LUNDS UNIVERSITET

Department of Economics

The Rebound Effect: Theory, Evidence and Implications for Energy Policy

Bachelor's Thesis

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Abstract

Improving energy efficiency is a popular means of reducing consumption of energy. When energy efficiency is improved, the marginal cost of energy and energy services will fall, leading to an increase in demand. This is called the rebound effect. This paper explains how the rebound effect arises and what determines the size of it. By examining existing research, it finds that rebound effects are ultimately determined by the price elasticity of demand for energy services, but that the research which is most reliable shows that these effects are small. The paper subsequently discusses the implications the rebound has on energy policy, with a focus on Swedish energy policy. It concludes that policies trying to induce energy efficiency improvements by attempting the raise the price of energy will also mitigate the rebound effect, indicating that these policies are more appropriate if rebound effects are large.

Keywords: energy efficiency, rebound effect, energy policy, energy economics

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1 Introduction

Improving energy efficiency is an important part of many countries' energy policies and is universally accepted as an effective means of reducing energy consumption (see e.g. Pacala & Socolow, 2003). One of the main objections to decreasing the use of energy is that since it is so inextricably linked to economic growth, reducing energy use may compromise living standards and wealth. Another fear is that that tighter restriction on energy use would make industry less competitive and cause businesses to migrate to places with less stringent regulations. The prospect of doing more with less, which incidentally is the title of a European Commission report on energy efficiency, has singled out energy efficiency as something of a silver bullet in the problem of lower the use of energy without hampering growth. Being able to sustain the recent levels of growth and welfare without having to worry about polluting emissions or any of the other negative consequences associated with increasing use of energy would obviously be desirable. The cost for governments to invest in energy efficiency is at the same time estimated to be lower than e.g. transitioning to more renewable energy sources, and are sometimes even associated with negative costs (i.e. there are profits to be made from investing in energy efficiency) (European Commission, 2006; McKinsey & Co, 2007). For these reasons and more, energy efficiency is an important part of many countries' energy policies.

Starting with William Stanley Jevons in 1865 and continuing with a number of energy economists from the 1970's and onward, a problem has been identified regarding the potential of energy efficiency in reducing energy consumption. During recent history, technological advances have led to ever increasing productivity in using energy as a factor of production. At the same time, the use of energy has increased exponentially. While this may come as no surprise (after all, energy increases with GDP and GDP has grown constantly over time), economic reasoning can be used in order to provide an explanation why energy efficiency may not be as effective as hoped. When energy is used more efficiently, the price of a given amount of energy falls, *ceteris paribus*. When prices fall, demand increases so that the improvement in efficiency indirectly is offset to some proportion by changes in consumption patterns. This is known as the rebound effect (Greening et al., 2000).

The aim of this paper is to examine what determines the occurrence and magnitude of the rebound effect according to economic theory. The characteristics of rebound effects will be handled with the help of fairly simply microeconomic tools and concepts such as elasticities and static equilibrium models. In light of my findings, policies on energy efficiency, with a particular emphasis on Swedish policy, will be evaluated to see which tools best mitigate the problems of rebound. In order to do so, I will review literature on the subject and present relevant findings.

While it is theoretically possible to show that energy efficiency is in fact entirely counter-productive, most empirical studies do show that pursuing energy efficiency is worthwhile as the rebound effect is at least less than 100 % and in some cases nearly insignificant (Sorrell, 2009). This paper finds that while there is a number of different policy measures used to promote energy efficiency, because the rebound effect is so tightly linked to the real price of energy services, policies which aim to increase the price of energy should be most effective in mitigating the rebound effect. As will be discussed, there are several problems associated with relying on price-policies, and mix of policy options is usually preferred (Sorrell et al., 2004, chap. 8).

The disposition of this paper will be as follows. Chapter 2 reviews some previous studies of the rebound effect and energy policy. The third chapter gives some definitions of terms and concepts which will be used throughout the text. The fourth chapter covers the reasons for why improving energy efficiency is desirable and how technological advances have led to efficiency gains in the past. The fifth chapter goes through the rebound effect theoretically and summarizes some of the empirical evidence for it. The sixth chapter covers what the barriers are to increasing energy efficiency, the government's roll in encouraging this and which policy instruments are used generally and more specifically in Sweden. The seventh chapter discusses policy options in light of the knowledge about the rebound effect. The eighth chapter concludes.

1.1 Delimitation

This paper focuses mainly on the microeconomic explanation of how rebound effects arise. There is much literature on how rebound effects occur at economy-wide levels of aggregation (see e.g. Saunders, 2000), and these findings will be presented insofar as they are necessary to analyze the implications of policies on energy efficiency. As will be presented below, the studies which have been conducted on the micro level give much more modest estimates of rebound effects and are at the same time subject to much less debate regarding the validity of their findings. The economy-wide debate surrounding rebound effects is rarely based on empirical data, but rather draws conclusions from theory and historical evidence. There is little consensus on how rebound effects manifest themselves at the macro level making it difficult to draw any definitive conclusions on the matter. For this reason, rebound effects at the macro level are only handled summarily, provided mainly to enable understanding of how the debate on the rebound effect has developed historically.

2 Earlier research

Sorrell (2007, 2009), Sorrell & Dimitropolous (2008), Berkhout et al. (2000) and Binswanger (2001) have studied the microeconomic interpretation of rebound effects. Reports by various organizations have been used to review general policies on energy efficiency (IEA, 2009; McKinsey & Co, 2007), as well as work by Schipper & Meyers (1992). A Swedish Government Official Report (SOU 2008:25, Energiutredningen, 2008) has been the basis of the review of Swedish energy policy.

While most studies on the rebound effect include analyses of policy implications, there are a limited number of studies which focus on the implications of rebound effects on energy policy in Sweden. The Swedish Environmental Protection Agency has issued a report (Naturvårdsverket, 2006) on the problems of rebound effects when designing environmental policy. This report focuses mainly on issues belonging to higher levels of aggregation than mine, such as welfare and economic growth and discusses how society is to deal with the surplus of energy created when energy efficiency increases. Sorrell (2007) has authored a report to the UK Energy Research Council on the rebound effect, with a section devoted to how energy policy, specifically British policy, can be adapted to mitigate the rebound effect. To this end, he finds that policies which target prices may be more effective than other policies. Levett has written a chapter in Sorrell & Herring (eds.) (2009) on how to design policy in order to account for rebound effects. He also points out some of the issues with using price-targeting as a policy response.

This paper attempts to specifically analyze Swedish policy in light of microeconomic findings of the rebound effect, an approach which as so far been missing from the corpus of research of the rebound effect and energy policy.

3 Definitions

In this section I will define some terms and concepts which will be made use of throughout the text.

The energy content of fuels, heat or electricity is commonly measured in Joules, which is the basic unit of measurement in the SI system. At the aggregate level, different units are often used when measuring total energy use. One of the most common is tons of oil equivalent (toe). The relationship between these are 1 EJ (exajoule) = 10^{18} Joules = 240×10^{6} toe. To get a sense of scale, annual per capita energy consumption is on average 5.7 toe in Sweden (compared to e.g. 8.35 toe in the United State and 3.64 toe in Denmark). The total global energy consumption is approximately 53 million toe (US Energy Information Administration, 2009-11-08).

When referring to electricity it is common to speak in terms of watts (W) and watt-hours (Wh) to measure effect. Most often kWh (= 1000 Wh) are used when speaking of personal consumption, whereas TWh (= 10^{12} Wh) in the case of consumption at higher levels of aggregation (Schipper & Meyers, 1992, p. xi). It is common to convert the entire energy consumption into TWh, and the total Swedish consumption of energy was approximately 624 TWh in 2007 (Swedish Energy Agency, 2008, p 54).

Technically, energy is neither produced nor consumed. According to the first law of thermodynamics, it can only be transformed between different states. Regardless, it is commonplace to use these terms when discussing energy in the same way as for “regular” goods and services. The second law of thermodynamics implies that as energy is transformed from one state to another, there will be losses from conversion. In other words, these processes are never completely efficient (see e.g. Areskoug, 2005, pp 62-63).

Energy efficiency can be measured in a number of ways. At the aggregate level, energy intensity is often used, which is defined as the amount of energy consumed per unit of GDP (see e.g. Schipper & Grubbs, 2000). At the basic level of aggregation, energy efficiency is measured as the amount of useful work received for a level of input of energy. This is often measured as the thermal efficiency, denoted by the Greek letter eta, η. I will use this notation for energy efficiency throughout the text. A more formal definition can be stated as

$$\eta \equiv \frac{W}{Q}, \qquad (3.1)$$

where W denotes the useful work or output, and Q the amount of energy put into the process (see e.g. Areskoug, 2005, pp 64-66). I will use these definitions throughout the text as well. For example, if a 60-watt incandescent light bulb emits around 3 watts of light, this yields a thermal efficiency of $\eta = 3/60 = 0.05 = 5\%$.

The output or useful work, W, will also be used to denote an energy service. In the above example, the energy service is the light provided by the light bulb. In other cases it could be driving a car, measured e.g. as the distance driven (where the appropriate input, Q, would be fuel), space heating or running a washing machine (Areskoug, 2005, pp 69-72). By definition, the energy efficiency is therefore improved if the amount of useful work for a given amount of energy increases. The reason for focusing on energy services is that consumption of energy per se can hardly be said to yield any utility. Rather, it is necessary to focus on what is actually accomplished with the energy that is consumed.

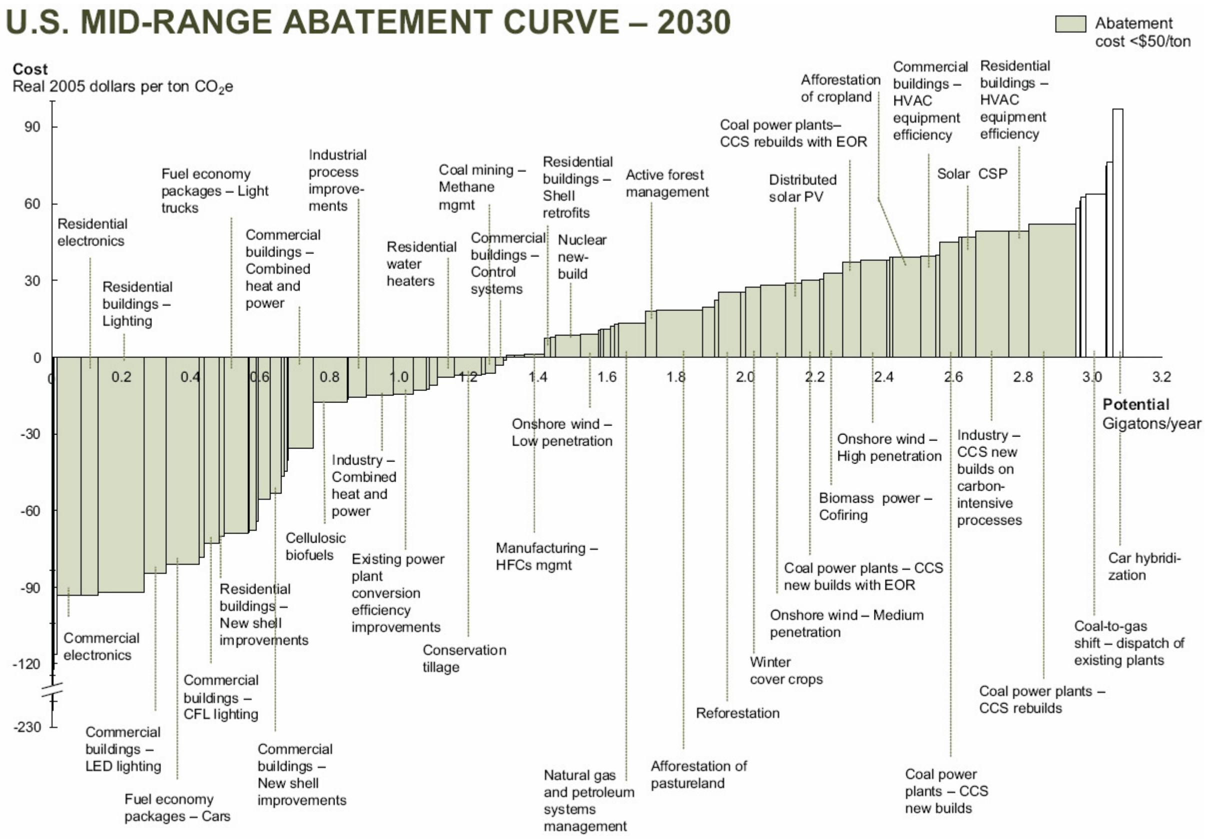
4 Energy efficiency

4.1 Reasons for Investing in Energy Efficiency

There are several reasons for promoting energy efficiency. In the case of dealing with a finite source of energy, improvements in energy efficiency are necessary in order not to deplete the resource. Dependence on foreign sources of energy are often seen as risky from a security perspective, and being able to be self-sufficient using domestic sources is often politically attractive. In the wake of the oil crisis in 1973 many countries started implementing energy efficiency policies in order to move away from dependence on oil, the price of which became higher and more volatile (IEA, 2009). Today, roughly 50 percent of the energy consumed in Europe is imported. This share is expected to rise to 70-80 percent over the next 20 to 30 years (European Commission, 2006). Currently, the argument for promoting energy efficiency receiving most attention is perhaps to enable the decrease in use of fossil fuels and the emissions of greenhouse gasses associated with it, reducing the need to make absolute cuts in the burning of fossil fuels, the consumption of which is strongly correlated with economic growth (Tietenberg & Lewis, 2009, chap. 8). The International Energy Agency, in its World Energy Outlook report for 2009, describe energy efficiency as the single most important source of CO_2 abatement, accounting for more than half of the reduction in carbon emissions hoped to be achieved by 2030. The improvement of energy efficiency is considered by many to be the most "economic, proven, and readily available means of achieving [a better use of the world's resources]" (IEA, 2009). The International Panel on Climate Change strongly urges governments to implement policies targeting improved energy efficiency: "World governments should exploit energy efficiency as their energy resource of first choice because it is the least expensive and most readily scalable option to support sustainable economic growth, enhance national security, and reduce further damage to the climate system" (IPCC, 2007, p 7).

Some energy consumption is hard to replace with substitutes. Energy services such as lighting and heating, or the power needed to run industrial equipment can come from a wide range of sources, fuel used in the transport sector is harder to replace. While there are substitutes to fossil fuels in the form of biofuels, the potential supply of these greatly falls short of the demand for fuel. Increasing energy efficiency in the transport sector is therefore important (IEA, 2008).

Energy efficiency will not be provided in adequate amounts by the market as energy use is associated with negative externalities (Tietenberg & Lewis, 2009, p 183). This is one of the barriers to implementing energy efficiency measures which will be discussed below. However, many improvements in the efficient use of resources are actually estimated to lead to “negative costs”. In other words, there is money to be made from investing in energy efficiency. The logic is that implementing measures to increase energy efficiency will lower the amount of energy consumed and thereby lowering costs, perhaps enough so that the investment is more than covered by the savings in lower energy costs over the life-span of the product. For example, in the building sector, improving the efficiency of lighting by replacing incandescent light bulbs with CFL:s (compact florescent lights) or LED:s (light-emitting diodes) is estimated to save both energy and money if implemented (McKinsey & Co, 2007, p 34-6). If all the options available to decrease CO_2-emissions were ordered according to the cost per ton of CO_2-equivalent, one would get a marginal abatement cost curve. An example of this curve is presented in Figure 3. As can be seen, many of the measures associated with negative costs are those which promote energy efficiency. There would seem to be a “free lunch” available here, as Brookes (2000) puts it.



Source: McKinsey analysis

Figure 1. Marginal abatement costs for reducing CO_2-emissions. Adapted from McKinsey & Co (2007).

4.2 Historical Advances in Energy Efficiency

Energy efficiency has improved constantly over the course of history due to technological progress, which can be characterized as occurring in irregular leaps. For example, Thomas Edison’s first electricity-generating plants in the 1880’s could convert less than 10 percent of the energy content of coal into electricity, and a light bulb of that era converted approximately 1 percent of the electricity into light. This meant that 0.1 percent of the energy stored in coal was converted into light. Comparable figures in 1994 were 40 percent efficiency in coal power plants and 20 percent for the best light bulbs, implying that 8 percent of the energy in coal was converted into light. The efficiency of light therefore increased 80-fold in a little over a century. Similar advances have been made in steam-driven machines, where the first engines could only convert a fraction of a percent of energy into useful work, whereas modern turbo generators are more than 40 percent efficient (Smil, 1994, p 12; p 229). Aside from the technological advances in energy conversion processes, the increasingly efficient use of energy has up until recently, and still is in many cases, a residual of other objectives, such as cost-minimization (Brookes, 2000).

Over the past 200 years, the energy intensity of the global economy has fallen as a result of technological improvements (Grübler, 1998, pp 280-290). This trend is continuing: since the first oil crisis in 1973, energy intensity has fallen considerably in the OECD-countries. In 2000, the energy intensity had fallen to two thirds of the energy intensity in 1973 (Geller et al., 2006). An implication of the ever increasing energy efficiency is that the cost of energy services has decreased (Berkhout et al., 2000).

5 Rebound effects

In this chapter I present the economic explanation for the presence of the rebound effect. I will also show how the magnitude of the direct rebound effect is related to the own price elasticity of demand for energy services and the efficiency elasticity of demand, and when more goods are added to the analysis, how the direct and indirect rebound effects can be explained in terms of the substitution and income effects. I also briefly review the debate regarding economy-wide rebound effects. Finally, I present some empirical estimates of the rebound effect.

5.1 Economic theory

When there is an increase in energy efficiency, this leads to a decrease in the marginal cost of providing an energy service. In a simple model of supply and demand, this is illustrated as an outward shift of the supply curve, as depicted in Figure 1. The efficiency gain is associated with a lower price corresponding to a larger quantity of the energy service being consumed.

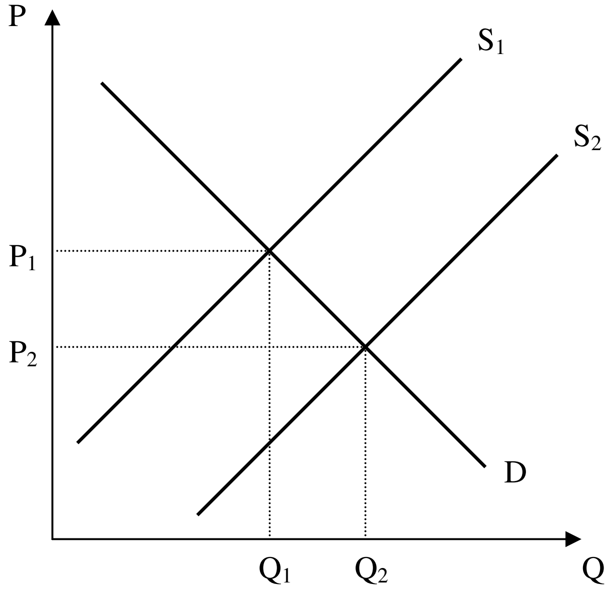


Figure 2. The effect of a lower marginal cost of an energy service.

Further, there will be effects on the quantity demanded of other goods as a lower price of one good means that the consumption possibilities of the consumer have expanded due to a larger budget. When energy efficiency increases, less energy is used to produce a given energy service, but because more of that service is demanded, more energy is consumed. This secondary effect is what is called the rebound or take-back effect (Sorrell, 2009). A simple example of this rebound effect is fuel efficiency in cars. Increased fuel efficiency means that a longer distance can be driven for a given amount of fuel. The price of fuel (in terms of cost per mile) would drop, which would mean that the demand for fuel increases. The consumer may then drive more because of cheaper fuel, which would increase the consumption of fuel. This is called the direct rebound effect. Further, the cheaper fuel may also expand the car owner's budget so that he can purchase more of other goods which also use energy as a factor of production. This indirect rebound effect illustrates the fact that the changes in price and energy use will have repercussions on other markets as well. These secondary effects could potentially be far-reaching. The energy efficiency improvement obviously causes rebound effects on many levels, the first-order effect being relatively easy to quantify, with each successive order proving more and more difficult to quantify (Berkhout et al., 2000).

The size of the rebound effect depends on the system boundaries within which it is studied. These boundaries could e.g. be a single firm, a market, several markets or the whole economy. Sorrell et al. (2009) define rebound effects on three levels:

- Direct rebound effect

  Increasing energy efficiency leads to lower real price of energy services, which causes demand for energy to rise. This effect may offset some or all of the energy saving made from increasing efficiency.

- Indirect rebound effects

  The lower cost of energy services means that the cost of energy services have decreased and the consumer's budget has expanded. The consumer can now purchase more of other goods and services, which also use energy as an input when produced. This will further increase the energy use as a consequence of the efficiency increase.

- Economy-wide rebound effects

  The lower real cost of energy causes changes in demand at the economy-wide level, with energy as a factor of production replacing other factors of production. The increased use of energy from this effect can partially or, arguably, totally offset the savings made from increased productivity.

Below, I will describe the rebound effects on the three levels more thoroughly, with an emphasis on the direct and the indirect rebound effect.

5.1.1 The direct rebound effect

In this section I will examine how the magnitude of the rebound effect depends on the price elasticity of demand of the energy service. It can then be established that the relationship between the rebound effect and the real price of energy services is a key to understanding how energy efficiency policy can be designed to take the rebound effect into consideration.

There are a few different methods of handling the direct rebound effect analytically, but they all have in common that they define the rebound effect as a function of price elasticity or efficiency elasticity of the energy service in question (Sorrel, 2009). I will use the most parsimonious one for clarity's sake. The efficiency elasticity explains the percentage change in demand for the energy service (i.e. the useful work) and energy (i.e. the input) respectively as the energy efficiency changes by one percent. Denoting the useful work as W and energy as Q, efficiency as η (where $\eta \equiv W/Q$), and the elasticity as ε, the two efficiency elasticites can be defined as

$$\varepsilon_{\eta W} = \frac{\partial W}{\partial \eta}\frac{\eta}{W}, \qquad (5.1.1.1)$$

which is the efficiency elasticity of demand for the energy service, and

$$\varepsilon_{\eta Q} = \frac{\partial Q}{\partial \eta}\frac{\eta}{Q}, \qquad (5.1.1.2)$$

which is the efficiency elasticity of demand for energy (See Sorrell & Dimitropoulos, 2008). The relationship between expressions (5.1.1.1) and (5.1.1.2) can be shown to be (see Berkhout et al., 2000)

$$\varepsilon_{\eta Q} = \varepsilon_{\eta W} - 1, \qquad (5.1.1.3)$$

which tells us that the if the demand for an energy service does not change when energy efficiency is increased by one percent, then the demand for energy decreases by one percent.

This would mean that net energy savings are the same as engineering savings. Expression (5.1.1.1), the efficiency elasticity of demand, can thus be interpreted as the direct rebound effect.

Due to data restrictions most research uses price elasticities to estimate the direct rebound effect (Sorrell, 2009). When deriving the rebound effect from the price elasticity of demand it is assumed that other inputs are held constant (Sorrell & Dimitropoulos, 2008). With the help of this exercise, it is possible to show more clearly how the size of the rebound effect is determined by the price elasticity of demand. The price of an energy service, P_W, can be expressed as

$$P_W = P_Q / \eta . \qquad (5.1.1.4)$$

The price of an energy service will go down, *ceteris paribus*, if the energy efficiency increases. From this it follows that the demand for an energy service (*W)* can be written as a function of energy prices and efficiency such that

$$W = w\left(P_Q , \eta\right).^{1}$$

Similarly, the demand for energy (*Q*) can be written as

$$Q = q\left(P_Q , \eta\right) / \eta .$$

The relationship of price elasticity of demand for energy and the efficiency elasticity of demand is

$$\begin{aligned} \varepsilon_{\eta Q} &= \frac{\partial Q}{\partial \eta}\frac{\eta}{Q} = \frac{\partial\left(W/\eta\right)}{\partial \eta}\frac{\eta}{Q} \\ &= \left[W\frac{\partial\left(1/\eta\right)}{\partial \eta} + \frac{1}{\eta}\frac{\partial W}{\partial \eta} \right]\frac{\eta}{W} \\ &= \left[-W\eta^2 + \frac{1}{\eta}\frac{\partial W}{\partial \eta} \right]\frac{\eta^2}{W} \end{aligned}$$

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[1] Note that *w* denotes a function, as does *q* in the subsequent expression.

$$= \frac{\eta}{W}\frac{\partial W}{\partial \eta} - 1 \qquad (5.1.1.5)$$

$$= \varepsilon_{\eta W} - 1$$

Using the fact that $\eta = P_Q / P_W$, equation (5.1.1.5) can be rewritten as

$$\begin{aligned} \varepsilon_{\eta Q} &= \frac{\eta}{W}\frac{\partial W}{\partial \eta} - 1 \\ &= \frac{P_Q/P_W}{W}\frac{\partial W}{\partial (P_Q/P_W)} - 1 \\ &= -\varepsilon_{PW} - 1 \qquad (5.1.1.6) \end{aligned}$$

Equation (5.1.1.6) says that the efficiency elasticity of demand for energy is equal to minus the price elasticity of demand for the energy service minus one. From this equation it is evident that a high price elasticity of demand for an energy service corresponds to a large rebound effect (Berkhout et al., 2000). Equation (5.1.1.6) implies that a 1 % increase in energy efficiency is followed by a decrease in energy demand equal to $(1 - |\varepsilon_{PW}|)\%$ (Binswanger, 2001). A good is said to be inelastic if $|\varepsilon| < 1$ and elastic if $|\varepsilon| > 1$ (see e.g. Varian, 2006, chap. 15).

In words, the efficiency elasticity of demand of an energy service, which can be interpreted as direct rebound effect, is inversely proportional to the price elasticity of demand for an energy service. If the price elasticity of demand for e.g. driving a car is large, then a change in the price of driving (from better fuel efficiency or lower fuel price) elicits a large change in the amount of driving done. As equation (5.1.1.6) shows, a high price elasticity of demand for an energy service will also be associated with a high efficiency elasticity of demand. The relationship between the price and efficiency elasticities of energy can be shown to be $\varepsilon_{\eta Q} = -\varepsilon_{PQ} - 1$, which shows that the rebound effect can be approximated as the own price elasticity of demand (Sorrell & Dimitropoulos, 2008). Generally speaking, the more price-elastic an energy service is, the larger the rebound effect will be. In addition to these, there are a number of definitions of the rebound effect which take into consideration such aspects as time costs. A highly elastic demand for energy could lead to the extreme case of the rebound effect, namely backfire.

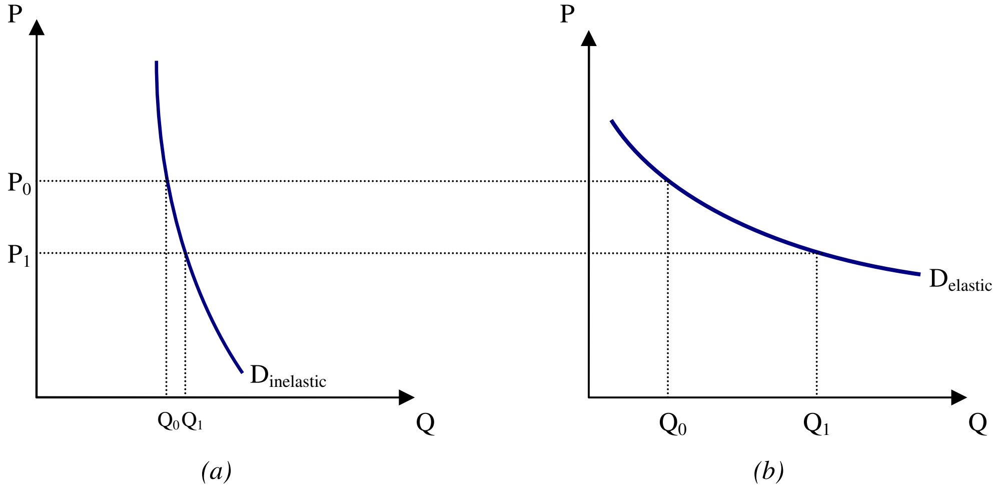

Figure 3. Change in demand due to lower price for different price elasticites.

Figure 3 clearly illustrates what happens to the quantity demanded of an energy service depending on the price elasticity. In panel (a), demand is very inelastic, and a price change therefore has little effect on the quantity demanded. Panel (b) displays an elastic demand, where a price change causes a larger effect on demand.

The exercise presented above begs the question of how elastic demand is for energy services. Empirical estimates of the price elasticity of demand for energy services show that they are usually inelastic (Sorrell et al., 2009). However, energy services are often interconnected and energy markets are full of feedbacks which can make it difficult to analyze them (see e.g. Levett, 2009). Energy services are provided through energy systems which include the energy source, primary and secondary conversion equipment as well as the equipment to actually distribute the energy. This could be, in the case of space heating, oil which is burned in a boiler which runs a radiator which in turn is distributed through air ducts. The efficiency of an energy system can be defined as the ratio of useful work to total energy input. How to measure this depends on what the boundaries of the energy system are and what energy services are to be included in the measure. For example, a car may be said to provide the useful work of transporting the passengers a certain amount of kilometers. A more energy efficient car would thus be one which could transport the passengers farther using the same amount of fuel. But it is entirely possible that if energy efficiency is improved, consumers choose to buy larger cars which consume more fuel, so that they travel the same distance for a given amount of fuel as before, leaving total fuel consumption unchanged. Under these circumstances, perhaps the useful work that is provided by cars should be defined as kilometer-tons. There is obviously a deal of complexity in deciding what actually useful work is, but this does have a profound consequence in estimating the rebound effect. There is evidence that the average fuel economy of cars in the United States decreased by about 10 % between 1987 and 2002 as a result of people buying larger cars (Stern, 2006, p 383). Therefore, ignoring the possibility of consumers changing cars will give misleading estimates of the rebound effect. A similar situation exists for e.g. refrigerators. While an increase in the energy efficiency of refrigerators probably will not cause consumers to use their refrigerators more, it is possible that larger refrigerators are purchased, which means there is a rebound effect. In Japan, average electricity use by refrigerators decreased 15 % between 1979 and 1997, but the average size increased by 90 % over the same period (Geller et al., 2006). Obviously, there are practical limits to how large refrigerators for domestic use can be. There is clearly decreasing marginal benefit from energy services so that at a certain point demand is saturated (Schipper & Grubb, 2000). If demand is saturated, price changes will only lead to minor responses from consumers (Naturvårdsverket, 2006). The size of the rebound effect will thus depend on how much the demand for energy services is actually constrained by high prices or limited resources of energy. If the consumer is actually held back from driving as much as he would like because the price of fuel is too high, then he would be expected to drive more with a more efficient engine. If he on the other hand does not demand more of an energy service the rebound effect is less of a problem (Greening et al., 2000). Of course, there is an obvious possibility that someone expecting to be doing more driving purchases a more fuel efficient car and subsequently drives more, which would not be a rebound effect (Small & Van Dender, 2007). Furthermore, it seems plausible that the lower price of an energy service should attract new consumers of the good whose willingness-to-pay were not met previously, which would cause demand for energy services to rise.

5.1.2 The indirect rebound effect

The technical derivations of the direct rebound effect generally assume that there is a single-service market so that the demand for an energy service ultimately is determined by the own-price elasticity of demand. The above treatment of the rebound effect is the one pioneered by Khazzoom in the early 1980’s and is associated with several restrictive assumptions. The single-service model implicitly assumes that there are no other services which might be substituted for as prices change, so that substitution and income effects are not taken into account. Failing to take these into consideration might lead to overestimating the rebound effect (Binswanger, 2001). With the determinants of the magnitude of the rebound effect explained, I will now explain when and why the rebound effect occurs with the aid of a simple microeconomic supply-and-demand model. Including another good in the analysis also allows for explaining the indirect rebound effect.

Consider a consumer who can choose to allocate his income between two goods, X being an energy service (such as driving) and Y being a composite good which is everything other than good X which the consumer wants to purchase. We assume that the consumer wants to maximize his utility so that he consumes at indifference curve which is located as far to the right of the origin as possible.

The consumer's budget constraint is

$$p_X X + p_Y Y \leq m \qquad (5.1.2.1)$$

where the p_i represents the price of each good, X and Y the quantity of each good, and m the consumer's budget.

In Figure 4, the initial budget line for the consumer is the innermost of the two thick lines. Consumption takes place at point A, which is associated with utility level U_0. When there is an increase in energy efficiency in the energy service, the price of that service will drop. The endpoints of the budget line represent the amount of each good that could be purchased if the consumer's entire budget were allocated to that good. The price of good X is lowered, so with the same budget the consumer can now purchase more of that good. The decrease of the price of X is illustrated as a pivot of the budget line around the vertical intercept. This allows the consumer to purchase commodity bundle B, which is associated with a higher utility level than A. He now consumes X_2 of the energy service which is higher than previously. The increase in energy efficiency is therefore associated with an increase in demand for the energy service, so that the consumption of energy increases. This is a simple illustration of what the rebound effect is.

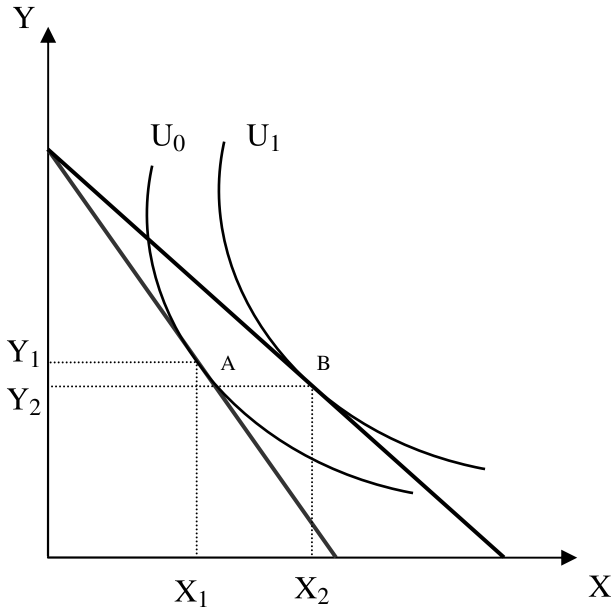

Figure 4. Rebound effect for the consumer. Adapted from Berkhout et al. (2000).

It may be illuminating to make a numerical example based on the explanation above. Borrowing notation from Berkhout et al. (2000), let E(X) denote the energy use corresponding to consuming amount X in the initial situation, and E′(X) the energy use corresponding to amount X after the increase in energy efficiency. The energy used in producing amount X will be smaller after the increase in efficiency, so that

$$E(X) > E'(X).$$

This allows the size of the rebound effect (RE) to be defined as

$$\text{rebound effect} = \frac{E'(X_2 + Y_2) - E'(X_1 + Y_1)}{E(X_1 - Y_1) - E'(X_1 - Y_1)} \times 100\%. \qquad (5.1.2.2)$$

Assuming that Y is a non-energy good so that the increase in energy efficiency does not affect it, (5.1.2.2) reduces to

$$\text{rebound effect} = \frac{E'(X_2) - E'(X_1)}{E(X_1) - E'(X_1)} \times 100\%. \qquad (5.1.2.3)$$

Consider a person who drives on average 10 km per day consuming 10 liters of fuel. Assume there is a gain in fuel efficiency so that only 6 liters of fuel is required to drive the 10 km but that the person now chooses to drive 12 km per day instead. The rebound effect will then be

$$
\begin{aligned}
&\frac{72-60}{100-60}\times 100\% \\
&=\frac{12}{40}\times 100\% \\
&=0.3\times 100\% \\
&=30\%
\end{aligned}
$$

The rebound effect in this case would be 30 %. The engineering savings are calculated as $(10-6)/10=4/10=40\%$. Of these 30 % are "taken back" due to the rebound effect, leaving net energy savings resulting from the increase in energy efficiency of $(1-0.3)\times 0.4=0.24=24\%$, instead of the 40 % originally predicted.

The rebound effect can be decomposed into an income effect and substitution effect, as illustrated in Figure 5 (Greening et al., 2000).

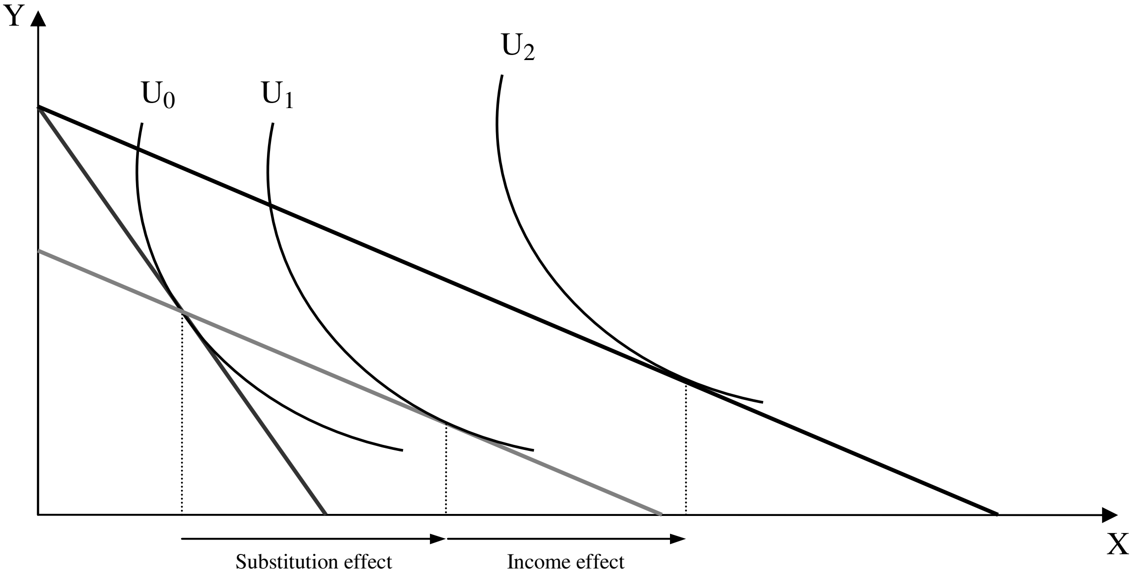

Figure 5. Decomposition of increased demand into substitution and income effects.

The substitution effect arises from the fact the lower price of the energy service allows the consumer to substitute consumption of other goods for the cheaper energy service, and the income effect comes from the increase in real income due to the increase energy efficiency which allows a higher consumption of all goods, including the energy service (Sorrell, 2009). The substitution effect thus corresponds to the direct rebound effect and the income effect to the indirect rebound effect. As was presented in section 4.1, one advantage of investing in energy efficiency is the money which can be saved as a result of the adoption of more efficient energy services. The higher the money-saving potential, the larger the income effect should be as more money is made available to spend on other goods and services. However, "[t]he size of the [indirect rebound effect] for a consumer is dependent on the share of the consumer's total income or total expenditures spent on energy services. Since energy is a relatively minor share of an individual consumer's total expenditures, the secondary effects are probably insignificant" (Greening et al., 2000). In other words, because expenditure on energy services generally do not constitute a large part of an individual's budget, the budget increase resulting from a lower real price of the energy service will not be very large.

An issue raised by Lovins is that many energy services become inferior goods at higher levels of income, so that the income effect may reduce the rebound effect (Binswanger, 2001). According to the Slutsky identity, the size of the total change in demand is identical to the substitution effect plus the income effect. The sign of the substitution effect is always the opposite that of the price change (i.e. if the price decreases, demand will increase and vice versa) (Varian, 2007, pp 142-3). This means that if an energy service were an inferior good, the size of the rebound effect would be smaller than otherwise. However, there is little empirical evidence for this, and studies of the OECD countries show that energy consumption increases with income levels (Binswanger, 2001).

The rebound effect also applies to firms. Consider a firm producing a good, Y, with two the two production factors energy, E, and capital, K, so that the production function can be written as

$$Y = f(K, E).$$

The production possibilities are illustrated in Figure 6 where the thicker curves are isoquants representing different combinations of K and E for which the same amount of output of Y can be attained. The rebound effect will affect a producer as "an improvement of energy efficiency implies that he can (a) shift the production factor mix in the long run, and (b), reduce the unit production costs, creating a margin for price setting – dependent on his market power." (Berkhout et al., 2000). Initially, the producer maximizes output at point A, which required K_1 capital and E_1 energy. As energy efficiency is improved, a given amount of output can be produced with the same amount of capital but with less energy than before. Because the isoquants represent the combinations of production factors required to produce a given amount of output, an increase in energy efficiency and the resulting decrease in energy required for production is illustrated as a leftward shift of the isoquant, from Y to Y′, which results in production at point B, with energy use now at E_2. However, it is evident that this is not an optimal point of production as it is possible to substitute energy (from E_2 to E_3) for capital (from K_1 to K_2) to produce the same amount of output but at a lower cost. Doing this brings production to point C which is associated with a lower production cost than A for the same amount of output. With perfect competition, prices will fall to reflect the new level of production costs. Depending on how elastic the demand is, the price drop will cause demand to rise and production to move to point D. Energy use now moves to E_4, and there is a second rebound effect, which will depend on how elastic demand is. It is possible that the demand is such that $E_4 > E_1$, illustrating a case of backfire (Berkhout et al., 2000).

As energy efficiency improves, the firm will increase the use of energy at the expense of other inputs. This will occur until the marginal productivities of all factors are equal. This will induce the firm to consume more energy services instead of other inputs. The elasticity of substitution will decide how much of the other inputs are substituted for energy services and is therefore an important determinant of how large the rebound effect will be. An elasticity of substitution of 1 implies that as marginal rate of substitution between two factors of production changes by one percent, the ratio of inputs to production change by one percent. If there is an increase in the productivity of energy and the elasticity of substitution between energy and, say, capital, is less than 1, then and increase in energy efficiency will lead to a net decrease in energy use. If it is greater than 1, then the total energy consumption will increase as a result of the increased productivity of energy (Greening et al., 2000).

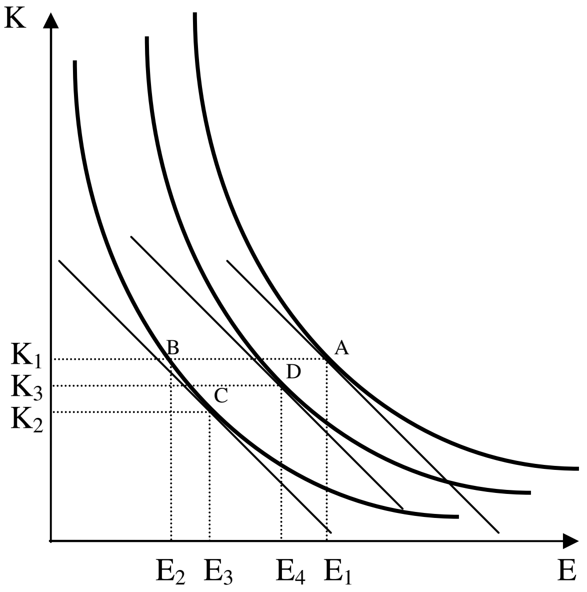

Figure 6. Rebound effects for a producer. Adapted from Berkhout et al. (2000).

It is, of course, entirely possible to extend this example to a consumer ”producing” household energy services such the temperature in a room using heating or insulation as mentioned above.

As mentioned above, when taking more markets and goods into account, elasticity of substitution, i.e. the ease with which one factor can be replaced by another in production is an important determinant of the size of the rebound effect (Birol & Kepler, 2000). Many energy efficiency improvements can be characterized as substituting capital for energy. An example of this could be the possible combinations of energy and capital in order to maintain a certain indoor temperature, where it is possible to substitute fuel (energy) for insulation (capital). However, the installation and maintenance of this capital also consumes energy. As a second example, if the energy efficiency in steel production were to increase, then the price of steel should drop. Industries which use steel as input in production would then be able to pass savings on to producers of goods further down the production chain, so that the price of e.g. cars would decrease, thereby increasing the demand for cars as well as fuel so that total energy use might increase. Because of the many possible feedback mechanisms and complexities, it is difficult to estimate these indirect rebound effects, but they are generally believed to be smaller than the direct rebound effect due to the fact mentioned above that energy constitutes a relatively minor share of both consumers’ and producers’ budgets (Sorrell, 2007).

Some studies point out that rebound effects with respect to energy efficiency can be partly explained by the invention and adoption of increasingly time-saving equipment. Many technological innovations are designed to save time (rather than to explicitly save energy), but also consume more energy. This is especially true for periods of low energy prices, as incentives to invest in energy efficiency will be lower. Illustrations include traveling by car instead of horse or on foot, using electric razors instead of visiting a barber and writing e-mails instead of letters. Each of these transitions speeds up the process of transportation, shaving and correspondence respectively, but may require more energy in order to do so. The "time cost" of performing these various tasks decreases, which, by the same reasoning as for the rebound effect with respect to energy, means that consumers demand more of that particular service. Similarly, with more time on their hands, consumers are now free to engage in other activities which in turn require energy. These effects should be stronger the higher wages are as the opportunity cost of time increases (Binswanger, 2001). Depending on how consumers chose to spend this extra time, there may be an increase in total energy consumption so that a rebound effect with respect to time is observed (Naturvårdsverket, 2006).

5.1.3 Economy-wide effects

At the highest level of aggregation, the rebound effects can be explained as the increase in energy consumption arising from productivity gains. The exact nature of this relationship is a matter of debate (Sorrell, 2009). The issue is whether it can be determined if the increase in demand can be attributed to improved productivity (Schipper & Grubb, 2000).

William Stanley Jevons is credited with first identifying this effect. Jevons's concern was identifying the risk of Great Britain's running out of coal, which at the time was the driving force behind the county's industry, and that in a more efficient usage of coal "we have, it is supposed, the means of completely neutralising the evils of scarce and costly fuel" (Jevons, 1865, p 137). However, Jevons refuted this notion: "It is wholly a confusion of ideas to suppose that the economical use of fuel is equivalent to a diminished consumption. The very contrary is the truth." (ibid, p 140). Additionally, Jevons outlines how an increase in efficiency in one factor of the economy, while it may not lead to increased consumption in itself, has repercussions on other parts, so that the increasingly efficient use of coal in one sector would put further strains on the coal reserves due to more activity in other sectors (ibid, pp 141-142).

Jevons' Paradox describes the most extreme version of the rebound effect, sometimes called "backfire" (Sorrell, 2009), a scenario where a gain in efficiency of using a resource will lead to a net increase in the use of it. As I have described above, measures to increase energy efficiency play a prominent roll in many countries' energy policies, especially in light of environmental issues associated with the use of fossil fuels. A case in point for Jevons is the 2/3 reduction of coal used to produce one ton of iron in Scotland between 1830 and 1863 leading to a ten-fold increase in the consumption of iron, "not to speak of the indirect effect of cheap iron in accelerating other coal-consuming branches of industry" (Jevons, 1865, p. 154). These feedback effects could be elaborated upon to claim that the lower cost of iron made both steam engines (which burn the coal) as well as railways (which transport the coal) cheaper, exacerbating the rebound effect (Sorrel, 2009).

Papers published by Khazzoom and Brookes during the late 1970's and 80's led to a heated debate regarding the merits of increasing energy efficiency as a means to reduce energy use. According to them, the energy consumption today is larger than it would have been had energy efficiency efforts not been undertaken. The papers sparked a debate between economists which was reignited in light of concerns of global warming in the early 1990's. While both camps seem to agree that there are microeconomic rebound effects, how this translates into effects at the economy-wide level, and whether or not increase energy efficiency leads to backfire has been a matter of fierce debate. The supporters of using energy efficiency as means to reduce energy use argue that there is a difference between improvements in energy efficiency arising from technological development and improvements arising as a result of political intervention. Sectors where technological advances are likely to be made are those where demand is sensitive to price, whereas markets where demand is inelastic are less likely to induce "naturally" occurring improvements in efficiency. But these are often the sectors where most gains can be realized, and therefore often the target of government policy. The markets where there are natural incentives to improve energy efficiency will be constrained by high prices or a limited supply of energy. In these cases there would be a risk of encountering large rebound effects, but on markets where there are no constraints the risks are smaller. The rebound effect arising from policy-driven gains in energy efficiency would therefore be significantly smaller than those caused by technological advances which are driven by the will to overcome constraints in the form of high prices or low supply. As a consequence, using the rebound effects seen in naturally occurring technological development as evidence for rebound effects in policy-driven energy efficiency-increases is not valid, according to those who do not believe large rebound effects at the economy-wide level (Grubb, 1990). Those who argue that improving energy efficiency causes backfire do not believe in extrapolating results obtained at the microeconomic level to the economy-wide level, but that this ignores certain complexities. They stress the importance of increased productivity in other factors of production as an explanation for the fact that energy intensity has fallen (Brookes, 1990). These claims have empirical support. Schurr (1985) shows that during the period from World War I to the oil crisis, energy use per hour worked in the United States rose, but that the energy intensity of the economy fell as a result of the economy growing faster than energy use. It is important to keep in mind that this debate centers on the question of whether there is backfire or not at the economy-wide level, i.e. if the rebound effect is greater than 100 %.

Saunders (1992) gives the hypothesis that increased energy efficiency at the micro level will lead to higher energy consumption at the economy-wide level the name the Khazzoom-Brookes postulate and incorporates it into a neoclassical growth model. He shows that with a Cobb-Douglas production function, increases in energy efficiency (energy-augmenting technological change) causes energy consumption to increase. At the same time, all technological improvements, which are the driving force behind economic growth in this framework, raise consumption per capita, so that more energy is demanded. While this is hardly contentious, the fact is that "pure" energy productivity gains caused energy use to increase due to cheaper energy substituting for capital and/or labor and the increase in consumption per capita in the model. Because energy use grows at the same rate as GDP in the absence of efficiency gains, the implication is that increased energy efficiency leads to higher levels of energy consumption. An economy-wide rebound effect can be seen as the increased use of energy due to higher GDP caused by improving energy efficiency (Schipper & Grubb, 2000). As the increase in productivity of any factor of production would raise total output, it is argued that the rise in multifactor productivity, whether from increases in the productivity of energy, labor, capital, etc., could completely offset the gains in energy efficiency by increasing the energy use. Therefore, a rise in productivity at the micro-level could at the highest level of aggregation of energy use lead to a net increase in the use of energy (Brookes, 2000). As Grübler (1998, p 289) puts it: "whatever technology has 'given' in the form of increase environmental productivity, it has more than ‘taken back’ through concomitant increases in output”.

While it is quite simple to demonstrate theoretically the existence of the rebound effect, empirically it has proven to be more difficult (Saunders, 2000). Economy-wide rebound effects have been estimated both using computer models and econometric estimates. Computer modeling gives varying results depending on how parameters are defined as well as general assumption of how markets and actors behave. Many of the findings from analyses at the micro-level are expected to be found at the economy-wide level as well: “Rebound effects may be expected to be larger in energy intensive sectors and also where the input mix is fairly flexible and where the demand for products is relatively price-elastic” (Sorrell, 2007, p 51). The existence of an economy-wide rebound effect is most often supported with historical evidence of ever increasing levels of technological advances coupled with more energy being consumed (Brookes, 2000).

5.2 Empirical estimates of the rebound effect

There are a number of studies which estimate the direct rebound effects for different energy services. The best documented are those for automotive transport and domestic space heating in OECD-countries as this is where most data is available. The size of estimations of the rebound effect will also be determined by the definition used, resulting in quite varying estimates (Greening, 2000).

Various studies employing different methods and definitions of the rebound effect have been conducted over the past years. Understandably, they come to quite different conclusions. The most well-documented rebound effects are the direct rebound effects, which are the ones which will be focused upon here. The conclusion of several studies is that demand for energy services is inelastic for OECD-countries, which means that there is little risk of large direct rebound effects or backfire. However, calculated elasticities must be treated with caution as they are rarely stable and vary with price-levels, price-change expectations and saturation (Sorrell et al., 2009). Personal transport is the energy service for which the rebound effect has been most frequently studied. Meta-analyses by Greening et al. (2000) and Sorrell et al. (2009) put the direct rebound effect for personal transport between 10 % and 30 %, but there is a rather large variance depending over different time scales, from 3 % to almost 90 %. In the case of the former interval, it would mean that energy efficiency improvements in the personal transport sector are associated with fuel savings of at least 70 % of the improvement in OECD countries.

Rebound effects for indoor heating are also relatively well-documented. Many of these studies also take a number of other variables into account, such as income of the household. Results show that the rebound effect is larger for low-income households, which may be due to the fact that their indoor temperatures are lower from the beginning. This is a good illustration of saturation, as indoor temperatures approach 21 °C, the rebound effect starts to decline. Reasonably, there is a limit as to how high someone would want their indoor temperature to be, much as there are limits to how much someone would drive regardless of the fuel prices. The rebound effects are estimated less accurately for indoor heating than transport, and are put at between 10 % and 60 %, with a mean value of 20 % (Sorrell, 2009).

End use	Range of estimates (percent)	"Best guess" (percent)
Personal automotive transport	3–87	10–30
Household heating	0.6–60	10–30
House cooling	1–26	1–26
Other consumer energy services	0–41	< 20

Table 1. Empirical estimates of direct rebound effects for different energy services. Source: Sorrel et al. (2009).

While not as numerous, there are estimates of the rebound effect in other household services as well, where the rebound effect for lighting is estimated to be less than 10 % (Sorrell, 2009) and the rebound effect for clothes washing is found to be around 6 % in a thorough study by Davis (2008).

Small & Van Dender (2007) argue that the rebound effects decrease with income levels as the cost of energy (fuel in their study) becomes a small part of the consumer’s budget. Rising incomes couples with decreasing real prices of fuel had led to the rebound effect for the years 1997-2001 being only half as large as the period 1966-2001.

Specifically for Sweden, Nässén & Holmberg (2009) have quantified the rebound effects and found it to be 5-15 % in most cases, while the rebound effect arising from switching from a large to a small car is 48 %.

While the distinction between the direct and indirect rebound effects are fairly straightforward to handle theoretically, as seen above, it is generally ignored in empirical estimates of the rebound effect (Binswanger, 2001), usually because of restrictions due to data availability (Greening et al., 2000).

Evidence for higher-order rebound effects is limited. Most of the findings are based on models and simulations (Greening et al., 2000). At the economy-wide level, the most common measure of energy efficiency is energy intensity, which can change without there being any change in the energy efficiency of individual equipment, thereby giving a misleading indication of energy efficiency improvements (Herring, 1998). The lack of evidence for economy-wide rebound effects means that the discussions have been mostly theoretical and speculative, using historical evidence as the main evidence for claims of large rebound effects (Sorrell, 2009). Evidently, it is hard to translate what happens with demand at the micro level when the efficiency of equipment is improved into how the entire economy reacts when the productivity of energy as a factor of production is increased.

6 Policy

In this section I will examine some of the barriers which explain why energy efficiency is not implemented to the extent that the cost-saving estimates presented earlier suggest it should be. Following this, I will present some of the basic ideas behind policies looking to overcome these barriers and summarize the specific policies in place in Sweden and what their results have been.

6.1 Barriers to implementing energy efficiency policies

This section reviews some of the factors that hinder the implementation of energy efficiency policies. The fact that these policies do not always lead to energy savings is one issue (see e.g. Oikonomou et al., 2009), but this section focuses on barriers to actually getting the policies in place. As described above, energy efficiency has improved considerably in the past through technological progress, but for reasons stated earlier, it is by many seen as desirable to speed up this process (European Commission, 2006). However, there are obstacles which hinder the implementation of such measures. The fact that energy efficiency is not as prioritized as it should be given the cost-saving potentials presented above, indicates the presence of hidden costs, market failures or other barriers (Stern, 2006, p. 378). One obstacle to switching over to more efficient technology is the cost. While neoclassical economic theory assumes that there are no adjustment costs in its models (Berkhout et al., 2000), this is obviously not true in reality. Even if it is plausible that a large initial investment in a new, more efficient piece of equipment will pay off over time as energy use and therefore costs decrease, it has been shown that consumers generally expect that household investments to have payback periods of 2-3 years. Even if this shortsightedness is overcome, consumers may not afford upgrading their existing stock of appliances (McKinsey & Co, 2007).

A second barrier is the pricing of energy. Energy prices are often lower than their true cost, a fact which affects investment decisions. There are several reasons for this, one being direct and indirect subsidies which lower the cost of energy to below marginal costs. A further issue is that the externalities associated with producing energy, such as pollution and emissions associated with the burning of fossil fuels are rarely reflected in the price of energy which is a typical case of a market failure leading to underinvestment in energy efficiency (Schipper & Meyers, 1992, pp 305-6).

A third barrier is the invisibility of energy consumption. For example, it is often difficult to determine how much each appliance in a household contributes to total energy consumption as this commonly lumped together in either in monthly or yearly electricity bills (McKinsey & Co, 2007). The energy use of households especially seems to be domesticated in a way that prevents individuals from realizing how the energy systems of their homes function (Löfström, 2008). This is perhaps not as big a problem for large firms as they tend to be more mindful of cost-saving potentials and have the technical staff to evaluate and implement these options (Schipper & Meyers, 1992, p 307). It may also be the case that households and small businesses do not care about energy costs as they often make up a small portion of total expenditure, and are therefore unwilling to take steps to increase energy efficiency (Grubb, 1990). The absence of a relevant price mechanism implies that consumers do not consider any budget optimization pertaining to energy costs (Birol & Keppler, 2000) In addition to not realizing the economic consequences of their energy use, consumers may not understand the environmental impacts their consumption patterns have (Stern, 2006, p 385).

A fourth barrier, common in the building sector, is the problem of "misplaced incentives" [2] (Schipper & Meyers, 1992 p 307). In many buildings, the constructor, owner and occupant are often different parties, which means that their interests in promoting energy efficiency are not always aligned. While the payer of the electricity bill wants this to be as small as possible, the construction firm may be more interested in cost-minimization and therefore installs cheaper but perhaps less efficient heating, appliances, etc. (McKinsey 2007). According to the IEA, of the energy used for refrigerators, space heating, water heating and lighting in the United States, more than 30 % was affected by problems of misplaced incentives (IEA 2007, p 191).

Another class of barriers is social and institutional norms which are strong determinants of behavior. In the case of perfect markets, market mechanisms are preferred to regulatory measures, but where there are barriers in the form of e.g. market failures, regulation may be appropriate. In a case where externalities are not included in the price of energy, banning certain chemicals or setting efficiency standards can remove the most environmentally harmful elements from the market entirely (Stern, 2006, p 377).

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[2] This is a case of a principal-agent problem (IEA, 2007) which is also known as the "landlord-tenant problem" (Stern, 2006, p 380).

These are some of the barriers which prevent energy efficiency investments from being as large as they optimally should. The aim of policies encouraging energy efficiency aim at removing these barriers or at least mitigate them.

6.2 General policy instruments for increasing energy efficiency

In this section is will summarize some of the policies used to promote energy efficiency in order to see how they affect the rebound effect. As several studies point out, investment in energy efficiency has been an integral part of many countries' energy policies since the oil crises of the 1970's. Policies aiming to increase energy efficiency will attempt to overcome the barriers to energy efficiency as discussed above. There are two main options for influencing energy efficiency through policy measures: changing relative prices so that energy becomes more expensive or introducing new, more productive technology. These are not mutually exclusive. Because energy efficiency gains and the energy intensities at higher levels of aggregation may deviate, as will be elaborated upon below, one of the main objectives of policies on energy efficiency must be to ensure that "improvements in technical energy efficiency translate to the largest possible extent into corresponding reductions in energy intensities" (Birol & Keppler, 2000).

The fact that energy prices do not reflect the true cost of energy is a market failure which limits the demand for energy efficiency savings. Other barriers are debatable if they actually are true market failures or rather normal aspects of a market economy, and if they can, or indeed should, be addressed by government policy. Appropriate energy policy may therefore see to correcting true market failures and provide information to consumers and investors in order to reduce uncertainty and risk associated with new technology. This can be done by targeting both existing and new goods and capital stock (Schipper & Meyers, 1992, pp 306-8).

As mentioned above, one of the main objectives of energy policy is to ensure that energy prices correctly reflect the societal cost of its use or at least that the price is equal to marginal cost. Many countries have subsidies which distort the price signals on the market. Removal of these, however politically unpopular, is one policy which would move the country toward encouraging energy efficiency. The production and consumption of energy is often associated with different externalities which are not reflected in the price. Most notable is pollution and emissions associated with the burning of fossil fuels. If energy prices were to internalize these externalities they would rise, causing energy efficiency investments to be more lucrative.

There are plenty of examples of how this could be done, e.g. by a tax on emissions, subsidies to more efficiency technology or by emission trading schemes (Schipper & Meyers, 1992, p. 311-25). As energy prices often are lower than what they would be if they reflected the entire societal cost, moving towards this theoretical equality would increase the price of energy. Following the induced innovation hypothesis posited by John Hicks, an increase in the price of a factor would spur innovation directed at economizing that factor (Newell et al., 1999). Raising the price of energy would therefore stimulate both a shift towards using the most efficient existing technology as well as spurring innovation where new technology is perfected.

Information may be provided in order to reduce the risk associated with investments in energy efficiency. This is especially important for households and small businesses (Schipper & Meyers 1992, p 312). This often comes in the shape of labeling of e.g. appliances, but there are also possibilities of energy auditing or counseling. Labeling of appliances combined with efficiency standards has been successful in reducing electricity usage in appliances (Geller et al., 2006). For example, two different television sets of similar type and size may differ in energy consumption by as much as 33 %. A clearer labeling of these differences may influence consumption choices (McKinsey 2007, p 37). Policies with goals of providing increased information are meant to tackle the problem of visualization described above. Apart from labeling, requiring utilities to provide clients with regular, accurate and informative energy bills is one way of informing households and firms of their energy consumption pattern. More sophisticated methods such as implementing smart meters in homes and workplaces, which give detailed information on energy use in real time, or gear shift indicators which let car drivers know when they should shift gears in order to maximize fuel efficiency, are other examples of how energy efficiency potentials can be revealed (Stern, 2006)

Imposing regulations and standards for equipment of buildings which regulate their energy efficiency is another common policy option used by governments. Design standards "can create scale economies for strategically important technologies" (Stern, 2006, p 383). Sometimes these come in the shape of agreements between the government and producers of certain equipment. (Schipper & Meyers, 1992, p 313) In Germany, an agreement between major industry and utilities to reduce the CO_2-intensity by 28 % between 1990 and 2005 is one example of this. Japan has enacted the "Front Runner" program, whereby the most energy efficient TV, refrigerator, toilet seat warmer etc. sets the standard for all products on that market to live up to. In the United States, standards for fuel economy in cars, CAFE-standards, have helped to increase the fuel efficiency in cars by more than 100 % from 1975 to 1988 (Geller et al., 2006).

Financial incentives are sometimes used to promote energy efficiency, either by offering rewards for efficiency in the shape of lower taxes, low-interest loans, exemptions from certain fees, etc, or by punishing poor efficiency with higher taxes or other fees (Schipper & Meyers, 1992, p 314-5). In many countries it is possible to obtain low-interest loans to support construction of buildings with low environmental impact (Geller et al., 2006, p 6).

Direct support to research and development of new technology is also a crucial policy instrument for governments to use. While private investments focus on short and medium term improvements in energy efficiency, government spending can be used to finance basic research which could improve energy efficiency in the long term as these are often less economically interesting for companies to invest in, as well as being associated with higher risk (Schpper & Meyers, 1992, p 315). Billions of dollars were granted to R&D related to energy efficiency in the United States following the oil crises. This was also a common policy response in Western European countries (Geller et al., 2006).

Both the use of energy and the efficiency with which it is used has increased immensely during the past centuries and decades, making the effect of energy efficiency programs hard to evaluate by simply observing time series of energy use. A common definition of energy efficiency at the economy-wide level is, as mentioned earlier, energy intensity. This is the ratio of units of GDP per unit of energy consumed. Energy intensity may be misleading, however, as in many advanced economies the service sector is replacing heavy industry as a source of income; the service sector consuming less energy than e.g. manufacturing. Usually, the impacts of energy efficiency investments are calculated based on hypothetical scenarios of what energy consumption would look like hade the investment not been made. Obviously, whether or not potential rebound effects are included in these calculation may have a large effect on what the impacts are found to be. As will be demonstrated in the next section, energy savings vary considerably depending on whether the full (potential) rebound effect is taken into account or not.

A recent report by the IEA (2009) reports data showing the effects of various energy policies on energy efficiency. Policies targeting households have played a key roll in improving energy efficiency in appliances and space heating since 1990, but these were offset by larger appliances being used as well as a larger number of small appliances. In the service sector, it is clear that energy intensity fell between the years 1990 and 2006, but it is difficult to determine whether or not this was the result of policies targeting energy efficiency. Most policies targeting personal transport have been aimed at increasing the fuel economy of cars. While this has increased by 15 % over the period surveyed, increased driving distances and number of cars has offset the gains from energy efficiency.

Most policies target end-use efficiency, i.e. the energy use in appliances, cars etc. rather than actually trying to alter consumer behavior (Geller et al., 2006) or increase the efficiency in the generation of electricity, the potential for which in many cases is approaching the theoretical maxima which the laws of thermodynamics dictate (Smil, 1994, p. 229).

6.3 Swedish policy

In this section I will summarize the policies used specifically in Sweden and what effects they have had on energy efficiency. In 2006, the European Union issued a directive mandating member states to undertake cost-effective, viable and reasonable measures in order to improve energy efficiency. A quantitative goal of 9 percent energy savings from energy efficiency of the baseline 2001-2005 values by 2016 was set. This is a part of the general target of reducing energy use by 20 % by 2020 set up by the EU, which, however, is not binding (Energiutredningen, 2008). Directives only specify the goal which is to be attained, the specifics of how this is done are up to the member states themselves to outline. Swedish policy on energy efficiency had been in place long before the directive, and earlier measures may in some cases be incorporated into the final 9 percent goal. In the case of Sweden, approximately half of the savings in 2016 (which are expected to exceed 9 percent) are savings derived from earlier energy efficiency policies between 1991 and 2005 (Energiutredningen, 2008). There are both specific policies targeting individual sectors of the economy, as well as more general policy measures such as energy taxes.

6.3.1 Taxes

Sweden taxes energy in a number of ways: both electricity and fuel are taxed, as well as emissions of CO_2 and sulfur dioxide (SO_2). The tax system is rather complex and differentiated depending on usage area and source, with industry receiving exemptions or reductions (Energiutredningen, 2008). Improving energy efficiency is one of the explicit goals of energy taxation (Swedish Energy Agency, 2008).

6.3.2 Buildings and residential sector

The building sector is where the largest gains from energy efficiency improvements are expected to be realized (Energiutredningen, 2008). The Swedish government subsidizes installation of more efficient heating systems in homes and places of business. There is a law requiring appliances to be labeled according to their energy efficiency with the aim of helping consumers in their purchasing decisions. The labeling is routinely followed up by controls at the locations of retailers. There is also a program of energy counseling where independent counselors help households, small businesses and organizations make decisions aimed at reducing energy use and increasing energy efficiency. In an agreement between the government and several agents in the building sector, banks, insurance companies as well as local government where the parties promise to work towards a set of goals which will promote sustainable development in the building sector, one of them being to reduce the amount of energy used through gains in energy efficiency (Swedish Energy Agency, 2007). In 2006, a law was passed that all new building must have energy declarations which are hoped to aid in identifying cost-effective efficiency improvements in individual buildings as well as clarifying the efficiency of a building for buyers, sellers and tenants. There are also minimum requirements pertaining to energy efficiency which must be fulfilled when renovating or constructing new buildings. In the long run, investments in research, development and demonstration are key instruments (Energiutredningen, 2008).

6.3.3 Industry

In 2004 the Program for Energy Efficiency was launched whereby a tax on electricity used by the manufacturing industry was imposed. Firms were given the possibility of receiving a full tax exemption provided they participate in a five-year program designed to help them improve the efficient use of electricity (Swedish Energy Agency, 2008). It is possible that this program will be extended to include smaller firms (Energiutredningen, 2008). A service called Energy Performance Contracting involves companies which analyze the technical and operational status of industries and buildings and compile the results into a program for increasing energy efficiency which the company performing the analysis guarantees will be profitable. This way, work dealing with making buildings and industries more efficient are outsourced to a third party, relieving the industries and operators of building of that burden (Swedish Energy Agency, 2007).

6.3.4 Transport

Fuel tax is the main way in which consumption of fuel is disincentivized and transition to low-energy modes of travel. Cars which can run on ethanol or biogas receive tax reductions, as do electric cars. Taxation of new automobiles (model 2006 or newer) is CO_2-differentiated, i.e. based on the amount of carbon dioxide they emit, as opposed to weight as was the situation previously, in addition to a basic tax. There is also a system of automatic speed control cameras erected along Swedish roads, a positive side effect of which is the reduction of fuel consumed by cars, as lower average speeds lead to lower fuel consumption of cars and can therefore be seen as a measure to increase energy efficiency. Education in "ecodriving" is now a part of Swedish driving school sessions, teaching prospective drivers how to drive more efficiently. In a longer perspective, improving social planning with respect to environmental issues and investments in research, development and demonstration are important policies (Energiutrednigen, 2008).

6.3.5 Policy results and forecasts

The Swedish Energy Agency estimates that energy use in Sweden has decreased by 82 TWh/year as a result of measures undertaken in order to increase energy efficiency. Forecasts of energy savings resulting from efficiency gains up 2016 are made under two scenarios, Scenario 1 where taxes are assumed to remain at the same level as in 2005, and Scenario 2 where taxes are assumed to rise at the same rate as during the period 1970-2005. Further, for each scenario savings are calculated both without the rebound effect taken into consideration as well as the full rebound effect taken into consideration.

Sector	**Scenario 1 Energy efficiency gains (TWh/year) 2016**		**Scenario 2 Energy efficiency gains (TWh/year) 2016**	
	Full rebound effect	**No rebound effect**	**Full rebound effect**	**No rebound effect**
Buildings	0,01	4,51	6,18 *	63,25 *
Industry (non-trading)	0,03	0,94	0,45	2,28
Transports	0,07	0,45	0,67	3,97
Total	**0,11**	**5,9**	**7,4**	**69,5**

*Table 2. Projected energy savings from improvements in energy efficiency. Source: Swedish Energy Agency. Note: * indicates insignificant estimates.*

Evidently, including a full rebound effect (i.e. 100 %) has a significant effect on estimates of how effective policies aiming at improving energy efficiency will be. The numbers presented in each column are the bounds between which the efficiency gains can be expected to end up depending on the size of the rebound effect. This interval is significant; it is obviously of interest estimating how large the rebound effects might be.

7 Discussion

Much hope is pinned on energy efficiency helping to reduce energy use and thereby emissions of greenhouse gases. However, taking the rebound effect into account, policies aiming to increase energy efficiency may not be as effective as intended. While few people would probably argue to try to halt technological progress, the source of many efficiency gains, it is perhaps relevant to question whether governmental policy should target energy efficiency as a means of reducing greenhouse gas emissions. There are, after all, many different options to achieve this (see e.g. Pacala & Socolow, 2003). Given the findings presented in section 5.2, the rebound effect only offsets a small portion of the reduction in energy use due to efficiency gains, meaning that energy efficiency probably still is worth pursuing for policymakers. This does not mean that the rebound effect should be ignored. The fact that energy efficiency seems to have so much potential for reducing energy consumption means that it should be of interest to mitigate these effects. Because the rebound effect arises mainly due to the price-sensitivity of end-users of energy services, policies which target the real prices of these services may be able to mitigate the rebound effect. However, as will be discussed shortly, there are problems associated with such policies.

In chapter 6, I presented some policies used to promote energy efficiency. These can be divided into those which directly target prices and those which do not. Obviously, energy taxation is the main example of these policy instruments, which is used in Sweden in e.g. the transport sector. In many parts of the world, energy is subsidized. Removing these subsidies would be one way to raise the price of energy services (Naturvårdsverket, 2006), but after they have been removed completely, some price-targeting policy would have to be implemented. Policies which do not target energy prices, such as information campaigns, and various programs like those in the Swedish building sector, would then not be able to cope with rebound effects.

As was presented in section 5.1.1, the direct rebound effects is closely related to the own price elasticity of demand for energy services. It is also the case that the price elasticity is lower when real prices are at a lower level. This means that rebound effects can be expected to be larger for those energy services that are relatively expensive and low for those that are relatively cheap.

As the direct rebound effect is expected to be larger where energy demand is more elastic, and research has indicated that the demand for energy services usually is inelastic, this would indicate that behavioral changes are not a threat to energy efficiency policies. Energy costs usually constitute small shares of both firms' and households' total budgets.

Assume governments where to try and keep the real price of energy from dropping by e.g. using taxes in order to compensate for gains in energy efficiency. This would mean that those who could not keep up with technological progress would face ever rising costs of energy services as they would face the barriers to energy efficiency as presented in section 5.1. Particularly, those who would be prevented from upgrading e.g. household appliances, cars due to the cost of doing so will most likely be low-income households, making such an approach seem unfair. Additionally, as was pointed out in section 4.2, technological advances are often made in "leaps", which makes them hard to foresee. If taxes were designed to reflect this, end-users who did not install the latest equipment would be subject to unpredictable prices, which is negative for investment (Schipper & Meyers, 1992, pp 312-3). Furthermore, should equipment be able to be replaced as energy efficiency improves, depending on how much could be recycled, the high turn-over rate for cars, household appliances, etc., would consume energy in order to produce new equipment. As pointed out by Levett (2009), the improvements in energy efficiency are different for different equipment, which, together with the inability for low-income households to keep up, "would have complex redistributive effects between different people and energy using products, and have more effect on some needed to neutralise rebounds, and less on others" (Levett, 2009, p 196).

Again, consider equation (5.1.1.4):

$$P_W = P_Q / \eta \, .$$

The objective of raising taxes on is to ensure that the price of the energy service, P_W, does not drop as a result of the energy efficiency, η, rising. This means that the energy price, P_Q, rises. An issue with this is that this is the price which will be visible to consumers, which could bring instances of money illusion, i.e. the phenomenon that consumers focus on nominal prices rather than real ones when making decisions, into play. Some research suggests that there is a bias towards nominal prices versus real prices in decision-making (Fehr & Tyran, 2001).

As described above, the debate regarding how energy productivity and energy consumption at the economy-wide level is yet to be resolved. In the case that there is a difference between policy-driven efficiency gains and those occurring “naturally”, as proposed by Grubb (1990), governments can continue promoting energy efficiency. If those who believe in economy-wide backfire are correct, then doing so would be entirely counter-productive. During periods of high oil prices such as during the oil crises of the 1970’s, energy demand is expected to fall. As explained above, during the same periods measures to increase energy efficiency were undertaken in order to reduce dependence on oil. According to Herring (1998), “whether this is due to the adverse consequences of higher fuel prices on economic activity or energy efficiency improvements, was a matter of fierce dispute.” The fact that the price elasticity of demand is proven to be quite small at the micro-level does not preclude that higher levels of aggregation bring with it increased consumption of energy as technological advancements are made. The lack of scientific consensus of what happens at the economy-wide level makes it impossible to conclude what implications there are for energy policy. Therefore, using the findings regarding the rebound effect at the micro level seems more appropriate.

Because the rebound effect arises when the price of energy decreases an implication is that policies which strive to raise the price of energy would be more efficient than non-price policies in terms of mitigating the rebound effect. As taxes can be set higher on goods and services for which the demand is inelastic (see e.g. Rosen & Gayer, 2009, chap. 16), energy is a prime candidate for high energy taxes, which is also the case in Sweden. Depending on how large the demand which is constrained by high prices or low supply is, the rebound effect will be large or small. Some research of how energy use at the economy-wide level is affected by energy efficiency improvements can lead to conclusions that pursuing policies aimed at increasing energy efficiency is counter-productive. Most research, however, does show while there are rebound effects, improving energy efficiency does reduce energy use.

8 Concluding remarks

Energy efficiency has often been regarded as something of a silver bullet to reigning in energy consumption which is desirable for a number of reasons, the most urgent of which, in recent years, is to decrease emissions of pollution associated with the burning of fossil fuels causing environmental degradation and contributing to climate change. Energy efficiency programs are an integral part of many countries' energy and environmental policies, among them Sweden.

This paper has showed how rebound effects arise as a result of consumption patterns adjusting to lower real prices of energy brought on by more efficient energy use. In the presence of rebound effects, policies which aim to promote energy efficiency may not be as effective as often assumed. Economists agree that there are rebound effects but not on their magnitude. Empirical studies at the micro level have shown that the rebound effects are small, usually no more than a few percent. Given the lack of empirical evidence at the economy-wide level for rebound effects and the evidence for an absence of large rebound effects at the micro level, a continued pursuit of energy efficiency as a means to reduce energy consumption seems to be suitable.

Rebound effects prove to be part of a system which is fraught with feedback loops, both positive and negative, which makes it dynamic, non-linear and hard to predict. Understanding how these effects arise and interact is crucial to designing effective policy. This paper has presented some, but surely not all of these feedbacks.

Government policy can be used to counteract the rebound effects. This paper has showed that the changes in real price of energy services caused by the efficiency improvement is a strong contributor to the rebound effect, implying that keeping the price of energy and thereby energy services high through government intervention may reduce the rebound effects. Because increasing the real price of energy is one way to induce the development of more efficient energy services, these policies may also have the benefit of mitigating rebound effects. However, targeting prices is not unproblematic: different energy-consuming equipment develops at different and often unpredictable rates, and not everyone will afford to keep upgrading their equipment.

8.1 Future research

There are many issues which would be interesting to study further in order to better understand how the rebound effect can be mitigated by policy measures. More research on how the economy-wide rebound effects work is desirable in order to resolve the debate regarding this. Without a deeper understanding of this, it is difficult to determine if energy policy should target energy efficiency. While there is a greater degree of consensus regarding rebound effects at the micro level, there are some areas which would benefit from more research. For example, it would be of great importance to determine if energy services which are the subject of energy efficiency policies targeting prices are more resilient to rebound effects, *ceteris paribus*, as the findings of this paper indicate should be the case.

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