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Reaction of Household Energy Demand to Improvements in Energy Efficiency: What about the Rebound Effect?

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Abstract

Energy efficiency improvements have become a major hope for decoupling the energy demand from economic growth and for achieving environmental goals. Nevertheless, the effectiveness of policies based on promoting energy efficiency may be undermined by behavioral responses. A more efficiently produced energy service becomes cheaper and economic theory then suggests that consumers should demand more of it, which will cause a loss of the potential technological saving. The phenomenon is called the rebound effect and it has become a focus of energy economists since early 80s. However, even today there is no clear consensus on its importance. Quantification of the rebound effect is mainly hampered by poor data availability and the comparison of results is not straightforward due to methodological differences. Our thesis concentrates right on the economic theory of the demand for energy services, definitions and methodology of its estimation. It provides a comprehensive overview of what was done in the domain and suggests which methodological approaches correspond the most to the economic theory.

Key terms: Rebound effect, Energy efficiency, Energy demand

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Abstrakt

Zvyšování energetické účinnosti se stalo jednou z hlavních nadějí na snižování poptávky po energii a na dosažení ekologických cílů. Efektivita politik založených na propagaci energetické účinnosti však může být podkopána změnou chování ekonomických subjektů. Efektivněji vyráběná energetická služba (například vytápění domácnosti) se totiž stává levnější a ekonomická teorie pak říká, že spotřebitelé by této služby měli spotřebovávat více, čímž se sníží potenciální úspory z lepší účinnosti. Tento jev je nazýván „rebound“ efekt a od počátku osmdesátých let se dostal do hledáčku mnoha energetických ekonomů. Ani dnes však neexistuje shoda na jeho významnosti. Kvantifikace „rebound“ efektu naráží zvláště na špatnou dostupnost dat a porovnání empirických výsledků je ztíženo metodologickou rozmanitostí jednotlivých studií. Tato práce se soustředí právě na teorii poptávky po energetických službách, definice a metodologii jejího odhadování. Poskytuje komplexní přehled studií v dané oblasti a nastiňuje, které metodologické postupy nejlépe odpovídají ekonomické teorii.

Klíčová slova: Rebound efekt, energetická účinnost, poptávka po energii

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Declaration of Authorship

Hereby I declare that this thesis was written on my own, using only the listed resources and literature.

Prague, May 20, 2010

Signature

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CONTENTS

1 INTRODUCTION

More energy efficient consumption and production has become the major hope for decoupling the energy demand from economic growth and achieving environmental goals. Especially since the late 70s governments have engaged in setting energy efficiency regulation and promoting use of less energy intensive appliances. In 1980 Daniel Khazzoom reacted to a wave of U.S. mandatory efficiency standards and pointed out, that predicted saving is not realistic if derived mechanically. Meaning that demand for energy is predicted to drop by 1 percent when the appliance efficiency rises by 1 percent. Instead, also household behavioral response has to be taken into account because it can partially or even completely subvert the potential energy saving. Indeed, a more energy efficient appliance will produce the same amount of service with lower energy cost and therefore the service becomes cheaper. Economic theory then suggests that consumption of the service should increase, causing certain loss of the potential saving. The phenomenon was called "take back" or "rebound effect" and its importance has become widely discussed among energy economists.

Even though the rebound effect was first defined on microeconomic (household) level, its application has widened to comprise also producers behavior and more aggregated, economy-wide levels. Khazzoom (1987, 1989) and Brookes (1990, 2000) argued that attempts to reduce energy consumption by raising energy efficiency at the micro level results in an increased aggregate energy demand across the economy. Their argumentation follows from what is known as Jevons paradox[1] - technological progress that increases the efficiency with which a resource is used, tends to increase (rather than decrease) the rate of consumption of that resource. In 1992 economist Harry Saunders depicted two ways, which lead to Jevons paradox: energy efficiency gains make the energy appear effectively cheaper than other inputs and increase economic growth, which pulls up energy use. Saunders named this effect Khazzoom-Brookes postulate, in literature also called backfire (Brookes, 2000). Opposed to these economists, for example energy physicist Armory B. Lovins in 1988 or Lee Schipper and M. J. Grubb in 2000 maintained that rebound effect is so small that it can be neglected. Their opinions are grounded in the household behavior and based on

[1] William Stanley Jevons in his 1865 book The Coal Question holds that "it is a confusion of ideas to suppose that the economical use of fuel is equivalent to diminished consumption. The very contrary is the truth". (Cited in Brookes, 2000)

arguments that the demand for energy services seems to be inelastic and the energy forms only a small fraction of the total costs of energy services (Sorrel and Dimitropoulos, 2007). Lovins' argumentation was also based on an assumption that there is a critical level of income beyond which energy-intensive activities become inferior good, however no empirical evidence is presented that would suggest that the majority of households in developed countries already surpassed the level (Binswanger, 2001). To the contrary, Binswanger suggests that with rising income preferences may shift to more time-efficient activities, which use to be also more energy intensive. The debate on purely microeconomic level is less polarized; nevertheless it is very heterogeneous in definitions, models and estimation techniques applied. The original concept of household behavior by Khazzoom was very simplistic, based on a single service model with exogenously given energy efficiency change and energy cost as the only cost of an energy service. Therefore, the main development of the empirical literature is towards more complex and realistic models of consumer choice, unfortunately often restricted by limited data availability. Theoretically, accounting for capital costs of more efficient appliances, for time and other costs generated by higher consumption, and also for possible endogeneity of energy efficiency to the model of household energy demand, the rebound effect importance diminishes.

Our motivation for examining the issue of rebound effect was among other driven by a policy concern. The household energy consumption constitutes around 25% of the total energy consumption of the Czech Republic[2] and similarly in other European countries, therefore any attempts to reduce countries' energetic dependence and the negative impacts of fuel combustion must be focused also on households. Given the efforts of the European Union to decrease energy consumption, demonstrated for example by the 2006 Action Plan for increased energy efficiency, an evaluation and quantification of a possible rebound effect is essential. If its negligibility is proved, the current way of energy efficiency promotion can lead to success. If otherwise, policies based on price mechanisms such as higher energy taxes, or promotion of clean and secure energy would turn out to be a superior policy for mitigating negative consequences of rising energy demand.

Since methodological differences between studying the rebound effect at the microeconomic and aggregate levels are substantial, our thesis is confined to the core underlying microeconomic behavior of household energy demand driven by the price and income

[2] http://www.czso.cz/csu/tz.nsf/i/energo_2004

factors. We study mechanisms and empirical evidence for what will be called the *direct* rebound effect, e.g. the effect on consumption of the same energy service whose appliance efficiency improved. The reason is that this is where practically all the previous research has been undertaken, notably due to the possibility of direct estimation through econometric analysis of secondary data without involvement of general equilibrium adjustments. We try to present a comprehensive theoretical framework for estimation of the demand for energy services based on the neoclassical consumer choice theory, with a special emphasis on the complexities of household decision-making. A careful attention is given to the construction of empirical models that follow the theoretical lines and to methodological differences among existing empirical studies.

The organization of the thesis is following. In the first, theoretical, section we define the main terms used throughout the paper; we start with the theoretical analysis of the demand for energy services based on Becker's household production model then we continue with the classification of the rebound effects. In the following chapter, different definitions of the direct rebound effect are derived, starting from the most general up to its decomposing to price and income factors. Finally, we discuss implications of relaxing some assumptions used to derive the main definitions, ranging from modification of the definitions to alternative, structural, models of the demand for energy services. The second section proceeds to empirical issues. First part is devoted to clarification of some basic notions and recapitulation of estimation methods. Afterwards, we provide an overview of the existing empirical literature and its results, with a stress on the demand for personal automotive transport. As empirical works differ in the rebound effect definitions, they are similarly heterogeneous in methodological approaches; our work was therefore considerably facilitated by already existing meta analyses of the rebound effect literature, notably Sorrel and Dimitropoulos (2007), Sorrel and Dimitropoulos (2008), Greening et al. (2000) and Berkhout (2000). Final chapter concentrates on possible data sources in the Czech Republic.

Theoretical Part

2 THE DEMAND FOR ENERGY SERVICES

In order to study the demand for energy we have to focus on the demand for energy services. Indeed, consumers do not demand energy commodity per se, but they want to consume services that are produced with an energy input. Energy demand is therefore derived from the demand for energy services and capital equipment that provides them.

Energy service (ES) is delivered by a combination of energy commodities and the associated energy systems that include energy conversion devices. As an example, mobility is an energy service provided by combination of gasoline and a car; other examples of energy services are residential heating, refrigeration or lighting.

- Essential feature of an energy service is **useful work (S)** (Sorrel and Dimitropoulos, 2008), which can be measured by a variety of physical or thermodynamic indicators.
  For example, useful work in residential heating can be defined as either changes in the thermostat set point or thermal comfort (which is determined by attitudes toward thermal comfort, individual activity levels, mean radiant temperature, air draft and humidity). Useful work obtained from passenger car(s) is mostly defined as vehicle kilometers, which can be decomposed as a product of the number (NO) and utilization (UTIL), where the latter is defined as the mean driving distance per car per year. Another definition could stand as passenger kilometers, where the decomposition would be into $NO * UTIL * LF$, where LF is the average number of passengers in a car.

- A unit of useful work is produced by a combination of different inputs such as **energy (E)**, **capital (K)**, **other market goods and services (O)** needed for operation and maintenance of the capital, and **time (T)**. As illustration, clothes washing is an example of energy service, which requires electricity (E), a washing machine (K), washing powder (O), and our time to load and unload the washing machine (T), even though the latter is probably negligible.

- Energy service has **quality attributes (A)** such as size, comfort, reliability or speed to be combined with useful work to provide the full energy service:

$$ES = es(S, A) \quad (1)$$

- **Energy efficiency**[3] **(ε)** of an energy system refers to its cost effectiveness of the use of fuel or electricity. An increase in energy efficiency means either raising engineering efficiency of conversion devices (less energy is needed to produce the same amount of useful heat or work) or increasing the effectiveness of the associated energy service (e.g. higher standards of house insulation). The definition of energy efficiency employed widely in the economic literature (e.g. Sorrel and Dimitropoulos, 2008; Frondel, et al., 2008) reads

$$\varepsilon \stackrel{\text{def}}{=} \frac{S}{E} > 0. \tag{2}$$

The definition reflects that for a given amount of useful work less energy is required when energy efficiency increases and it can be for example vehicle kilometers traveled per litre. If we denote **the unit price of energy P_E, the energy cost of useful work (P_s)** defined as $P_S \stackrel{\text{def}}{=} \frac{E \cdot P_E}{S}$, can be expressed as

$$P_S = P_E/\varepsilon. \tag{3}$$

- Total cost of an energy service is the sum of the **energy cost (P_S), annualized capital cost (P_K), operation & maintenance cost (P_O)** and **time cost (w)**

$$P_{total} = P_S + P_K + P_O + w\,. \tag{4}$$

The proportion will clearly differ for different energy services. It is likely that in the case of personal automotive transport higher consumption requires also larger time and maintenance inputs besides gasoline. On the contrary, for residential heating the energy will be the major cost (at least when electricity or gas is the energy input).

In order to model the demand for energy services we will depart from a general framework of Becker's household production model (Becker, 1965), where a household produces energy services by combining energy, capital, time and other market goods. For example, mobility is produced by combination of gasoline, a private car, driving time and maintenance expenditure. Likewise, cooking requires electricity, electric cooker, cooking time and ingredients.

[3] We follow definition typically used in the economic literature, also called „economic" energy efficiency (Brookes, 2000).

The analysis will be done in the neoclassical framework with following underlying hypotheses:

1) Rationality – the consumer has transitive, reflexive, complete and insatiable preferences and maximizes his utility
2) Certainty and complete information (e.g. awareness of all items on the monthly bill)
3) Adjustment costs of moving to optimum are negligible

Useful work (S) for a particular energy service can be described as the output of an exogenously given *production function*, which represents the current available technology (for example the energy efficiency). The production function for an entire energy service reads

$$ES_i = es[s(E_i,K_i,T_i,O_i);A_i], \tag{5}$$

where E_i is an energy input, K_i is capital equipment, T_i is time spent on producing the energy service i and O_i are other goods needed for the production. Since provision of quality attributes A_i stems from the qualities of capital K_i, the production function can be simplified to

$$ES_i = es(E_i,K_i,T_i,O_i). \tag{6}$$

If it is assumed that household utility is derived only from these services, utility function becomes

$U = u(ES_1, ES_2, ..., ES_n)$, which is an increasing and concave function for each ES_i :
$\frac{\partial U}{\partial ES_i} > 0$ and $\frac{\partial^2 U}{\partial ES_i^2} < 0$, for i = 1,...,n.

The household's budget is limited by its non-wage income (V) and wage income given by wage rate (w) and time spent on working (T_w). The budget constraint is then defined as

$$V + wT_w \geq \sum_{i=1}^{n}(P_E E_i + P_K K_i + P_o O_i), \tag{7}$$

where P_E and P_O represent the unit price of energy and other market goods respectively. P_K represents the annualized capital cost of an energy service.
Since a household's total available time to be spent on producing energy services is given by the constraint $T_{total} = T_w + \sum_{i=1}^{n} T_i$, we can substitute T_w into the budget constraint and rearrange to get

$$B \stackrel{\text{def}}{=} V + wT_{total} \geq \sum_{i=1}^{n}(P_E E_i + P_K K_i + P_o O_i + wT_i). \tag{8}$$

Then the utility maximization subject to the budget constraint corresponds to the maximization of Lagrangian L,

$$L \stackrel{\text{def}}{=} u(ES_1, ES_2, \dots, ES_n) - \lambda[\sum_{i=1}^{n}(P_E E_i + P_K K_i + P_o O_i + wT_i) - B]. \qquad (9)$$

If we rule out the possibility of a joint production function, the first order condition with respect to the energy service j reads

$$\frac{\partial U}{\partial ES_j} = \lambda\left(P_E \frac{\partial E_j}{\partial ES_j} + P_K \frac{\partial K_j}{\partial ES_j} + P_o \frac{\partial O_j}{\partial ES_j} + w \frac{\partial T_j}{\partial ES_j}\right). \qquad (10)$$

The first order condition (10) then implies a trade-off between inputs into the production of useful work and therefore between different types of an energy service that require different proportions of the inputs.

Another implication of the first order condition is that for a given budget, the provision of better quality attributes (A_i) is likely to reduce the amount of useful work (S_i) because less money would be available for inputs into its production[4]. This would imply a trade-off between consumption of S and A of an energy service. Nevertheless, better A is likely to raise the utility from consuming the energy service, which other things equal would lead to its higher consumption and thus higher consumption of S. Influence of the provision of quality attributes on the demand for useful work is therefore ambiguous.

Even though the neoclassical assumptions on consumer behavior are arguably strict, this model is advantageous for energy studies because it recognizes that utility is derived from consumption of energy services and not directly from energy commodities. What is more, as it assigns to households also the role of producers, time is recognized as an important input, which can offer a useful insight into the determinants of energy-related behavior as suggested by Binswanger (2001) and also discussed further in Chapter 4.

In the same manner as the energy demand is derived from the demand for the energy service associated with it, the demand for appliance equipment is derived. The demand for appliance equipment therefore stems from the demand for energy service. On the other hand, as we suggested above, the utility from consuming an energy service is also affected by its quality attributes and therefore by qualities of the capital. To address the mutual

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[4] The assumption is that capital equipment which provides better A of the energy service has higher annualized cost.

relationship Dubin and McFadden suggested a model, which will be described and discussed in Chapter 4.4.

3 CLASSIFICATION OF THE REBOUND EFFECT

Consider a situation where the energy efficiency improves, consumption and costs of other inputs remain unchanged, as well as consumption of quality attributes of the energy service. Then if consumption of useful work doesn't change, demand for energy would decline proportionally to the change in energy efficiency (let's call it potential energy saving). However, the efficiency improvement will lower the energy cost and hence also the total cost of useful work. Assuming that the energy service is a normal good, consumers will demand more useful work and the potential savings will be partly offset. **The percentage of the potential saving lost due to the change in the energy service consumption is then called the direct rebound effect**. At the beginning, the term "rebound effect" was applied only to this phenomenon. Afterwards, it was widened to comprise also secondary effects on consumption of other goods and services through higher real income and effects on the supply side which, summed up with the direct effect, provided a base for general equilibrium or economy-wide effects.

As to clarify the discussion, the rebound effect is classified into three categories according to the system boundary and mechanisms at work (Sorrel and Dimitropoulos, 2007; Greening, et al., 2000).

- **Direct/pure price effect:** The increase in demand for an energy service, whose price diminishes due to improved efficiency. For example, when a car engine becomes more fuel-efficient, the price of a kilometre driven decreases and according to economic theory, other factors constant, the driver should drive more in response. The mechanism will encompass both substitution and income effect, similarly to the price reduction of any commodity. The energy demand associated with the given energy service is then subject to two competing forces: the improvement in efficiency drives it down but increase in the demand for the energy service pulls it up again. The direct rebound effect can be thus derived from price elasticities of the demand for useful work and estimated by quasi-experimental studies and econometric studies of secondary data. Similar mechanism would be in work for the direct rebound in production.

- **Indirect/secondary effects** – An indirect effect of the lower price of more efficiently produced energy service is, ceteris paribus, the rise in real income, which can be spent on other commodities than the particular energy service. To the extent that the other goods or services are also energy intensive, the demand for energy rises. Other form of indirect effects stems from so called embodied energy consumption (Sorrel and Dimitropoulos, 2008): an initial investment into equipment may be needed to attain the higher energy efficiency and production and installation of the equipment will itself be energy intensive to some extent (house insulation can be an example). Estimation of indirect effects already requires analysis of cross-price and income elasticities of the whole consumer basket and therefore input-output models or Almost Ideal Demand Systems (AIDS) are applied.

- **Economy wide effects/price and quantity readjustments** – Aggregate changes to total energy consumption influence composite price of energy services as changes in energy demand will translate into changes in energy prices. General equilibrium mechanisms are therefore involved as innovations (such as higher energy efficiency) increase potential income of the economy. These aggregate effects can be then estimated by Computable General Equilibrium (CGE) models.

- Transformational effects – Greening et al. (2000) identify another, the most general rebound effect. In long term, changes in technology may change consumers' preferences, alter social institutions or rearrange the organization of production, e.g. fuel efficiency and human activity. Nevertheless, they admit that there are many other technological advances that altered the allocation of time and they are difficult to identify and qualify. That is why this conception of the rebound effect is neglected in the literature.

The direct rebound effect is also distinguished <u>with respect to time horizon</u>. It may be expected that importance of the rebound effect increases over time as behaviour, markets and technology adjusts. Even though the terms "short-run" and "long-run" rebound effect are used in the literature, we didn´t find any common exact definition. Generally the short-run rebound effect refers to a change in utilisation of a given stock of appliances (e.g. driving more kilometres) while the long-run rebound effect comprises also a change of the appliance stock (e.g. buying more and/or larger cars).

4 THE DIRECT REBOUND EFFECT

In what follows, we provide an analysis of mechanisms and measurements of the direct rebound effect (RE), where we elaborate on the model of demand for energy services described in Chapter 2. As we shall see, definitions of the direct rebound effect vary in the literature. The variation, however, doesn't stem from different theoretical approaches, it is more a result of data (in)availability.

4.1 The Direct Measure

Let's denote S_1 the consumption of useful work before an efficiency improvement and $\mathbf{S_2}$ the consumption of useful work after the efficiency improvement. Let's denote $\mathbf{E(S_1)}$ the energy use corresponding to consumption of useful work S_1 and $\mathbf{E(S_1)^*}$ the energy use corresponding to the same amount when efficiency improvement is introduced. Then we assume that $\mathbf{E(S_1)} > \mathbf{E(S_1)^*}$ and $E(S_X) > E(S_Y)$ when $S_X > S_Y$ for any S_X and S_Y. Furthermore, let's define **POT** as the potential energy saving from increased energy efficiency and **ACT** as the actual percentage saving in energy consumption.

Then generally, the direct rebound effect (RE) is defined as the difference between the potential and actual savings to the potential savings (Berkhout, et al., 2000)

$$RE = \frac{POT - ACT}{POT} \cdot 100\%, \tag{11}$$

where $POT = \frac{E(S_1) - E(S_1)^*}{E(S_1)} \cdot 100\%$ and $ACT = \frac{E(S_1) - E(S_2)^*}{E(S_1)} \cdot 100\%$ and therefore

$$\mathbf{RE} = \frac{E(S_2)^* - E(S_1)^*}{E(S_1) - E(S_1)^*} \cdot 100\% \tag{12}$$

The choice of the consumption S_2, will depend on the responsiveness of the demand for useful work to changes in the energy efficiency, holding other factors constant. In other words, the direct rebound effect will be determined by the ***efficiency elasticity of the demand for useful work***, which is commonly taken as its direct measure (Berkhout, et al., 2000)

Definition 1 $\eta_\varepsilon(S) = \frac{\partial S}{\partial \varepsilon} \cdot \frac{\varepsilon}{S}$

Let's define the ***efficiency elasticity of the demand for energy*** $\eta_\varepsilon(E) = \frac{\partial E}{\partial \varepsilon} \cdot \frac{\varepsilon}{E}$. Then the impact of the direct rebound effect on the energy demand can be seen from the following relationship.

By plugging ε = S/E into the latter and taking partial derivatives we obtain

$$\eta_\varepsilon(E) = \frac{\partial E}{\partial \varepsilon} \cdot \frac{\varepsilon}{E} = \frac{\partial\left(\frac{S}{\varepsilon}\right)}{\partial \varepsilon} \cdot \frac{\varepsilon}{\left(\frac{S}{\varepsilon}\right)} = \left(\frac{\partial S}{\partial \varepsilon} \cdot \frac{1}{\varepsilon} - \frac{S}{\varepsilon^2}\right)\frac{\varepsilon^2}{S} = \frac{\partial S}{\partial \varepsilon} \cdot \frac{\varepsilon}{E} - 1 = \eta_\varepsilon(E). \qquad (13)$$

Relationship 1 $\eta_\varepsilon(E) = \eta_\varepsilon(S) - 1$

Only when $\eta_\varepsilon(E)$ is equal zero will the actual savings be equal to engineering predictions. If the demand for useful work is inelastic ($0<\eta_\varepsilon(S)<1$) energy efficiency improvements will reduce the demand for energy even though not as much as predicted by engineering estimates. Theoretically, there could be a case of an elastic demand for useful work which would imply higher energy demand after the efficiency improvement, a backfire.

Useful work (S) may be decomposed in the way that the efficiency improvement may lead to more energy conversion devices (NO), higher average size (CAP), average utilization (UTIL) and/or average load factor (LF). Then Definition 1 takes the form of:

$$\eta_\varepsilon(E) = \eta_\varepsilon(NO) + \eta_\varepsilon(CAP) + \eta_\varepsilon(UTIL) + \eta_\varepsilon(LF) - 1 \qquad (14)$$

Relative importance of these variables will depend on the particular energy service. For example, when passenger cars become more oil efficient consumers may buy more cars, buy larger cars, drive them further or share them less. If we look at refrigerators, average utilization and load factor are unlikely to change, on the other hand people may increase the stock of refrigerators and/or buy larger ones. By decomposing the demand for energy we can therefore detect different channels of the rebound effect, which can be otherwise overlooked.

4.2 Indirect Measures

When data provide little or no variation in energy efficiency, alternative indirect measures are employed. However, they correspond to the direct measure only under certain assumptions.

4.2.1 The own-price elasticity of demand for useful work

(A1) The only impact of an energy efficiency change on the demand for useful work is through the change in the energy cost of useful work (P_S). Then the relationship $P_s = P_E/\varepsilon$ implies symmetry between the reaction to a change in energy prices and energy efficiency.

(A2) If we hold *income,* quality attributes *and cost of all other inputs constant*[5]*,* the demand for useful work can be written solely as a function of energy prices and energy efficiency:

$$S = s(P_S) = s\left(\frac{P_E}{\varepsilon}\right) \quad (15)$$

(A3) Assuming that the *energy price doesn't depend on energy efficiency* ($\frac{\partial P_E}{\partial \varepsilon} = 0$), we can express the efficiency elasticity of the demand for useful work as the own-price elasticity of the demand for useful work:

$$\eta_\varepsilon(S) = \frac{\partial S}{\partial \varepsilon} \cdot \frac{\varepsilon}{S} = \frac{\partial S(P_S)}{\partial \varepsilon} \cdot \frac{\varepsilon}{S(P_S)} = \frac{\partial S(P_S)}{\partial P_S} \cdot \frac{\partial P_S}{\partial \varepsilon} \cdot \frac{\varepsilon}{S(P_S)} = \frac{\partial S(P_S)}{\partial P_S} \cdot \frac{\partial (\frac{P_E}{\varepsilon})}{\partial \varepsilon} \cdot \frac{\varepsilon}{S(P_S)} = \frac{\partial S(P_S)}{\partial P_S} \cdot -\frac{P_E}{\varepsilon^2} \cdot \frac{\varepsilon}{S(P_S)} = \frac{\partial S(P_S)}{\partial P_S} \cdot -\frac{P_S}{\varepsilon} \cdot \frac{\varepsilon}{S(P_S)} = -\eta_{P_S}(S) \quad (16)$$

Therefore, the direct rebound effect will be determined by **the own-price elasticity of the demand for useful work** (Greene, et al., 1999; Berkhout, et al., 2000; Sorrel and Dimitropoulos, 2008) defined as:

Definition 2 $\eta_{P_S}(S) = \frac{\partial S}{\partial P_S} \cdot \frac{P_S}{S}$

The impact on the demand for energy associated with the energy service can be expressed as in the Relationship 1 by substituting the own-price elasticity for the efficiency elasticity:

Relationship 2 $\eta_\varepsilon(E) = -\eta_{P_S}(S) - 1$

It is important to note that magnitude of the rebound effect may be expected to depend on the share of energy cost in the overall cost of an energy service. If considerably higher capital, maintenance or time costs are induced by higher consumption of the service, the rebound effect will be probably diminished.

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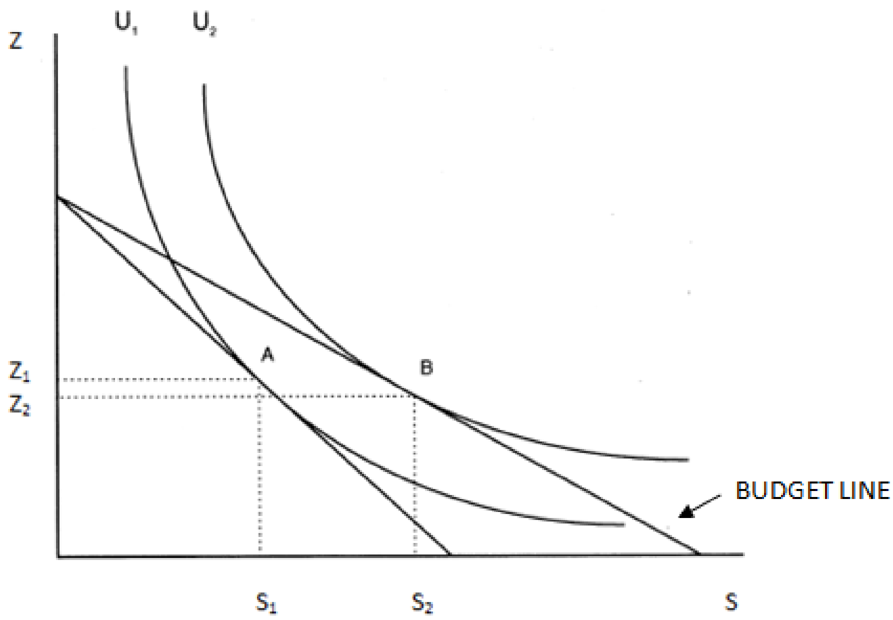
[5] Note that this assumption requires quality attributes (A) and other inputs to be independent from energy efficiency. However, when higher efficiency is attained e.g. by driving smaller car, it may reduce comfort or safety of driving, which in turn may influence the demand for S. It is also likely that a more energy efficient energy system incurs additional capital costs, etc. Relaxation of this assumption will be discussed further in the text.

We can illustrate a simplified concept of the direct rebound effect based on the energy cost of useful work in the two commodity model of consumer choice.

Let's consider the consumer that has a given preference structure represented by the utility function **U** and budget constraint that is given by her disposable income and prices of consumer goods and services. In our case **S** represents useful work for a particular energy service and **Z** the other goods and services consumed. All the information provided, the consumer decides how much of S and Z she will purchase to maximize her utility and an optimal bundle A is chosen.

An energy efficiency improvement of the equipment that provides useful work S will reduce the relative price of S as illustrated in Picture 1 by rotation of the budget line. A rational consumer will then reevaluate the optimal bundle and choose combination B.

Picture 1 – Change in consumption after an energy efficiency improvement



Choice of the new optimal consumption of S will depend on the responsiveness of the demand for useful work to changes in the energy cost of useful work (P_S), holding income, the price of other goods and preferences constant. In other words, on the own-price elasticity of the demand for useful work η_{P_S}(S).

The change in consumption induced by a change in the energy cost of useful work can be decomposed into a substitution and an income effect:

$$\eta_{P_S}(S) = \eta^{C}_{P_S}(S) - \eta_{Y}(S) * \frac{P_S \cdot S}{Y}, \tag{17}$$

where Y is the total expenditure (income) of a household, $\eta^{C}_{P_S}(S)$ is the *income compensated own-price elasticity*[6] of the demand for useful work that represents the *substitution effect* and $\eta_Y(S)$ the *income elasticity* of demand for useful work that, multiplied by the service's share in total expenditures, represents the *income effect*.

The substitution effect is negative because a decrease in the own price induces an increase in the demand. Its magnitude will depend upon the availability of substitutes for the relevant energy service. Income effect can have different signs according to the nature of the service and its importance depends on the service's share in total expenditures. If the service is *normal*, demand increases when income increases and the income effect is positive. In contrast, if the service is *inferior*, the income effect is negative. Hence if the service is normal, the income and substitution effect reinforce each other.

4.2.2 The own-price elasticity of demand for energy

Alternatively, if we assume (A4) *energy efficiency constant*, the symmetry argument implied by (A1) allows expressing the own-price elasticity of the demand for useful work as the own-price elasticity of the demand for energy, the definition originally put forward by Khazzoom[7]:

$$\eta_{P_S}(S) = \frac{\partial S}{\partial P_S} \cdot \frac{P_S}{S} = \frac{\partial(E \cdot \varepsilon)}{\partial\left(\frac{P_E}{\varepsilon}\right)} \cdot \frac{\frac{P_E}{\varepsilon}}{E \cdot \varepsilon} = \frac{\varepsilon\, \partial E}{\frac{1}{\varepsilon}\partial P_E} \cdot \frac{\frac{P_E}{\varepsilon}}{E \cdot \varepsilon} = \frac{\partial E}{\partial P_E} \cdot \frac{P_E}{E} = \eta_{P_E}(E) \tag{18}$$

Definition 3 $\eta_{P_E}(E) = \frac{\partial E}{\partial P_E} \cdot \frac{P_E}{E}$

By plugging the Definition 3 into the Relationship 2, we can see that under the assumptions (A1) to (A4) the efficiency elasticity of the demand for energy can be expressed as the own-price elasticity of the demand for energy.

Relationship 3 $\eta_{\varepsilon}(E) = -\eta_{P_E}(E) - 1$

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[6] That determines the change in consumption when income is adjusted so that utility would remain constant.

[7] Khazzoom (1980) as cited in Sorrel and Dimitropoulos (2008).

Approximation of the RE by **the own-price elasticity of energy demand** for the relevant energy service is convenient when a precise measure of useful work is missing. The assumption (A4) implies that energy efficiency is not affected by energy prices. However, if it is not the case, and energy efficiency is not controlled for, Definition 3 provides biased estimates because the symmetry argument will no longer be valid (Sorrel and Dimitropoulos, 2007). What is more, Definition 3 is meaningful only when the observed energy demand relates to a single energy service. This is usually not the case in practice when only energy demand for a collection of energy services is available.

Many authors (e.g. Greening, et al., 2000; Berkhout, et al., 2000; Sorrel, et al., 2008) took advantage of the Definition 3 to approximate the direct rebound effect by already existing estimates of the own-price elasticity of energy demand. Nevertheless, as we shall see, these estimates can be at most taken as its upper bound. We also know from the existing empirical literature that the own-price elasticity of energy demand varies widely between different energy commodities, end uses, countries and levels of aggregation. Berkhout et al. (2000) stress that the elasticity is increasing with price level and importantly, Haas and Shipper (1998) find that it tends to be higher for periods of rising energy prices. The rationale behind their finding can be that high energy prices induce technological improvements[8], which are not reversed afterwards and/or that energy efficiency requirements may become embodied in regulations. Indeed, empirical estimates based upon periods of rising prices would then overestimate RE, because an appropriate proxy for efficiency improvements is reduction in energy prices.

4.3 Limitations to the Indirect Measures

4.3.1. Correlation between energy efficiency and other input costs

Energy efficiency improvements may generally stem from an energy-saving technological change, substitution between energy and other inputs, and substitution between useful work and quality attributes of an energy service.

When obtaining Definitions 2 and 3 we assumed by (A2) that other than the energy cost of an energy service can be held constant when the energy efficiency changes. In reality *more efficient energy systems are often associated with higher capital costs* as for example price of

[8] Note that this would also mean violation of the assumption (A4)

house insulation or higher price of an efficient car engine[9]. This would correspond to the mix of the first and second type of energy efficiency improvement and implies that annualized capital costs need to be controlled for when estimating the rebound effect. Sorrel and Dimitropoulos (2007), Frondel et al. (2008) and others considered this limitation and suggest the following definition.

We assume that capital costs of an energy service are dependent on efficiency: $P_K(\varepsilon)$, therefore $S = s\left[\frac{P_E}{\varepsilon}, P_K(\varepsilon)\right]$, then (19)

$$\eta_\varepsilon(S)= \frac{\partial S[P_S,P_K(\varepsilon)]}{\partial \varepsilon} \cdot \frac{\varepsilon}{S} = \frac{\partial S[P_S,P_K(\varepsilon)]}{\partial P_S} \cdot \frac{\partial P_S}{\partial \varepsilon} \cdot \frac{\varepsilon}{S(P_S)} + \frac{\partial S[P_S,P_K(\varepsilon)]}{\partial P_K} \cdot \frac{\partial P_K(\varepsilon)}{\partial \varepsilon} \cdot \frac{\varepsilon}{S(P_S)} = -\eta_{P_S}(S) + \frac{\partial S}{\partial P_K} \cdot \frac{P_K}{S} \cdot \frac{\partial P_K}{\partial \varepsilon} \cdot \frac{\varepsilon}{P_K} = -\eta_{P_S}(S) + \eta_{P_K}(S)\eta_\varepsilon(P_K) \quad (20)$$

Definition 4 $\eta_\varepsilon(S) = -\eta_{P_S}(S) + \eta_{P_K}(S)\eta_\varepsilon(P_K)$

Compared to Definition 2 there is a new term: the product of the elasticity of the demand for useful work with respect to the capital cost $\eta_{P_K}(S)$ and the elasticity of capital cost with respect to energy efficiency $\eta_\varepsilon(P_K)$. It is likely that the elasticity of demand for useful work with respect to capital costs is negative because in the long run higher capital costs induce lower number of appliances (NO), lower capacity (CAP) and/or purchase of other conversion devices[10]. Assuming that more energy efficient capital equipment is more expensive, then the new term is positive and the RE is lower than absolute magnitude of the efficiency elasticity of energy demand. Studies that estimate the RE primarily from the variation in energy prices (as is often the case even when Definition 2 is used) will then produce upward biased results. In this context, the advantage of the decomposition of the demand for useful work becomes evident: if we look only at the utilization (UTIL), such as vehicle kilometers per year, capital costs become sunk costs and their effect on overall demand for kilometers traveled will be overlooked.

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[9]This assumption is far from being true for all energy services. For example in computing the improvements in energy efficiency and *reductions* in capital costs were simultaneous.

[10] Holding quality attributes unchanged, a rational consumer will buy a new efficient device only when the discounted stream of additional consumer surplus from higher demand for useful work is higher than present value of additional capital costs. (Sorrel and Dimitropoulos, 2007)

The conclusion of lower RE is valid only if consumer faces the full cost of the purchase decision. On the other hand, if energy efficient devices are subsidised and made even cheaper than inefficient devices, the RE may be amplified.

Impact of regulatory efficiency standards on the energy demand will be probably ambiguous because if the discounted stream of additional consumer surplus from higher demand for useful work is not higher than present value of additional capital costs consumers may also resort to delay replacing existing equipment, purchase second-hand (inefficient) devices or go without the energy service altogether (Sorrel and Dimitropoulos, 2007). In all cases, the effect of an energy efficiency improvement will be different from that of energy price changes, which are not correlated with capital costs.

4.3.2. Correlation between energy efficiency and quality attributes of an energy service

Khazzoom (1980 cited in Sorrel and Dimitropoulos, 2008) avoided the problem of capital costs by assuming no correlation with energy efficiency. As an example, he put the case of smaller cars that are more efficient and have lower capital costs as well. However, in that case, higher efficiency is substituted for quality attributes of the energy service (comfort, safety), which may in turn reduce the utility from consuming the energy service and diminish the direct rebound effect as well. In other words e*nergy efficiency improvement without additional capital costs is likely to have been achieved at the expense of quality attributes of the energy service* (negative correlation between ε and A). Each attribute then may have non-zero elasticity with respect to the energy cost of useful work and long-term response to the reduction in energy cost will depend on the trade-offs between useful work and these attributes.

4.3.3 Dependence of energy efficiency on energy prices

Khazzoom focused on mandatory energy efficiency standards for household appliances, in which case energy efficiency improvements are exogenously given in the demand equation. In practice however, there are several reasons why the energy efficiency can be suspect of being endogenous to the demand equation.

The energy efficiency is partly endogenous because it is expected to be influenced by current and historical energy prices (Greene, et al., 1999; Small and Van Dender, 2006). Rising energy prices may in the short term alter the usage of existing equipment (driving efficiently, car sharing), in the long term consumers will opt for more efficient devices.

Therefore we assume that energy efficiency is a function of energy prices: $\varepsilon(P_E)$. It implies

$$S = s\left(\frac{P_E}{\varepsilon(P_E)}\right) \text{ and then}^{11} \quad (21)$$

Definition 5 $$\eta_\varepsilon(E) = -1 - \left[\frac{\eta_{P_E}(E) + \eta_{P_E}(\varepsilon)}{1 - \eta_{P_E}(\varepsilon)}\right]$$

This definition suggests that instead of directly estimating the energy cost elasticity of demand for useful work (as Definition 2 does), one can estimate the own-price elasticity of energy demand for the relevant energy service $\eta_{P_E}(E)$ and the elasticity of efficiency with respect to energy prices $\eta_{P_E}(\varepsilon)$. It also reflects the assumption (A3) that only when energy efficiency is independent of energy prices will the energy cost elasticity of useful work be equal to the own-price elasticity of energy demand for the relevant energy service.
Since the energy price elasticity of energy efficiency can be expected positive (high energy prices incite purchases of more efficient appliances and/or their more efficient use) it can be derived that $|\eta_{P_E}(E)| \geq |\eta_{P_S}(S)|$[12] and therefore Definition 3 will overestimate the RE compared to Definition 2. The previous literature on the own-price elasticity of energy demand can thus serve only to set an upper bound on the direct rebound effect.

4.3.4 Constraints on the demand for useful work

It is likely that *the assumption of insatiability does not hold* for all energy services. Majority of the energy services has an upper bound on consumption reasonably low to be real. For example once a household can afford to heat its apartment up to some 25°C it is unlikely it would demand more heat even if the cost would converge to zero.

The demand for useful work may be also constrained by *the opportunity cost of time*. There is a limited time we can devote to driving a car or cooking during a day. It is likely that the higher our opportunity cost of time, the lower the potential of the RE. However, for example travelers can in some cases switch from a car to a plane, it means to switch from more efficient and more time consuming device to less efficient and less time consuming one.[13]

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[11] Derivation of Definition 5 is based on the same principles as for the previous ones. For full derivation see Sorrel and Dimitropoulos, 2007, pp. 96.

[12] Hanly et al. (2002) have derived the following relationships that should hold for all econometric estimates: $|\eta_{P_S}(E)| \geq |\eta_{P_E}(E)| \geq |\eta_{P_S}(S)| \geq |\eta_{P_E}(S)|$.

[13] This theme is further developed in the following part of the Chapter.

The two constraints then suggest that **the direct rebound effect could be higher among low income groups**, because these are further from satiation in their consumption of individual energy services (Sorrel and Dimitropoulos, 2008) and have lower opportunity costs of time (if approximated by wage). As income grows, the time cost gains importance over the energy cost and the demand for useful work can be expected less sensitive to the energy cost changes (Greene, 1992).

In certain cases *the opportunity cost of space* can be an active constraint. We are limited in how many refrigerators or lights we have because they must fit somewhere into our apartment. The importance of this constraint is, contrary to those mentioned above, likely to be decreasing with rising income because people in high income groups tend to have larger average living space.

4.4 Endogeneity[14] of the Energy Efficiency and Quality Attributes

To include energy efficiency as a purely exogenous variable, one would have to assume that all improvement is due to regulatory standards imposed by government or/and producers technology. In other words, a given level of energy efficiency would be independent of the household choice. However, once we allow the household to choose an energy efficiency level of its appliances, the variable becomes endogenous to the model of demand for energy services because it is likely that the choice will be conditional upon the anticipated demand for the energy service. Again an example from personal transportation – if a family buys a new car, the frequency of use and distances to commute will be taken into account. The higher anticipated kilometers traveled the greater emphasis will be given to fuel efficiency. That would imply a positive correlation between efficiency and demand for useful work in addition to the direct rebound effect (Sorrel and Dimitropoulos, 2007). On the other hand, the family may also choose more comfortable (larger) car, which uses to have higher fuel consumption and then the correlation would be negative and the total effect ambiguous. In each case however, we expect that the energy efficiency is also a *function of the anticipated demand for useful work*, which obfuscates the causal relationship between these two variables and makes the logic behind Definition 2 circular – S depends

[14] An explanatory variable in a multiple regression model is considered endogenous when it is correlated with the error term, either because of an omitted variable, measurement error or simultaneity (Wooldridge, 2004).

upon P_S, which depends upon ε, which in turn depends upon S. In this case, also estimates based on Definition 1 will suffer from the same problem. The endogeneity then implies that estimating the effect as if the causality goes only in one direction will result in biased estimates. If the positive correlation is the case, the direct rebound effect will be overestimated when the endogeneity is not accounted for.

In the case of personal vehicle travel, the fuel efficiency (if measured as on-road efficiency) is also likely to be dependent on the demand for vehicle travel because large distances can be on average traveled more efficiently.

Another source of endogeneity not only of energy efficiency but also of appliance portfolio characteristics and its ownership, used as control variables in the demand equation, arises in empirics when some *unobserved factors* (such as household's tastes or environmental attitudes) *influence both the appliance stock and the demand for useful work*. For example unobserved factors which increase the utility of air conditioning (e.g. poor natural ventilation of a housing unit) are likely to increase both its probability of purchase and its intensity of use (Dubin and McFadden, 1984). For vehicles, a household concerned with environment is likely to purchase more efficient car and drive it less.

If a simple equation for the demand for useful work is estimated, the sample is limited to households which already own an appliance. Since it is likely that the ownership of an appliance is not random in the population but is correlated with its usage or influenced by the same unobservable factors, the choice of having a car is endogenous to the usage equation and the problem corresponds to *a sample selection bias*.

As suggested, the demand for appliance stock and intensity of its use are separate but interconnected choices. Some energy economists therefore opt for a system of simultaneous equations to express explicitly this structure and avoid biased and inconsistent estimates.

4.4.1 Model 1- Simultaneous equations with a dummy endogenous variable

Departing from a seminal study by Heckman (1978), Dubin and McFadden (1984) developed for energy services a demand system of simultaneous equations with a dummy endogenous variable - also termed a **discrete/continuous model**. In the system, the discrete choice of an appliance portfolio with a given set of characteristics (such as number, fuel type, engine size, etc.) is analyzed as interconnected and contemporaneous with the usage decision[15]. While Dubin and MacFadden or Nesbakken (2001) applied the model to the demand for household heating, Goldberg (1996) and West (2004) adopted it for personal automotive transport.

Let's consider a utilization equation of a following general form

$$S_i = s(i, P_S^i, Y - P_i, \mathbf{A_i}, \mathbf{X}, \epsilon_i, \mu), \qquad (22)$$

where S_i denotes the demand for useful work of an appliance portfolio *i*, i is a variable indicating the choice of a portfolio *i*, Y is the household's annual income, P_S^i is the cost of useful work, $\mathbf{A_i}$ is a vector of observed attributes of portfolio *i*, $\mathbf{X}$ is a vector of observed household characteristics, ϵ_i are unobserved attributes of portfolio *i* and μ are unobserved characteristics of the household. P_i is the price of portfolio *i*, which is a sum of annualized capital cost P_K^i and annual operational cost $(P_S^i + P_0^i)\, S_i^E$, where P_0^i is operation & maintenance cost and S_i^E is the expected usage of portfolio *i*.

In the equation (22), a coefficient on the energy cost of useful work would determine the direct rebound effect. However, elasticities derived from such an equation will be biased because the portfolio specific attributes (i, P_i, P_S^i, $\mathbf{A_i}$) are likely to be endogenous to the model. Therefore, the choice of the portfolio must be modeled simultaneously with the utilization equation.

The appliance portfolio choice model is developed from *a conditional indirect utility function*. The reason is that a consumer's utility from an appliance holding is derived from the flow of services provided by its ownership and therefore is best characterized as indirect. In this setting, for example, the consumer faces a trade-off between capital costs for energy efficient appliances and operating costs[16], where her expectation on future utilization, future energy prices and current financing decision will be crucial for the optimization problem (Hausman, 1979). Provided the consumer chooses from N mutually exclusive, exhaustive appliance portfolios indexed *i*=1,...,N, her conditional indirect utility function associated with appliance portfolio *i* reads

$$V_i = v(i, P_S^i, Y - P_i, \mathbf{A_i}, \mathbf{X}, \epsilon_i, \mu)\ . \qquad (23)$$

[15] The model does not involve intertemporal considerations; an assumption realistic only if there are perfect competitive rental markets for consumer durables (Dubin and McFadden, 1984).
[16] In the case suggested in Chapter 4.3.1 where higher efficiency is positively correlated with capital costs.

The probability that portfolio *i* is chosen is then described by a random utility model

$$\Pi_i = \text{Prob}\ [V_i\ (i, P_S^i\ , Y - P_i, \mathbf{A_i}, \mathbf{X}, \epsilon_i, \mu) > V_j\ (i, P_S^j\ , Y - P_j, \mathbf{A_j}, \mathbf{X}, \epsilon_j, \mu), \text{ for } j \neq i]. \qquad (24)$$

By application of Roy's identity to the indirect utility function, we obtain the demand for useful work (*the utilization equation*) conditional on the choice of appliance portfolio, which will correspond to the equation (22)

$$S_i = \frac{-\partial V_i(i, P_S^i, Y - P_i, \mathbf{A_i}, \mathbf{X}, \epsilon_i, \mu)/\partial P_S}{\partial V_i(i, P_S^i, Y - P_i, \mathbf{A_i}, \mathbf{X}, \epsilon_i, \mu)/\partial Y} = s(i, P_S^i\ , Y - P_i, \mathbf{A_i}, \mathbf{X}, \epsilon_i, \mu). \qquad (25)$$

For empirical implementation Dubin and McFadden suggested a function *v*, which has the necessary and sufficient properties of an indirect utility function and is computationally tractable[17]

$$V_i = (\alpha_0^i + \frac{\alpha_1}{\beta} + \alpha_1 P_S^i + \beta(Y - P_i) + \mathbf{A_i}'\gamma + \mathbf{X}'\delta_i + \mu) \cdot e^{-\beta P_S^i} + \epsilon_i, \qquad (26)$$

where α, β, γ and δ denote parameters of the model.

This indirect utility function leads to an appliance portfolio choice probability

$$\Pi_i = \text{Prob}\ (\xi_j - \xi_i < W_i - W_j \text{ for } j \neq i), \qquad (27)$$

where $W_i = (\alpha_0^i + \frac{\alpha_1}{\beta} + \alpha_1 P_S^i + \beta(Y - P_i) + \mathbf{A_i}'\gamma + \mathbf{X}'\delta_i) \cdot e^{-\beta P_S^i}$ and $\xi_i = \mu \cdot e^{-\beta P_S^i} + \epsilon_i$.

By application of Roy's identity to the indirect utility (26) we obtain a utilization equation linear in income

$$S_i = \alpha_0^i + \alpha_1 P_S^i + \beta(Y - P_i) + \mathbf{A_i}'\gamma + \mathbf{X}'\delta_i + \mu, \qquad (28)$$

where α_1 determines the *short-run* direct rebound effect, because it is conditional on the chosen appliance portfolio.[18] We will further develop this equation in Chapter 5.3 where the estimation techniques are discussed.

[17] For methods of obtaining a specification of discrete/continuous demand system see Dubin and McFadden (1984)

[18] Note that due to the specific form of the indirect utility function in (26), the unobserved attributes of portfolio *i* (ϵ_i) drop out when applying the Roy's identity and does not enter the utilization equation (28).

4.4.2 Model 2- Simultaneous equations

Another approach identifies the possible endogenous variables in the utilization equation and establishes a classical system of simultaneous equations (e.g. Small and Van Dender, 2006). Usually, the number of appliances (NO) and the energy efficiency (ε) are identified as endogenous and the system generally reads

$$S = s(NO, \varepsilon, P_E, \mathbf{A}, \mathbf{X_1}, \mu_1) \quad (29a)$$

$$NO = no(P_K, \text{anticipated } S, \varepsilon, P_E, \mathbf{X_2}, \mu_2) \quad (29b)$$

$$\varepsilon = f(P_E, \text{anticipated } S, R_\varepsilon, \mathbf{A}, \mathbf{X_3}, \mu_3), \quad (29c)$$

where P_E is the price of energy, **A** is a vector of vehicle stock characteristics R_ε are regulatory standards on efficiency of new devices, $\mathbf{X_i}$, i=1,2,3 is a vector of exogenous variables corresponding to each equation and μ_i are unobserved household characteristics corresponding to each equation.

In this model, utilization of appliance portfolio is conditional on the portfolio characteristics as in the previous model but only the number and efficiency are assumed to be interdependent with the utilization choice. Implications of changes in exogenous variables are more complex and may entail greater changes in energy demand than with single-equation models. For example, regulatory standards directly raise energy efficiency in (29c) then higher energy efficiency raises the demand for useful work directly through lower price of energy service in (29a) and indirectly through the number of devices in (29b). The net increase in demand for useful work in turn stimulates higher energy efficiency. Therefore, the resulting equilibrium energy efficiency and demand for energy service will be higher than the in the other models (Sorrel and Dimitropoulos, 2007). The short-run rebound effect in this model will be determined by the coefficient on energy efficiency (ε) in (29a) and the long-run rebound effect by the coefficient on ε when equation (29b) is substituted into the equation (29a).

Greene et al. (1999) suggested for personal vehicle travel a system in which the price of gasoline is also endogenously determined as it depends on the demand for useful work and fuel efficiency. The authors consider the gasoline price as a choice variable because the actual price paid by consumer varies with fuel properties, brand, location, convenience and other features among which consumer may choose. Also, people who drive longer distances have wider choice of petrol pumps and therefore can find cheaper gasoline.

4.4.3 *Model 3- Multiple equations*

Many studies refrain from the simultaneous equations and simply depart from a decomposition of the equation for energy demand $E = NO \cdot UTIL/\varepsilon$, where NO and ε has the same meaning as above and UTIL is an average utilization of each appliance (for example kilometers traveled with a car from the vehicle stock). Each component is then modeled separately, which, as opposed to single equation models, allows identification of not only the magnitude of price and income effects on the demand for useful work but also their mechanisms. This leads to a general system of multiple equations similar to Model 2

$$UTIL = util(NO, \varepsilon, P_E, \mathbf{X_1}, \mu_1) \tag{30a}$$

$$NO = no(P_E, \varepsilon, \mathbf{X_2}, \mu_2) \tag{30b}$$

$$\varepsilon = f(P_E, R_\varepsilon, \mathbf{X_3}, \mu_3), \tag{30c}$$

where the variables have the same meaning as before. While the mutual relationship of utilization and appliance portfolio characteristics is ruled out in this model, NO and ε are still likely to be endogenous to the utilization equation due to the same unobserved factors that influence all equations. Utilization is still conditional on the appliance portfolio characteristics (in this case the number and energy efficiency). A change in efficiency will have an impact both on the utilization and the number of appliances, where the former can be viewed as the short-run rebound effect and the long-run rebound effect would be obtained by substituting equation (30b) into (30a).

It is worth noting that in empirical application, Model 2 and 3 are used only when the explained variables are continuous, while Model 1 accounts only for endogeneity of discrete characteristics of the appliance portfolio. Even though a combined model is thinkable, it has not occurred in the literature so far, most likely because of its computational complicatedness. In Model 1 the potentially endogenous continuous variable, which is obviously of our concern, is the energy efficiency. However, the problem can be ruled out on the theoretical ground when we can assume that it is mainly determined by the portfolio characteristics modeled as choice variables. That is, when for example a vehicle portfolio is characterized by number, age, engine size and vehicle class, then the energy efficiency of such a portfolio is likely to vary negligibly.

4.5 The Rebound Effect with Respect to Time

Binswanger (2001) suggested that in analogy to the rebound effect with respect to energy efficiency a rebound effect with respect to time can be defined. As suggested in Chapter 2 time is an important input in some energy services production and its cost will be relevant for the energy service consumption. Based upon Becker's household production model, *time cost* (w) can be measured by average hourly wage for the household and therefore should vary among different households.

Among other attributes of energy conversion devices (the other than energy efficiency) there is *time efficiency* (θ) defined as the amount of useful work produced with a unit of time

$$\theta \overset{\text{def}}{=} S/T. \tag{31}$$

Also analogously to the energy cost of useful work, the time cost per unit of useful work (P_T) is defined as

$$P_T = w/\theta. \tag{32}$$

Increased time efficiency of production of a particular energy service will decrease its cost therefore increasing its consumption and the derived energy consumption. Since time saving innovations also tend to be associated with increased energy intensity (Binswanger, 2001) the consumer faces a trade-off between technologies with different time and energy efficiencies in providing a particular energy service.

Therefore an increase in the time cost relative to energy prices should induce a substitution away of time towards energy in producing a particular energy service and analogously a substitution from time-intensive towards energy-intensive energy services (Sorrel and Dimitropoulos, 2007). Since wages appear to have grown faster than energy prices in recent decades (Binswanger, 2001), increases in energy demand could therefore have been driven as much by the substitution of energy for time as by the overall increases in income.

Empirical part

Literature surveys already published (Greening, et al., 2000; Berkhout, et al., 2000; Sorrel, et al., 2009) provide a good basis for an overview of empirical evidence. They summarize scientific state of the art concerning different energy services consumed by households and focus on four main areas of research: personal automotive transport, residential heating and cooling and other services provided by household electrical appliances. One of the main characteristics of the empirical studies on the rebound effect is that their findings vary considerably. There are three basic reasons: a use of different data, different definitions (e.g. specifications of useful work), and different methods of estimation. Especially due to the lack of detailed data, many studies use methods that may result in biased estimates (Sorrel, et al., 2009). However, only Sorrel et al. devote space to a discussion of the methodological differences and stress that these lead to very limited possibilities of comparison of results from different studies. As an example that methodology matters one can compare studies of Goldberg (1996) and Puller and Greening (1999); both analyze the data on personal automotive transport from the same rotating panel in largely overlapping periods. While Goldberg concludes from a discrete/continuous model that the direct rebound effect is virtually equal to zero, Puller and Greening finds from their simultaneous equation model the direct rebound effect of 49%.

5 MODEL SPECIFICATIONS AND ESTIMATION METHODS

A single equation model of the demand for useful work (S) corresponding to the rebound effect Definition 1 generally reads[19]

$$S = \alpha + \beta_1\varepsilon + \beta_2 P_E + \beta_3 P_K + \gamma Y + \mathbf{X'}\delta + \mathbf{A'}\lambda + \mu, \quad (34)$$

where ε is the energy efficiency, P_E is the energy price, P_K id the annualized capital cost, Y is income, **X** is a vector of household characteristics and **A** is a vector of appliance portfolio attributes, the Greek letters stand for parameters to be estimated.

A single equation model corresponding to Definition 2 reads

$$S = \alpha + \beta_1 P_S + \beta_2 P_K + \gamma Y + \mathbf{X'}\delta + \mathbf{A'}\lambda + \mu. \quad (35)$$

Alternatively, the rebound effect corresponding to Definition 3 is estimated from

$$E = \alpha + \beta_1 P_E + \beta_2 P_K + \gamma Y + \mathbf{X'}\delta + \mathbf{A'}\lambda + \mu, \quad (36)$$

where E stands for the energy demand.

The direct rebound effect is given by the coefficient β_1. Provided the functional form includes the dependent variable, ε, P_S, alternatively P_E in logarithms, β_1 directly represents the elasticity and therefore the RE.

5.1 Dynamic or Static Methods

To allow for certain inertia in consumer behaviour, studies based on time series or aggregate panel data incorporate lagged effects (e.g. a dynamic method). An appropriate lag structure can be also a solution to the problem of autocorrelated residuals, usually encountered with the time series data. Inclusion of the lagged dependent variable is a standard approach, but if the first order serial autocorrelation is assumed, a transformation that includes also lagged independent variables will be suitable (Greene, 1992). This method leads to a model estimated by nonlinear least squares. Another source of autocorrelated residuals may be unobservable factors that don't change with time, for that reason Small

[19] Indexes are omitted as they depend on the data structure.

and Van Dender (2006) apply a fixed effects specification to their panel data. A limited number of studies used a static estimation method, which is adequate only with cross-section data, where we expect the demand to be in an equilibrium point. With time series it would have to be assumed that all reaction takes place immediately within one period, which is unlikely to hold when adjustment in appliance stock is considered.

When discussing the time frame of adjustment, it is necessary to return to the definitions of the short- and long-run.

5.2 Long-term and Short-term Responses

As Hanly, et al. (2002) observe, the terms are well defined when using dynamic methods of estimation. Studies that work with time series data consider the short-term to be one period (usually a year or a quarter) while the long-term corresponds to the expected equilibrium state reached after some empirically defined number of periods. For transport literature the greatest part of the response comes within the first 3 to 5 years (Hanly, et al., 2002). Using discrete/continuous or simultaneous equation models on cross-section or panel data, the short-run is usually defined as the change in utilisation, while the long-run comprises also the change in appliance stock[20]. If other static model is used on cross-section data, the elasticities estimated are widely believed to be in equilibrium and should therefore correspond to the long-term responses. For time series without lags the effect is sometimes claimed to be short- sometimes long-run. The interpretation of the two latter estimations is however just by assumption (Hanly, et al., 2002)..

5.3 Methods Accounting for Endogeneity

In Chapter 4.4, we have already outlined models that explicitly address the potential endogeneity of some explanatory variables (either discrete or continuous) in the utilization equation. It must be verified empirically if the joint dependence of some or all variables is strong enough to not to be ignored or whether it is present at all. If the joint dependence is relevant, OLS estimation of each equation would result in biased and inconsistent estimates due to a *serial correlation between a regressor and the error term*. The serial correlation may

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[20] Greene, et al. (1999) argue that the effect from vehicle ownership is small because fuel costs form less than 10% of vehicle ownership costs.

stem from a mutual dependence of the explained and an explanatory variable when the causality goes in both ways (as in Model 2). Alternatively, even if the causal relationship is only one-way, a presence of unobservable factors that influence both variables would induce correlation between residuals of each equation and therefore cause endogeneity of the explanatory variable (as can be a case also in Model 3).

Simultaneous equations such as Model 2 are mostly applied in personal automotive transport analyses based on aggregate data – the reason is that only studies using aggregate data can consider the number of cars a continuous variable (when normalized to population or number of drivers). Equations in the system are usually estimated by *Two Stage Least Squares* (2SLS). This technique is based on the concept of instrumental variable where the instruments are the expected values of all endogenous variables as obtained from regressions on all exogenous variables in the system. Even though 2SLS estimators are consistent, higher efficiency can be attained by system methods which estimate the equations jointly and therefore make use also of the cross-equation correlations of the disturbances (Greene, 2003). The most popular is *Three Stage Least Squares* (3SLS) - essentially a Feasible Generalized Least Squares estimator based on 2SLS residuals.

With disaggregate data the number of appliances would have to be treated as a discrete choice. Some authors then simply restrict the model to the two continuous equations for useful work and energy efficiency (e.g. Puller and Greening, 1999) or apply Model 1 – the discrete/continuous model.

Estimation of the discrete choice is usually done from the *logit* model (conditional or nested in the case of estimating multiple portfolio characteristics[21]). The utilization equation (28) from Model 1 can be for estimation purposes rewritten as

$$S_i = \sum_{j=1}^{N}(\alpha_0^j + \alpha_1 P_S^j + \beta(Y - P_j) + \mathbf{A_j}'\gamma + \mathbf{X}'\delta_j) \cdot D_j + \mu \,, \qquad (37)$$

where j represents the alternative appliance portfolios and D_j is a dummy equal to 1 if j=i.

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[21] Conditional logit is based on the assumption of independence of irrelevant alternatives (IIA), e.g. on that the ratios of probabilities of each choice are independent of the other probabilities. However, this assumption often seems an inappropriate restriction on consumer behavior. A modification, which groups the alternatives into subgroups and allows relaxing the restriction across the subgroups, while maintaining it within them, is called the nested logit. For a comprehensive discussion of these models see e.g. Greene (2003)

To estimate the utilization equation Dubin and McFadden (1984) proposed three methods which bear consistent results in the presence of endogeneity. An *instrumental variable* technique employs the estimated probability of choosing the alternative j as instrument for D_j. A *reduced form* method is similar but the estimated probabilities are applied as a direct proxy for D_j. Alternatively, the *conditional expectation correction* method (also called Heckman's method) employs the estimated probabilities to compute the Inverse Mill's Ratio, which is then included as a regressor in the utilization equation. In all three cases OLS is usually applied. Note that similarly to 2SLS with classical simultaneous equation model, all three methods estimate the two equations (discrete and continuous) one at time. A system estimator such as *Full-Information Maximum Likelihood* then again yields more efficient results because it estimates the discrete and continuous choice jointly.

Either of the simultaneous equations models is advantageous because it helps to identify both the long- and short-run rebound effect, while respecting the potential source of endogeneity bias. Nevertheless, we already mentioned the shortcoming that the endogeneity of only either discrete or continuous variables is explicitly controlled for.

If panel data are at disposal, the fixed-effects specification can help to avoid biased and inconsistent estimates as it eliminates the time invariant unobservable factors, which affect both the choice of appliance and its usage. This method however has several disadvantages, notably a loss of possibility to estimate the effect of time invariant explanatory variables and a potential loss in variability of regressors.

6 LITERATURE OVERVIEW

The already mentioned Sorrel et al. (2009) reviewed 31 empirical studies and obtained some "best guess" magnitude of the direct rebound effect for particular energy services. In personal automotive transport the evidence is most numerous and suggests that the long-run direct rebound effect lies between 10% and 30% with high degree of confidence. The evidence for residential heating is less persuasive and ranges from 10% to 30% as well. In the case of space cooling and other energy services the "best guess" ranges from 1% to 26% and 0% to 20% respectively, the degree of confidence is low though. Notwithstanding the variation in estimates, the direct rebound effect is always lower than 100% and therefore increases in energy efficiency will result in overall reduction in energy consumption.

In what follows, the largest space is given to the analysis of studies on personal automotive transport, which use household-level data. The reason is that we believe that the use of micro data is more plausible for estimation of household behavior than aggregate data and due to larger data availability, studies in personal automotive transport have gone the furthest in developing models that incorporate the complexities of a household decision-making studied in the Chapter 4.4.

The overview will focus not only on the estimates of the rebound effect but also on nature of the data and methodology. This will enable us to compare the results of different methodologies and can guide us in designing a model for our future research.

6.1 Personal Automotive Transport

Empirical research on the rebound effect in automotive transport is the most extensive and diverse one. Contrary to the other types of energy services, demand for useful work in transportation is estimated both from macro- and micro-level data, and therefore models and estimation methods differ substantially. Except for four studies, all are based on U.S. data. The majority of macro data are time series or aggregate panel data, there is only one exception - Wheaton (1982) estimated a model based on cross-national data. Micro-level data are drawn from consumer expenditure surveys and travel surveys. Both panel and cross-section data are used in that case.

6.1.1 Definitions of useful work

For personal automotive transport, aggregate studies usually use the annual total distance traveled (vehicle miles traveled - VMT) by cars and light trucks (e.g. Greene, 1992; Gately, 1990). Some authors estimate VMT normalized to the number of vehicles, licensed drivers or adults (only Small and Van Dender, 2006). Studies using disaggregate data express the useful work as the distance traveled per vehicle or per household. The latter however overlooks the possibility of multi-vehicle households to switch among vehicles with different fuel efficiencies. Some studies include also business mileage (e.g. Goldberg, 1996), which can be expected less responsive to the changes in fuel cost of travel (Sorrel and Dimitropoulos, 2007).

6.1.2 Results

Many studies that work with *aggregate data* use multi-equation models where simultaneity is either rejected empirically (e.g. Wheaton, 1982) or ruled out on theoretical basis (e.g. Gately, 1992). **Wheaton (1982)** estimated the rebound effect based on the energy efficiency elasticity of the distance traveled per vehicle $\eta_{\varepsilon}(S)$. He estimated a cross-national model for automobile ownership, fleet efficiency and driving per vehicle. The data collected for the study used the same definitions and measurements standards as the U.S. time-series data. Full data set was obtainable for 42 countries and covered the year 1972. Fleet fuel efficiency was constructed by averaging data on the designed fuel consumption of different makes and models (EPA data). Miles driven per vehicle were obtained by dividing fuel consumption per vehicle by the measure of fleet efficiency. Wheaton uses a structural model, where he assumes that a household chooses an automobile portfolio characterized by the number of vehicles (NO) and their fuel efficiency (ε). Conditional on the choice a household decides how much to use each vehicle (UTIL). Both three equations include price of gasoline; the opportunity price of imported automobiles and the level of urbanization enter the NO and ε equations. Finally, the country land area enters only the UTIL equation. Based on Box-Cox test, log-linear form is used for UTIL and NO equations and linear form for ε equation. Specification test didn't suggest that there would be correlation between the error term in UTIL equation and the variables NO and ε. Therefore Wheaton applies OLS to estimate the equations with the resulting rebound effect of **6%**. It is notable that the elasticity of demand for vehicle miles traveled with respect to gasoline price is -50% and the gasoline price effect on fuel efficiency and number of cars is very low (elasticity of 14% and 16%). **Gately (1992)** concentrates on asymmetric responses of U.S. gasoline demand to price increases and declines as well as price-reversibility of average fleet fuel efficiency. The analysis is done for the period 1966-1988, for cars and light trucks. Gately stresses that the vehicle miles must be studied on per-driver basis because during the period the portion of licensed drivers in population grew rapidly. A static log-log equation is used, which implicitly assumes that all the change takes place in the first period and therefore the long- and short- run effects are the same. The direct rebound effect is estimated as the elasticity of vehicle miles per driver with respect to fuel cost per mile $\eta_{P_S}(S)$ with the result of **9%.** Notably, Gately encountered a significant serial correlation in errors in the VMT equation, but did not include a lagged dependent variable and therefore could use standard autocorrelation correction techniques.

Among the studies using single equation, **Greene (1992)** appears as one of the most rigorous. He focused concretely on the direct rebound effect using data from 1957 to 1989 for cars and light trucks (vehicles for business purposes are therefore included). The model estimated is a dynamic equation for VMT, however, in accord with Gately (1992), Greene argued that all the adjustment took place in the short run, this time because the lagged dependent variable was found insignificant once the estimation properly accounted for autocorrelated residuals. Greene also tested whether to include number of licensed drivers or stock of cars as an explanatory variable, he concluded that they are so closely correlated that their effects on VMT are indistinguishable and the coefficient of fuel cost per mile (CPM), the rebound effect, is not sensitive to which variable is included. The resulting elasticity of VMT with respect to CPM $\eta_{P_S}(S)$ appears insensitive to functional form; when a linear model is estimated, the rebound effect exhibits a trend toward zero, from 19% in 1966 to near 5% in 1989, the logarithmic functional form gives the rebound effect of **13%**. **Orasch and Wirl (1997)** estimate the direct rebound effect for France, Italy and UK in years 1971-1993. They assume that consumer cannot determine the efficiency because it is supplied by the automobile industry. They therefore estimate a single dynamic equation with the lagged dependent variable. The resulting short-run rebound effect $\eta_{P_S}(S)$ is equal to **18% in France**, **19% in Italy** and **10% in UK**, while the long-run effect is higher at **34%**, **33%** and **27%** respectively.

Small and Van Dender (2006) presents an elaborated system of simultaneous equations to estimate the rebound effect for automobile and light-truck use, defined as the elasticity of VMT per adult with respect to fuel cost per mile. The model is based on aggregate panel data at U.S. state level from 1966 to 2001 and contains three simultaneous equations for aggregate VMT per adult, vehicle stock per adult and efficiency. In each equation, one-year lagged value of dependent variable is included to allow for behavioral inertia and error terms are assumed to exhibit first-order serial correlation. They applied fixed effects specification to cope with unobserved state-specific characteristics, and transformation to nonlinear model to cope with autocorrelation. The short-run rebound effect is captured by the coefficient on fuel cost per mile in the VMT equation $\eta_{P_S}(S)$ and is estimated at **4.5%**, the long-run effect is the coefficient in the reduced form equation for VMT after the equation for vehicle stock is substituted into it and equals **22.2%**. Interestingly, interactions of CPM with income, level of urbanization and CPM itself are introduced, which allows the rebound effect to vary with different levels of these variables. Small and Van Dender found that 10% rise in income reduces the short-run rebound effect by 0.58%. It is also to say that even though the rebound effect is defined as elasticity with respect to fuel cost per mile (P_E/ε), in their dataset it is just the variation in fuel price that mainly identifies the rebound effect and they couldn't satisfactorily test the symmetry of the effects of fuel price and fuel intensity.

Household survey data are harder to collect, and therefore the studies using micro data are rarer. **Puller and Greening (1999)** estimate non-business gasoline demand in U.S. and concentrate on the adjustment process during the first year after a price change. They decompose the adjustment to vehicle miles traveled by household and the average efficiency of household's vehicles. The data are taken from Consumer Expenditure Survey for periods 1980-1981 and 1984-1990. To estimate the model, random- and fixed effects estimators are found unsatisfactory and therefore pooled model is estimated by 2SLS technique. They also test three types of restrictions on parameters because estimates from unrestricted model show unexplainable waviness, which is likely due to strong collinearity. All restrictions are rejected at all standard testing levels; however, according to the authors, they are not invalid with respect to behavioral model and are needed to deal with the collinearity while giving only slightly higher estimate of the total effect. The model preferred is with restrictions on lagged parameters (gasoline prices) such that they should lie along a line (first-order polynomial). The rebound effect $\eta_{P_S}(S)$ is estimated at **49%**. Interestingly, the elasticity of composite miles per gallon (MPG) with respect to gasoline price is negative (-22%), which the authors argue consistent with households reacting to higher prices by reducing high-efficiency miles such as vacation trips and suggests that households adjust more through reduction in miles traveled than by altering driving and maintenance behavior or changing vehicle stock. **Greene et al (1999)** work with very rich dataset from six surveys conducted by the U.S. Energy Information Administration on residential transportation energy consumption. The dataset covers the period 1979 – 1994 for cars and light trucks and it is divided into five databases according to the number of usable vehicle records per household resulting in sample sizes from 1,320 to 10,204 households. The authors apply a system of simultaneous equations for each car in a household, in which the miles traveled, fuel efficiency and fuel price are modeled interdependently. The miles traveled by each vehicle are dependent on miles traveled by the other cars used by a household. This specification allows uncovering how households adjust the usage of cars with different fuel efficiencies in reaction to change in fuel prices. Greene et al. test the symmetry of response to changes in price and in fuel efficiency by restricting the coefficients of the logged MPG and logged P_E in the VMT equation to sum to zero. The data did not contradict the hypothesis. Estimates of the rebound effect of household travel with respect to energy efficiency[22] range from 17% for three-vehicle households to 28% for one-vehicle household. A weighted average for all household vehicles is then **23%**. The results also suggest that households with one vehicle react more elastically to changes in fuel prices than multi-vehicle households. The authors present their result as long-run effect because the data are cross-sectional spanning over 15 years period, nevertheless the model does not incorporate the effect of fuel price and efficiency on changes in vehicle stock including buying a car for the first time. **Goldberg (1996)** is one of the first who apply the discrete/continuous model to the travel demand. She primarily studies the effect of the U.S. Corporate Average Fuel Efficiency Standards (CAFE) on the data from Consumer Expenditure Survey covering the period 1984-1990. In the first stage, the probability of a household buying a car, choosing new or second-hand vehicle, choosing one of the nine vehicle categories of new cars and choosing between domestic and foreign make is estimated by nested logit model. In the second stage, Goldberg applies both the reduced form and instrumental variable approach. The resulting short-run[23] rebound effect, estimated as the elasticity of VMT with respect to the cost per mile $\eta_{P_S}(S)$, is negative which would imply that rising fuel efficiency leads to less driving. The coefficient is however insignificant and Goldberg therefore concludes that the direct rebound effect is **zero**. Interestingly, when the reduced form equation is estimated by OLS method, the rebound effect is equal to 22%, suggesting that the endogeneity bias can be

[22] In this case $\eta_\varepsilon(S) = -\eta_{P_S}(S)$ by the restriction imposed on the model.

[23] The effect of fuel efficiency on buying any car is not accounted for in the model, the long-run rebound effect is therefore not determined. On the other hand, an average fuel cost elasticity of demand for a particular model is estimated at 50%, signalling a larger rebound effect in the long run.

substantial. The energy efficiency is treated as exogenous but the vehicle category is based mainly on the efficiency and therefore the endogeneity may be largely accounted for. Following Goldberg, **West (2004)** applies the discrete/continuous model this time to an analysis of distributional effects of vehicle pollution control policies. She relies on cross-sectional data from U.S. Consumer Expenditure Survey from 1997 supplemented by data on energy efficiency. In the first stage, a nested logit model is estimated for probability of owning a car (or two) and then which engine size and how old car to have. The continuous VMT equation is estimated by the conditional expectation correction method. As in Puller and Greening (1999) the miles traveled are estimated for a household. West puts together the price per mile and maintenance and tire cost per mile to form a variable called total operating cost. Due to this aggregation the resulting elasticity of VMT with respect to the cost per mile cannot be determined because West doesn't provide a breakdown of the total operating cost. The **87%** elasticity of VMT with respect to the total operating cost then provides only an upper bound to the direct rebound effect. Statistical significance of the correction term in VMT equation suggests that a simple OLS would lead to biased estimates. The possible endogeneity of fuel efficiency is ignored though. **Frondel and Vance (2009)** studied the rebound effect in Germany. They use data from German Mobility Panel (GMP) spanning 1997 through 2006, in which each household is surveyed over a six-week period for three consecutive years. Randomly selected households without car were added to the sample so that they represent roughly 20%. GMP contains detail data on vehicle miles driven, price paid for the fuel and fuel efficiency. Household and car specific control variables, however, are a few. Interestingly, the study compares the three definitions of the RE - $\eta_{\varepsilon}(S)$, $\eta_{P_S}(S)$, $\eta_{P_E}(E)$ and its results can be compared to a study by Frondel, et al. (2008) which analyzed the same data but used a single equation model. Frondel and Vance applied a Two-Part model, in which the VMT by car are conditional on the choice whether to own a car or not. To exploit the panel dimension data they employ the fixed-effects estimator[24]. The estimation yields the short-run[25] rebound effect between **49% and 52%** and a hypothesis of symmetric reaction to a change in energy prices and efficiency was not rejected. On the other hand, a hypothesis that the own-price elasticity of energy demand $\eta_{P_E}(E)$ is of the same order as $\eta_{\varepsilon}(S)$ was rejected. It is notable that the Two-Part model

[24] This specification was employed also in the 2008 study, where the fixed-, between- and random-effects estimators were compared and yielded similar results.

[25] As it is conditional on having a car and the fuel efficiency is not an explanatory variable in the discrete choice model, long-term adjustments are not accounted for.

accounts for the possible correlation between the choice of owning a car and its usage due to some unobserved factors. Moreover, the fixed-effects specification allows controlling for the time-invariant unobserved factors. Compared to the study by Frondel, et al., the estimates are smaller, which indicates that the endogeneity of having a car (in other words sample selectivity in this case) is not fully caught by fixed-effects specification. The results are nevertheless higher than those of a study on German aggregate data by Walker and Wirl (1992) who found the *long-run* rebound effect between 30% and 50%. The omission of capital costs as an explanatory variable could potentially bias upwards the estimate based on $\eta_{P_S}(S)$ and ignorance of potential endogeneity of the energy efficiency as well.

Following observations emerge from the empirical evidence on passenger vehicle transport:

- Three studies (Greene, et al., 1999; Frondel, et al., 2008; Frondel and Vance, 2009) test and do not reject the symmetry argument, which suggests that estimates of the direct rebound effect from the efficiency and the own-price elasticity of the demand for useful work should bear similar results.

- Estimation of a single equation model bears higher direct rebound effect compared to multiple equation models estimated by appropriate methods (Goldberg, 1996; West, 2004; Frondel and Vance, 2009). The cause for endogeneity of some vehicle attributes is therefore reflected in empirical evidence.

- The theoretical endogeneity of the fuel efficiency and the number of vehicles on the microeconomic level is not reflected in a majority of aggregate data.

- The long-run rebound effect is found considerably higher than the short-run effect by a majority of studies which estimated both. We can therefore infer that the energy efficiency has an important impact also on the vehicle stock.

- The direct rebound effect is found decreasing with income (Small and Van Dender, 2006; West, 2004). This also implies a caution in comparing results from different periods and countries as they differ in levels of income per capita.

- Provision of better quality attributes, proxied by premium vehicle dummy or by capital cost associated with them, is found to influence positively the demand for useful work (in Frondel et, al., 2008; West, 2004). Therefore it can be deduced that the utility from an energy service with better attributes exceeds the cost of their provision and the trade-off between useful work and quality attributes is not necessary.

- The issue of different reaction of single- and multi-vehicle households to changes in energy efficiency is not settled by results of empirical studies as Greene, et al. (1999) find higher short-run elasticity but Frondel, et al. (2009) find no statistically significant difference. On the other hand, the reaction to an increase in energy prices is found higher for single-vehicle households by both studies, which is in line with a common sense that multi-vehicle households can readily substitute towards a more efficient car.

6.2 Household Heating

Econometric evidence on the rebound effect in household heating is based on household survey, cross-section data. Unlike with the personal automotive transport, these studies are fewer, but besides U.S. they offer evidence also on the rebound effect in Canada, Austria and Norway. However, most studies estimate the own price elasticity of the demand for energy, and therefore provide only an upper bound to the possible rebound effect. There are only two studies that estimate an efficiency elasticity; **Schwarz and Taylor (1995)** estimated efficiency elasticity of useful work, where the efficiency was defined as the thermal resistance of a house and useful work as either thermostat setting or thermal comfort, their long-term effect result for U.S. is very low - **between 1.4% and 3.4%**; **Haas et al. (1998)** estimated the efficiency elasticity of energy demand, where the energy efficiency was defined either as thermal resistance of the house or efficiency of the heating system, their long-term effect result for Austria is **between 15% and 48%**. Both studies use a single equation model with logarithmic functional form. Guertin et al. (2003) and Klein (1988) estimated the own price elasticity of the demand for useful work – this time measured as thermal comfort. While **Guertin** applied also a single equation model and found the long-run rebound effect in Canada from **29% to 47%**, **Klein** applied a multi-equation model derived from the concept of household production function in which the demand and cost function for useful work, and the relative share of capital and fuel are simultaneously determined. Consequently, the model is estimated by 3SLS with short-run results between **25% and 29%**.

A discrete/continuous model was used by **Dubin and McFadden (1984)** for U.S. households and by **Nesbakken (2001)** for Norway with short-run results of **25%-31%** and **21%** respectively. However, they provide evidence for the rebound effect only from the own-price elasticity of energy demand without controlling for efficiency, which can be an inaccurate proxy as suggested in the Chapter 4.3.

6.3 Other Household Energy Services

Studies examining other than household heating and transport are very scarce. Only two studies deal with estimation of demand for energy used for space cooling, both using discrete/continuous model estimated by nested logit and instrumental variable technique. **Hausman (1979)** presented a comprehensive framework for estimating the demand for space cooling and a discrete choice of appliance energy efficiency, modeling the decision as a trade-off between the capital costs of the equipment and its operating costs. His estimates are **4%** for the short-run and **26.5%** for the long-run. However, the data include only 46 households, which can be hardly considered a representative sample. **Dubin et al. (1986)** estimated efficiency elasticity of the energy demand on cross-section data from Florida. Energy efficiency is this time defined as a composite of thermal insulation of the house and energy efficiency of the cooling system. The resulting short-run rebound effect is very low ranging **between 1% and 26%**. The direct rebound effect was also estimated by Guertin (2003) for small appliances and lighting and by Davis (2007) for clothes washing. Since the data availability is very restricted, these studies are the only ones that deal with other household services and provide extremely limited evidence on the possible rebound effect in this domain.

To summarize the existing empirical literature on the direct rebound effect, the evidence is very heterogeneous. Many studies try to cope with the theoretical endogeneity of certain control variables by applying a model based on simultaneous equations. Some studies also try to control for the capital costs so that they would avoid biased results. However, data at disposal are often insufficient to construct proper control variables or are simply missing. Even though the concept of a discrete/continuous choice is theoretically very relevant for household energy services, it is applied only in few studies. All the studies provide evidence only on the direct rebound effect that stems from higher utilization and larger appliance stock. The effect on purchasing appliances with higher capacity (such as SUVs), which are more energy intensive is not captured by the empirical estimates.

7 CZECH DATA SOURCES ON THE TRANSPORT DEMAND

To estimate the Czech demand for transport we crucially need data that contain at least two of the three following information – distance driven (S), fuel efficiency (ε) and fuel consumption (E) (alternatively fuel expenditures). When only ε and E are at disposal, S can be computed from $S=\varepsilon E$. In the same manner ε can be computed when we know only S and E. Having the fuel expenditures, S and ε have the advantage of computing also the actual price paid for fuel. The data should moreover give information on income, capital cost of the vehicle and other household and vehicle characteristics.

7.1 Aggregate Data

The Ministry of Transport together with the Transport Research Centre publishes yearly transport books. The only data included concerning the personal automotive transport volume are passenger kilometers traveled aggregated over all types of vehicles. The data needed are vehicle kilometers traveled (VKT) divided according to types of fuel used. Such information enables obtaining the average on-road fuel efficiency because consumption of fuels by passenger cars is available. What is more, a proper price of fuel can be matched with the data, which is important because unlike in U.S., almost 20% of the VKT are driven in diesel cars[26]. However, the data on VKT are disposable only for 1990, 2000 and 2005 when a transport survey was conducted and therefore no source for aggregate estimates is available.

7.2 Household Budget Survey

The household budget survey is run by the Czech Statistical Office and contains data on 3000 households and their expenditures on fuel, capital and other operation costs connected to the use of personal vehicles. There is also information on passenger vehicles owned and the year of purchase. However, unlike U.S. consumer expenditure surveys, it lacks further details on the vehicle stock owned. It is therefore not possible to even approximate the energy efficiency and consequently, neither the distance traveled. The survey thus contains no information to estimate the travel demand.

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[26] Transport Research Centre, 2009. *Study on transport trends from environmental viewpoints in the Czech Republic 2008.* Brno.

7.3 ENERGO

A pilot survey on the household energy consumption was run by the Czech statistical office in 1997 and comprised 6000 households. It was followed up by a more extensive survey in 2004, which covered already 40 000 households, a representative 1% sample of all Czech households.

The information on household's passenger cars includes number of cars, their average fuel efficiency, the total distance driven per year and the main type of fuel used. Unfortunately, there is no information on expenses on fuel and therefore the fuel prices would have to be taken from a different source. Furthermore, age and capital costs are missing as well as any other vehicle characteristic.

The main problem of this survey is that it contains minimum information on households - only the number of household members, type of dwelling and whether they live in an urban location. Missing above all is the household income.

In summary, ENERGO survey contains the three main variables for estimating the direct rebound effect in personal automotive transport, e.g. the total distance driven by a household, number of cars and their average fuel efficiency. All other important explanatory variables are nevertheless missing and those such as income would be difficult to impute.

7.4 The Transport Demand Survey

The survey was run by Charles University Environment Center in 2008 in five Czech agglomerations – Prague, Brno, Hradec Kralove, Pardubice and Pilsen and covers 691 households. The main subject of the survey was the choice of the means of transport for daily needs with an accent on public transportation. An emphasis was also given to household vehicle equipment and fuel consumption. Therefore, the survey contains information on the number of vehicles disposable to the household, their age and whether they are owned by the household. For a car used to city travels, there is a type of fuel, fuel efficiency in city and either total monthly fuel consumption of that car or fuel expenses. The survey also asks the percentage of fuel expenses falling to city travel and if multiple-vehicle household, either total monthly fuel consumption or distance traveled or fuel expenses for all vehicles.

The main variables (mainly the distance traveled) are not straightforwardly determined in the survey and for multiple-vehicle households the average fuel efficiency is likely to be indeterminable (if total distance traveled is missing). In the case of one-vehicle household, we know either the monthly fuel consumption (E), then fuel efficiency in city can be used as proxy for overall fuel efficiency (ε) in computing the monthly distance traveled ($S = E \cdot \varepsilon$), or monthly fuel expenses ($P_E \cdot E$) and then fuel price from a different data source would have to be used to get the monthly distance traveled ($S = (P_E \cdot E) \cdot \varepsilon / P_E$). In the case of multiple-vehicle households the same information is available only for a city-travel car. For a part of the households that state the total distance traveled for all vehicles, the average fuel efficiency could be determined. However, for those who state either total monthly fuel consumption or expenses there is only the city fuel efficiency of the city-travel car – an unsuitable proxy for the average fuel efficiency of the household's vehicle stock.

Unlike ENERGO, this survey contains an exhaustive information on household characteristics that should figure as explanatory variables of vehicle travel: household income, number of licensed drivers, number of children, number of economically active members, cost of parking, whether the travel cost are paid by employer, ownership of a summer house, distance from the place of residence to city center, number of commutation tickets as a proxy for public transport availability.

To resume, this survey includes data on miles traveled by one car in a household, under the assumption that we can use fuel efficiency in city as a proxy for overall fuel efficiency. There are also the most important vehicle stock attributes – number and age, while quality attributes such as vehicle category or capital cost are missing. On the other hand, the household specific data provide a solid range of control variables.

8 CONCLUSIONS

Approaches to modeling and estimation of the demand for energy services are miscellaneous and when the research question is aimed at the reaction to changes in energy efficiency, the economic literature is not even unified in the basic definitions. We tried to provide an overview of the definitions and approaches and outline relationships between them so that they become comparable, which helps to assess already existing results and prepares theoretical ground for future research.

In the theoretical part, we explained the nature of energy services and how they can be perceived as a combination of useful work and quality attributes. We called the direct reaction of the demand for an energy service to changes in energy efficiency the direct rebound effect and suggested that under certain assumptions it is equivalent to the reaction to changes in the energy cost of useful work and alternatively also to the reaction to changes in energy prices. It was shown, however, that in reality, some of the assumptions are likely to be violated. Definitions based on elasticities with respect to energy cost or energy price can lead to biased estimates as they abstract from the interdependency of energy efficiency and other than energy costs. Moreover, even the definition based on the efficiency elasticity neglects the possibility that not only the demand for useful work depends on energy efficiency but also vice versa and that energy prices can be also partly endogenous. Last but not least, the correlation between the energy efficiency and the time efficiency may gain importance in determining the energy demand. Therefore, albeit we discussed only a part of the whole rebound effect, the theoretical part suggested that modeling even such a restricted household behavior can involve a chain of trade-offs and simultaneous decisions that can considerably complicate an empirical analysis. We presented models that explicitly express the manner of household decision-making and methods of their estimation. For their relative data exigence they are applied sparsely but the empirics show that the theoretical endogeneity of the appliance stock characteristics is very relevant and its ignorance leads to biased estimates.

The empirical evidence is most robust in United States, arguably due to their good databases and a wave of studies focused on evaluation of the Corporate Average Fuel Efficiency standards. In automotive transport the studies accounting for endogeneity of some explanatory variables estimate the short-run direct rebound effect between zero and 16% while the long-run effect around 22%. For Europe the evidence is limited and the reaction in the short-run varies between 6% and 52% while in the long-run between 6% and 66%. It can be inferred that households react to energy efficiency improvements by driving more with a given vehicle stock and in longer term also by enlarging of the vehicle stock. Nevertheless, the effectiveness of policies based on promoting fuel efficiency in the United States would not be considerably harmed by the household adjustments. In Europe on the other hand, half of the potential saving from higher fuel efficiency may be taken back, if the direct rebound effect is somewhere near the upper estimates. The empirical evidence furthermore supports the notion that the reaction to rising fuel efficiency should be higher for poorer households and therefore countries, which are not at the income and equipment level of the Western Europe and the United States, may possibly face much higher rebound effect. Studies focused on household heating are fewer and quantify the direct rebound effect between 21% and 31% in the short run and between 2% and 48% in the long run.

Our thesis should serve as a good basis for orientation in the methodological approaches to estimation of the demand for energy services and will be followed by their empirical implementation on the Czech data. However, the potential data sources for estimation of the direct rebound effect in the Czech Republic are only in the area of personal automotive transport and even those are very limited. Each dataset misses some of the crucial variables. Only the transport demand survey by Charles University Environment Center offers relatively enough information and therefore will be exploited in our future research.

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APPENDIX

Bachelor thesis proposal

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Proposed title: Energy efficiency improvement and the rebound effect of household energy demand

Topic characteristics

Energy efficiency improvements help to contain the energy demand increase and contribute to the sustainable development. However demand for energy is derived from the demand for energy services. Therefore if the energy services become relatively cheaper due to energy efficiency improvement, the demand for them can increase and offset, partially or completely, the energy savings. The percentage lost from the potential technical energy savings is called the rebound effect. For example having purchased more fuel-efficient car, the consumer may change behavior and drive longer distances or more often because the cost per kilometer decreased.

To estimate the rebound effect CGE models, evaluation studies and econometric models are used. In our work we focus on the econometric approach. Since the estimation of indirect rebound effect is rather complex, the published studies concentrate on the direct effect. Its estimation is based on the energy efficiency elasticity either of the demand for useful work (energy service) or for energy. Alternatively as the energy price elasticity of the demand for useful work or for energy. The techniques differ considerably in terms of data used and model structures.

The aim of our work is to summarize the existing findings about the rebound effect of the household energy demand and to provide a comprehensive overview of the econometric techniques used for its estimation. Finally we concentrate on the possibilities to estimate the rebound effect for the Czech households.

Outline

Household demand for energy – personal transportation
- heating and cooling
- other electric appliances services

Definition of the rebound effect
- direct – decomposition into the substitution and income effect
- indirect

Overview of the literature and approaches to the econometric estimation of the direct rebound effect.
- personal transportation
- heating
- cooling
- other electric appliances

Survey of the data availability for the estimation of the rebound effect for the Czech households.

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