1.

2.2.2. Adjustments to conventional micro-economic analysis

In our micro-economic analysis of rebound effects we deviate from the conventional textbook approach of consumer demand. In such an approach the object of interest would be commodities, including energy carriers, and their market prices.

In our adjusted analysis the 'utility' of a household does not (directly) depend on market commodities, including energy carriers such as electricity , natural gas or gasoline. Instead, the household utility is a function of (the useful outputs of) "energy services". Examples of household energy services are heating, space cooling, ventilation, domestic hot water, cooking, lighting, appliances and mobility. Because energy services in general produce more than one output, not all of them desirable (e.g. mobility by private car not only 'produces' passenger transport, but also noise and air pollution), we will explicitly refer to the "useful output of an energy service". Rather than quantities of goods and services (or commodities), we will only consider the levels of (useful outputs of) energy services.

As we shall explain in more detail in chapter 4, and following Becker [1965], Lancaster [1966] and Muth [1966], we prefer to describe the delivery of energy services as a "production household function". To "produce" the useful outputs, the consumer has to purchase certain market commodities, which will serve as inputs into the household production function. Those inputs consist, amongst others, of durable (or capital) goods (e.g. a boiler for home heating or a car for mobility), energy carriers (such as electricity, natural gas, heating fuel oil, diesel or gasoline), and

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[28] In economics the terms "rational choice theory" and "neoclassical economics" are often used interchangeably [Green, 2002, p. 51].

(market) services (such as boiler or car maintenance). In other words, we treat the demand of all commodities, including energy, as *derived* demands. Those demands are derived in the sense that these goods and services serve as inputs for the production of useful outputs of energy services

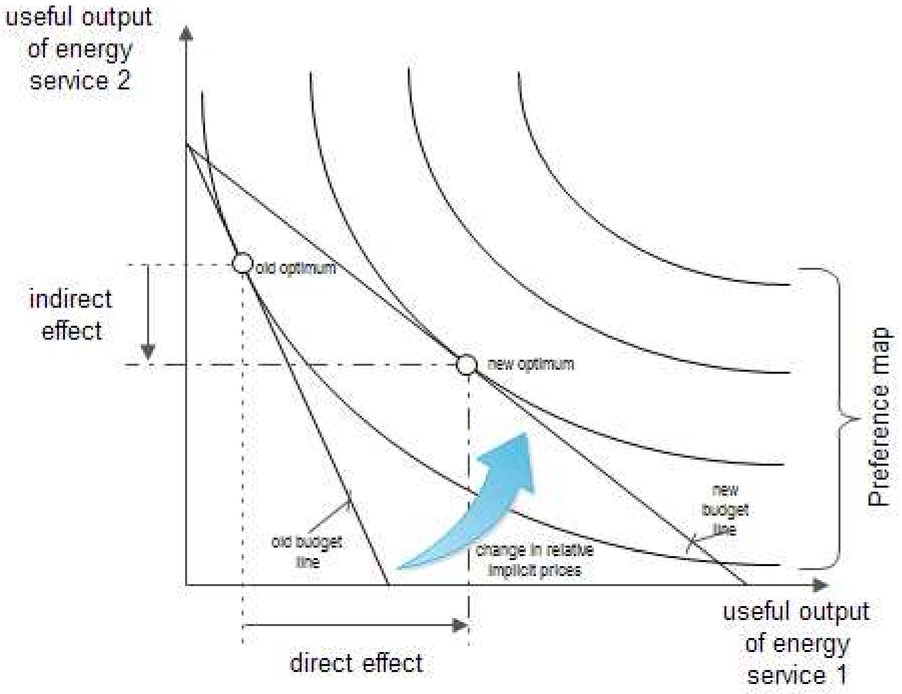
Our interest lies in analyzing how the demand for the useful output of an energy service changes, given an energy efficiency improvement in providing that energy service (e.g. by replacing a conventional boiler with a condensing boiler or by buying a more fuel efficient car). As a consequence, we are not at all interested in how demand for an energy carrier changes as a result of a change in relative market energy prices. On the contrary! A technological innovation improving the energy efficiency of an energy service makes the production of the useful output of that energy service “cheaper”, not because of a decrease in market energy prices, but because one needs less energy to supply the same amount of useful output of that particular energy service. Therefore, to examine a change in demand for the useful outputs of energy services resulting from an energy efficiency improvement in the “production” of one of those outputs, we have to assume that all market energy prices remain constant (or for that matter, the prices of all other inputs needed to provide that energy service)! So, instead of looking at changes in relative energy market prices, we have to consider changes in the relative “overall marginal costs of energy services”, which we previously called “implicit” or “effective” prices. In our analysis, only the implicit prices of the energy services are relevant. Those implicit prices depend not only on prevailing market prices of the commodities needed for providing those services, but also on the (energy) efficiency of those services.

Whereas in conventional analysis the budget set refers to the combinations (or ‘bundles’) of market commodities that a consumer can afford given his/her limited income (wealth) and the market prices of those commodities, in our analysis it refers to the combinations of useful outputs of energy services a consumer can afford, given his/her limited income (wealth) and the *implicit* prices of those energy services. The budget constraint means that the sum of the total costs of supplying the useful outputs of all energy services has to remain within the boundaries set by the household’s budget.

2.2.3. The direct (rebound) effect

For cost-reducing energy efficiency improvements in the households sector, the micro-economic approach distinguishes direct rebound and indirect rebound effects. The direct effect in turn is the sum of the substitution effect and the (direct) income effect.

Figure 6: The direct rebound effect



The adjusted model of household behaviour can explain the rebound effect at the household level. An energy efficiency improvement leads to a change in the *relative* implicit price (or overall marginal costs) of providing the useful output of the energy service under consideration. This in turn leads to a shift of the ‘budget line’, and consequently to a new preferred (or ‘optimal’) combination of levels of useful outputs of energy services. It is important to note that, apart from the energy efficiency improvement and the household’s subsequent change in consumption behaviour, everything else is kept constant, including income level but also all commodity prices (including *market energy prices*)!

Given a certain change in relative implicit prices, both direction and magnitude of the direct and indirect rebound effects depend – ceteris paribus – strongly on the shape of the household’s preference map (which, by the way, is also assumed to be constant). Because preferences can differ substantially from household to household and because preferences are not directly observable[29], it is extremely difficult if not impossible – on theoretical grounds alone – to accurately specify beforehand the direction and magnitude of these rebound effects.

The ‘direct effect’ in figure 6 shows the change (increase) in the demand for (the useful output of) energy service 1, as a result of an energy efficiency improvement of energy service 1, *ceteris paribus*. Dividing this by the new energy efficiency yields the “actual” energy (inputs) demand as a result of the efficiency improvement.

Figure 7: Energy as a derived demand and the direct (rebound) effect

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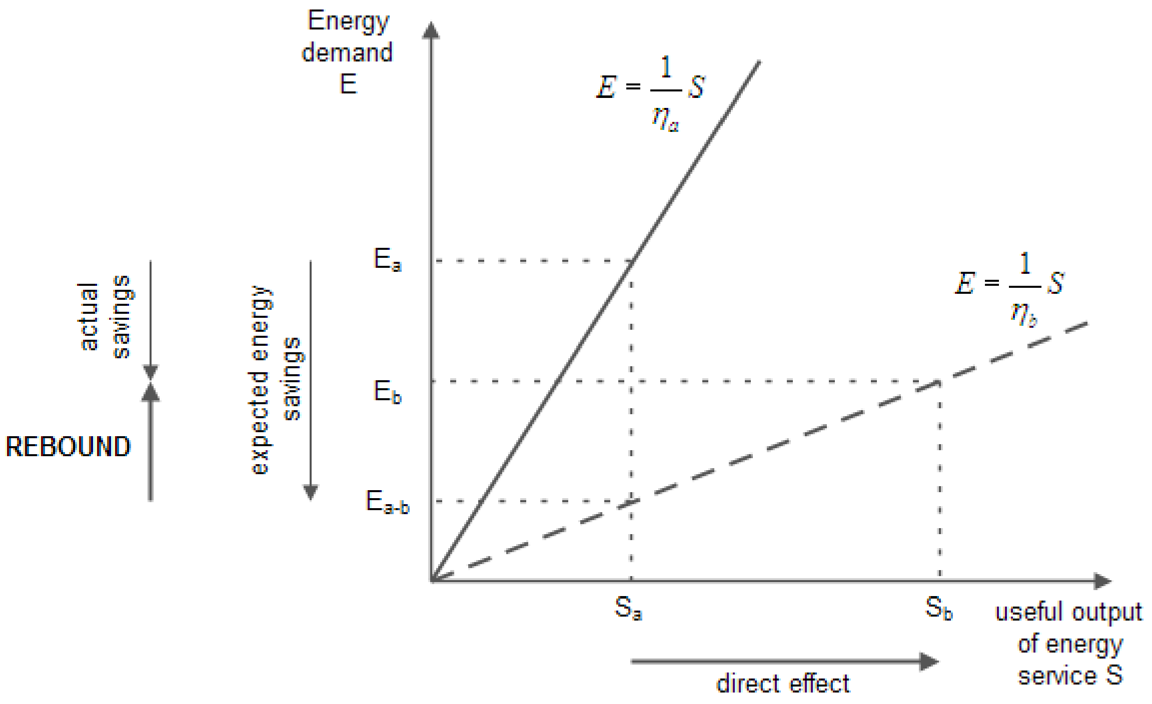
[29] But market transactions and other choices can be observed, and presupposing that choices have the same properties as preferences, choice data can be used to infer preference orderings (see also [Samuelson, 1948] and Revealed Preference Theory).



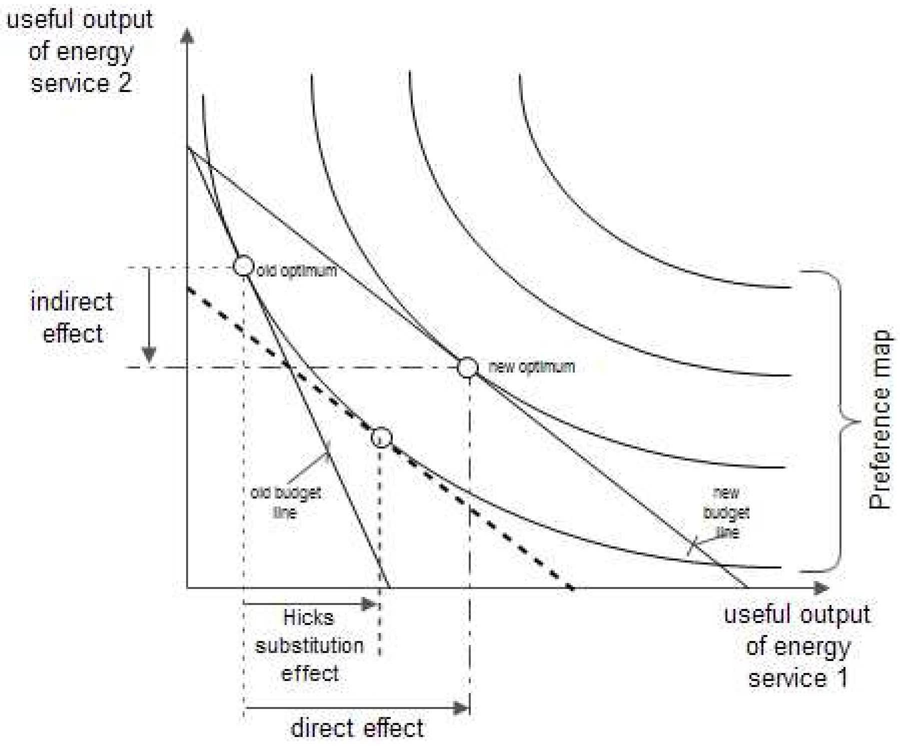
It is straightforward to calculate both the “expected” (or engineering) energy savings and the “actual” energy savings (fig. 7). The expected energy savings are the difference between on the one hand the energy demand before the efficiency improvement (obtained by dividing the original demand for an energy service by the original energy efficiency of that energy service), and on the other the “virtual” energy demand obtained by dividing the original demand for the energy service by the new energy efficiency. The actual energy savings are the difference between on the one hand the original energy demand, and on the other hand the energy demand obtained by dividing the new demand for the energy service by the new energy efficiency. The direct rebound effect is the difference between expected and actual energy savings, divided by the expected energy savings.

2.2.4. Substitution and income effects

The direct effect consists of a ‘substitution effect’ and an ‘income effect’. There are two ways to decompose the direct effect into an income and a substitution effect: the Hicksian method and the Slutsky method.

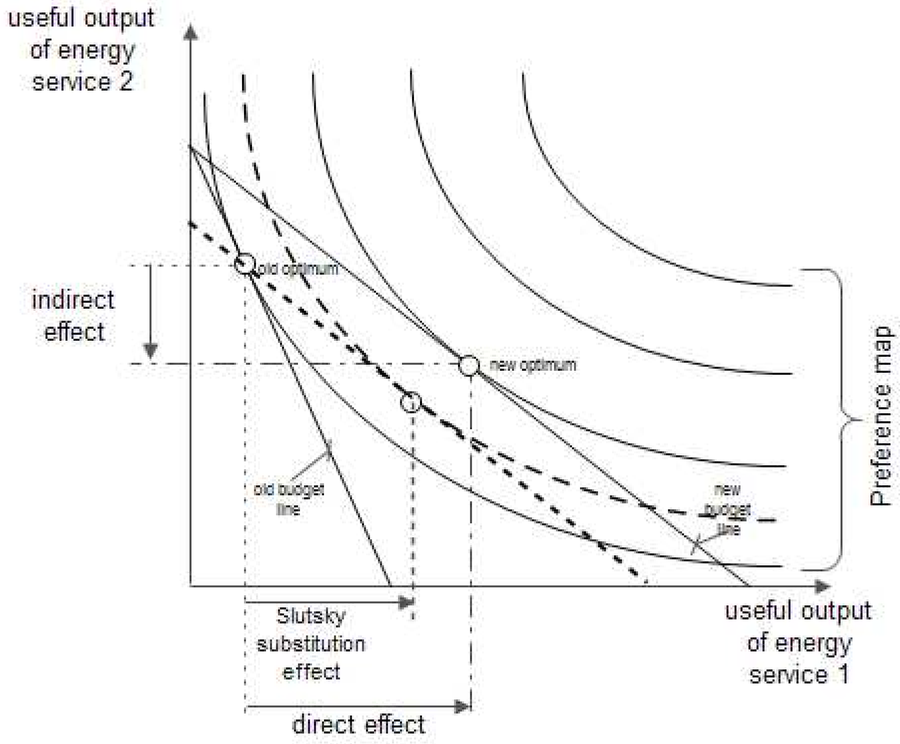
The Hicksian substitution effect is a change in relative implicit prices that alters the slope of the budget constraint but leaves the consumer on the same indifference curve. In other words, it illustrates the optimal combination of useful outputs of energy services that would prevail if the consumer was ‘compensated’ (reduction in income) in such a way that he/she maintained his/her original utility level.

Figure 8a: Hicks substitution effect



The Slutsky substitution effect is a change in relative implicit prices that alters the slope of the budget constraint but that allows the consumer to afford the original combination of useful outputs of energy services.

Figure 8b: Slutsky substitution effect



In both cases, the (direct) income effect is the difference between (total) direct effect and the substitution effect.

2.2.5. The indirect effect

Figure 6 also shows (on the vertical axis) the 'indirect effect', i.e. the change in consumption of the useful outputs of other energy services. The analysis is by no means not restricted to two energy services, but economists find it convenient to assume that energy service 1 is the object of interest and that the other energy service (2) is a "composite" (or numeraire) representing consumption of everything *but* energy service 1.

The indirect effect is (also) an income effect, because after enjoying the (extra) quantity of useful output of the energy service whose energy efficiency has improved, there may be either less or more income to spend on the useful outputs of other energy services.

2.3. Methods to estimate the direct rebound effects in the household sector

The extent of the rebound effects depends on parameter values whose determination is an empirical issue [Madlener & Alcott, 2007, p.3]. Two different approaches may be chosen in estimating the direction and magnitude of direct rebound effects for households: the quasi-experimental or engineering approach, and the econometric approach.

2.3.1. The quasi-experimental or 'engineering' approach

The quasi-experimental approach consists of measuring the actual saved resources (ASR) before and after an efficiency improvement, holding all other factors constant. The actual saved resources are compared with the expected saved resources (ESR), which – in principle – can be derived from engineering models (see also definition of the rebound effects). This methodology is mainly focused on household heating. There are two possibilities: one measures the change in demand for the useful output of the energy service before and after the improvement (e.g. measuring the change in heat output following the installation of a fuel efficient boiler), or one measures the change in energy inputs (e.g. the fuel consumed by the boiler) [Sorrell, Dimitropoulos & Sommerville, 2009, p. 208].

The (application of this) methodology has several weaknesses [Sorrell, Dimitropoulos & Sommerville, 2009, p. 208-209]:

- The quality of most studies is relatively poor, the majority using simple before-after comparisons, without the use of a control group and without explicitly controlling for confounding variables;
- The methodology is vulnerable to selection bias, since households are not randomly assigned but rather choose to participate themselves;
- The sample sizes are typically small;
- The monitoring periods are often too short to capture the long-term effects;
- The relevant independent variables show large variations, both within and between studies (e.g. households receiving different types of energy efficiency measures, or combinations of measures);
- The researchers often fail to present the error associated with the estimates;
- The engineering estimates of the expected saved resources (ESR) are not always satisfactory. The installation may be deficient, the performance of the equipment could be inadequate,

the energy efficiency improvement of household heating may change other physical factors (e.g. airflow) that may encourage other behavioural changes not directly related to lower heating costs, etc. Necessary simplifications in engineering models can result in overestimating savings by as much as 50%, especially for space conditioning [McKinsey, 2009, p. 33].

Also, different studies may use different terms for the same concepts as well as the same terms for different concepts. [Sorrell, Dimitropoulos & Sommerville, 2009, p. 208-209]

2.3.2. The econometric approach

The more common approach to estimating direct rebound effects in the household sector is econometric analysis. These estimates require secondary data sources that include information on the relevant energy service, the demand for energy, and / or the energy efficiency of that service. Time series data allow the estimation of both short-run and long-run elasticities, depending on whether a fixed or variable stock of energy conversion devices is assumed. Cross-sectional data usually provide estimates of long-run elasticities [Sorrell, Dimitropoulos & Sommerville, 2009, p. 209].

Preliminaries

In practice, direct rebound effects are estimated from either *energy-efficiency elasticities* or *price elasticities*.[30] The choice of elasticity measure partly depends on data availability. Data on energy consumption [E] and energy prices [P_E] are more readily available than data on the useful outputs [S] of the energy service. Data on energy efficiency [η] are in many cases either unavailable or inaccurate [Sorrell, Dimitropoulos & Sommerville, 2009].

Energy efficiency [η] is defined as the ratio of useful output [S] of an energy service to total energy inputs [E], or $\eta = \frac{S}{E}$

Energy costs are only one component of the overall costs of providing a unit output of energy service. Overall costs should also include annualised capital, maintenance, repair and operations (MRO) costs and opportunity costs of time and space. In most empirical literature, however, the energy costs per unit of useful output of an energy service are (incorrectly) taken as the “implicit price” of that energy service. The energy costs [C_E] of providing a unit output of energy service are defined as the ratio of the energy price [P_E] of the energy inputs to energy efficiency [η], or $C_E = \frac{P_E}{\eta}$

The efficiency elasticity of the energy service demand

Following $\eta = \frac{S}{E} \rightarrow S = \eta E$, the demand for the useful output of an energy service can be written as a function of the energy efficiency of that energy service, or $S = S(\eta)$. The efficiency elasticity (of the

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[30] A standardized (partial) derivative is used to measure how responsive one variable $y = y(x_1, \dots, x_n)$ is to a change in another variable x_i. By weighting the partial derivative with the levels of variables under consideration, the scale effect is removed and a unit-free measure of responsiveness is obtained. This standardized derivative is called elasticity. The elasticity gives the percentage change in y given a percentage change in x_i. Elasticity can be expressed in logarithmic form: $\varepsilon_{y,x_i} = \frac{\delta y}{\delta x_i}\frac{x_i}{y} = \frac{\delta ln y}{\delta ln x_i}$

useful output) of the energy service demand [$\epsilon_\eta(S)$] is taken as the immediate and most general measure of the direct rebound effect (RE).

$$RE \cong \frac{\delta \ln S(\eta)}{\delta \ln \eta} = \epsilon_\eta(S)$$

The efficiency elasticity of the energy service demand [$\epsilon_\eta(S)$] gives the relative (percentage) change in demand for the useful output of the energy service following a percentage increase in the energy efficiency of that energy service.

The rebound effect will be zero [*RE* = 0 %] if and only if the demand for the useful output of the energy service remains unchanged following an energy efficiency improvement, i.e. if the efficiency elasticity of useful output equals zero [$\epsilon_\eta(S)] = 0$]. In that case, the actual saving in energy consumption equals the expected or predicted energy savings from engineering calculations. A positive rebound effect implies that $\epsilon_\eta(S) > 0$.

Although the efficiency elasticity of the energy service demand should in all cases be the preferred, or in fact the only acceptable estimator of the direct energy rebound effect, insufficient data forces researchers to employ alternative estimators.

The efficiency elasticity of energy demand

In most cases it is very difficult to obtain measures of the useful output (*S*), whereas data on the total inputs or energy demand (*E*) for the relevant energy service are more commonly available. In those instances, the efficiency elasticity of energy demand (plus one) is used as an alternative for the efficiency elasticity of the energy service demand.

Following $\eta = \frac{S}{E} \to E = \frac{S}{\eta}$, the demand for total energy inputs of an energy service can be written as a function of the energy efficiency of that energy service, or $E = E(\eta)$. Assuming that the demand for the useful output (*S*) of the energy service solely depends on its energy costs per unit of useful output (C_E), it is shown (see annex X) that the efficiency elasticity of the energy service demand equals one plus the efficiency elasticity of energy demand.

$$RE \cong \frac{\delta \ln S(\eta)}{\delta \ln \eta} = 1 + \frac{\delta lnE(\eta)}{\delta \ln \eta} = 1 + \epsilon_\eta(E)$$

The efficiency elasticity of energy demand [$\epsilon_\eta(E)$] gives the relative (percentage) change in energy demand (i.e. demand for total energy inputs) following a percentage increase in the energy efficiency of the energy service.

The rebound effect will be zero if and only if the elasticity efficiency of energy demand equals minus one [$\epsilon_\eta(E) = -1$]. In that case, 100% of the potential energy savings due to an energy efficiency improvement can be realized. A positive rebound effect implies that $|\varepsilon_\eta(E)| < 1$.

The "implicit price" elasticity of the energy service demand

Even if data on the useful outputs (S) of an energy service are available, data on energy efficiencies often are not, or the obtainable data on efficiencies provide only limited variation in efficiencies. In those cases the (negative) "implicit price" elasticity of the energy service demand is sometimes used as an alternative for the efficiency elasticity.

Following $C_E = \frac{P_E}{\eta} \rightarrow \eta = \frac{P_E}{C_E}$ and $S = \eta E \rightarrow S = \left(\frac{P_E}{C_E}\right) E$, the demand for the useful output of an energy service can be written as a function of the energy costs per unit of useful output, or $S = S(C_E)$.

Assuming that the demand for the useful output (*S*) of the energy service solely depends on its energy costs per unit of useful output (C_E) *and* assuming that energy prices are exogenous (i.e. P_E does not depend on η), it is shown (see annex X) that

$$RE \cong \frac{\delta \ln S(\eta)}{\delta \ln \eta} = -\frac{\delta \ln S(C_E)}{\delta \ln C_E} = -\epsilon_{C_E}(S)$$

The term $\epsilon_{C_E}(S)$ is essentially a price elasticity, given that "the energy costs per unit of output" is regarded as the "implicit price" of the energy service. The "implicit price" elasticity of (the useful output of) the energy service demand gives the relative (percentage) change in the demand for the useful output of the energy service following a percentage change in the energy cost per unit of output of that energy service.

The energy price elasticity of the energy demand

Because measures of the useful outputs (*S*) and data on the energy efficiencies (η) of an energy service are both very difficult or even impossible to obtain, empirical estimates of the direct rebound effect are often necessarily based on the (negative) energy price elasticity of energy demand of the relevant energy service.

Assuming that:

1. the demand for the useful output (*S*) of the energy service solely depends on its energy costs per unit of useful output (C_E);
2. energy prices are exogenous (i.e. P_E does not depend on η);
3. the energy efficiency (η) of the energy service is exogenous, i.e. energy efficiency is unaffected by changes in energy prices

it is shown (see annex X) that

$$RE \cong \frac{\delta \ln S(\eta)}{\delta \ln \eta} = -\frac{\delta \ln E(P_E)}{\delta \ln P_E} = -\epsilon_{P_E}(E)$$

The term $\epsilon_{P_E}(E)$is the own-price elasticity of energy demand, i.e. the relative (percentage) change in energy demand (total energy inputs for the energy service) following a percentage change in energy price.

The rebound definition based on the negative own-price elasticity of energy demand is a very restrictive one, as it requires the validity of three preconditions. It was nonetheless this definition that was originally introduced by Khazzoom [1980, p. 38] as the definition of the (direct – or in our terminology – primary) rebound effect.

The energy price elasticity of the energy service demand

If only measures of the useful outputs (S) of an energy service and energy prices are available, one could use the (negative) energy price elasticity of the (useful output of the) energy service demand as an alternative.

Again, assuming that the demand for useful output solely depends on its energy costs per unit of useful output and that both energy prices and energy efficiency are exogenous, one proves (see annex X) that

$$RE \cong \frac{\delta \ln S(\eta)}{\delta \ln \eta} = -\frac{\delta lnS(P_E)}{\delta lnP_E} = -\epsilon_{P_E}(S)$$

The term $\varepsilon_{P_E}(S)$ is the energy price elasticity of (the useful output of) the energy service demand, i.e. the relative (percentage) change in demand for the useful output of the energy service following a percentage change in the energy price.

2.3.3. Problems with the use of econometric estimates

Caveats in econometric estimates of the (direct) rebound effects at the household level, can be summarized as follows:

- Most econometric (empirical) studies are partial, i.e. limited to a single energy service (e.g. either heating or mobility, but not both at the same time);
- Econometric studies should include the *overall* costs of the energy service, not merely the energy costs. In particular, the opportunity costs of time (and perhaps space as well), should also be taken into consideration;
- The availability and reliability of the data, or lack thereof;
- The use of price elasticities instead of efficiency elasticities

Single service versus multi service models

Most econometric studies of the direct rebound effect are based on a single service model. Households have to decide on a single energy service (e.g. heating) only. In reality, households have to decide on many energy services, which all cost money. The multi-services model corrects some of the weaknesses of the single service model: "*it considers multiple choices and accounts for the income limiting possible investments*" [Hens et al., 2010, p. 106].

We already discussed the theoretical background of the multi-services model in some detail (§ X) Empirically speaking, and accepting all the axioms of rational choice theory, all one has to do is – within a pre-specified space (location) and time (period) frame – observe 1) the change in energy efficiency of the energy service under consideration, and 2) the changes in the quantities demanded of useful outputs of *all* energy services, ***while everything else (income level, all commodity prices including energy prices, energy efficiencies of the other energy services, external factors such as weather conditions, etc.) remains unchanged***. In principle, multivariate regression would suffice to estimate the efficiency elasticities of the demand for useful outputs of all energy services. This would require extensive data, not only on the (changes in) energy efficiency of the energy service under consideration and the useful outputs demanded of all energy services, but also on dozens of other explanatory (independent) variables. Omitting relevant variables may lead to inconsistent and biased estimators (omitted variable bias)[31]. The (indeliberate) inclusion of so-called confounding variables[32]

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[31] Although Clarke [2005] argues that omitted variable bias is unavoidable because it is impossible to include all relevant variables in a regression equation, and that the inclusion of *a subset* of relevant control variables in some circumstances may not only increase the bias caused by omitted (relevant) variables, but may also cause additional biases through measurement error [id., ibid., p. 17].

would also spell trouble. A further complication is that a significant number of those variables are most probably interdependent (endogenous variables), necessitating the identification and estimation of a simultaneous equation model (SEM). Not doing so may equally lead to inconsistent and biased estimators (simultaneity bias). With a correctly specified model and using the proper statistical techniques textbook analysis demonstrates that the estimated coefficients (e.g. efficiency elasticities) are minimum variance unbiased. A more realistic way to avoid specification bias is to base the specification of the model on a broad theory (or competing broad theories), to "control" for unmeasured effects through careful sample stratification, and to test those broad theories in narrow, focussed, controlled circumstances [Clarke, 2005, pp. 16-17].

In a multi services model it is difficult to make general statements about the relevance of the rebound effect. "*In this case, the overall effect of an increase in energy efficiency on total energy use depends on the assumptions about the substitutability between the services considered and the direction of the income effect*" [Binswanger, 2001, p. 2001].

In estimating direct and indirect rebound effects for Swedish households from both technical improvements and behavioural changes, Nässén and Holmberg [2009] come to the rather obvious conclusion that total rebound effects may be expected to be higher for cost effective investments, for efficiency improvements in price-elastic energy services, and for situations where cost savings are re-spent on more energy-intensive goods and services.

Overall costs of energy services

A number of variations on the above mentioned elasticities have been employed in empirical research, to take into account the following situations:

- An improvement in energy efficiency may lead to an increase in the number of energy conversion devices, their average size, their average utilisation and / or their average load factor;
- The demand for the useful output does not only depend on the energy costs of the energy service, as is the conventional assumption in literature, but also on capital costs, costs of commodities other than energy, and / or opportunity costs of time.

These considerations require some alterations to the definitions of elasticities given earlier. We shall not investigate these matters further, and refer to Sorrell and Dimitropoulos [2008] for a more detailed analysis.

Availability and reliability of data

High quality base data are a necessity "*as this informs the assumptions and the overall evaluation of the model's validity*" [EEA, 2010, p. 37] . Data on energy consumption and energy prices are more available than data on the useful outputs of energy services. Data on energy efficiency are often unavailable or inaccurate. For this reason, energy price elasticities (of energy demand) are frequently estimated as alternative (and inaccurate) definitions of the direct rebound effect.

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[32] A confounding variable is an extraneous variable in a statistical model that correlates (positively or negatively) with both the dependent variable and the independent variable.

Price elasticities instead of efficiency elasticities

All of the above alternative estimators of the direct rebound effect (which are) defined as "price elasticities" (whether it be "implicit price" or "energy price"), rely on two crucial assumptions:

1. Energy prices are exogenous (i.e. P_E does not depend on η);
2. The energy efficiency (η) of the energy service is exogenous, i.e. energy efficiency is unaffected by changes in energy prices (i.e. η does not depend on P_E);.

Neither are very realistic. We already mentioned (§ X) that efficiency improvements may reduce *aggregate* demand for a particular energy carrier, leading to a possible reduction in market prices for that energy carrier. Concerning the second assumption, empirical studies find that energy-efficient innovation is also significantly determined by changes in energy prices (See Popp et al. [2009] for a literature review).

All, if not most, econometric estimates of the direct rebound effect are inferred from long-run energy own-price elasticities. Empirical literature shows that long-run elasticities are larger than short-run elasticities, notwithstanding significant variations from one study to another [Kriström, 2008, p. 99]. When energy price increases are persistent, they are more likely to affect the adoption of energy-efficient technologies. Estimates of the direct rebound effect based on long-run price elasticities assume that consumers' reactions to changing prices are symmetric. Implicitly, they assume "reversibility" of investments in energy saving equipment. However, demand responses to rising prices may differ from responses to falling prices. As energy prices increase, consumers invest in energy efficient technology. Conventional econometric models assume that households constantly adjust their capital stock to new optimal levels whenever capital and energy prices change. But a large part of investments in energy-saving devices seems to be of an "irreversible" nature [Binswanger, 2001, p. 122-123]. "*When the energy price goes down again, the investment stays in place, and the energy demand does not increase as much as one would expect based on the price elasticity measured during the period of rising energy prices*" [Hertwich, 2005, p. 87]. Thus, in reality households probably react less to a decrease in energy price than suggested by many econometric studies.

As a matter of fact, price elasticities might not only be different for price increases and decreases, they might also vary over time [price elasticities may not be stable over time], over income groups, across household sizes and, in general, across other household characteristics that affect demand [Kriström, 2008, p. 102]. Even though estimates of price elasticities reflect very partial and temporary indicators of behavioural responses to changes in the implicit prices of energy services, many empirical studies of the rebound effect depend heavily on them [van den Bergh, 2011, p. 52].

In conclusion, it would appear that (implicit or energy) price elasticity based estimators of the direct rebound effect are not suitable alternatives to the efficiency elasticity of energy service demand. But given the lack of data on efficiencies, they are the ones used most in empirical research.

2.4.Empirical results

2.4.1. Estimates of the direct rebound effect

Beginning with Khazzoom [1980], there have been a series of estimates of the direct rebound effect for different energy services. [Sorrell, Dimitropoulos, Sommerville, 2009, p. 1356] The most comprehensive, systematic overviews of econometric estimates of the direct rebound effect so far were made by the Energy Research Centre of the UK (UKERC) [Sorrell & Dimitropoulos, 2007] and the U.S. based Breakthrough Institute [Jenkins et al., 2011].

Table X: Estimates of the long-run direct rebound effect for consumer energy services in the OECD

End-use	Range of values in evidence base (%)	'Best guess' (%)	No. of studies	Degree of confidence
Personal automotive transport	3 – 87	10 – 30	17	High
Space heating	0.6 – 60	10 – 30	9	Medium
Space cooling	1 – 26	1 – 26	2	Low
Other consumer energy services	0 - 41	< 20	3	Low

Source: Sorrell (2009).

The UKERC results suggest that "*the mean long-run direct rebound effect for personal automotive transport, household heating and household cooling in OECD countries is likely to be 30 per cent or less and may be expected to decline in the future as demand saturates and income increases.*" [Sorrell, 2009, p. 214] However, the UKERC research team clearly indicates a number of important limitations of the evidence, including the neglect of marginal consumers, the relatively limited time periods over which the effects have been studied and the restricted definitions of 'useful output' that have been employed [Sorrell, 2009, p. 215].

In developing countries, where unmet demand for energy services is strong, the potential for direct rebound effects may be much larger, in the order of 42% to 80% (albeit based on only two studies). [Jenkins et al., 2011, p. 27]

The evidence remains sparse and inconsistent. Interpretation of the evidence is furthermore greatly hampered by the extreme diversity of the studies in terms of the definitions, terminology, notation, methodological approaches, and data sources used [Sorrell, Dimitropoulos, Sommerville, 2009, p. 1356]. Almost without exception the empirical surveys are partial (i.e. limited to only one application of energy use), confined to a limited number of consumer energy services (notably household heating and personal automotive transport), and focused on developed countries, in particular the United States [Berkhout, 2000, p. 429; Sorrell, Dimitropoulos, Sommerville, 2009, p. 1356; Jenkins et al., 2011, p. 8]. "*The main reason for this is the lack of suitable data sources for other types of energy service in other sectors and countries*" [Sorrell, Dimitropoulos, Sommerville, 2009, p. 1356].

Experts contacted within the context of a study commissioned by the European Commission have suggested that, given the inherent uncertainty, "*attention and efforts not be directed at additional attempts to derive a precise value for the rebound effect, but rather to focus on developing policies which will be effective despite such inherent uncertainty*" [EC, 2011, p. 39].

2.4.2. Estimates of the indirect rebound effect

There has been little effort to rigorously quantify the 'indirect' rebound effect (a.k.a. re-spending effect) at the household level, and the available evidence to date remains too limited to draw precise conclusions about the scale of these effects [Jenkins et al., 2011, p. 21].

Druckman [2010] gives an overview of the relatively few studies that have attempted to estimate the "indirect" as well as the direct rebound effect. Cost-saving 'green' household consumption choices in these studies consider both cost-effective energy efficient technologies (e.g. choosing a more fuel-efficient car) as well as "conservation behaviour" (e.g. reduced vehicle use). Furthermore, by "indirect effects" they refer to the increase in *embodied* energy consumption and GHG emissions as a result of the increased consumption of (the same and other) goods and services. Hence, in our classification of rebound effects, they are in effect referring to the "embodied effects" at the macro-level, and not at the indirect effects at the micro-level. Nonetheless, we will give a brief outline of their main findings.

- Lenzen and Dey [2002] exploring a change to "low carbon diets" in an Australian context estimate that, allowing for the re-spending effect, the *embodied* rebound effects would be 53% (highest income quintile) to 55% (lowest income quintile) in terms of energy consumption, and 31% to 35% in terms of GHG emissions.
- Alfredsson [2004] estimates that if Swedish households were to switch to an overall 'greener' consumption pattern in food, housing and travel (including not only efficiency improvements such as using a more fuel efficient car but also behavioural changes such as car sharing), while keeping total income constant, the *embodied* rebound effect would take back around 31% of the expected reduction in energy requirements, and around 14% of the expected decrease in CO_2 emissions in 2020 relative to the base case 1996. To study the "indirect" and direct energy requirements of Stockholm inner city households, Carlsson-Kanyama et al. [2005] use a similar method as Alfredsson, namely the Dutch energy analysis program (EAP), but adapted to Swedish conditions. Their published figures do not allow to ascertain their estimates of the *embodied* rebound effects.
- Brännlund et al. [2007] find that for Swedish households a 20% increase in the energy efficiency for both personal transportation and heating, will actually lead to an increase of CO_2 emissions by approximately 5%, as a result of increased expenditures on transport, heating, and other goods and services. This translates into *embodied* rebound effects of [20-(-5)/20] or 125% ('backfire') in terms of CO_2 emissions. Mizobuchi [2008] using a similar approach as Brännlund finds similar *embodied* rebound effects for Japanese households (approximately 115%), although the rebound effects reduces to around 27% when explicitly taking capital costs into account.

Druckman et al. [2011] estimate that the *embodied* rebound effects for three abatement actions by UK households (reducing internal temperatures by 1 °C by means of lowering the thermostat: reducing food purchased by one third by eliminating food waste; and walking or cycling instead of using a car for trips of less than 2 miles) is around 34% in terms of GHG emissions. Targeting re-spending on goods and services with a low GHG intensity would reduces this to a minimum of around 12%, while re-spending on goods and services with a high GHG intensity may lead to backfire.

Using Australian data, Murray [2011] estimates that at the median household income level the *embodied* rebound effects (in terms of GHG emissions) would be close to 25% for choosing a fuel efficient vehicle, approximately 18% to 21% for vehicle fuel conservation (driving less); around 7% for electricity efficiency (replacing incandescent light bulbs with CFL light bulbs), and 5% to 8% for electricity conservation (behavioural changes such as turning lights off when leaving a room, turning off stand-by appliances, etc). A key finding is that at higher income levels the "indirect" effects becomes a larger proportion of the *embodied* rebound effects [Murray, 2011, p. 36]. A second key finding is that opting for conservation measures produces much lower *embodied* rebound effects than choosing efficient technologies [id., ibid., p. 36-37].

The results of these studies appear sensitive to methodology and assumptions used, technical and / or behavioural changes examined, types of households analyzed, level of commodity aggregation employed, data sources consulted, etc [Druckman et al., 2010, p. 10].

2.5.Policy instruments as suggested by micro-economic analysis

2.5.1. Command and control

It is theoretically possible that authorities restrict the demand levels for the useful outputs of certain energy services by means of command-and-control policies. Such restrictions are often set by technological standards, e.g. capacity limits for appliances or vehicle speed limits. Rebound effects as a result of energy efficiency improvements could thus be partly offset by non-voluntary energy *conservation* measures, i.e. by doing with less, or even without.

However, economists tend to prefer pricing interventions to quantity restrictions, because price- or tax-based interventions selectively induce those who can adapt most readily and at lowest cost to do so, and because pricing policies generate revenues that can be used to mitigate adverse wealth effects for those who suffer under the higher price of a desired activity. Regulation of activities can neither selectively identify the efficient adjusters, nor generate any revenue to soften the wealth impact of the restrictions [Pozdena, 2009, p. 10].

We will not further investigate the use of quantity restrictions, although we will explicitly consider voluntary (i.e. not stimulated by command-and control) behavioural (or lifestyle) changes to mitigate the rebound effects.

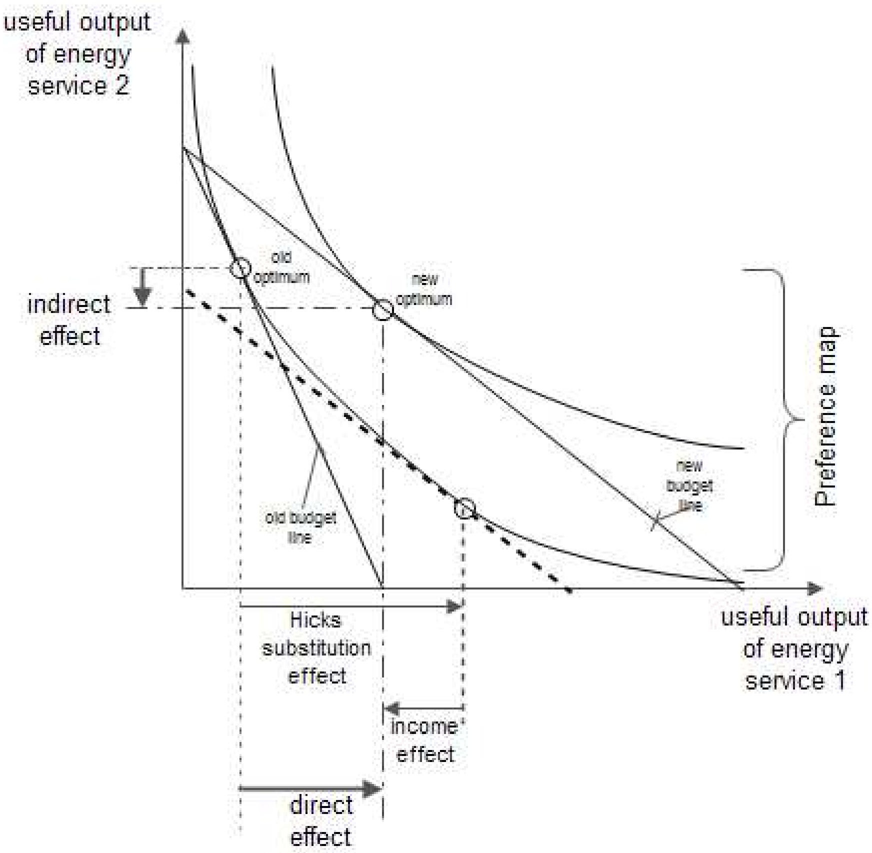
2.5.2. Pricing policies

The theoretical analysis of the rebound effect leads to the following price and income options to mitigate the rebound effects for 'normal' energy services:

- Raising the overall marginal costs of the energy service whose efficiency has improved to their original level (i.e. before the energy efficiency improvement). One possibility to increase the implicit or effective price of the energy service would be to raise the market price of the relevant energy carrier, e.g. through energy or carbon taxes. Alternatively, one could increase the price of capital, making the purchase of energy-saving equipment more expensive! Similar remarks apply to the costs of labour (e.g. maintenance) or materials;
- Hicksian compensation, where the consumer is deprived of a certain amount of income (wealth), to compensate for the decrease in the relative implicit price of the energy service, thus keeping the consumer at the exact same level of utility as before the introduction of the energy efficiency improvement;
- Slutsky compensation, where the consumer is deprived of a certain amount of income (wealth), to compensate for the decrease in the relative implicit price of the energy service, thus allowing the consumer to afford the exact same combination of useful outputs of energy services as before the introduction of the energy efficiency improvement.

Both the Hicksian and Slutsky compensation would only eliminate the (direct) income effect, and retain the (pure) substitution effect. In case of *inferior* energy services, both compensation mechanisms could make matters worse! If the (direct) income effect (partly) offsets the substitution effect (i.e. if the energy service is inferior), then both Hicksian and Slutsky compensation would as a matter of fact increase consumption of the useful output of the energy service under investigation. That said, we could not find any examples of inferior energy services in literature.

Figure 9: Adverse consequences of Hicksian compensation in case of inferior energy services



The only workable policy option is to increase energy prices (e.g. through carbon pricing policies and / or energy taxes), to keep the implicit price of the energy service whose energy efficiency has improved approximately constant. At the macro-level, this would "*likely require substantial and rising energy prices over time and sustained over the multi-decadal periods relevant to climate policy, such that rising energy prices keep pace with the improvements in energy productivity*" [Jenkins et al., 2011, p. 53]. Ecological economists like Wackernagel and Rees [1997] even go so far as to suggest that in a globally inter-linked economy we can afford cost-saving energy efficiency "*only if efficiency gains are taxed away or otherwise removed from further economic circulation*" [Id., ibid., p. 20]. On a side note, *uniform* economic instruments (either a harmonized global tax rate or a global carbon emission permission market) are no suitable instruments for tackling climate change, because "*reality is too diverse and dogged in diversity…*" [Verbruggen, 2010, p. 10]. Although overlooked in literature, a similar remark applies to the micro-level.

2.5.3. Incentives for adopting energy efficient technologies

Uniformly raising energy prices would not only affect the demand for energy services whose energy efficiency has improved, but also the demand for all other energy services, possibly leading to an overall decrease of the household's "utility" or "quality of life". This particularly applies to appliances, where electricity is effectively the only relevant energy carrier. One way out could be the use of "intelligent appliances" in the context of smart microgrids, where energy pricing would not only depend on energy supply conditions but also on the energy efficiency (and perhaps other attributes) of the appliance itself. However, it is not obvious what (other) incentives households would have to choose energy efficient technologies, once they realize that the share of energy expenses in their household budget remains constant.

The extent to which energy or carbon tax schemes will accelerate adoption of new, more energy efficient technologies is not clear. The turnover of capital tends to be slow (buildings, equipment and vehicles have long lives), and the new capital has to be both more efficient and cheaper to acquire. For example, "*for vehicle replacement to be economical, the higher-efficiency vehicle has to cost less than the market value of the old vehicle plus the present value of expected carbon tax savings relative to the old vehicle, everything else being equal*" [Pozdena, 2009, p. 10]. This may partly explain why (in the U.S.) the average (vehicle) fleet efficiency has changed relatively slowly in spite of rapid improvements in new vehicle fleet average fuel efficiency, or why vehicles are staying in the fleet much longer [id., ibid., p 10].

2.5.4. Equity

Another issue to be addressed is the *heterogeneity* of households, and in particular the problem of "energy poverty". Evidence suggests that the size of the rebound effects varies greatly with household income level. Boardman [2004] defines energy poverty or "fuel poverty" as occurring when a household has to spend more than 10% of its income to provide an adequate standard of warmth and other energy services (hot water, lighting, etc.) The consequences of energy pricing policies will differ considerably across households with different income and other characteristics. Studies indicate a tangible relationship between high rates of energy poverty, low level of domestic thermal efficiency and reduced health and comfort status [Clinch & Healy, 2003, p. 565]. Low-income households are to some extent prepared to "*…accept lower temperatures, intermittent and/or partial heating regimes, lower hot water consumption and lower use of energy for other uses (lighting, cooking and appliances), in order to have lower energy bills*" [Clinch & Healy, 2003, p. 565]. A number of ex-post studies evaluating thermal efficiency improvement programmes estimate that for lower income households (especially those living in energy inefficient dwellings) 25% to 30% of potential programme benefits are taken as *increases in thermal comfort*, and 'only' 75% to 70% as *energy cost savings*. Higher income households, on average, would appear to translate the benefits of improving the thermal efficiency of their dwellings into a relatively larger reduction of their energy expenditures, due to their saturation of demand for thermal comfort [Milne & Boardman, 2000; Sheldrick, 1998; Skumatz, 1996; Energy Saving Trust, 1994]. Evidence also points to indirect (embodied energy) rebound effects becoming more significant than direct effects over time and with increasing incomes [Murray, 2011, p. 36]. This might suggest that pricing policies should primarily be targeted at higher income households [Milne & Boardman, 2000, p. 422]. From an equity point of view, the impact of increased energy prices will depend on how revenues are returned. For example, revenues "*could be partly used to bring energy efficiency improving technologies to the market*" [Koerth-Baker et al. , p. 11]

2.5.5. Behavioural changes

If "behavioural failures" lead to sizeable rebound effects, policy instruments addressing market failures (e.g. price or income taxes) may not be well-suited to mitigate the rebound effects.

Mainstream economics does not consider the option of changing the preference map (indifference curves) and / or the “choice mechanisms” (utility maximization) of the household. Shifts in preferences would change the rebound effect. Reverting consumer behaviour from consumerism to a more sustainable lifestyle may be an effective option to mitigate the rebound effect. This might entail *consuming differently*, i.e. shifting consumption towards “greener” goods or services with a lower environmental impact or increasing expenditures on services rather than goods, or simply *consuming less* or “downshifting”. Energy conservation policies could try to direct re-spending decisions to (relatively) energy-extensive goods and services [van den Bergh, 2011, p. 55]. Wilhite and Norgard [2003] advocate policies aimed at reducing absolute energy consumption, e.g. by discouraging the demand for more and even bigger homes, appliances, cars, etc. Ouyang et al. [2010, p. 4274] suggest that if (Chinese) households set their requirements for the “high quality life” a little lower, the rebound effect could be mitigated to some extent. The widespread adoption of a “sufficiency”[33] ethic faces numerous psychological and socio-cultural obstacles and is unlikely to develop through voluntary action alone [Sorrell, 2010, p. 1793-1794]. These topics will be investigated more thoroughly further on.

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[33] Sufficiency is a social organising principle that builds upon restraint and modification to provide rules for guiding collective behaviour. [Princen, 2003]

3. Conceptual problems with mainstream theory of the consumer

The theoretical foundations of econometric estimates of the (direct) rebound effect are rational choice theory or its subjective expected utility (SEU) variant. The assumptions of traditional consumer theory may seem rather strange when it comes to explaining processes of long-term change [Linscheidt, 2001, p. 5]:

- Preference orderings rely on formal axioms which are ad hoc and do not conform to real-world situations;
- Preferences are assumed to be 'non-satiable', i.e. an individuals 'wants' or 'needs' are essentially unlimited;
- Preferences are assumed to be (strictly) convex;
- Consumers' preferences are assumed to be unaffected by their consumption in the past (preferences are specified as time-separable functions). This effectively excludes 'habit formation';
- Consumers' preferences are assumed to be unaffected by the actions of other consumers (there is no preference-interdependence), therefore excluding 'social factors'.
- A consumer is a 'homo economicus', a hyper-rational person capable of processing massive amounts of information to make optimal decisions in his or her own interest. The implicit assumption that a consumer never makes mistakes in computation and choices excludes cognitive and affective limitations;
- Consumers (only) differ because of income[34], not because of skills, decision-making routines, etc. (See homo economicus). A 'representative consumer' represents different micro-agents (all sharing identical 'average' preferences) of the same (average income) class. A change in price would change the budget sets of all consumers, thus changing the behaviour of *all* consumers. In other words, there is no or very limited heterogeneity of consumers;

In discussing the assumptions of rational choice theory, we will use the more conventional approach, i.e. commodities (market goods and services) rather than (useful outputs of) energy services and market prices of commodities rather than implicit prices of energy services.

3.1.Axiomatic preference theory

Utility has been a central concept in economics for a long time [Kapteyn, 1985, p. 1]. Early economists identified utility with conscious experience, and accepted the idea that introspection was a scientifically acceptable means to explore those conscious states [Angner & Loewensein, 2006, p. 7-8]. In the original Benthamite version [Bentham, 1780], utility was conceived as a sensory experience of pleasures and avoidance of pains and, thus, as an 'objective', measurable notion [Witt, 2005, p. 2]. In that sense utility is roughly synonymous with "pleasure", "satisfaction", "well-being", "welfare", "happiness", etc. The use of a common cardinal hedonistic scale implies that the magnitude of utility differences is a meaningful quantity, and that utilities can be added and interpersonally compared. The marginalists (second half of the nineteenth century) still retained a degree of measurability of cardinal utility.

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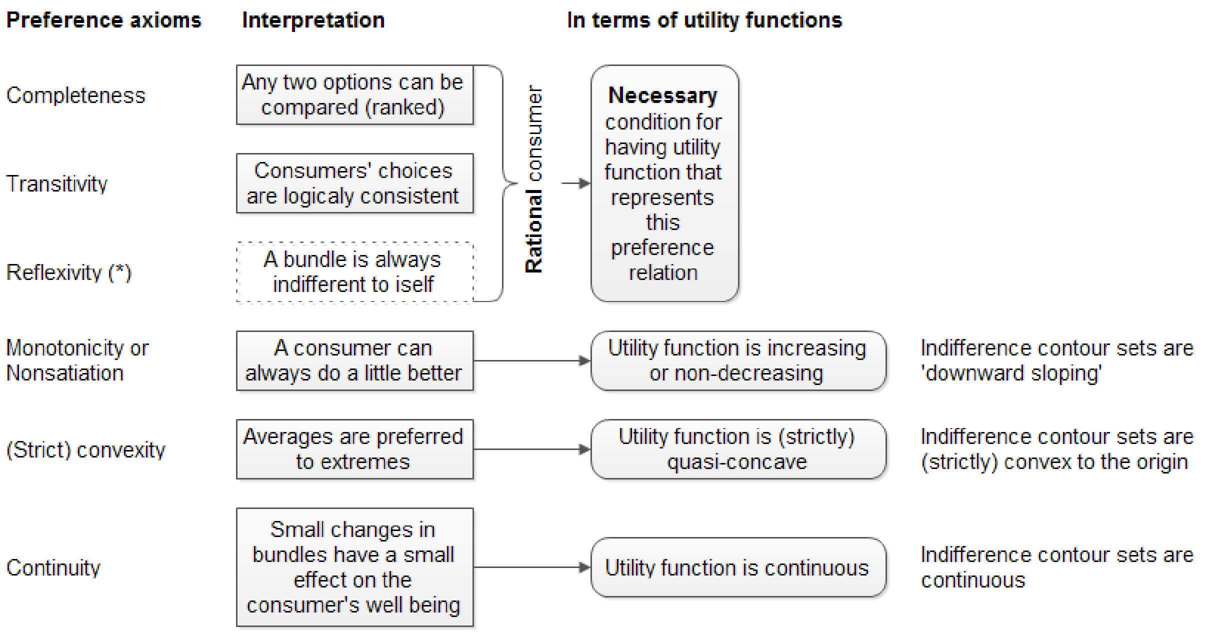
[34] In some neoclassical models all consumers even share the same income level.

However, neoclassical economists in the first half of the 20th century rejected all introspective and hedonistic elements.

Since the work of Vilfredo Pareto [1916], utility has been taken as an *ordinal* concept. According to ordinalism [cf. Hicks, 1975] the fundamental assumption is that individuals have preferences[35]. Consumer preferences consist of well-informed desires for specific goods and services available on the market [Ackerman, 1997, p. 652]. A person's preference ordering just represents his or her ranking of whatever options are available, nothing more, nothing less [Angner & Loewenstein, 2006 p. 9]. Ordinal utility theory is based on assumptions regarding the decision maker's preferences regarding a set of possible choices [Dubas & Jonsson, 2005, p. 5]. Preferences are considered 'rational' if they satisfy a number of formal axioms, in particular completeness and transitivity (figure 10). If the preference relation satisfies certain axioms of choice, among which completeness and transitivity, it may be represented by a utility function (for a mathematical treatment, see Annex 1). Ordinal economists simply use the term 'utility' as an index of preference satisfaction that has nothing to do with pleasure, pain or any other psychological state.

Figure 10: Preference axioms in general choice theory and their implications.



(*) Reflexivity is only required if the preference ordering is expressed as an indifference relation.

The von Neumann-Morgenstern [1944] expected utility theorem (EUT) shows that a preference relation defined over a lottery[36] space has an expected utility representation, provided that it is a binary relation that satisfies a number of 'preference axioms' including transitivity, continuity and

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[35] In ordinal utility theory, preference ordering rather than utility is seen as the primitive element of consumer theory. In revealed preference theory, the primitive is observed choice data (in the form of a choice function), from which it is possible to construct a so-called revealed preference relation $\succsim^R$. The theory of revealed preference was constructed to solve the problem that neither utility nor preference can be measured directly with any precision that would be useful for economics.

[36] Lotteries (a.k.a. 'gambles' or 'prospects under risk') are probability distributions over a known, finite set of outcomes.

independence[37] [~~Neuman, 2010, p. 408~~]. The major drawback of this model is that the outcomes realize with *objective* probabilities that are somehow known to the decision maker [Al-Najjar & De Castro, 2010, p. 4]. In the (standard) subjective expected utility (SEU) model, individual consumers make choices "*on the basis of rational deliberations that consist of individual evaluations of subjectively expected outcomes. The value attached to an outcome is often called the 'utility' of that outcome …*" [Jackson, 2005, p. 29]. Savage [1954] proposed the first complete axiomatic subjective expected utility theory. Savages theorem states that a decision maker behaves like an individual who possesses a probability distribution over the states of the world and a utility function over the outcomes, and that he / she maximizes the sum of the (expected) utilities of the outcomes weighted by the (subjective) probabilities that the outcomes will occur [Gilboa et al., 2008, p. 177]. Savage postulated four conceptually important axioms, the first of which are the classical assumptions from consumer theory that preferences are complete and transitive.

In all three models of rationality (general choice, expected utility and subjective expected utility theory), the preference structure is depicted by a set of axioms. "*In the normative interpretation these axioms are regarded as tenets of rational choice and should be judged by their normative appeal. In the positive interpretation these are principles that are supposed to govern actual choice behavior, and must be evaluated by their predictive power*" [Karni, 2011, p. 10].

Mainstream neoclassical theory does not provide any theoretical basis for the axioms of choice. "*Lacking psychological foundations, the axioms of preference theory instead persist as primitives, unexplained and unjustified*" [Mandler 1999, p. 66]. Those axioms are ad hoc and do not conform to real-world situations [Binder & Niederle, 2005, p. 3]. As early as the 1970s research indicated that both sophisticated and naïve respondents will consistently violate axioms of rational choice in certain situations[38] [Tversky and Kahneman 1974; Kahneman and Tversky 1979]. Surveys of literature examining when and how individuals violate the axioms of rational choice include Shogren and Taylor [2008], McFadden [1999], Camerer [1997], Rabin [1998], Thaler [1991] and Machina [1989]. Given that all the axioms are highly idealized assumptions, the empirical content of the theory remains controversial [Witt, 2005, p. 6].

Postwar neoclassical economists are unable to say anything how preferences are formed [Anger & Loewenstein, 2006, p. 13]. Axiomatic preference theory explicitly excludes such questions as: why do individuals or households have different preferences, do we universally share some preferences across individuals; are our preferences innate, or learnt; and if preferences change, how do they develop in time and is there a systematic way to describe their change? [Binder & Niederle, 2005, p. 3] [Witt, 2001, p. 24] [Metcalfe, 2001, p. 40] Orthodox preference theory does not explain why consumers order their preferences in the observed way, what it is that people want to consume and why they do so, how and why earlier demand experiences affect demand at later stages, or why variations in income affect the demand for different goods and services quite differently [Witt, 2005, p. 3].

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[37] If a preference ordering over a given set of lotteries (gambles) is complete, transitive, continuous, and it satisfies the independence axiom, then utility is linear in objective probabilities. In contrast to normal utility functions, which are just ordinal, von Neuman-Morgenstern utility functions are not entirely ordinal [].

[38] Neoclassical economists try to counter this by assuming that consistency only holds within similar types of "choice situations". This makes the theory non-falsifiable, because whenever consistency is violated, one could simply define a new "choice situation".

Green [2002] conveys his impression that "*most economists would much rather change assumptions about constraints rather than change assumptions about preferences*" [id., ibid., p. 15]. Many important problems of modern economics, such as the role of demand for innovations, can hardly be addressed on such a basis [Witt, 2005, p. 3]. So far, only a few attempts have been made to return to a research program of sensory utilitarianism (see X).

3.2.The shape of the indifference curves

In the mainstream theory of consumer demand, the shape of the indifference curves of preferences clearly determines the rebound effects (see figure X). Indifference curves are typically represented to be *negatively sloped*, (strictly) *convex* to the origin, and *continuous*. This shape reflects some of the more critical assumptions of consumer theory, including (local) non-satiation (more of a specific good[39] is in principle always better than less).

3.2.1. Non-satiable preferences ('downward sloping' indifference curves)

The neoclassical approach assumes either (strong) monotonicity, or a weaker condition called local non-satiation. Strong monotonicity means that for any bundle the consumer would rather have a bundle with at least as much of all commodities and strictly more of at least one commodity. Given any bundle (x_1, x_2), there is always a bundle that has more of at least one commodity that the consumer strictly prefers to (x_1, x_2) [Miller, 2006, p. 9]. Monotonicity captures the notion that "consumers always prefer more to less", and rules out the situation where consumers may actually prefer less of a commodity to more of it. Strict monotonicity implies downward sloping indifference curves. Local non-satiation implies that for every bundle (x_1, x_2) there is always another bundle "nearby" that the consumer strictly prefers to (x_1, x_2), and this is true no matter how small you make the definition of "nearby". Local non-satiation allows for the fact that some commodities may be "bads" in the sense that the consumer would sometimes prefer less of them (like waste or noise). However, if preferences are non-satiated, it is not possible for all commodities to always be bads [Miller, 2006, p. 32].

Figure X illustrates satiated preferences, i.e. the local satiation or bliss point where all the households' wants for the two commodities x_1 and x_2 are satisfied.

Figure 11: Satiation or bliss point

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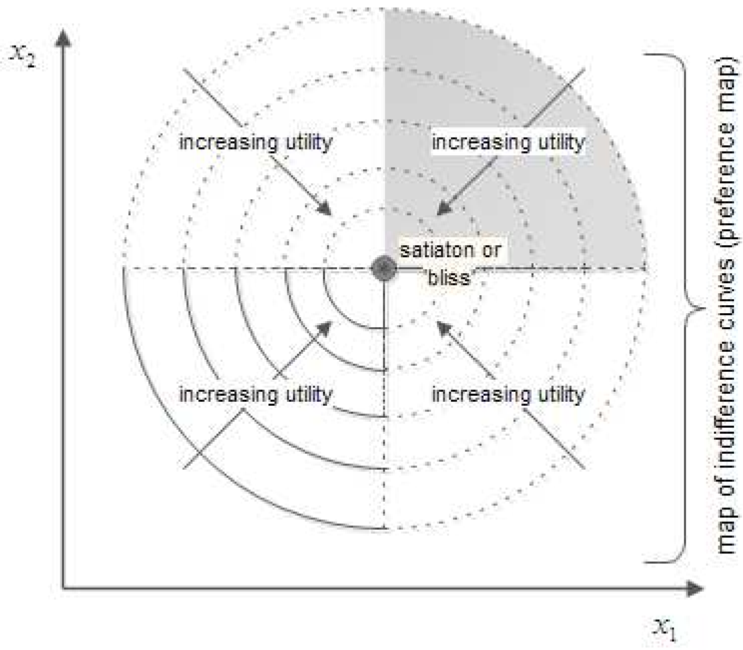
[39] Local non-satiation however does not exclude the existence of some 'bads'. A bad is by definition an undesirable commodity where consuming more of the bad results in a decline in utility (e.g. waste).



Prior to bliss point, all the relevant axioms hold. Once in (global) bliss, who cares what axioms hold? [Wetzstein, 2005]

Ever since Engel's Law[40] [1856], most economists readily admit that for many commodities demand can reach a point of satiation [Witt, 2001, p. 24]. The satiation point is "*an upper limit on the amount of expenditure that is allocated by households to any one particular good or service, regardless of how much household income grows*" [Chai & Moneta, 2008, p. 1].

Satiation levels of consumer needs have been identified as an important factor behind the (direct) rebound effect. Behavioural changes to energy efficiency improvements, and hence to the corresponding changes in relative *implicit* prices, may face a boundary. It might very well be that "*…rebound effects as a reaction to technological change will only occur as long as the consumer needs addressed by this technology are not yet satiated*" [Woersdorfer, s.d., p. 13].

Sorrell and Dimitropoulos [2007] give the example of household heating, where "*direct rebound effects from improvements in the energy efficiency of household heating systems should decline rapidly once whole-house indoor temperatures approach the maximum level for thermal comfort*" [id., ibid, p. 8]. Or, "*…homeowners heating their homes may get little utility out of raising the thermostat beyond seventy degrees Fahrenheit despite having lowered their electricity costs through home weatherization, leading to little direct rebound* " [Jenkins et al., 2011, p. 8]. A related remark is made by Hens [2010, p. 6]. Hertwich [2005] makes a similar observation. Poor households heat only a few selected rooms and only during periods when they are occupied. Insulation and / or the introduction of central heating, which is more efficient, allow households to heat more rooms, continuously. Strong rebound effects are therefore most likely to be detected in lower income groups [id., ibid., p.88].

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[40] Engel's Law states that the richer a household is; the less percentage of that income will be devoted to food expenditure. This does not necessarily imply the existence of a satiation point. Neither does the existence of a satiation point exclude the possibility that people consume beyond their satiation point, i.e. purchase but not consume commodities (in other words, "waste" them).

This hypothesis has two important implications:

- At the micro-level, direct rebound effects will be higher among low-income groups, since these are further from satiation in their consumption of many energy services [Milne and Boardman, 2000];
- At the macro-level, (primary) rebound effects will be much larger in poorer regions or countries with an abundance of 'marginal consumers', i.e. consumers who were previously unable or unwilling to purchase a particular energy service[41]. Those strong rebound effects may only be partly offset by saturation effects among existing consumers [Roy, 2000].

Pasinetti [1981, p. 72] relates the existence of a satiation point to the physiological nature of human needs. Once a certain physical need is satisfied, further increases in consumption expenditure are redirected to other goods and services[42]. Witt [2001, p. 32] posits that satiation points can be avoided by the innovative act of modifying the commodities to appeal to other, non-satiated wants (see also chapter X).

3.2.1. Convex indifference curves

Preferences are assumed to be strictly convex (to the origin).

In the two commodity case, if the quantity consumed of one commodity x_1 increases, total utility would increase if not offset by a decrease in the quantity consumed of the other commodity x_2. The "substitution assumption" states that *to leave the consumer indifferent*, there is a maximum amount that the consumer will give up of the other commodity x_2 to get one additional unit of the one commodity x_1. The "*marginal rate of substitution*" MRS (defined as the negative of the slope of the indifference curve)[43] shows how much of commodity x_2 a consumer is willing to sacrifice in exchange for one more unit of commodity x_1. For most commodities the marginal rate of substitution is not constant. The so-called "law" (or rather axiom) of *diminishing marginal rate of substitution* dictates that the marginal rate of substitution (or slope of the indifference curve) declines (in absolute value) as you move down and to the right along the indifference curve. This means that as a consumer increases consumption of the one commodity x_1 in successive units, he or she is willing to give up successively smaller amounts of the other commodity x_2 to keep total utility unchanged. A diminishing marginal rate of substitution[44] implies that consumers prefer well-balanced, diversified bundles of commodities to bundles that are heavily weighted toward one commodity, or in other words: "averages are preferred over extremes" [Hall, 2005]. The interpretation that consumers have "a love for diversity" is an abstraction that may not always hold, and whose main purpose is to facilitate the mathematical solution of the utility maximization problem.

Figure 12: Decreasing marginal rate of substitution along the indifference curve

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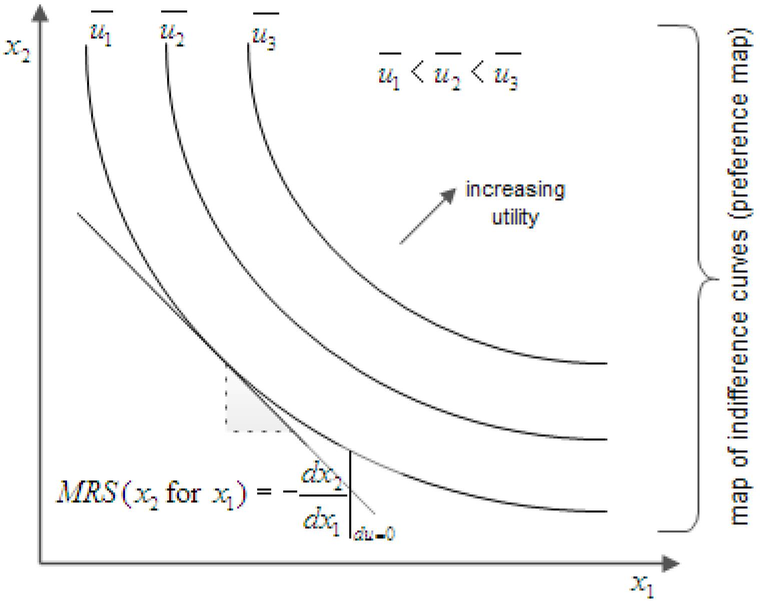
[41] As compared to developed countries, demand for energy services may be more elastic and far from saturated in developing countries, where a (limited) number of studies have found much larger rebound effects. [Jenkins, 2011, p. 9]

[42] Or to savings, an option not discussed here.

[43] $MRS(x_2 \text{ for } x_1) = -\frac{dx_2}{dx_1}\Big|_{U=constant}$. Where $U = constant$ indicates that utility is being held constant as the slope changes.

[44] The assumption of (strictly) decreasing MRS along an indifference curve is equivalent to (strict) convexity to the origin of indifference curves.



Source: Based on Hall [2005].

Although we discussed convex preferences in terms of a decreasing marginal rate of substitution (MRS), the characterisation of preferences in terms of MRS requires differentiable indifference curves (or a differentiable utility function), which is a stronger condition than is necessary for convex preferences. Therefore, in the general case, economists assume (strictly) convex preferences. Convex preferences imply that a consumer who is indifferent between two distinct bundles at least (weakly) prefers every convex combination[45] of those bundles to either of them.[46] Preferences are (strictly) convex, if and only if the utility function is (strictly) quasi-concave, or alternatively, if and only if the indifference curves are (strictly) convex to the origin. Quasi-concavity of the utility function is an ordinal property (whereas concavity is a cardinal property).

Figure X: Convex preferences

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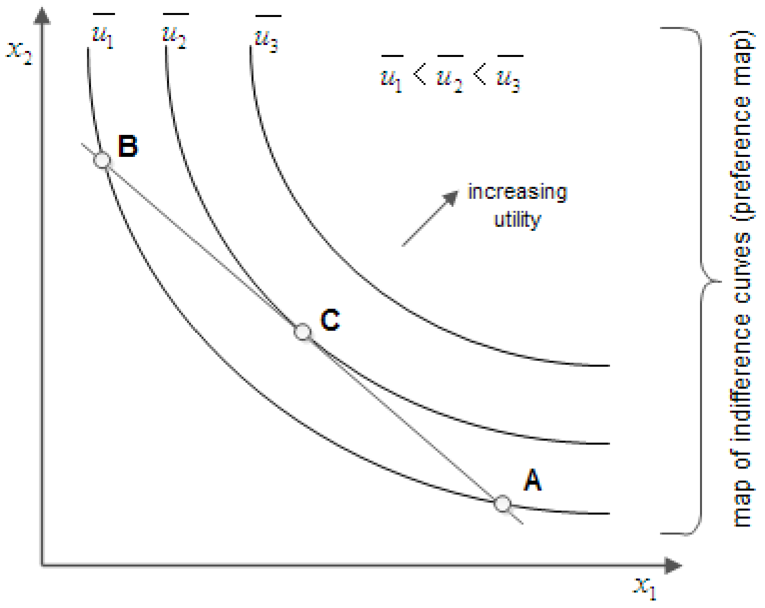
[45] A convex combination of two bundles is a weighted average of those two bundles based on “weight”, where weight is simply a fixed number between 0 and 1.

[46] A consumer’s preferences are *strictly* convex if for any pair of bundles $A = (x_1^A, x_2^A)$ and $B = (x_1^B, x_2^B)$, and any fixed α with $0 < \alpha < 1$, a weak preference for A over B implies that bundle C is strictly preferred to B, where C is the convex combination $\alpha A + (1 - \alpha)B$



If preferences are non-convex, behaviour could change substantively in response to small changes in the exogenous parameters (such as income, the prices of the commodities or, in terms of the rebound effect, the implicit prices of the energy services). Economists choose to model consumers as having convex preferences, since non-convexities result in predictions that do not accord with how they feel consumers actually behave [Miller, 2006, p. 49].

If the consumption set (i.e. the set of mutually exclusive feasible bundles or 'choices') is convex and compact and the preference relation is *strictly* convex, then the preference relation has a *unique* maximal element (optimal bundle) in the consumption set.

Continuous indifference curves

If a rational (i.e. complete and transitive) preference relation is *continuous*, then there exists a continuous utility function u that represents this preference relation (Representation Theorem). Continuous rational preference relations generate continuous indifference curves.

The assumption of continuity rules out certain preference relations. For example, lexicographic preferences violate the assumption of continuous preferences. Strict lexicographic preferences[47] imply that certain commodities always take precedence in an individual's expression of preferences over all other commodities. A more tenable form of lexicographic preferences are modified lexicographic preferences based on thresholds. There may exist thresholds, or minimum levels of a commodity, that are necessary and prior to choices for other commodities (e.g. someone who is starving will not exchange food for a luxurious home) [~~Gowdy & Mayumi, 2001, p. 228~~]. Lexicographic preferences can be shown to be complete, transitive, strongly monotonic and strictly convex, yet they cannot be represented by a utility function (or by indifference curves[48]). "*The lack of a utility representation excludes lexicographic preferences from the scope of standard economic models, although they are derived from a simple and commonly used procedure*" [Rubinstein, 2011,

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[47] Preferences are lexicographic if $(x_1^A, x_2^A) \succ (x_1^B, x_2^B) \Leftrightarrow (x_1^A > x_1^B) \vee (x_1^A = x_1^B). \rightarrow x_2^A > x_2^B$. When faced with two bundles the consumer prefers the bundle with the most of commodity 1. If the two bundles have the same of commodity 1, he / she prefers the bundle with the most of commodity 2.

[48] With lexicographic preferences, all indifference sets are singletons (or indifference curves are single points).

p.18]. Empirical evidence seems to support the existence of lexicographic preferences for some environmental goods [Rosenberger et al., 2001, p. 2]

If the consumption set is compact and the (weak) preference relation is continuous, then there exists at least one maximal element (optimal bundle) in the consumption set.

Utility functions need not be continuous. Economists generally assume that utility functions are continuous and twice differentiable, not for 'empirical' reasons, but because "*it is felt that the benefits of more tractable models overwhelms the costs of reduced realism and narrower applicability*" [Congleton, 2006, p. 3]. If the continuity assumption leads to empirically false predictions, other various tools (e.g. from set theory) can be applied instead of calculus.

3.3.Time consistency

Neoclassical economists have been reluctant to accept the idea that preferences are not stable. Mainstream consumer theory assumes that consumer's preferences are given (exogenous to the system) ands stable, i.e. remain constant over time (at least over the period of time under study). If a bundle $A = (x_1^A, x_2^A)$ is preferred over bundle $B = (x_1^B, x_2^B)$ it should always be preferred over $B = (x_1^B, x_2^B)$. In other words, once a rational ordering of the preferences across all the consumption bundles is made, they thereafter remain unchanged [Neuman et al, 2010, p. 407]. Stigler and Becker [1977] state it rather graphically as follows: "*One does not argue over tastes for the same reason that one does not argue over the Rocky Mountains – both are there, will be there next year, too, and are the same to all men*" [id., ibid., p. 76].

Origins of the proposition that the overall level of satisfaction derived from a given level of consumption depends, not only on the current consumption level itself, but also on how it compares to some benchmark level, can be traced back as far as Smith [1759] and Veblen [1899]. The first effort to provide these ideas with some micro-economic foundations was made by Duesenberry [1949]. There is a growing body of evidence that challenges the stability function [Neuman, 2010, p. 409]. One line of research states that accumulated past experience with the commodity under discussion might be an important factor in the *construction* of preferences. Rabin [1998] gives an overview of this literature. For example, von Weizsäcker [1971] and Day [1986] claim that human behaviour is governed by adaptive procedures, but they do not offer any systematic theory or empirical tests of this hypothesis. Another line of research emphasizes the role of interplay between the individual and the group on the formation of preferences. Bowles [1998] gives a survey of this literature. Yet others turn to biological metaphors. Population dynamics of preferences in markets determines outcomes. Market forces select those decision rules that are 'most fit', favouring some kinds of preferences over others. Consequently they determine the composition of the population's preference orders in the next round [Neuman et al, 1010, p. 409].

Two types of time non-separable preference functions, in which utility depends not only upon current consumption, but also on some benchmark or "habit" level of consumption determined from past behaviour, have been identified [Alvarez-Cuadrado et al, 2004., p. 1]:

- "Habit formation". A specific class of time non-separable preferences are those exhibiting "*habit formation*" [Dynan, 2000, p. 391]. The "benchmark" or reference consumption level is based on the household's own past consumption levels. The household is described as being "inward-looking";

- "Catching up with the Joneses"[49]. The reference consumption level is based on the past consumption of some external reference group, typically the average consumption of the overall economy. Habit is modelled as "outside" the household. The household is described as being "outward-looking".

"*The concepts of habit and status have long been acknowledged as being important characteristics of human behaviour*" [Alvarez-Cuadrado et al, 2004, p. 1]. Both habit formation and social interdependence are sources of behavioural stability over time.

The specification of consumer preferences as time-separable functions remains standard practice in mainstream consumer theory. The consumers' preferences at one instant are assumed to be unaffected by his or her consumption the instant before.

If in reality preferences do change over time, this may limit the direct and indirect rebound effects. For example, under the idea of sustainable consumption, the aim should be to move away from using commodities as the basis of our identity toward some other, more sustainable "sense of self" [Jackson, 2005]. Or, rather than purchasing market commodities, certain "needs" of households may be satisfied in other (less energy consuming) ways [Gatersleben, 2001, p. x]. The introduction of sustainable consumption to consumers may therefore avoid further rebound effects [Hofstetter & Madjar, 2003, p. 13].

3.3.1. Habit formation

In Triandis' integrated social psychological model, the 'Theory of Interpersonal Behaviour' (TIB), behaviour in any given situation is a function of a person's intentions, his/her habitual responses, and the situational conditions and constraints in which the person operates [Jackson, 2005, p. 93-95]. Jager et al. [2000] explicitly distinguish between 'reasoned behaviour' and 'automated reactions'. While economic models largely focus on reasoned, deliberative behaviour, much of consumers' daily behaviours are based on habits and routines [Martiskainen, 2007, p. 19]. Nelson and Consoli [2011] also make a distinction between "*circumstances where the purchases of goods and services are largely a matter of routine, involving little in the way of self-conscious selection, and circumstances which require the household to dedicate a certain amount of thought, and effort, to deciding what to do*" [Nelson & Consoli, 2010, p. 673]. Hence, consumption behaviour is also influenced by habits and routines which people undertake without the actual need to think about them [Martiskainen, 2007, p. 12]. In particular, "*Energy use in the home is mostly invisible, and our energy consuming behaviour is based on habits and routines*" [Brohmann et al, 2009, p. 6]

Most economists would agree that in their present choices, consumers rely heavily on their past consumption patterns. "*One of the key factors in sustaining certain consumption patterns over time is the mechanism of habit formation*" [Linscheidt, 2001, p. 9].

Economic theory has dealt with this problem in two ways [Linscheidt, 2001, p. 9-10]:

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[49] "Consumption externalities" exist when consumers are directly affected by knowledge about the consumption of others. In literature, the terms interdependent preferences, Veblen preferences, competitive consumption and keeping up or catching up with the Joneses have all been used to refer to consumption externalities of this kind [Barrington-Leigh, 2011, p. 1]

- The first approach is founded on psychological learning theory, where habitualization is seen as a result of continuous reinforcement over time [Witt, 1987, p. 135]. This approach sees habit formation as an endogenous change of preferences[50]. As the consumer is basically content with his or her present choices, routine behaviour gradually replaces problem-solving responses. New solutions are sought after only if current behaviour is seen as no longer appropriate;
- The transaction cost approach is based on the household production theory [Stigler & Becker, 1977, p. x; see also x]. This approach states that consumers may have no other choice than to rely on proven routines. The costs of searching for the information required for evaluating the costs and benefits of all the alternatives in a world of uncertainty are so huge that habit is often a more efficient way to deal with moderate or temporary changes in the environment.

In economic literature, the relevance of habit formation seems very mixed. “*Past studies of time non-separable preferences based on aggregate consumption data yield mixed conclusions about the strength of habit formation*” [Dynan, 2000, p. 391]. Also, “*…in micro data the evidence of habit formation is inconclusive*” [Gayle & Khorunzhina, 2010, p. 3].

Deciding on the significance of habit formation in the context of the rebound effect is no easy task. For instance, one cannot assume that the importance of habit in one situation (e.g. energy conservation) is as high as it is in another (e.g. travel mode choice) [Jackson, 2005, p. 101]. Of particular interest in understanding the rebound effect are *conscious* processes through which consumers recognize and react to the emergence of *new* energy-saving technologies [Nelson & Consoli, 2010, p. 673].

3.3.2. Social interdependence

Consumption patterns have a social character in that they are guided and stabilized by the institutions of a society. The kind of behaviour a consumer considers appropriate is deeply rooted in the socio-cultural structure (e.g. informal institutions such as conventions, norms and ideologies). These institutions usually have a high degree of persistency, to fulfil their function of reducing uncertainty by providing a stable structure for everyday life. As long as behavioural patterns (even inferior or environmentally harmful ones) remain rooted in an existing, widely accepted institutional framework, it may be very difficult to change them [Linscheidt, 2001, p. 10-11].

The economic approach: preference interdependence

Mainstream neoclassical consumer theory assumes ‘selfishness’. The choices of a consumer are solely based on his or her own preferences. As stated by Ackerman [1997], “*Consumer desires and preferences are exogenous; they are not affected by social or economic institutions, interactions with others, or observation of the behaviour of others*” [id., ibid., p. 652]. This assumption of ‘asocial individualism’ excludes altruistic behaviour or envy among consumers.

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[50] For example, in some habit formation models the instantaneous utility function $u(c_{it}, x_{it})$ of individual i not only depends on current consumption c_{it} but also on habit levelx_{it}. Only $(c_{it} - x_{it})$, the component of an individual’s consumption over and above the habit level, contributes to utility. The habit level of individual i is calculated as$x_{it} = x_{i0}e^{-a_i t} + b_i \int_0^t e^{a_i(s-t)} c_{is} ds$, where x_{i0} is the initial condition and a_i and b_i are individual-specific constants.

In reality, individuals are not only influenced by their past experience, but also by the behaviour of other individuals in society [Linscheidt, 2001, p. 10].

"*The fact that consumer preferences are influenced by the behaviour of others is well-documented in the psychological and sociological literature, yet it is almost universally ignored in the micro-studies of consumer demand*" [Alessie & Kapteyn, 1991, p. 404]. (see also § X and X) Economic models of consumer behaviour typically do not recognize that preferences and choices are interdependent [Yang & Allenby, 2003, p. 282]. Although the social character of individual behaviour has a long tradition in economic thought, it is hardly ever used in standard neoclassical approaches [Linscheidt, 2001, p. 10]. Or in the words of Drakopoulos [2010], the majority of mainstream economists continue to assume independent individual preferences, notwithstanding the fact that the concept of interdependent preferences is present in the works of a substantial number of economists in the history of economic thought [id., ibid., p. 2]. (Examples of those economists here)

Manski [2000] defines interdependent preference as "*occurring when an agent's preference ordering over the alternatives in a choice set depends on the actions chosen by other agents*" [id., ibid., p. 120]. In literature, this effect is also known as 'preference interaction', 'peer influences', 'neighbourhood effects', 'bandwagon effect' and 'conformity'.

An individual's preference for a particular commodity may by influenced by the consumption choices of others in many ways. Drivers of preference interdependence are e.g. social concerns, social identification (consumers who identify themselves with a particular group often adopt the preferences of that group), the signalling effect of other consumers' ownership on inferred characteristics of the commodity (e.g. others may have information not available to the consumer), and reduced transaction costs (i.e. network externalities in consumption, as a result of people engaging in multiple activities with family, co-workers, neighbours and friends[51]).

Drakopoulos [2010] cites three reasons for the continued mainstream resistance towards interdependent preferences:

1. The full incorporation of interdependent preferences and of the related concept of the comparison of relative income, in economic theory, would cast serious doubts on many well established and important theoretical results (e.g. of economic growth and income distribution theories);
2. The orthodox conception that economic agents are characterized by selfish preferences. Self-interest is in fact one of the cornerstones of the traditional model of individual economic behaviour ("homo economicus");
3. The reluctance of mainstream economists to consider psychological and sociological aspects of human behaviour in their economic analysis.

Nevertheless, since the 1990s there is an increasing use of ideas such as reference income, target income, relative income and positional goods, which are all based on the concept of interdependent preferences [Drakopoulos, 2010, p. 19].

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[51] For example, users sharing the same software can easily exchange files or share information about short-cuts or bugs.

The marketing (psychological) approach

The marketing synthesis sees consumption behaviour as very much a *social* behaviour [Goodwin et al., 2008, p. 3]. The experience of groups to which consumers compare themselves create reference groups, to which individuals evaluate their own well-being [id., ibid., p. 3]. Marketers examining the reasons why individuals conform to the behaviour of a reference group have identified three sources of social influence on consumers' behaviour [Yang & Allenby, 2003, p. 283]:

1. Identification. Identification occurs when consumers adopt from others because the "*behaviour is associated with a satisfying self-defining relationship*" [Burnkrant and Cousineau 1975, p. 207] to the other. Some economic approaches model social interdependence as a mechanism of endogenous preference formation. Conformity is interpreted as a way of fulfilling basic needs like social acceptance and recognition, which can only be achieved by adapting to the dominant behavioural patterns of society or a certain group [Becker, 1996, p. 12]. 'Symbolic Interactionism' and 'Symbolic Self-Completion Theories' refer to the tendency for consumers to purchase goods and services not only for their practical value but also to construct their identity [Jackson, 2005, p. 14]. Consumers use those commodities to signal social status, group membership or self-esteem. Thus, tangible physical characteristics (e.g. technological characteristics such as energy efficiency) may be secondary, what counts are the socially agreed symbolic values these commodities have for transmitting the above mentioned signals [Witt, 2009, p. 1]. For example, the overwhelming reason that a particular make and model of hybrid vehicle was chosen in the US was not because of fuel economy or low emissions but because the car was seen by consumers to make '*a statement about me*' [CNW Marketing Research, 2007, p. 75]. The incorporation of intangible use values such as the status element of certain commodities enriches our understanding of consumer behaviour[52], but does not invalidate marginal concepts [Dubas & Jonsson, 2005, p. 7];
2. Internalization. Internalization occurs when consumers adopt other people's influence because they believe it could help them make a better decision that optimizes their own returns. Imitation is sometimes explained by information costs and bounded rationality. "*In situations of high uncertainty, it may be cheaper to rely on others than to gather the information required for an autonomous decision*" [Linscheidt, 2001, p. 10];
3. Compliance. Compliance occurs when "*the individual conforms to the expectations of another in order to receive a reward or avoid punishment mediated by that other*" [Burnkrant and Cousineau, 1975, p. 207]. Rewards and fines serve to reduce the internal motivation of individuals. Behaviours are intrinsically motivated if individuals do something because they like them; and extrinsically motivated if they do something for monetary payment or because they are in some way obliged or ordered to do them [Policy Studies Institute, 2006, p. 47].

Conformity is likely to make the rebound effect less likely to occur, as it stabilizes consumption patterns (i.e. locks in consumers' choices) [Lorenz & Woersdorfer, 2009, p. 20].

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[52] For example, in the fashion market consumers may attribute positive and negative symbolic meanings to certain products. Consumers make purchases based on their feeling of self-esteem and whether a product would improve that self-esteem, and they avoid certain purchases in order to protect their self-esteem. Thus, most people feel more comfortable dressing like part of a group. They fear being talked about poorly for fashion choices with negative symbolic meaning.

The sociological approach: socio-cultural factors

Empirical research suggests that energy consumption patterns vary over ethnic groups and cultural practices [Kriström, 2008, p. 99].

As a case in point, Chappells and Shove [2003] maintain that connotations and realisations of thermal comfort indoors "…*are culturally, historically, technically, seasonally and climatically contingent*" [id., ibid., p. 4]. Thus, thermal comfort is not only a fixed and 'natural' condition (satisfying a physiological need) or a condition to be met by a process of adaptation (satisfying the psychological need of individuals to exercise control over their thermal environment); it is also something that is socially and culturally constructed. "…*studies reveal how comfort is culturally relative and is framed by issues of social convention, symbolism and status that cannot be reduced to thermal physiological or psychological parameters*" [Chappells & Shove, 2003, p. 6]. For example, studies of energy use behaviour in Fukuoka (Japan) and Oslo (Norway) by Wilhite et al. [1996] find significant cross-national differences in end use patterns for space heating, lighting and hot water use related to both economic *and* cultural factors.

Likewise, the energy service 'clothes washing' is not only motivated by the physiological need for a healthy body (cleanliness as a hygienic standard), in terms of meeting social requirements (cleanliness as a social standard) it also represents a "socio-cultural construct" [Lorentz & Woersdorfer, 2009, p. 15].

The application of relevant behavioural insights through a variety of intervention levels would include recognizing the opportunities and constraints associated with socio-cultural considerations in the shaping of individual and organizational behaviours [Ehrhardt-Martinez, 2009, p. 7-8]. Understanding how social and cultural institutions frame practices of sustainable (energy) consumption may open up new policy options [Chappells & Shove, 2003, p. 7]. This approach recognizes that society does shape or co-shape individual preferences [Kriström, 2008, p. 10].

Social norms, social networks and social status play an important role in the way consumers routinely obtain information and determine (both consciously and sub-consciously) their course of action [Ehrhardt-Martinez, 2009b, p. x].

- A social network refers to individuals or an infrastructure of individuals with whom we interact on a regular basis (e.g. family members, friends, and colleagues, members of a club or organization, and/or online communities). Social networks help identify the "acceptable" and "appropriate" behaviours and technologies to buy;
- A social norm is generally defined as a shared expectation of behaviour that indicates what is considered culturally desirable and appropriate[53]. Descriptive norms convey information regarding which behaviours are and aren't socially popular. Injunctive norms convey information regarding which behaviours are and aren't socially approved. Deviant behaviours are often subject to acts of social regulation or social control. Consumers use social norms to determine which behaviours they should and should not adopt, and which technologies they should and should not accept;
- Social status and identity. Social status conveys a level of "social esteem" or prestige as well as access to limited resources. Consumers often buy commodities (such as designer clothing,

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[53] Like rules or regulations they are prescriptive, but norms lack the formality of rules.

> high performance cars or large houses) not because those items provide additional functional benefits, but because they are markers of social status. Likewise, consumers may use commodities as tools to define, redefine and express their self-concept and identity.

Within much of the literature on innovation and demand, there is an awareness of the key role played by specialist groups, communities of latent users who provide a ‘cultural imperative’ to sustain the development of a particular technology, and act as a vehicle to identify and publicise unmet needs [Metcalfe, 2001, p. 40]. Recent efforts to facilitate reductions in energy consumption use existing social networks to disseminate information and technologies and to achieve higher levels of commitment among individuals [Ehrhardt-Martinez 2008; Egan 2001].

Several studies have explored the role of social norms in determining energy saving behaviour. For example, a field experiment in which normative messages were used to promote household energy conservation, indicated that providing households with a descriptive, normative message detailing average neighbourhood energy consumption produced desirable energy savings when the household’s energy consumption was above the neighbourhood average, but also produced an undesirable ‘boomerang effect’ (increased energy consumption toward the mean) when the household was already engaging in the desired behaviour (energy consumption below the neighbourhood average). However, adding an injunctive message (conveying social approval or disapproval) eliminated this boomerang effect. It seemed that the effects of the normative messages continued to be strong even four weeks after the initial intervention [Schultz et al., 2007].

Many of the readily observable choices concerning social status and identity also confer important energy implications [Heffner et al 2006].

3.4.Rational choice theory versus bounded rationality

3.4.1. Behavioural economics

Rational choice theory as a descriptive model of human behaviour assumes “*…that preferences are defined over outcomes, that those outcomes are known and fixed, and that decision makers maximize their net benefits, or utilities, by choosing the alternative that yields the highest level of benefits (discounted by costs). The subjective expected-utility variant of rational choice integrates risk and uncertainty into the model by associating a probability distribution, estimated by the decision maker, with outcomes. The decision maker maximizes expected utility*” [Jones, 1999, p. 299].

A massive amount of evidence seems to indicate that people systematically violate predictions derived from rational choice theory or its expected utility variant [Grüne-Yanoff, 2008, p. 4]. “*The evidence that consumer decisions are not always perfectly rational is quite strong…*” [Gillingham et al., 2009, p. 15]. Some literature has focused more closely on the decision-making behaviour of households, identifying potential “behavioural failures” (i.e. consumer behaviour that is inconsistent with utility maximization, or energy cost minimization). This literature is motivated at least partly by results from the field of behavioural economics.[Gillingham et al., 2009, p. 2]. Behavioural economics is an attempt to develop a radically new paradigm, combining economics and psychology in order to improve our understanding of consumer behaviour [Darroch & Jardine, 2010, p. 503 & 505)]. It refers to the effort to increase the explanatory and predictive power of economic theory by providing it with more psychologically plausible foundations [Angner & Loewenstein, 2006, p. 1].

The behavioural economics' approach is drilling down to the level of the individual in order to identify how individuals might behave. Katona [1980, p. 3] identifies three features of behavioural economics that sets the discipline apart from neo-classical economics:

- Its starting point is empirical investigations of the behaviour of consumers. "*The behaviour of decision makers must be examined, whether in the laboratory or in the field*" [Jones, 1999, p. 299];
- It focuses on the process of decision making, rather than the outcome. For example, laboratory studies have found that people tend to use simple rules of thumb when making decisions, resulting in systematic judgment errors [Cumming, 2008, p. 1];
- It measures and analyses psychological antecedents, such as motives, attitudes and expectations, that influence economic decisions.

Two propositions unite the diverse strands of behavioural economics [Cumming, 2008, p. 1]:

1. The classical economic assumption of 'homo economicus' is not an accurate depiction of human decision-making;
2. Taking cognitive types of error (a.k.a. 'cognitive biases') into account will allow economists to predict patterns of human behaviour more accurately. One example is the observation of 'framing effects'[54], where "*seemingly inconsequential changes in the formulation of choice problems caused significant shifts of preference*" [Tversky and Kahneman, 1981, p. 457]. Other anomalies as sources of sub-optimality in decision making include the underweighting of opportunity costs, the failure to ignore sunk costs, non-linear probability weighting, etc. [e.g., Thaler, 1980].

The empirical literature testing behavioural failures specifically in the context of energy decision making is very limited [Gillingham et al., 2009, p. 18].

A review of the behavioural economics literature and literature in psychology and sociology (e.g. Stern [1985]; Lutzenhiser [1993, 1992]) reveals that several systematic biases in consumer decision making may exist, that could lead to underinvestment in energy efficiency and overconsumption of energy. However, a more complete understanding of these deviations from perfect rationality, disentangling them from informational and other market failures, and measuring the ability of practicable policies to address these behavioural failures remains an important area of future research [Gillingham et al., 2009, p. 18].

3.4.2. Critique of behavioural economics

Behavioural economics is subject to a number of general criticisms.

Behavioural economics, in its attempts to bring together economics and psychology, does not offer a complete alternative to rational choice theory. None of the theories capture human behaviour perfectly. In particular, to date, behavioural economics has largely overlooked affective states (as opposed to cognitive states). Only since beginning 2000 has the role of affect in decision making and behaviour become a major focus of research. At best, moving away from EUT gives theories that are a little less false [Grüne-Yanoff, 2008, p. 17; McAuley, 2007, p. 13]. And as Lane [1993, p. 920]

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[54] 'Framing' means that the way choices are presented to us often affects the decision we make.

suggests, although behavioural economics is capable of accounting for much market behaviour, it is unable to explain the operation of markets.

Behavioural economics is woefully fragmented [Lane, 1993, p. 920]. Critics point out that behavioural economics is not a unified theory, but is instead a collection of tools [Camerer & Loewenstein, 2002, p. 47]. "*So the question arises whether the increased predictive and explanatory potential of the bounded rationality theories is great enough to offset the undeniable decrease of parsimony of the new theories when compared to EUT*" [Grüne-Yanoff, 2008, p. 17].

Many of the ideas of behavioural economics have only been tested in the laboratory, even though since the mid-1990s – and in large part driven by concerns about the external validity of laboratory experiments[55] – behavioural economists have increasingly relied on data gathered "in the field". Given the lack of 'real world' evidence, it is unclear whether psychological models would be better to underpin policymaking than the assumption of self-maximisation [Grüne-Yanoff, 2008, p. 17]. Or in the words of Darroch and Jardine [2010], "*…why behavioural economists would want to combine psychology and economics together in order to advance our understanding of consumer behaviour is not clear, given that marketers have been doing this for around 40 years*" [Darroch & Jardine, 2010, p. 505].

Finally, one might ask why these theories insist on (bounded) rationality at all. Behavioural economists do not criticize orthodox decision theory as a normative or prescriptive theory of decision [Angner & Loewenstein, 2006, p. 37]. Although behavioural economics began as a descriptive enterprise, a program of "light paternalism" or "libertarian paternalism" [Thaler & Sunstein, 2008] to help people make better choices has gained prominence. However, a theory of consumer choice does not have to be (exclusively) prescriptive. A descriptive theory of behaviour could just be a causal theory, allowing any kind of irrationality, if needed [Grüne-Yanoff, 2008, p. 17].

3.5. The "representative" consumer

3.5.1. Flexible demand systems in macro-economics

"*Through marginal analysis, the negatively sloped consumer demand curve is derived from the consumer's utility function which is based on SEU model*" [Dubas & Jonsson, 2005, p. 5]. The market demand for a commodity is the horizontal summation of individual household demand curves, assuming that individual demands are independent of each other. The *aggregate* demand function is treated as if it were generated by a 'fictional representative consumer' whose preferences satisfy the standard axioms of choice [Felli, 2006].

The specification of theoretically consistent aggregate demand is a difficult problem in consumer theory. The micro-economic theory of demand is developed in the context of an individual consumer. The transition form micro- to macro-economics of consumer behaviour is known as the "aggregation problem".

Macro-econometricians often only have data at the aggregate level and would like to model aggregate demand of households as a function of households' *aggregate* income or aggregate wealth (e.g. GDP) [Larsen, 2004, p. 1]. In general, aggregate demand depends on prices and on the

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[55] There is reason to think that people might make different decisions in the lab than they make in the real world.

consumers’ specific income levels. The problem arises from income effects. Income effects generally mean that aggregate demand will change when the income distribution changes. But an aggregate demand function is by definition a function of aggregate income, not the distribution of income [Nelson, 2011, p. 1].

The aggregate demand stated as a function of aggregate income implies that aggregate demand has to be invariant to any redistribution of income that sums to the same level. This condition holds at any price p if the income effect is the same whatever consumer we look at and whatever his or her level of income. More flexible functional forms for demand analysis have been developed in recent years (see annex X). These demand systems replace the requirement that aggregate demand behaves like the sum of individual demands by the weaker assumption that the demand system generates the observed budget (or expenditure) shares. Flexible demand systems based on a “representative consumer” however do not remedy aggregation bias (arising from not considering potential income distribution changes). Evidence suggests that aggregation bias tends to be small under certain demand systems and in the short term, when income distribution dynamics remain stable [Cirera & Masset, 2011, p. 2824]. In the long term, significant deviations from distribution-neutral income growth increases aggregation bias. Recent emphasis on micro-micro data sets, empirical models and methods may have decreased the prominence of aggregation in empirical work [LaFrance & Pope, 2006, p. 1].

3.5.2. Heterogeneous households

Stigler and Becker [1977] state that preferences are not only fixed and exogenous (see §X) but also identical across individuals.

Empirical research shows that energy consumption patterns vary significantly across similar households with identical observable economic and socio-demographic characteristics (e.g. income, social class, education, household size (in particular number of children), average age of occupants, sex, etc.), living in the same category of buildings (dwelling type, degree of urbanity), and even with the exact same equipment or appliances [e.g. Lindén et al., 2006,p. 34; Lutzenhiser, 1993, p. 249, Socolow, 1978[56]]. If preferences are so heterogeneous across the population, responses to energy efficiency (or price) changes may well differ between otherwise identical households [Kriström, 2008, p. 98].

The significant variation in human behaviour regarding energy demand leads to the conclusion that – in order to understand the rebound effect – a theory of substantive preferences is required. (refer to X)

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[56] A classic case is Princeton University’s Twin Rivers Project, a five year study of physically identical buildings with identical floor plans, furnaces and appliances, occupied by demographically similar families. An interdisciplinary research team concluded that energy use for space heating is substantially assignable to the resident rather than structural features that persist independent of the resident [Socolow, 1978].

4. Towards a more complete (energy) consumption behaviour model

4.1.Rationale

4.1.1. Why use models of consumer behaviour to study the rebound effect

The key problem is that it is not possible to run historical "control" experiments on society to see whether total energy use is higher or lower than if there had been no energy efficiency improvements [Herring & Roy, 2007, p. 198]. It is difficult or even impossible to conduct economic experiments on households let alone society. This necessitates the use of sophisticated models of (energy) consumption behaviour.

Empirical research based on sound theoretical models may allow strong conclusions on the direction and magnitude of the rebound effect at the micro-level of household, without ever reaching absolute scientific certainty [Herring, 2008]. The value of such (hypothetical) models would not be so much the degree of realism of their assumptions, but rather the usefulness of the conclusions that can be derived from them. Computational simulation of consumer behaviour would allow conducting various "experiments" on households, which can be tested for the accuracy with which they represent reality.

In rational choice theory, consumers choose 'bundles' in a consistent way, and therefore their behaviour is predictable [Kwan Choi, 2009]. If all consumers acted purely at random or if most behaviour cannot be explained, it would not be possible to predict their behaviour[57]. In order to fully comprehend the rebound effect at the micro-level of households, it is necessary to understand how and why the various households consume. Such an understanding should also lead to better insights in the occurrence of the so-called "energy efficiency gap".

However, a solid understanding of specific mechanisms through which improvements in energy efficiency affect individual behaviours is still lacking [Safarzynska, 2011, p. 6].

4.1.2. Why the need for an integrated model?

Since the mid-1970s, a succession of established disciplines has sought to develop theoretical models of human energy-related behaviour grounded in the perspective of each particular discipline [Parnell & Larsen, 2005, p. 791]. Although existing models (rational choice model, attitude-behaviour model, folk model, categorization of energy users, diffusion of innovations) have been found to have merit in some though not all aspects of the human-energy relationship, "*no overarching model to predict, influence, or categorize human behaviour on energy efficiency has emerged*" [Egan, 2001, p. 12].

Recent literature has seen the emergence of a multidisciplinary approach to energy-use behaviour as part of the wider study of environmentally responsible behaviour (ERB) [Parnell & Larsen, 2005, p. 792].

As stated by Ehrhardt-Martinez [2009, p. 4], research on energy-efficient technologies and practices would clearly benefit greatly from the adoption of a behavioural toolkit. "*Such a toolkit would include the use of insights from a variety of social and behavioral fields including sociology, psychology,*

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[57] The belief that behaviour can be explained distinguishes economics from other social sciences.

anthropology, demography, public policy, behavioral economics, marketing, and communications" [Ehrhardt-Martinez, 2009, p. 4].

In economic literature, "*Most studies analyzing the rebound effect are based on neo-classical economic models and therefore ignore sociological and psychological aspects*" [Peters et al., 2012, p. 11]. The development of "sustainable" consumer demand models must include a) the integration of psychological as well as sociological aspects; and b) the detailed treatment of consumption as a complex process [Kletzan et al., 2002, p. 137].

We propose a consumer model that contains at least the following ingredients:

Category	Sub-category
Mainstream neoclassical elements	Prices and income (budget set) do matter
	Consumption possibility set
Extended neoclassical approach	Household production function (HPF)
	Opportunity costs of time (and space)
	Attributes (or 'characteristics) of commodities
Themes from behavioural economics	Bounded rationality
	Heuristic decision making
	Prospect theory
Elements from psychology (motivation)	The 'wants & needs' of consumers
Social interactions	Agent based modelling (ABM)

We discuss each of these elements in more detail.

4.2.Mainstream neoclassical elements

4.2.1. Constraints in the SEU model

Income and market prices

Prices and income do matter. Changes in income and / or market prices of commodities will definitely influence consumer behaviour to a large extent.

In economics, households determine which bundle maximizes their utility function, given the household's limited income and fixed commodity prices. Based on rationality and complete information the economic agent chooses an optimum. "*Every time when a change occurs (in prices or income) he chooses a new optimum, corresponding to the new conditions*" [Berkhout et al., 2000, p. 426]. Changes in consumer behaviour are thus attributed to changes in the constraints. Those constraints are determined by the (exogenous) variables income (wealth) and (commodity) prices. Changes in the environment that do not affect the budget set should not affect the consumer's choices [Miller, 2006, p. 10]. The "pure theory of consumer's behaviour" [Samuelson, 1947, p. 90-91] deals with quantities demanded, prices, and incomes only. Or, in the words of Ackerman [1997], "*Only prices, incomes, and personal tastes affect consumption – and since tastes are exogenous to neo-classical economics, there is little point in talking about anything but prices and income*" [Ackerman, 1997, p. 651].

The predictive power of the standard theory of consumer behaviour arises primarily from the nature of the constraints on consumer behaviour, not from the particular hypotheses made about preferences [Metcalfe, 2001, p. 41].

The techno-economic framework

With techno-economic framework we refer to 'associated systems of provisions' that determine factors such as the accessibility of energy efficient products in the market place [Parnell & Larsen, 2005, p. 793].

Consumption activities are frequently connected to a certain techno-economic framework which has been developed and refined over long periods of time [Kemp, 1997, p. 276]. "*This framework reinforces traditional consumption patterns because the infrastructures and technologies required for an alternative way of life are usually unavailable in the short term*" [Linscheidt, 2001, p. 10-11].

In general, diffusion of new (energy saving) technologies cannot proceed until supporting infrastructure is built [Brown, 1981, p. 104]. For example, the influence of electrification and the automobile upon consumption patterns depended on establishing capital intensive infrastructure and a supporting maintenance system [Metcalfe, 2001, p. 39]. The automobile system is a convenient means of transport partly due the high technological standards cars have attained over time but also partly due to the quality of the existing road system [Linscheidt, 2001, p. 11]. "*An equivalent techno-economic framework for a different, ecologically less harmful transportation system does not exist and would require a long time to evolve. Consequently, having no car currently means a difficult and time-consuming way of life*" [Linscheidt, 2001, p. 10-11].

In mainstream economics, the consumption (possibility) set is the set of (realistic or reasonable) commodity bundles that the individual can conceivably consume given the *physical and institutional constraints* imposed by the environment.

4.2.2. Neoclassical elements in the (energy) consumption behaviour model

From standard economic theory we retain the relevance of the budget set. As in neoclassical theory, income along with market prices determines the budget set, i.e. the set of "affordable" (feasible) bundles of market commodities.

Purchasing and consuming market commodities naturally presupposes the existence of markets. The availability of commodities is determined by a technological-economic framework. One simply cannot buy products that do not (yet) exist, or one generally does not buy products whose consumption is made impossible by the fact that the required infrastructure is not (yet) in place. These constraints are as a matter of fact implicit in the neoclassical theory of consumption in its definition of the feasible consumption set.

Innovation, in particular the energy efficiency improvement of a durable good, constitutes a change in the technological-economic framework. Whether households will buy (and use) the more energy efficient durable is the result of complex (household decision) processes, which a model of (energy) consumption behaviour should try to capture.

4.3.Extended neoclassical approach

4.3.1. Household production function (HPF)

A number of postwar neoclassical economists significantly reformulated traditional microeconomic consumer theory to overcome particular conceptual difficulties of mainstream theory. Consumer theory as originally proposed by Richard Muth [1965], Gary Becker [1965] and Kelvin Lancaster [1966] in the mid 1960s regards households as autonomous actors producing their own utility. In this model, consumers do not gain utility directly from the market goods or services that they purchase, but instead they transform combinations of these purchased commodities into something that they do value.

Consequently, the utility function a household maximizes is directly related to outputs of a so-called household production function (HPF). The wants or needs of households are satisfied by outputs[58] that the household itself produces. The demand for market goods and services is only derived from the household's production objectives [Witt & Woersdorfer, 2010, p. 4-5].

4.3.2. Opportunity costs of time

The standard framework to solve the problem of the often omitted costs other than energy (e.g. capital costs, opportunity costs of time) is the 'household production function" (HPF) approach, first proposed by Becker [1965].

Becker uses the metaphor of 'household production technology' to describe the transformation process. Commodities (market goods and services), together with human capital (reflecting the skills and experiences of the household) and time are merely inputs of the consumption process. The, in the words of Becker, "more basic commodities" of the household, like 'the seeing of a play' or 'sleeping', rather than the actors, script, theatre and playgoer's time, or bed, house and time, are what the consumer really cares about. These, what we prefer to call the 'household production outputs', are the arguments that directly enter the utility function of the household. The utility function is thus not defined over market goods and services (or commodities in the conventional sense), but over the outputs of the household production process.

The marginal costs of maximizing the household utility function to multiple constraints and to the household production relations – their "shadow prices" – consist of the expenditures on market goods or services, and the opportunity costs of time per unit of that want or need [Becker, 1965, pp. 496-497].

In particular, time is being recognized to put a constraint on consumer behaviour, as does the limited household budget. The household has to allocate a limited amount of time between market labour (its only potential to earn income, with which the commodities can be purchased that go into the household production process) and unpaid (nonmarket) home-production activities (that produce the useful outputs that enter the utility function). Thus, all unpaid uses of time have opportunity

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[58] The terminology in the seminal papers is very confusing. Muth [1966, p. 669] calls the outputs "goods produced", which are in turn arguments of a conventional utility function of the household. Becker [1965, p. 495] oddly uses the term (more basic) "commodities" to denote these household production outputs. We will follow the more conventional terminology, where commodities are regarded as market goods or services. In Lancaster's model [X] goods possess "characteristics". These characteristics, which we can identify with Becker's "commodities", are the arguments of the household's utility function.

costs[59]. These ideas are reflected in the 'full income" constraint, which combines the budget and time constraints [Witt & Woersdorfer, 2010, p. 4-5]. A more detailed discussion is given in appendix X.

In conclusion, the opportunity costs of space but mainly time do matter. We retain from Becker the addition of a constraint imposed by time (and space / location), next to the constraint imposed by the budget set.

Binswanger [2002], Jalas [2002] and Sorrell and Dimitropoulos [2008] use the general framework of Becker to study 'time rebound effects'.

4.3.3. Attributes or 'characteristics' of commodities

From Lancaster and marketing literature we retain the idea of "characteristics" of commodities, although – for reasons explained further on – we prefer the more modern concept "attributes".

Commodities (market goods and services) often have several features that Lancaster [1966; 1971] labelled "characteristics". Lancaster stated that consumers are not interested in commodities by themselves, but rather in the (desirable) characteristics of those commodities. For example, consumers do not demand food in itself, but rather the nutrients and flavours in the food. These characteristics are *objectively*[60] measurable and can be represented by some real numbers (e.g. the Calorie of a nutrient)[61]. Hence, Lancaster's approach decomposes each product into its constituent characteristics, and obtains estimates of the value of each characteristic.

A 'consumption technology' transforms commodities (or combinations of commodities) into characteristics (such as heat, transport, shelter, nutrition, etc.) that provide utility to the individual. Consumers either choose between commodities with a similar set of characteristics[62], or they choose between particular combinations of commodities that give specified bundles of characteristics[63]. Rather than comparing bundles of commodities, consumers compare bundles of characteristics. Preference orderings thus apply to bundles of characteristics only (i.e. preferences are defined over a set of characteristics and not over a set of commodities as in mainstream economics). One advantage of this approach is that utility is defined over *a limited set* of characteristics rather than a potentially very large number of commodities.

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[59] A modern washing machine can save some absolute amount of time in clothes washing, compared to the situation of doing the laundry by hand. The overall marginal costs of the energy service 'clothes washing' thus decreases (less time spent washing is less expenses on opportunity costs of time; or clothes washing at home becomes cheaper, ceteris paribus), leading to behavioural responses of the household (the so-called time rebound effect).

[60] The concept of "attributes" widely used in marketing and psychology are not assumed to be objective.

[61] Implying that utility can be measured (cardinalist approach)

[62] Many characteristics will be shared by more than one commodity. For example, fruit juice and mineral water share some common characteristics. If a consumer prefers fruit juice over mineral water to quench his thirst, it is because of its intrinsic properties on which a consumer differentiates between the two. These are called one-shot purchases, where the consumer chooses one product from a set of alternatives.

[63] Commodities in combination may possess characteristics different from those pertaining to the goods separately. For example, the utility a consumer derives from having coffee at a Barista in the company of his friends might be higher than the utility the consumer derives from drinking the same coffee at home, or from enjoying the company of his friends elsewhere. Alternatively, the joint consumption of two goods, like watching T.V. and listening to the radio at the same time, may lead to a decrease in utility.

Lancaster used his theory to explain particular cases of apparent ‘irrational’ behaviour (suboptimal consumer choice).

- Market demand sometimes shifts very suddenly rather than always gradually as marginal analysis indicates. Consumers may continue to buy a particular good with the desired combination of characteristics, even as the price of this good continues to increase, until at some point they switch entirely to another good with a better combination of characteristics and price [Dubas & Jonsson, 2005, p. 6-7];
- Inefficiencies in consumption may persist to a certain degree, even in a highly competitive market system, because consumers are not aware that certain commodities possess certain characteristics. The market mechanism does not eliminate these inefficient consumers [Lancaster, 1966a, p. 19].

Lancaster’s work has the merit of drawing attention to the economically significant quality dimensions of goods and services. But unlike Becker, Lancaster does not attribute utility to the ‘productive activities’ of households [Witt, 2005, p.18].

The relevance for our new (energy) consumption behaviour model, and in particular for explaining the energy efficiency gap, is as follows. Incomplete markets for energy efficiency exist in part because the energy efficiency of a good or service is typically ‘bundled’ with a host of other ‘attributes’ provided (e.g. style, appearance, varied functionalities). It is not the commodities as such that consumers are interested in, but rather their “perceived” attributes (including price and energy efficiency, but perhaps even more so comfort, social status, etc.) This perception is heavily influenced by the knowledge and attitudes of consumers. Those attributes are often not broken out for consumers. Moreover, features such as “higher energy efficiency” are rarely treated as separate commodity options and priced differentially. Consequently, consumers are unable to purchase a given commodity priced differentially on the basis of energy inputs, energy efficiency in operation, energy costs, greenhouse emissions, and so on [Press & Arnould, 2009, p. 106; Brown 2001, p. 1203].

4.3.4. Integrating household production in the (energy) consumption behaviour model

The Becker-Lancaster household production model provides a useful framework for understanding the demand for energy services, albeit with some substantial modifications.

A household produces useful outputs by combining energy, capital (durable goods) and other market goods or services, together with human capital (skills), some of the household’s own time, space and information[64]. Examples of such household activities are heating a room, driving a car, preparing a meal or cleaning clothes. The outputs of such household production processes are e.g. room temperature, kilometres driven, prepared meals or clean clothes. For example, for heating or mobility the household combines durable goods like a boiler or car, labour (e.g. maintenance) and energy (e.g. electricity, fuel oil or petrol). To conform to the energy economics literature, we might call these outputs of the household production processes the ”useful outputs of energy services”. But perhaps “own-produced household services” would be a better word[65]. Unlike the Becker-Lancaster

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[64] Space and information were not explicitly mentioned in Becker’s seminal paper.

[65] As mentioned previously, in his seminal paper Becker [1965] called the outputs of the household production function “more basic commodities”, Lancaster [1966] called them “characteristics”, and Shaw and Pirog [1997] combine the two into “commodity-characteristics”.

model, the outputs are real (physical) outputs. Purchased commodities are thus merely inputs into a real household production process, together with time and the skills of the consumer and (available) information.

In some instances, like e.g. mobility, the households might decide to directly purchase a "marketable energy service" straight from the market (e.g. public transport), rather than produce that service themselves (private transport).

The new model should include the trade-off households have to make between either buying household services straight from the market in exchange for less household time and more work time, or producing household services themselves in exchange for less "income". Time spent on producing useful outputs of (energy) services to satisfy a certain combination of wants, is time *not* spent on either other household production activities or external work (i.e. earning income / wealth). A more complete scheme has to include the (external) labour market. The inclusion of time allows the study of "time rebound effects" and the effects of introducing time-saving technology innovations, whether the latter are also energy-saving or not.

FIGURE X: choices and household production in the (new) energy consumption model

[use concrete example in figure]

From Muth, Becker and Lancaster we retain the idea of the "household production function" (HPF), although we prefer to dissect the conventional household production function into at least three different kinds of processes, hereby making a clear distinction between two types of mental processes (choice and satisfaction) and one physical type of process, the own production of 'useful outputs of energy services' (or household services in our terminology).

In the (cognitive) "choice processes" a household first decides to either buy the required (outputs of) services straight from the market or to produce them within the household (the "make or buy" decision). In the latter case, the household first "chooses" or selects what market commodities to buy, and then "utilizes" (some of) those commodities to produce the desired useful outputs of household / energy services[66]. From Lancaster we borrow the notion that it is certain 'characteristics' of both market commodities and of the useful outputs of household / energy services that households are interested in. Contrary to Lancaster, these 'characteristics' – which we prefer to call attributes – do not immediately affect the "utility" of a household. In a first stage, they enter the household "choice processes" as *information* inputs in determining what market commodities to purchase. Some attributes, like 'status value' of a purchased good, may then enter as inputs in (affective) "satisfaction processes" whose outputs directly contribute to the satisfaction of certain wants, e.g. 'social standing'. The chosen market commodities themselves may enter household production processes as (physical) "factor inputs", where they are transformed into "own-produced household services" or "useful outputs of energy services". The attributes of these useful outputs are inputs into the "satisfaction processes", whose outputs are required to satisfy (other or similar)

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[66] This is inspired by the two stage model of household consumption in marketing, where an explicit distinction is made between the "purchasing process" (acquisition of goods and services in the markets) and the "consuming process" (utilization of goods and services) [Shaw and Pirog, 1997, p. 19]. In this marketing model the outputs of purchasing are the "commodities purchased" and of consuming "psychological satisfactions" [id., ibid., p. 20]

wants or needs, such as shelter / thermal comfort, desire to travel, nutrition, clothing, health or entertainment / recreation. In this way, certain attributes of both (purchased) market commodities and (own-produced) useful outputs of energy services are sensory data used as inputs in satisfaction processes that transforms "bundles of attributes" into "satisfaction" of certain wants and needs of the household.

We prefer the concept "attributes", because unlike characteristics in the Lancaster scheme, they need not always be objectively measurable (the horsepower of a new car be exactly measurable, the symbolic value such as social status far less so), and because certain attributes (like price or energy efficiency) are in principle only needed as data in the selection and utilisation of commodities, but do not by themselves directly contribute to the satisfaction of wants. Although models incorporating the concept of attributes are fairly common in economics (hedonic price models) and especially in marketing (e.g. MAU models) [see annex X], their usefulness for the new consumption behaviour model remains limited, partly because they assume that attributes of commodities directly enter a "utility function".

4.4.Behavioural economics

The cognitive abilities of consumers are limited (or "bounded"). Consumers do not "optimize" their behaviour in the sense of neoclassical economics. From behavioural economics we accept that "satisficing" choice mechanisms and resulting choices may still be called "rational". As such we would describe the new (energy) consumer behaviour model as "positive" (descriptive) rather than "normative" (prescriptive).

4.4.1. Themes from behavioural economics

Three primary themes that emerge from behavioural economics and have been applied in the context of energy efficiency are bounded rationality, heuristic decision making and prospect theory [Gillingham et al., 2009, p. 16].

Bounded rationality

The term 'bounded rationality' most probably first appeared in print in 'Models of Man' [Simon 1957]. Simon developed what he termed a procedural model of rationality, based on the psychological process of reasoning. Simon was concerned only with finding a choice mechanism that would lead individuals to pursue a "satisficing" rather than an "optimizing" path, permitting them satisfaction at some specified level of all their needs [Simon, 1957, p. 270-271]. The fundamental characteristics of this mechanism include [Jones, 1999, p. 301]:

- The bounded cognitive abilities of the individual in processing information as well as the complexity of the environment in which he operates limit his ability to plan long behaviour sequences. Individuals are limited by the information they have, the cognitive constraints of their minds, and the finite amount of time they have to make decisions. As Wiseman [1991, pp 151-152] notes, people have incomplete knowledge of the past, partial information about the continuous present and only opinions rather than information about the future. Decision-makers are unable to perform any complex computations when making decisions because they have limited cognitive resources for handling such decisions. For example, Marschak [1968] found that people can generally only process between 8-10 bits of information per second with any accuracy;
- The tendency of the individual to set aspiration levels for each of the multiple goals he faces;

- The tendency of the individual to operate on goals sequentially rather than simultaneously because of the "bottleneck of short-term memory". For example, Miller [1956] found that people typically keep seven, plus or minus two, things in their mind at the same time;
- The decision-maker is a "satisficer", seeking a satisfactory solution rather than the optimal one. "*…rather than maximising utility, people often satisfice by accepting a solution that falls within an acceptable boundary – hence the term bounded rationality*" [Darroch & Jardine, 2010, p. 500]. An alternative satisfices if it meets aspirations along all attributes. If no such alternative is found, a search is undertaken for new alternatives [Simon, 1996, p. 30].

Bounded rationality thus suggests that in using heuristics to assist with their decision-making, consumers are rational[67], even though it may seem irrational by the normative standards of deductive economic theory [Gillingham et al., 2009, p. 16; Darroch & Jardine, 2010, p. 500].

It is difficult to empirically test bounded rationality in energy decision-making, because there is no single consensus model. Friedman [2002] finds that the empirical specification consistent with bounded rationality where consumers over-consume energy if the block structure of electricity rates is increasing and under-consume if it is decreasing, has more predictive power than one based on utility maximization.

Heuristic decision making

Heuristic decision-making encompasses a variety of decision strategies that differ in some critical way from conventional utility maximization in order to reduce the cognitive burden of decision-making [Gillingham et al., 2009, p. 16].

Katsikopoulos [2010] defines (psychological) heuristics are models for making inferences that (1) rely heavily on core human capacities (such as recognition, recall, or imitation), (2) do not necessarily use all available information and process the information they use by simple computations (such as lexicographic rules or aspiration levels), and (3) are easy to understand, apply, and explain [Id., ibid., p. 3]. In general, these problem-solving techniques are very fast, require relatively few data, and usually produce a good solution when information is scarce or uncertainty high, although they do not guarantee optimal solutions [Hofmann & Hahn, 2007, p. 22].

For example, in the theory of elimination-by-aspects [Tversky, 1972], consumers use a sequential decision-making process where they first narrow their full choice set to a smaller set by eliminating commodities that do not have some desired characteristic (e.g. cost above a certain level), and then they optimize among the smaller choice set.

Heuristic decision-making is likewise difficult to test empirically. Kempton and Montgomery [1982] find that for decisions regarding energy-efficient investments, consumers tend to use a simple payback measure, using the energy price at the time of savings and ignoring (likely) future increases

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[67] Following Simon, an economic agent is 'procedurally' rational if his/her decisions result from an appropriate process of deliberation, the duration and intensity of which are free to vary according to the perceived importance of the problem that presents itself; whereas an agent is 'substantively' rational if he/she has a clear criterion for success and is never satisfied with anything less than the best achievable outcome with respect to this criterion.

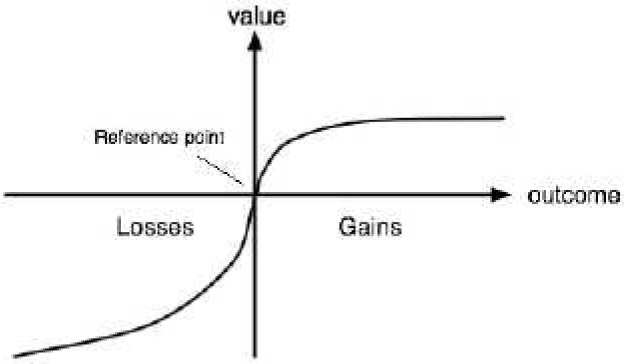
of energy prices[68]. Similarly, Kempton et al. [1992] find that consumers systematically miscalculate payback for air conditioner investments, leading to overconsumption of energy.

Prospect theory

Prospect theory [Kahneman & Tversky, 1979] treats the deliberation process as divided into two stages, editing and evaluation.

- Editing. The different choices are ordered following a variety of heuristics so that the evaluation phase is simpler;
- Evaluation. The evaluation of prospects starts from a reference point (usually the status quo). Prospects above this point are seen as gains, prospects below it as losses.

Figure: the S-shape of the value function in prospect theory



Source: Grüne-Yanoff [2008, p. 15]

The value function passing the reference point is 1) concave for gains and convex for losses, and 2) it is steeper below the reference point. The first property is interpreted as “diminishing sensitivity”, i.e. the psychological evaluation of an incremental increase of gain or loss will decrease as one moves further away from the reference point. The second property is interpreted as “loss aversion”[69], i.e. the value (welfare) change is much greater from a loss than from an expected gain of the same magnitude.

For example, in studying the consumer valuation of reliable electric service, Hartman et al. [1991] find that the status quo effect[70] posited in prospect theory is significant, suggesting that consumers are ‘irrationally’ reluctant to move from the status quo and are likely to accept more interruptions in electricity service.

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[68] ‘Excessive discounting’ means that we tend to underestimate the significance of future events, exaggerating the importance of the present. Interestingly, David Hume already wrote about the human tendency to favour the present over the future. Behavioural economics suggests that a simple hyperbolic time discounting function of $d(t) = \frac{1}{(1+kt)}$ tends to fit experimental data much better than exponential discounting [e.g., Laibson, Repetto and Tobacman, 1998].

[69] ‘Loss-aversion’ means that most of us value a loss much more than the equivalent gain. Disproportionate aversion to loss was already known to Adam Smith [1759/1892, p. 311].

[70] ‘Status quo bias’ means that most of the time, most of us would prefer to stay with the current situation (in other words, we rarely change pre-selected default settings).

4.4.2. Bounded rationality in the (energy) consumption behaviour model

The purchase of market commodities [whether or not for the production of useful outputs of (energy) services] are the result of certain "choices" made by the household. In this respect we accept that choices (in the marketplace), albeit not necessarily the (most) primitive element of consumer theory (as in the postwar neoclassical approach), are certainly one of the most directly observable ones.

Figure X: inputs of the (cognitive) choice process

Important inputs of the choice process are – next to a number of economic variables such as income and time – the "consumption skills" of the household. One could refer to these household skills as "human capital". Behavioural economics finds that those skills are limited, and that rationality is "bounded". In accepting "satisficing" rather than the strict "optimization" behaviour of neoclassical homo economicus, we consider the new model to be positive (descriptive) rather than normative (prescriptive).

The skills of consumers are limited. For a quantitative description of these skills, we refer to behavioural economics literature. Depending on the situation (e.g. buying an expensive durable such as a television versus routine purchases of food), the techniques employed may vary, from "habits" and "simple heuristic rules" to more complicated consumption strategies. Alternative decision processes, other than "optimization", are continuously being explored in the branch of "behavioural economics".

From marketing we uphold the idea that "perceived" rather than actual attributes matter. Inadequate skills may be the root cause why consumers are unable to correctly value the objective attributes of the useful outputs of energy services or of market commodities The new model should thus allow making a distinction between inadequate information as both a market failure and / or a behavioural failure.

The new model should also allow simulating how skills and resulting choices evolve as internal and external factors are altered. For example, households can improve their (consumption) skills over time as a result of "self-learning". Or, skills may change as a result of energy or climate change policies (e.g. "energy education").

4.5. The "wants" of consumers (motivation)

Sociologists of technology argue that consumer expectations are malleable with technological possibilities and that behavioural adjustments as a result of technological progress have long-term effects in the form of upward shifts in collective expectations as well as habits. Neo-classical economists see consumer behaviour as rational responses to changes in relative (implicit or explicit) prices and income.

Neither of them examines consumer "motivations" to explain what behavioural responses will follow from technological progress, given the "wants" appealed to by an energy service whose energy efficiency has improved [Lorentz & Woersdorfer, 2009, p. 29].

Theorizing about the consumers' wants has a long tradition in economics [Menger, 1871; Marshall, 1890; Georgescu-Roegen, 1954]. Menger [1871] already submitted that there is a demand for commodities because people have wants, and they have learnt that their wants can be satisfied by (consuming) these commodities. In their efforts to develop an evolutionary behavioural alternative to the neoclassical theory of consumer behaviour, a number of economists [Nelson and Consoli, 2010] [Witt, 2005; 2001] [Pasinetti, 1993] [Ironmonger, 1972] have found it extremely useful to work with the idea that individuals and households have a set of distinguishable wants that they aim to satisfy through the purchase and use of certain goods and services.

4.5.1. Innate or universal wants (or "needs") versus acquired or culturally-specific wants

It is important to distinguish between truly universal wants and culturally-specific wants [Diener & Lucas, 2000, p. 45-46].

Some wants are fairly basic and linked to biological needs (e.g. adequate nutrition), which must be met at least to a certain degree, before other wants can begin to be attended. Because of their genetic determination it is assumed that these wants are universally shared (with the usual genetic variance) and beyond the control of free will. These wants are sometimes called (physical) "needs". For example, the physical need of maintaining body temperature requires the consumption of goods (food of a certain quality, clothing), but in some circumstances also of (energy) services (room heat supplied by a heating system)[71]. Even in so-called primitive societies the range of wants goes far beyond physiological needs (breathing, water, food, sex, sleep, etc.). Other examples of innate or genetically determined albeit more sophisticated wants are the longing for safety, affection, social recognition (status) and self-realisation.

Witt [2001, p. 28-29] makes a distinction between (relatively limited) *innate wants* and (numerous) learned or *acquired wants*. Idiosyncratic acquired wants emerge from a few innate wants through (non-cognitive) associative learning over a lifetime. For example, regular joint consumption of food in company of particular people in especially aesthetically arranged settings, satisfies the innate wants of nutrition and social interaction, but may after a while lead to the emergence of an acquired want, namely enjoying aesthetically arranged settings, even if no longer accompanied by eating and social activity. Examples of acquired wants are wants for money, power, public attention, etc. "*Because acquired wants are often conditioned on several innate wants which are rarely all satiated at the same time, the intensity of acquired wants can be relatively high over a long period of time*" [Witt, 2001, p. 29].

4.5.2. Hierarchy of wants

Attempts are sometimes made to define a hierarchical order in which people strive to satisfy wants[72] [e.g. Maslow, 1954 or Ironmonger, 1972].

Georgescu-Roegen [1954a] introduced the "principle of the subordination of wants", implying that if another want always appears after the next lower has been satiated, an individual's total consumption will never be satiated.

Like Georgescu-Roegen, Ironmonger [1972, p. 23] acknowledges a multiplicity of wants which are assumed to be so ordered that at a given income and prices the consumer will satiate as many wants

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[71] Wants may be satisfied by the direct consumption of a good (e.g. a raw vegetable) or indirectly through the useful output of an energy service (cooked meal).

[72] A hierarchy of wants or needs can be described by lexicographic preferences.

as possible, going down the order of priority from most important toward the least[73]. But unlike Georgescu-Roegen he presumes that the number of units of satisfaction of all these different wants can be merged to give a homogenous utility measure. Thus, the (technical) 'characteristics' of commodities generate, when consumed, a certain number of units of satisfaction of a want[74]. It is the latter that enter the utility function and not the characteristics as in Lancaster [Witt, 2005, p. 24].

In principle, the subjective importance of priority which the different wants have for the consumers can be expressed by weights, which can be normalized so that they always sum up to one [Witt, 2005, p. 24-25].

4.5.3. Links between wants and commodities

The motives for consumption rest upon the individual perception of the instrumental relationship between commodities and wants.

In general, a want may be satisfied by a combination of commodities (e.g. thermal comfort by means of clothing, room heating[75], etc.); whereas one commodity may be able to serve several wants at the same time (e.g. a car may satisfy the need for mobility but also social recognition; or clean clothes satisfy the need for hygiene but also the need to conform to the normative expectation of absence of body odour).

Georgescu-Roegen [1954a] explicitly attributes indifference curves to wants. This means that each want corresponds to exactly one source of utility. Utility can be achieved by actions involving a set of alternative commodities, and each commodity in turn may be involved in satisfying yet other wants. The hierarchical order of wants is a central argument in Georgescu-Roegen's interpretation. The commodity 'water' may be used to satisfy the wants of drinking, cooking, washing, laundering and gardening, in that order of importance.

Households engage in various 'activities' that contribute to the satisfaction of a not yet satiated want. An activity may result in the simultaneous satisfaction of more or less complex combinations of innate wants [Witt, 2001, p. 29]. The effective employment of such activities requires (subjective[76]) knowledge (e.g. the nutritional value of food) and skill (household competences, e.g. cooking). Broad (consumption) knowledge may exist in culture and be acquired by communicating with, observing and imitating other consumers; but non-trivial knowledge and skill are also strongly conditioned and acquired by personal experience and inventiveness. People reflect and learn about how to instrumentalize the inputs (commodities) for the satisfaction of their wants (cognitive learning). Witt [2001] ties cognitive learning to non-cognitive learning and to influences of collective behaviour. Cognitive learning is also shaped by the "agenda-setting effect". The wants households attend and the means of satisfying those wants, not only vary greatly across households within a given society (variations in particular experiences or circumstances), but also across societies (variations in socio-

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[73] These priority patterns help explain why only so much of a particular brand is desired per unit time.

[74] The household production function transforms the characteristics of commodities to 'units of satisfaction of wants', and not commodities to 'characteristics'.

[75] Room heating in turn is the useful output of an energy service, requiring a combination of several goods and services, such as a heating system, energy carriers, periodic maintenance, etc.

[76] For example, advertising tries to enhance consumer knowledge about available commodities and the not yet sufficiently satisfied wants they are supposed to serve. In this context there is an important distinction between the objective "characteristics" of a good and the "attributes" as perceived by the consumer, and how the latter changes in response to advertising.

cultural surroundings)[77]. The (consumption) knowledge within intensely communicating groups tends to develop in much the same direction and may give rise to sub-cultural commonalities in consumption patterns [Witt, 2001, p. 30].

Nelson and Consoli [2010] state that a household can roughly assess whether particular wants are being met and even judge with some consistency whether a particular want is being met better or less well in one situation as compared with another. But, "*once basic levels of want satisfaction are met, households can have difficulty in judging whether they are better or worse off when one want is met better and another less well than in an earlier situation, and their evaluations of this can be inconsistent*" [Nelson and Consoli, 2010, p. 670].

A systematic analysis of wants and the relations between them and between commodities is still lacking, and this analysis would undoubtedly be enormously complex.

4.5.4. The role of wants in the new (energy) consumption behaviour model

The conjecture is that a household has a set of particular "wants", and that the goods and services that it purchases are intended for use in meeting those wants. Also, for at least a number of "wants" consumers may reach a local satiation level (or "local bliss point" – see §X). We thus reject the neoclassical assumption of "more is always better".

We accept from psychology that 'personal motives' do matter, hereby returning to the early (classical) economic theories where "utility" is a measure or indicator of "happiness", "subjective well-being" or "life satisfaction", rather than just a convenient mathematical representation of revealed ordinal preferences. Hofstetter and Madjar (2003) see happiness as the affective (emotional) aspect and life satisfaction as the cognitive (realization) aspect, whereas subjective well-being combines both aspects. Quality of life combines subjective parts (well-being) with objective parts (measurement of explicit standards like wealth) [id., ibid. p. 15].

Starting point is "quality of life" rather than "utility". Each household tries to "satisfice" rather than "optimize" its quality of life. That is, each household tries to attain at least a certain standard of living. The desired quality of life is determined by the extent certain "wants" (both basic and more sophisticated needs, or innate and acquired wants) are satisfied. Both the desired levels of these wants as their share (or "weight") in total quality of life (mix of wants) are important. Quality of life can thus be seen as a kind of weighted sum of wants (we leave the exact functional form open at this moment). This is very different from the postwar neoclassical approach, where a utility function is merely a mathematical representation of some ordinal revealed preferences. Quality of life is an objective reality, and perhaps even to a certain extent measurable. For modelling purposes, we have little alternative than to assume that we can attach some value (point or interval) to this quality of life of a household (a return to the "cardinalist" approach).

In terms of the new (energy) consumer behaviour model, the attributes associated with useful outputs of energy services and with market commodities are only means to an end, and serve as inputs themselves to satisfy the wants of consumers. Concerning the satisfaction of wants, one has to distinguish between the "desired" levels, and the "actual" levels. To arrive at the desired levels of wants, the household has to produce certain "household services", or in energy economics

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[77] For example, food demand is dictated not only by nutritional requirements, but also by tastes that vary across countries and time.

terminology, useful outputs of energy services, like room temperature, kg of clean clothes, passenger-km driven, etc. Obviously, one useful output can partly satisfy more than one want, whereas one want may partly be satisfied by several useful outputs of household / energy services. In other words, there is not a one-to-one relationship between useful outputs of (household / energy) services" and "wants". Again we leave the exact functional connections betweens useful outputs and wants open for the time being.

FIGURE X

The desired "level" of a want is a very important element in the new consumption behaviour model, because it leaves open the possibility to incorporate "satiation levels" or local bliss points. This is particularly important in the analysis of rebound effects. Once the desired amount of thermal comfort is achieved, an increase in real income does not imply that households will start "overheating" their home by turning the thermostat higher an higher (although the possibility of wasting heat is a real one and cannot be dismissed beforehand). Of course, the additional real income can and will be used to satisfy other, unmet wants. Equally relevant is that these "satiation levels" may be amenable to outside influences, in particular from the socio-cultural framework (opening a perspective for modelling transition paths of society to more sustainable lifestyles).

The desired levels of wants are determined by the "mental states" of the households. Those elements would consist of cognitive and affective elements, and of motives (although terminology in psychological sciences frequently includes words such as attitudes, beliefs, etc.) Although there exists a vast literature on the psychology of (energy) consumption, or rather energy conservation behaviour, for modelling purposes this literature does not appear very useful. Fortunately, for quantification purposes there are some useful results from marketing sciences and the application of agent-based models (e.g. the CUBES model). At the moment, the exact specification of these psychological elements that comprise the (consumption) "psychology" of a household remains tenuous.

4.6.Modelling social interactions

Households are very heterogeneous. They possess many different 'characteristics', including the conventional differences in income levels and socio-demographic characteristics (family size, age, gender, education level of household members, etc), but also differences in their "mental functions" (e.g. cognitive abilities like "skills" or "knowledge", affective states like "attitudes", or conative elements like motives or striving) We thus reject the idea of "average economic man" or "the representative consumer".

Consumers continuously interact with other consumers and with their environment in general, as a result of which their behaviour may change over time. The evolution of both "wants" and "choice mechanisms" is not only the result of innate (genetic) processes, but also of strong interactions with the environment and other economic agents in particular. Moreover, indicators of "quality of life" (e.g. health, safety / security, environmental quality, leisure time / work, social relations, privacy, freedom, etc.) may be valued differently in different cultures (e.g. individualistic versus collectivistic societies). From sociology (of technology) we accept the importance of the social-cultural framework ("institutional constraints"), together with the constraints imposed by the technical-economic framework (already implicit in the concept of feasible consumption set in neoclassical economics) and market barriers concerning information.

4.6.1. Agent-based simulation (ABS)

The main competitor of the mainstream perspective on consumer behaviour is evolutionary economics [agent-based models of consumer purchase decisions]. Agent-based models (ABM) of consumer behaviour integrate economic, marketing, psychology, sociology, engineering and computer sciences [Piana, 2004]. For this reason we will focus on ABM.

Agent-based simulation (ABS) is a relatively new bottom-up technique to model complex systems[78] composed of interacting, autonomous 'agents'. Agent-based models (ABM) can be used "*…to model social systems that are composed of agents who interact with and influence each other, learn from their experiences, and adapt their behaviours so they are better suited to their environment*" [Macal & North, 2010, p. 151].

A more detailed description of ABM is given in appendix X.

Agent-based models have been developed in the field of economics, creating a new field called Agent-based Computational Economics (ACE). ACE is the computational study of economic processes modelled as dynamic systems of interacting agents [Tesfatsion, 2005, p. 6]. Agent-based models allow relaxing the standard assumptions of economic theory, such as economic agents are rational, economic agents are homogeneous, preferences show diminishing marginal rate of substitution, etc. (see chapter X).

So far, few evolutionary-economic models have introduced 'environmental' preferences in the utility functions of consumers, or have specified energy as an input in production [Safarzynska, 2011, p. 3].

4.6.2. Examples of the use of ABM for analyzing rebound effects

de Haan et al. [2009] use an agent-based micro-simulation model of consumer choice of new cars to assess the potential occurrence of rebound effects, including potential direct rebound effects (more vehicles being purchased, increase in average car size, more kilometres being driven) but excluding indirect rebound effects (increased consumption of other goods or services).

Lorentz and Woersdorfer [2009] are among the first to use an agent-based model (ABM) to study the rebound effects, in particular in relation to the demand for washing machines. They abandon the neo-classical concepts of non-satiation, optimization and perfect information, and integrate the concept of consumer 'wants' into the body of literature on rebound effects. They conceptually capture needs as individually or socially determined "standards", where standards represent the consumption level the consumer believes to be necessary for achieving need-satisfaction [Lorentz & Woersdorfer, 2009, p. 22] The behaviour of consumers is "bounded rational", relying on preferences resembling "lexicographical preferences". Households are modelled as heterogeneous agents. Their choices or "actions" include both purchases and utilization of washing machines. Those actions are driven by social standards of cleanliness and budget constraints. As social standards evolve, and energy efficiency of washing machines (exogenously) improves, consumption patterns change, in turn changing (decreasing) not only energy prices but also (increasing) social standards of cleanliness. They study the rebound effect by comparing potential energy savings, given technological progress, and actual energy savings. However, at this stage their work is still very preliminary. For example, their model does not yet include an individual "hygienic standard". Also, the only attributes or

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[78] A system is defined to be complex if it is composed of interacting unit and exhibits emergent properties, i.e. properties arising from the interactions of the units that are not properties of the individual units themselves.

characteristics of washing machines considered are “price” and “energy efficiency”. Time constraints are not taken into account.

To study the rebound (backfire) effect at the economy-wide level, Safarzynska [2011] propose an evolutionary-economic model, where technological change results from interactions on three markets: heterogeneous power plants, final products, and boundedly rational consumers. Consumers’ preferences are interdependent and change over time as a result of a “snob effect” (i.e. a desire for distinction through special status commodities) and a “network effect” (i.e. imitation of others within their social networks). The analysis aims to provide insights to the role of technological change, supply-demand co-evolution, and status-driven consumption in explaining the rebound effect.

4.6.1. The (energy) consumption behaviour model and ABM

The economic agent under consideration is the household. Households are motivated by trying to reach a certain satisfaction level for their “quality of life”. The notion of “quality of life” and the desired levels and weights of “wants” required to reach a particular level of quality of life not only differ significantly across households within one society, but also across societies. Moreover, this notion evolves over time. So, the idea of what constitutes quality of life does not only depend on the personal characteristics of a household, but also on the interaction of that household with other economic agents in society. This would – in theory – allow the introduction of policies that aim at transforming society to a more sustainable one, by means of “convincing” consumers to adhere to “greener values” than they do at present. In other words, even if an improvement in energy efficiency leads to an increase in real income, environmentally-aware consumers may decide to re-spend the extra money on activities that are far less energy-intensive than they would have done otherwise (e.g. not spending the money on holidays abroad but on bicycles instead to go cycling with the family).

In a truly agent-based model, one would have thousands or even millions of such households (each different from each other), who would continuously influence each other. It would also be necessary to explicitly model other agents, such as social and cultural actors or institutions, producers, etc, each with their own ‘goals’ and ‘behavioural rules’. All this is beyond the scope of this research, but important to get a correct assessment of the size and direction of the rebound effect.

4.7.Outline of a new model – putting it all together

4.7.1. Simulating (energy) rebound effects with the new model

Whether households will buy (and use) a more energy efficient durable is the result of a complex choice process, involving income and time constraints, available information on the attributes of the new durable, the consumption skills of the household (human capital), and the way the household “judges” that purchasing this particular good will contribute positively to the satisfaction of its quality of life, weighed against all possible other actions the household can take (e.g. spending the money on other market commodities). This judgement depends heavily on the perceived discrepancy between desired and actual satisfaction of certain wants. Purchasing and consuming a good is supposed to add to the actual satisfaction of a weighted combination of wants, whereas the actual satisfaction of those wants may also depend on the consumption of (many) other commodities. The desired satisfaction in turn depends on personal characteristics of the household, including socio-demographic variables and psychological ‘states of mind’. The latter can and will also be influenced by the environment in which the household operates, in particular the socio-cultural framework. This institutional framework includes social networks (interactions with family, friends, colleagues, …), social norms, etc. This is important, because it means that society cannot only influence consumer behaviour through market and regulatory instruments (prices, taxes, subsidies, technological standards, etc.) but also through soft policy instruments like sensitisation campaigns, 'education', etc.

A new conceptual model should allow simulating the conventional micro-economic approach of analyzing the rebound effect at the level of households. Even if the more energy efficient durable is more expensive (higher capital costs) than similar goods, the household – using its consumption skills and the available information on the attributes of the good – may still judge it worthwhile to buy that durable, because using that good will either allow the increased satisfaction of a particular want (e.g. thermal comfort) without having to sacrifice the satisfaction of other wants ("direct" rebound effect), or it will allow maintaining the same satisfaction level of that particular want, and free additional real income which may be used to pursue the increased satisfaction of other wants through purchasing other market commodities ("indirect" rebound effect, a.k.a. "re-spending effect").

It would also allow simulating the time rebound effect. Purchasing a time-saving device permits a household to dedicate the saved time to other activities, which it "believes" will increase its overall level of quality of life. Whether this will lead to an net increase in the energy consumption of the household not only depends on the energy efficiency of the time saving device (less, equal or more than similar non-time saving devices), but also on the "energy intensity" of the other activities the households decides to engage in.

4.7.1. Dynamics of the (energy) consumption behaviour model

There are a number of dynamical aspects to this proposed model. The main driver is the attempt to equalize the desired and actual levels of wants with the final goal of reaching a satisfactory quality of life. Changes in consumer behaviour over time are mainly due to changes in a large number of variables, both inside and outside the realm of the household.

The budget and time constraints

Important inputs of the choice process are a number of economic variables, the main ones being income and time. They are important because they internally[79] "constrain" the set of choices. As in mainstream economic theory, income (along with market prices) determines the budget set, i.e. the set of "affordable" (feasible) bundles of market commodities. Limited income may be a semi-*permanent* source of discrepancy between desired and actual satisfaction of wants (i.e. the steady state is never reached). That would help explain why an increase in real income would almost automatically lead to an increase in consumption levels. Another significant internal economic factor input in the choice process is (household) time. With the introduction of both income and time constraints we stay well within the neoclassical paradigm of consumption behaviour, although we refer to constrained "satisficing" rather than constrained optimization.

Equalizing actual and desired levels of wants

The choice and household production processes are driven by the fact that certain levels a of desired wants are not met. This discrepancy is the main internal *dynamic* element of the new household

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[79] As opposed to external constraints such as available infrastructure and technologies.

(energy) consumption behaviour model. From the moment onward that the household reaches a steady state regime, where all the actual levels equal the desired levels, consumption levels of market goods and services would stay the same for each individual household. However, both actual levels and desired levels, as well as the "weights" attached to the desired levels, may change over time, as a result of changes in internal and external factors.

Changes in consumer behaviour

Internal factors (i.e. specific to the household) that drive changes in consumption behaviour are the conventional economic (net disposable income) and socio-demographic variables such as household size[80], and age, gender, education level, etc. of the household's constituent members. Changes are thus induced by household members ageing, being born, going to school, leaving home, finding or loosing a job, etc.

External factors include socio-cultural influences, technological-economic constraints, and the environment at large.

There are important connections between the external and internal framework. Changes in some internal factors are partly due to changes in external factors, the main one being how socio-cultural elements may influence certain "psychological" elements of households, hereby affecting desired levels and weights of wants and perhaps even "consumption" skills. Other external-internal connections include market imperfections (inadequate information corrupting the choice mechanism). Quantifiable information on the connections between external socio-cultural elements and internal psychological elements remains very scarce in literature. So far, only a few agent-based models (ABM) have studied such relationships.

Innovation, in particular the energy efficiency improvement of a durable good, constitutes an important change in the technological-economic framework.

Finally, the "environment" (weather, nature, …) is an important external factor that may influence the 'household choice process' (e.g. lower outside temperatures may require setting the thermostat higher to produce more inside useful heat).

4.7.2. Future work

At the moment, this "new" model is little more than a concept. The energy rebound effect is an emergent phenomenon. It is the result of very complex processes, not only within households themselves but especially between households and all other agents in society. The proper way to study this phenomenon would probably be the use of an agent-based model (ABM). Time and resources in this project were far too limited to construct a full-fledged ABM. Further research is needed.

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[80] Strictly speaking, a household can consist of more than one member, and the psychology of a household would thus be the result of a complex interaction between the psychologies of its individual members. Modelling these interactions is beyond the present scope of our research.

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6. Annex 1: Rational choice theory – preference based approach

A (commodity) bundle x is a vector $x = (x_1, x_2, \dots, x_m) \in X$ that specifies the quantities of the different commodities. The consumption (possibility ~~/ feasible~~) set $X \subset \mathbb{R}_+^m$ is the set of (realistic or reasonable) commodity bundles that the individual can conceivably consume given the *physical and institutional constraints* imposed by the environment. Properties of X include *non-negativity*; it is a *closed set* and *convexity*. Time and space (location) are included in the definition of a commodity. Commodities consumed at different times and locations are viewed as different commodities, although in practice, economic models involve some aggregation over time and location.

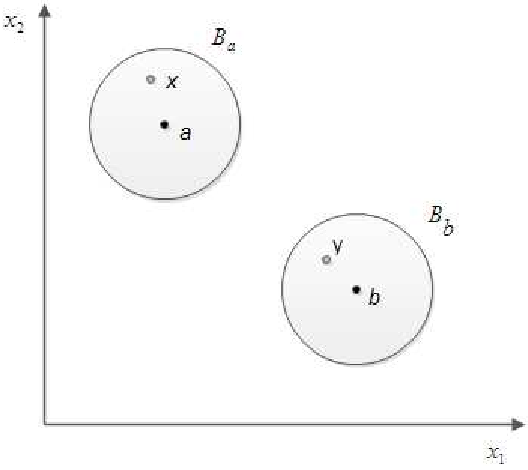
In essence, consumer preferences are a *ranking* of the different commodity bundles. A (weak) preference relation $\succsim$ is a binary relation on X which compares couples $x, y \in X$. $x \succsim y$ reads "x is preferred over or equivalent to y", or "x is at least as good as y".

A preference relation $\succsim$ defined on a consumption possibility set X is termed 'rational' if it satisfies the axioms of completeness ($\forall x, y \in X\colon x \succsim y \vee y \succsim x$) and transitivity ($\forall x, y \in X\colon x \succsim y \wedge y \succsim z \Rightarrow x \succsim z$). Completeness means that the consumer can rank all the commodity bundles in the consumption set. Transitivity imposes a minimal sense of consistency. The complete transitive binary relation that models an economic agent's preferences is sometimes called 'weak order', 'complete pre-ordering', 'complete weak order', 'complete ordering' or simply 'preference relation'. The indifference (preference) relation $\sim$ is defined as $x \sim y \Leftrightarrow (x \succsim y) \wedge (y \succsim x)$, and this binary relation in addition has to satisfy reflexivity ($\forall x \in X\colon x \sim x$).

The axioms of choice may also include (strong) monotonicity or local non-satiation. Strong monotonicity means that for any bundle the consumer would rather have a bundle with at least as much of all commodities and strictly more of at least one commodity, or $\forall x, y \in X\colon (x \geq y) \wedge (x \neq y) \Rightarrow x \succ y$, where the strict (strong) preference relation $\succ$ is defined as $x \succ y \Leftrightarrow x \succsim y \wedge y \not\succsim x$. Strong monotonicity is also called the "more is better" assumption. The weaker assumption of local non-satiation is defined as $\forall x \in X, \forall \epsilon > 0, \exists y \in X\colon (\|y - x\| < \varepsilon) \wedge (y \succ x)$, where $\|y - x\| = \sqrt{\sum_{i=1}^{m} (x_i - y_i)^2}$ denotes the Euclidean distance between x and y in vector space. Local non-satiation implies that for every bundle x there is always another bundle y "nearby" that the consumer strictly prefers to x, and this is true no matter how small you make the definition of "nearby". Local non-satiation rules out "thick" preferences.

Another important concept is (strict) convexity. A preference relation $\succsim$ is strictly convex, if and only if $\forall x, y, z \in X, x \neq y, x \succsim z \wedge y \succsim z \Rightarrow \forall \lambda \in \,]0,1[, \lambda x + (1 - \lambda) y \succ z$. The intuition behind the convexity assumption is that consumers prefer balanced consumption bundles to unbalanced consumption bundles.

Figure : Continuity of preferences



Finally, a preference relation $\succsim$ on X is continuous if whenever $a \succ b$, there are balls (neighbourhoods in the relevant topology) B_a and B_b around a and b, respectively, such that $\forall x, y: x \in B_a \land y \in B_b, x \succ y$. Continuity is primarily a mathematical assumption. It is sometimes justified by the intuition that "sudden preference reversals" do not happen.

The consumer's utility function summarizes and represents the preferences of a consumer in an ordinal fashion. A utility function is a mapping $u: X \longrightarrow \mathbb{R}$ that assigns a number ('utility') $u(x_1, x_2, \ldots, x_m)$ to any given set of values for $x = (x_1, x_2, \ldots, x_m)$. A utility function represents a preference relation if $\forall x, y \in X: x \succsim y \Leftrightarrow u(x) \geq u(y)$. It is simply a convenient device for summarizing exactly the same information about consumer preferences as the preference relation does, no more and no less.

If (weak) preferences are rational and continuous, then there exists a continuous utility function that represents them (Utility Representation Theorem, Debreu []). This theorem is lengthy and very hard to prove. Adding the strongly monotonic assumption on the preference relation makes it easier to prove that a rational consumer with continuous preferences makes choices according to a continuous utility function (the 'Easier' Representation Theorem, Jehle & Reny []). Again, strict monotonicity is not required to prove the Debreu theorem. Continuous functions are much more tractable analytically than binary relations.

The properties of a large number of specific function forms for $u(x)$ have been considered. One of the most commonly used utility functions is the Cobb-Douglas function $u(x_1, x_2) = A{x_1}^{\alpha}{x_2}^{\beta}$, where α and β are both between 0 and 1. Another popular utility function is the constant elasticity of substitution (CES) function $u(x_1, x_2) = [\alpha{x_1}^{\rho} + \beta{x_2}^{\rho}]^{1/\rho}$.

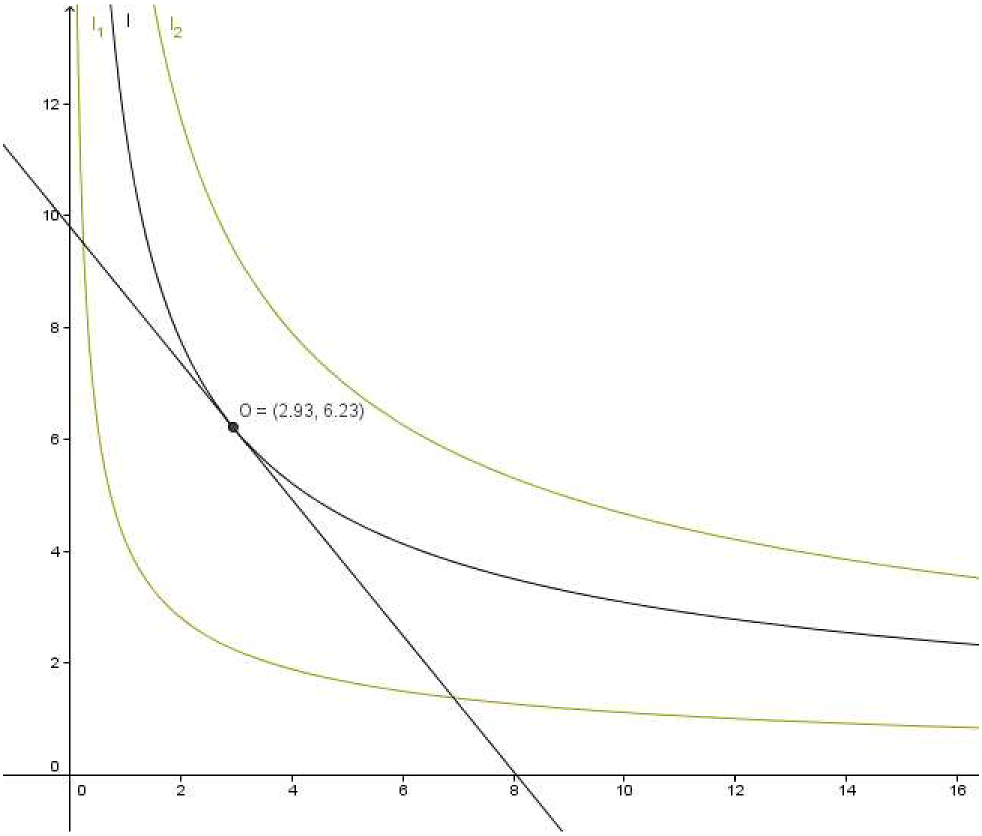
The (Walrasian) budget set is the set of (reasonable) bundles the consumer can afford given his or her wealth and the prices of the various commodities. Formally, $\mathcal{B}(p, m) = \{x | p \cdot x \leq m, x \in X\}$ where p is the vector of prices and m the level of income. The term 'Walrasian' is appended to remind us that there are no limits on the amount of a commodity that a consumer can buy (rationing) or that the price of a commodity does not depend on how much the consumer buys (this is the standard 'price taking' assumption made in models of competitive markets) [Miller, 2006, p. 7].

A consumer maximizes utility, i.e. chooses the preferred alternative among available alternatives in the presence of constraints. A typical constraint in a simple one-period consumer choice problem is the budget constraint (a consumer cannot spend more than his or her income). This translates the consumer's problem into a mathematical exercise in constrained optimization, or $\max_{\{x\}} u(x)$ subject to $x \in \mathcal{B}(p, m)$. The solution to the constrained optimization problem generally leads to a decision rule. The decision rule shows how utility-maximizing choices vary with changes in circumstances such as changes in income or in the prices of commodities [Green, 2002, p. 8].

An indifference curve is a locus of commodity bundles that represent equal levels of utility or satisfaction. An indifference curve is an equivalence class for the indifference relation: $I(\bar{x}) = \{x \in X : x \backsim \bar{x}\}$. The axioms of choice ensure that each bundle is part of an indifference curve (completeness) and that two indifference curves cannot cross (transitivity). Strict monotonicity implies downward sloping indifference curves.

The consumer can afford all combinations on the budget line and the (shaded) region below it. Strictly speaking, the budget constraint is linear only if prices per unit of commodity are constant over all possible demand levels.

Figure X: Optimisation in case of a Cobb-Douglas utility function



In the case of two commodities x_1 and x_2, and given rational, monotonous and continuous preferences, the consumer's problem is reduced to $\max_{x_1, x_2} u(x_1, x_2)$ subject to $p_1 x_1 + p_2 x_2 = m$, where p_1, p_2 are the commodities' prices (or implicit prices in case of energy services) and m is the household's income. The budget line can be rewritten as $y = \frac{m}{p_2} - \frac{p_1}{p_2} x$, with slope $-\frac{p_1}{p_2}$. If the prices change, the slope of the budget line also changes. Setting up the Lagrangian $\mathcal{L} = u(x_1, x_2) -$

$\lambda(p_1x_1 + p_2x_2 - m)$ and taking partial derivatives on the $\mathcal{L}$ function to obtain the first order conditions, we obtain the tangency condition for the optimum, $\frac{\frac{\partial u}{\partial x_1}}{\frac{\partial u}{\partial x_2}} = \frac{p_1}{p_2}$ with $\frac{\frac{\partial u}{\partial x_1}}{\frac{\partial u}{\partial x_2}} = -\frac{dx_2}{dx_1}\Big|_{U=constant}$. When the marginal rate of substitution $MRS = -\frac{dx_2}{dx_1}\Big|_{U=constant}$ is strictly decreasing, the tangency condition is a sufficient (but not necessary) condition for the optimal choice.

7. Annex 2: Aggregate demand and the representative consumer

The aggregate demand stated as a function of aggregate income implies that aggregate demand has to be invariant to any redistribution of income that sums to the same level. This condition holds at any price p if the income effect is the same whatever consumer we look at and whatever his or her level of income. Special cases in which this is true is when all consumers have identical and homothetic preferences, or when all consumers have (not necessarily identical) preferences that are quasi-linear with respect to the same commodity [Felli, 2006].

Homothetic preferences can be represented by a utility function $u(x)$ such that $u(\alpha x) = \alpha u(x)$ for all x and $\propto > 0$. A famous homothetic utility function is the Cobb-Douglas utility function.

Quasi-linear preferences can be represented by utility functions that take the form $u(\mathbf{x}) = x_1 + f(x_2, \dots, x_m)$. The function f is usually a concave function such as $\ln$.

In general, the preferences of all consumers must admit indirect utility functions of the "Gorman Polar Form". Gorman [1953, 1961] proved that a sufficient and necessary condition for writing aggregate demand as a function of prices and aggregate income is that preferences admit indirect utility functions of the form $v^h(p, m^h) = \frac{m^h - f^h(p)}{g(p)}$, with $g(p)$ is common to all households h. An *indirect* utility function gives the consumer's maximal utility as a function of prices and income. Formally, $v(p,m) = \max_x\{u(x){:}\, m - \sum_i p_i x_i \geq 0 \text{ and } x \geq 0\}$. A consumer's indirect utility can be computed from his or her utility function by first computing the most preferred bundle by solving the utility maximization problem; and second, computing the utility the consumer derives from that bundle. The advantage of using an indirect utility function in explaining consumer behaviour is that prices are *exogenous*. If utility functions take the Gorman form, which many don't, aggregate demand can be thought of as being generated by a single "representative consumer".

More flexible functional forms for demand analysis have been developed in recent years, although they do not correct the aggregation problem. These demand systems replace the requirement that aggregate demand behaves like the sum of individual demands by the weaker assumption that the demand system generates the observed budget (or expenditure) shares [Honohan & Neary, 2003, p. 199]. Muellbauer [1975, 1976] extended the Gorman polar form to a non-linear function of income. Gorman [1981] extended this further to a complete system that is a finite sum of functions of (nominal) income, each multiplied by a vector of price functions. These so-called "Gorman systems" can represent most existing empirical models of consumer behaviour, including Rotterdam model, linear and quadratic expenditure systems, exactly aggregable translog demand system, almost ideal demand system (AIDS) and quadratic AIDS or QUAIDS, etc. Lewbel [1990] identifies three classes of so-called full rank[81] Gorman systems. For rank one demand systems, budget shares are the same for all income levels m. For rank two, budget shares are linear in $\ln(m)$. And for rank three, budget shares are quadratic in $\ln(m)$. Rank three systems (e.g. QUAIDS) are of particular interest, because

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[81] The rank of a Gorman system is the maximum number of linearly independent vectors of price functions. The rank describes the 'flexibility' of a rational demand system. A Gorman system has full rank if the rank of the matrix of price functions equals the number of unique income functions.

they produce non-linear budget shares on income[82]. LaFrance and Pope [2006] extend the set of full rank nominal and deflated income demand systems to rational demand systems of any rank and present a unifying expression for the indirect preferences of all full rank models.

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[82] The indirect utility for a rank three system is $v(p,m) = \left[\left(\frac{\ln(m) - ln(\theta_1(p))}{\theta_2(p)}\right)^{-1} - \theta_3(p)\right]^{-1}$, with price function $\theta_1$is homogeneous of degree one in p and θ_2 and θ_3 are homogeneous of degree zero in p.

8. Annex 3: Household production function applied to energy services

Along the lines of Becker's household production model, it is assumed that individual households produce useful outputs of energy services (S), by combining capital (K), some of the households own time (T), energy (E) and other commodities (O). The production function for (the useful output of) a specific energy service S_i may be written as:

$$S_i = f\left(K_{i,}, T_i, E_i, O_i\right)$$

If one assumes that the household's utility solely depends on the useful outputs of those energy services, the utility function becomes:

$$U = u(S_1, S_2, S_3, \dots, S_m)$$

The household is assumed to be subject to two constraints, an income (or budget) constraint and a constraint on available time.

$$V + P_W T_W \geq \sum_{i=1}^{m} (\delta_K K_i + P_E E_i + P_O O_i)$$

$$T = T_W + \sum_{i=1}^{m} T_i$$

Where:

- V represents non-wage income
- P_W represents average wage rate
- T_W represents the time spent in the labour market
- δ_K represents the discount factor so that $\delta_K K_i$ represents annualized capital costs
- P_E and P_O represent the unit price of energy and other goods respectively
- T represents the households own time
- T_i represents time spent in producing energy service S_i

Both constraints can be combined into a single "full income" constraint:

$$V + P_W T \geq \sum_{i=1}^{m} (\delta_K K_i + P_W T_i + P_E E_i + P_O O_i)$$

The concept of energy efficiency is perfectly in line with Becker's idea of household production function, according to which households are not interested in the amount of energy required for a certain amount of service, but in the energy service itself. The energy cost per unit output of energy service, given by the ratio of energy costs to useful output of energy service, is smaller the higher the energy efficiency is (with unit price of energy remaining constant).

$$C_E = \frac{P_E E}{S} = P_E \frac{E}{S} = \frac{P_E}{\eta}$$

9. Annex 3: MAU and hedonic models

Consumption models that can be traced back to the pioneering work of Lancaster (e.g. the hedonic consumption model in economics or conjoint analysis in marketing) often use an *additive* utility model at the attribute level[83]. A consumer's overall judgment of a product is decomposed into utilities for each characteristic. In essence, these models assume that there is a separate market for each attribute [Dubas & Jonsson, 2005, p. 7].

9.1. Multi-attribute utility (MAU) models in marketing

The first step in multi-attribute utility (MAU) studies involves identification of the attributes relevant to the consumer, e.g. through the use of personal interviews or focus groups. The attributes evaluated are often *subjective* in nature, such as style or comfort.

In conjoint analysis [Luce and Tukey, 1964] goods or services are defined on a limited number of relevant attributes (typically, fewer than eight), each with a limited number of levels (generally, two to four)[84]. These commodities, called (product) *profiles*, have to be evaluated[85] by respondents.

In the additive (linear) compensatory preference model[86] it is assumed that the utility a consumer attaches to profile j is given by

$$U_j = \sum_{i=1}^{m} w_i s_{ij}$$

Where U_j is the utility of profile j, s_{ij} the evaluative (affective) rating of characteristic i of profile j and w_i is referred to as the weight assigned to attribute i. The attribute weight reflects the relative importance of attribute i to the consumer's preference formation. The contribution of an attribute to the total utility, namely $w_i c_{ij}$, is called the "part-worth utility" or simply "part-worth". Total utility is the sum of the "part-worths".[87] The relative magnitudes of the attribute weights reveal the tradeoffs the consumer makes among the attributes when assessing commodity utilities [Multi attribute utility models, p. 395]. These attribute weights have to be estimated. Average weights pertaining to a 'representative' consumer do not reflect the heterogeneity of consumer tastes very well. Individual-level analysis on the other hand allows grouping the population into segments [Nelson, x, p. x].

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[83] Assuming that the strength of preference for the values of one attribute can be expressed *independently* of the values of others, the utility function can be written as a sum of single-attribute sub-utility functions, or $u(\boldsymbol{c}) = \sum_{i=1}^{m} u_i(c_i) = \sum_{i=1}^{m} \lambda_i v_i(c_i)$, where λ_i are scaling constants (or 'trade-off weights') and v_i local value functions.

[84] For example, attributes of a car may include selling price, style, ease of handling and riding comfort, with levels varying from below average, average to above average.

[85] Evaluations are done either by rating or ranking or by discrete choice (i.e., buy or non-buy) decisions.

[86] Non-linear, non-compensatory models proposed by social-psychologists include the 'conjunctive' model and the 'disjunctive' model. The conjunctive model assumes the individual judges the product on its minimum performance on all characteristics. The individual dismisses from consideration any product having any attribute level below its cut-off. The disjunctive model assumes the individual judges the product on its best characteristic regardless of the other attributes. It is possible to represent these models as multi-attribute utility functions if extremely non-linear functions are allowed.

[87] The decompositional nature of conjoint analysis clearly rests on traditional concepts of what constitutes rational decision making. Homo economicus carefully considers all pieces of information and integrates them into (expected) utility, following a complex (attribute) weighting scheme [Dickman et al., 2009, p. x].

9.2.Hedonic models

In hedonic models [e.g., Rosen, 1974] each consumer is characterized by a utility function that depends on the attributes characterizing the product, as well as on some individual characteristics. Consumer heterogeneity is an important feature of hedonic models. Two consumers participating in the same hedonic market but with different characteristics (e.g. different income level) will generally choose different bundles of characteristics and will obtain different levels of utility. It is also assumed that the list of product attributes is *complete* and *known to the consumer*.[88] The hedonic model further assumes that there is a continuous function relating the price of a product to its attributes (the hedonic price function). This hedonic price function describes the equilibrium relationship between the economically relevant attributes of a product (or bundle of products) and its price[89] [Nesheim, 2008].

In the general hedonic demand model, given a price function for the attributes, each consumer demands the vector of attributes that maximizes his or her utility.

$$max\{u[\boldsymbol{x}, \boldsymbol{z}, p(\boldsymbol{z})]\}$$

Where

- $\boldsymbol{x}$ is a vector of consumer characteristics (such as income, education, age ,sex or preference parameters) that affect utility;
- $\boldsymbol{z}$ is a vector of product characteristics. This bundle is obtained either by buying a single product that embodies these characteristics, or by buying a combination of products that together produce the bundle of characteristics;
- $p(\boldsymbol{z})$ is the hedonic price function or hedonic cost. The theory of hedonic prices places no restrictions on the hedonic price functional form.

The solution is the hedonic demand function for this particular consumer.

Hedonic models make various assumptions about whether the space of feasible characteristics is discrete or is a continuum, and whether the characteristics embodied in different products can be bundled or unbundled [Nesheim, 2008].

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[88] There may be other characteristics that affect ex post utility but that are not known to the consumer.

[89] For example, in a housing economics model, the hedonic house price might describe how the price of a house depends on geographic location, age of the dwelling, size, and quality.

10. Annex 4: Agent-based modelling (ABM)

A typical agent-based model has three elements:

- A set of agents;
- A set of agent relationships;
- The environment.

Zhang and Zhang [2007, p. 921] set out the necessary steps for conducting ABM research:

1. Set the simulation scope and define the agents;
2. Design the algorithms to control the agents' behaviours, actions and interactions;
3. Calibrate algorithms and models;
4. Program and run the model;
5. Test, validate and optimize the model;
6. Observe and analyze the results.

The most difficult step is designing the algorithms based on the agents' counterparts in the real world, as their behaviour, actions and interactions may be very complex.

10.1. Agents

An (intelligent) agent is a highly abstract concept, and there is no universal agreement in the literature on the precise definition of an agent, except that an agent is any entity that has the essential property of *autonomous behaviour*. Agents make independent decisions and initiate actions to achieve their internal goals [Macal & North, 2010]. The actions (e.g. consumption) of the agents (e.g. households) can be assigned a value (e.g. 'utility'), so that the agents behave in such ways as to improve this value over time [Fonseca & Zeidan, 2004].

Essential and / or useful characteristics of agents include:

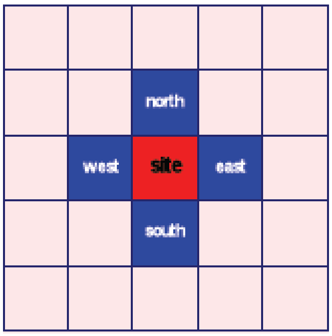
1) having attributes that allow the agents to be distinguished from and recognized by other agents (agents are *self-contained*);
2) being able to function independently in its interactions with other agents and with its environment (agents are *autonomous*);
3) having a *state* (a set or subset of its attributes) that varies over time;
4) having interactions with other agents that influence their behaviour (agents are *social*);
5) having rules or more abstract mechanisms that modify their behaviour (agents may be *adaptive*);
6) having objectives to maximize or satisfice (agents may be *goal-directed*);
7) showing a full range of diversity across a population (agents may be *heterogeneous*) [Macal & North, 2010, p. 153].

Everything associated with an agent is either an agent *attribute* or an agent *method* that operates on the agent. Attributes may be static (e.g. the agent's name) or dynamic (e.g. the agent's memory of past interactions). Methods include behaviours (e.g. simple rules or routines that update dynamic attributes), behaviours that modify behaviours, etc. Agent-based models of consumer behaviour may begin with a normative model in which agents attempt to optimize utility, as a starting point for developing a simpler, more descriptive, but realistic heuristic model of behaviour [Macal & North, 2010, p. 154].

10.2. Interacting agents

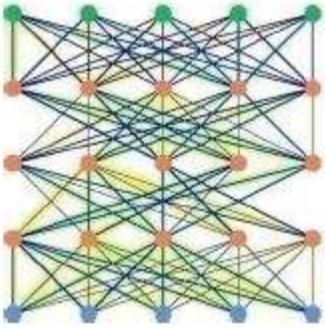
Two primary issues of modelling agent relationships and interactions are specifying who is, or could be, connected to who; and the mechanisms of the dynamics of the interactions.

Figure: topologies commonly used to connect agents

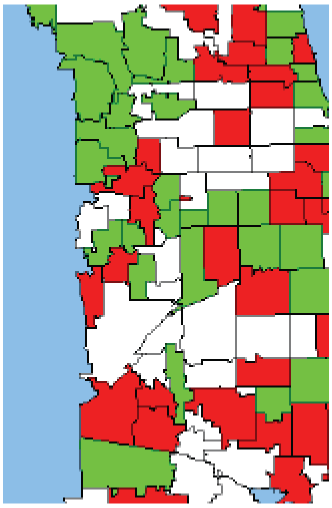


cellular automata

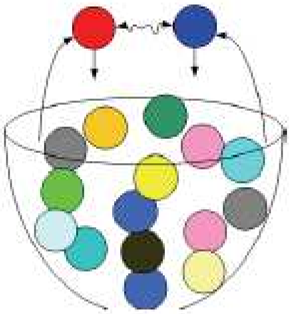
Euclidean space



network



GIS



Aspatial or “soup” model

Source: Macal [2010]

A topology or connectedness describes how agents are connected to each other. Topologies include:

a) *cellular automata*: agents move from cell to cell in a grid, no more than a single agent occupies a cell at one time, the agent state is either ‘on’ or ‘off’ at any time, and each agent interacts with a fixed set of neighbouring agents/cells;
b) *Euclidean space* models: agents roam in two or higher dimensional spaces;
c) *networks* of nodes (agents) and links (relationships);

d) geographic information systems: agents move from patch to patch over a realistic geo-spatial landscape;
e) aspatial or ‘soup’ models: agents are randomly selected for interaction and then return to the ‘soup’ [Macal & North, 2010, p. 155].

One of the tenets of ABS is that only *local information* is available to an agent, obtained from an agent’s *neighbours* (not any agent or all agents) and from its localized environment (not from any part of the entire environment). There is no central authority than sends out globally available information or that controls the behaviour of the agents to optimize system performance.

10.2.1. Agent’s environment

Agents interact with their environment. The environment may be used to simply provide information on the spatial location of an agent relative to other agents, to track agents as they move across a landscape, or to constrain their actions within complex environments. For example, in an agent-based energy system the environment would include the required energy infrastructure.