Quantifying the Rebound Effects of Energy Efficiency and Energy Conserving Behaviour in Sweden

Jonas Nässén and John Holmberg
Chalmers University of Technology, Physical Resource Theory

ABSTRACT

Doubts have recurrently been raised on the extent to which energy efficiency can reduce the demand for energy since efficiency improvements may "rebound" due to decreasing prices of energy services (the price effect) as well as by increasing the budget for consumption of other goods and services (the income effect). The magnitude of such effects is crucial to whether energy efficiency should be a strategy for environmental policy or not. This paper aims to derive a general expression of the rebound effects of household consumption in a parameterized form where available data can be tested. The paper analyzes how different parameter assumptions affect the quantification of rebound effects and what may be reasonable ranges.

Income effects are quantified using data from the Swedish Household Budget Survey of different goods and services split on income classes. The changes in consumption with increasing income are used to establish the composition of marginal consumption. Combined with energy intensities derived from input-output analysis, this gives a model of how money saved on energy use in one sector may lead to increased energy use in other sectors.

The total rebound effects of energy efficiency appear to be in the range 5-15% in most cases, but these results are fairly sensitive to assumptions of energy service price elasticities. Cases with low or negative investment costs for energy efficiency may also result in much higher rebound effects as the income effects become more important. Energy conserving behaviour (reduced energy service demand) affecting direct energy use such as heating and transport fuels gives rise to rebound effects in the order of 10-20%, depending on the price per primary energy for different fuels and energy carriers.

1. Introduction

Energy efficiency is often identified as the single most important strategy for climate change mitigation. For example, the IIASA-WEC "ecologically driven" scenarios presume global reductions of energy intensities (energy/GDP) by 1.4% per year for the next 50 years, which results in more than twice as large reductions of carbon dioxide emissions as the substitution of fuels in these scenarios (Nakićenović et al, 1998). However, doubts have also been raised on to what extent energy efficiency can reduce environmental impacts since efficiency improvements may "rebound" through increasing consumption. The magnitude of such effects is crucial to whether energy efficiency can play its projected role and whether it should be a strategy for environmental policy or not.

The majority of previous quantitative studies on rebound effects analyze price-induced rebound which is often referred to as direct rebound. For example, Dubin et al (1986) found that the actual energy savings of energy efficient technologies were 8-12% below engineering estimates for heating and 13% below for cooling in the US. Haas & Biermayr (2000) found higher values (20-30%) for heating in Austria. Price-induced rebound effects have also been analyzed for private transports (e.g. 5-15% in Greene (1992), 30% in Jones (1993) and 20% in Greene et al (1999)).

Rebound may also occur in other sectors if energy efficiency saves money that can be redirected to other consumption. This can be termed income-induced or indirect rebound. Quantitative analyses of income rebound are much fewer than for price rebound. Alfredsson (2004) studies the rebound in other sectors if households were to adopt "green" consumption patterns, but does not analyze the effects of energy efficiency. Another recent study by Brännlund et al (2006) looked at both price and income effects and found very high rebound effects for energy efficiency in Sweden, concluding that net carbon dioxide emissions may even increase due to energy efficiency. However, the generality of that study may be questioned as it models energy efficiency as an exogenous factor of zero investment cost.

The aim of this paper is to derive a general expression of the rebound effects of household consumption in a parameterized form where available data and data ranges can be tested. Questions asked are: In what way do different parameter assumptions affect the quantification of rebound effects? What are the reasonable ranges for price and income induced rebound of energy efficiency and energy conserving behaviour?

2. Method

The method presented in this paper handles rebound effects due to changes in energy service price (the price effect) and changes in the real income of households (the income effect) but does not capture general equilibrium effects such as the adjustment of energy prices to aggregated demand.

2.1. Rebound Effect Model

We assume a constant budget m. The consumption is divided on N types of goods i, where A (i = 1) is a certain energy service (e.g. vehicle-km or the difference between indoor and outdoor temperature) and B represent all other consumption (i = (2:N)).

	Expenditures (USD)	Energy intensity (MJ/USD)
Energy service A	c_A	e_A
Other consumption B	$c_B = \sum_{i=2}^{N} c_i$	$e_B = \frac{1}{c_B} \sum_{i=2}^{N} c_i e_i$

Thus the total energy use E can be written as:

$$E = E_A + E_B = c_A e_A + c_B e_B \tag{1}$$

The initial energy use is denoted E^0. Let us assume an energy efficiency investment with an annuity of q which gives an expected reduction of the energy use in A by $\beta E_A{}^0$, so that:

$$E'_A = (1-\beta)E_A^o \tag{2}$$

E' is the expected energy use after the energy efficiency improvement given that only technology changes, i.e. if the energy service consumption x_A remains constant.

Price effect. The energy efficiency improvement also results in a reduction in *energy service price* p_A^0 to p''_A (e.g. USD/vehicle-km), and the energy use in A may thus rebound from E'_A to E''_A. The price-induced rebound effect R_{Price} can then be written as:

$$R_{Price} = 1 - \frac{E''_A - E^o_A}{E'_A - E^o_A} \tag{3}$$

The demand for energy services x_A depends on the energy service price p_A (e.g. fuel cost per km) with an *energy service price elasticity* α:

$$p''_A = (1-\beta)p^o_A \tag{4}$$

$$x_A = Kp^{\alpha}_A \tag{5}$$

Where K is a constant. Eq. (4) and (5) give that:

$$x''_A = (1-\beta)^{\alpha} x^o_A \tag{5}$$

$$E''_A = p''_A x''_A e_A = (1-\beta)^{\alpha+1} p^o_A x^o_A e_A = (1-\beta)^{\alpha+1} E^o_A \tag{6}$$

Inserting Eq. (2) and (6) into (3):

$$R_{Price} = 1 - \frac{(1-\beta)^{\alpha+1} E^o_A - E^o_A}{(1-\beta)E^o_A - E^o_A} = 1 - \frac{1}{\beta}(1-(1-\beta)^{\alpha+1}) \tag{7}$$

Income effect. In addition to the price-induced rebound effect within sector A, we may also have rebound effects due to changes to the budget. Money saved when moving from c^0_A to c''_A at the cost of q (the annuity of the energy efficiency investment at available interest rates) may be spent on any of the N types of goods i (including the energy service A). Thus the energy use in A and B may rebound further from E''_A to E'''_A and $E^0_B = E'_B = E''_B$ to E'''_B. The total rebound effect R_{total} can then be written as:

$$R_{Total} = 1 - \frac{E'''_A - E^o_A + E'''_B - E^o_B}{E'_A - E^o_A} \tag{8}$$

So, the two questions here are basically how much money is saved and how is it spent. In the special case of a break-even investment, the annuity q_{BE} is simply βc_A^0. The money saved is:

$$c^o_A - c''_A - q = c^o_A(1-(1-\beta)^{\alpha+1} - \beta\frac{q}{q_{BE}}) \tag{9}$$

We further define a marginal consumption factor γ for all goods i so that $\sum\gamma_i = 1$ (this factor is explained further in Section 2.2):

$$\gamma_i = \frac{dc_i}{dm} \tag{10}$$

The new consumption levels can be written as:

$$c_i''' = c_i'' + \gamma_i c_A^o (1-(1-\beta)^{\alpha+1} - \beta \frac{q}{q_{BE}}) \tag{11}$$

$$c_A''' = c_A^o (1-\beta)^{\alpha+1} + \gamma_A c_A^o (1-(1-\beta)^{\alpha+1} - \beta \frac{q}{q_{BE}}) \tag{12}$$

$$c_B''' = \sum_{i=2}^{N} (c_i^o + \gamma_i c_A^o (1-(1-\beta)^{\alpha+1} - \beta \frac{q}{q_{BE}})) \tag{13}$$

The new levels of energy use E'''_A and E'''_B:

$$E_A''' - E_A^o = c_A^o e_A ((1-\beta)^{\alpha+1} - 1) + \gamma_A c_A^o e_A (1-(1-\beta)^{\alpha+1} - \beta \frac{q}{q_{BE}}) \tag{14}$$

$$E_B''' - E_B^o = \sum_{i=2}^{N} \gamma_i c_A^o e_i (1-(1-\beta)^{\alpha+1} - \beta \frac{q}{q_{BE}}) \tag{15}$$

Inserting Eq. (2), (14), and (15) into (8):

$$R_{Total} = 1 - \frac{1}{\beta}\left[1-(1-\beta)^{\alpha+1} - \frac{1}{e_A}\sum_{i=1}^{N} \gamma_i e_i (1-(1-\beta)^{\alpha+1} - \beta \frac{q}{q_{BE}})\right] \tag{16}$$

If we use Eq. (7) we can rewrite Eq. 16 as:

$$\boxed{R_{Total} = R_{Price} + \frac{1}{e_A}\sum_{i=1}^{N} \gamma_i e_i (1 - R_{Price} - \frac{q}{q_{BE}})} \tag{17}$$

Where R_{Price} is a function of α and β.

We have now shown that the total rebound effect can be written as a function of four dimensionless parameters:

- The energy service price elasticity α
- The share of energy saved initially β
- The ratio of investments to break-even investments q/q_{BE}
- The ratio of energy intensity in A to the total marginal energy intensity $\sum\gamma_i e_i/e_A$.

In the case of *energy conserving behaviour* (i.e. reduction of energy service consumption such as lowering indoor temperature or driving fewer kilometers), R_{Price} and q are zero. We also need to modify the factor $\sum\gamma_i e_i/e_A$ slightly to exclude rebound in sector A:

$$R_{Behaviour} = \frac{\sum_{i=2}^{N} \gamma_i e_i}{(1-\gamma_A)e_A} \tag{18}$$

2.2. The Data

From Eq. 16 we see that three sets of data are required: (1) the shares of marginal household expenditures γ_i, (2) the energy intensities of the consumed goods and services e_i, and (3) the energy service price elasticity α. The parameters β and q/q_{BE} are case specific.

Marginal expenditures. The marginal expenditure shares on goods and services γ_i for an increase or decrease in real income are significantly different from the share of average expenditures. To estimate this distribution we utilize expenditure data from the Swedish Household Budget Survey (HBS) 2003 (Statistics Sweden, 2004) which divides household expenditures in four income segments (quartiles) and four household types (single persons with and without children, and cohabiting persons with and without children).

We look at the expenditures in each household type separately in order to avoid including differences which depend on the size of households (a larger portion of households with two adults are found in the upper household income quartiles). By means of the least square method we estimate how the expenditures c_i of each good i increase for increasing income (dc_i/dm) for the four different household types and take the weighted average of these figures. The result is normalized to assure that $\sum\gamma_i = 1$.

Energy intensities. The energy intensities e_i of different goods and services are calculated as primary energy use per final household expenditure. The data is taken from an input-output analysis (covering 2003) from the Environmental Accounts at Statistics Sweden. In this methodology primary energy use per unit of final consumption is calculated using monetary transactions between sectors together with multipliers of direct energy use in each sector. Thus the method re-allocates energy use from production to consumption, including indirect contributions from an unlimited number of upstream sectors. The underlying method for compilation and analysis of input-output matrices is well described in a publication by the United Nations (1999).

Figures on primary energy use for electricity production depend on the definitions used. In this analysis we use conversion efficiencies of 0.37 for nuclear and thermal power based on the national energy supply statistics (Statistics Sweden, 2005). For hydro and wind, primary energy is calculated as produced electricity plus internal energy use. This gives a weighted average conversion efficiency of 0.52 from primary energy to electricity.

Energy service price elasticities. The energy service price elasticity α reflects behaviour only. Estimates of more conventional energy price elasticities also capture changes in technology, since households can handle increasing energy prices both by reducing energy service demand (lowering indoor temperature, driving less) [1] and by investing in more energy efficient

[1] This is also reflected in the asymmetries of energy price elasticises found by for example Walker and Wirl (1993) and Haas & Schipper (1998). At least in the short-run, technology does not change under decreasing energy prices and thus the price elasticity is lower than under increasing energy prices.

technology (e.g. hybrid cars or attic insulation). In this case, we are only interested in the first part.

For private transports, the energy service can be defined conveniently as for example vehicle-kilometers,[2] which gives a measurable energy service price elasticity. A brief compilation of price elasticities for vehicle-km to fuel cost per km from different sources is provided in Table 1.

For residential energy use, the energy services are less apparent and more difficult to measure. There is for example no reliable data on the development of the indoor temperatures over time. One possible approximation of the price elasticity of an energy service is to look at the short-run price elasticity of energy. We may expect that the short-run response to an energy price increase corresponds to the behavioural change while technical response takes longer time. For example, if the price of heating fuel goes up households may initially reduce temperature and if the price continues to be high they may consider investing in energy saving technology like attic insulation or energy efficient windows. This is not entirely true since we also see that energy service price elasticities are higher in the long-run than in the short-run. However, from the more abundant studies on transports, we note that in Goodwin (1992) the mean short-run gasoline price elasticity (-0.27) is about the same as the long-run vehicle-km price elasticity (-0.33), and that in a survey of over a hundred studies, Dahl & Sterner (1991) found a fair degree of agreement of short-run gasoline price elasticities in the same range (with an average of -0.24).

Table 1. Literature on Price Elasticities for Vehicle-km to Fuel Cost per km. Short-Run Effects Measure the Adjustment over One Period of the Time-Series (Typically One Year) While Long Run Effects Should Capture the Total Adjustment.

	Short-run	Long-run	
Greene, 1992	-0.13	not significant[1]	US 1966-89
Greene et al., 1999	-	-0.23	US 1979-94
Johansson & Schipper, 1997	-0.11[2]	-0.17[2]	12 OECD countries 1973-92
Goodwin, 1992	-0.16	-0.33	Meta-analysis of time-series estimates

[1] Greene states short-run effects account for essentially all of the adjustment
[2] Mean of the time series estimates (this study also include cross-section estimates).

Estimates of short-run energy price elasticities appear to be lower for residential energy than for transport fuels. Haas & Schipper (1998) found price elasticities of specific heating ($kWh/m^2/yr$) of around -0.1 in most countries (-0.11 in Sweden). Nässén et al (2005) found similar results with short-run price elasticities for specific heating ($kWh/m^2/yr$) in Sweden of -0.20 in detached buildings and -0.08 in multi-dwelling buildings.[3] Brännlund et al (2006) also estimated the price elasticity of heating to -0.13. There must also be some saturation level in space heating demand where an increase in indoor temperature reduces comfort and the price elasticity for falling prices reaches zero.

For electrical household appliances such as refrigerators, short-run energy price elasticities can be expected to be very low since they are hardly turned off or on due to changing

[2] With this definition we look only at the amount of car transportation and not other services related to a car such as comfort, safety or acceleration performance.
[3] The difference between dwelling types may reflect that tenants in Swedish multi-dwelling buildings often do not pay a variable heating cost, since heating is a fixed part of the rent.

electricity prices. For example, Haas et al (1998) found price elasticities very close to zero for the electricity consumption of household appliances.

There are clearly great variations as well as uncertainties in the estimates of price elasticities in literature. However, we conclude that long-run energy service price elasticities of -0.2 to -0.3 for private transports and 0 to -0.2 for residential energy use appear to be reasonable ranges (assuming that long-run energy service price elasticities correspond to short-run energy price elasticities).

3. Results

In Section 2.1 we showed that the rebound effect of energy efficiency can be expressed as a function of four dimensionless parameters: (1) the energy service price elasticity α, (2) the share of energy saved initially β, (3) the ratio of investments to break-even investments q/q_{BE}, and (4) the ratio of energy intensity of the energy service A to the total marginal energy intensity $\sum\gamma_i e_i/e_A$.

The results vary only marginally as a function of β.[4] Moreover, β depends only on technical factors which are known in most cases. For comparability we assume an initial energy saving of 30% in all examples ($\beta = 0.3$).

The parameter $\sum\gamma_i e_i/e_A$ can be estimated for different sectors as described in Section 2.2. These intermediate results are presented in Section 3.1. The remaining parameters α and q/q_{BE} are more uncertain and case dependent and different cases of energy efficiency improvements are discussed in Section 3.2.

3.1. Marginal Energy Intensities

Table 2 shows the average and marginal expenditure shares γ_i and energy intensities e_i of household consumption in Sweden. Comparing average and marginal expenditure shares, we see that housing and food products constitute relatively smaller shares on the margin while transport related consumption such as purchase of vehicles and transport fuels constitute relatively larger shares.

Looking at the energy intensities in Table 2, we see that not surprisingly direct energy use such as electricity, heating, and transport fuels are considerably more energy intensive than other products and services. Moreover, the energy intensity of electricity and heating is twice as high as for transport fuels. There are two main reasons for this. First of all, electricity is fairly cheap in Sweden, while it is produced with great conversion losses, which gives high primary energy per household expenditure. Secondly, there are substantial energy and CO_2 taxes on gasoline and diesel (in 2003 the fuel price constituted only 38% of the total price), which results in lower primary energy per household expenditure.

Now we can calculate the parameter $\sum\gamma_i e_i/e_A$ as well as the similar expression for rebound effects of energy conserving behaviour (Eq. 18) for different consumption categories. Electricity and heating are lumped in Table 2, due to lack of data to estimate separate marginal expenditure shares γ. However, the energy intensities can be separated to 67.4 MJ/USD for electricity and 47.6 for heating fuels and district heating. The results are given in Table 3.40

[4] $R_{Price} \leq -\alpha$ for all β and $R_{Price} \approx -\alpha$ for $\beta \rightarrow 0$.
E.g. for $\alpha = -0.2$: $\beta = 0.1 \Rightarrow R_{Price} = 0.19$; $\beta = 0.3 \Rightarrow R_{Price} = 0.17$.

Table 2. Average and Marginal Expenditure Shares and Energy Intensities of Household Consumption in Sweden. The Data Sources Are Described in Section 2.2.

	Share of household expenditure		Energy
	Average	Marginal	intensity[1]
		γ	e
	USD/1000 USD	USD/1000 USD	MJ/USD
Bread, cereals	21	6	5.8
Meat	24	8	7.9
Fish, seafood	7	3	10.7
Milk, cheese, eggs	20	8	8.2
Oils, fats	3	0	7.5
Fruit	9	2	2.9
Vegetables	13	4	7.5
Sugar, confectionary etc	12	3	6.4
Salt, spices etc	10	7	5.0
Coffee, tea, cocoa	4	1	7.0
Mineral water, soft drinks, juices	7	1	7.1
Alcoholic beverages	17	18	2.3
Tobacco	9	4	1.2
Clothing	46	52	3.1
Footwear	10	3	1.9
Housing (excluding energy)	210	119	2.1
Secondary residences	13	35	1.3
Electricity and heating	43	25	60.6
Furniture	25	46	5.6
Household textiles	5	8	3.1
Household appliances	29	37	4.3
Household non-durables	9	3	8.5
Household services	24	28	2.1
Health products and services	24	- 3	2.7
Purchase of vehicles	65	150	4.3
Spare parts for personal transports	5	8	4.3
Transport fuels	42	70	28.4
Services related to personal transports	32	53	3.6
Passenger transport services	17	28	14.0
Radio, TV	10	7	1.7
Games, toys, hobbies etc	23	31	3.1
Cameras, watches etc	4	6	3.4
Package holidays	29	47	5.1
Accommodation services	10	16	4.4
Restaurants, cafés	35	53	3.9
Articles for personal care	12	8	4.0
Child care	5	4	0.7
Insurance	18	22	2.1
Other leisure activities	38	37	8.1
Entertainment	7	14	2.5
Books, papers, TV-license etc	33	22	4.2
Telephony	24	6	1.8
Sum	*1000*	*1000*	

[1] Here energy intensity is defined as primary energy per household expenditure.

Energy conserving behaviour. If we stick to the assumptions that the household budget is constant and that any saved money is spent in proportion to the expenditure shares of an income increase, then energy conserving behaviour is essentially a matter of increasing the proportion of goods and services with low energy intensity. Any consumption change will result in some rebound effect according to Eq. 18, but this effect is small for goods and services with very high energy intensity (around 9% for electricity, 14% for heating and 20% for transport fuels as shown in Table 3). Contrary, for goods and services with very low energy intensity, the rebound effect may be very high (e.g. over 600% for tobacco).

Table 3. The Energy Intensity of Three Categories of Direct Energy Use Compared to Total Marginal Energy Intensity. A Similar Expression Gives Estimates of the Rebound Effect of Energy Conserving Behaviour.

	$\sum_{i=1}^{N}\gamma_i e_i / e_A$	Rebound of energy conserving behaviour: $\sum_{i=2}^{N}\gamma_i e_i /(1-\gamma_A)e_A$ (Eq. 18)
Electricity	0.11	0.09
Heating fuels and district heating	0.15	0.14
Transport fuels	0.26	0.20

3.2. Energy Efficiency Rebound

The rebound effect of energy efficiency as defined by Eq. 17 depends strongly on α and q/q_{BE}. Figure 1 shows price rebound, income rebound and total rebound as a function of these parameters in the case of private transports. While α is a parameter that may be difficult to measure accurately (see Section 2.2), q/q_{BE} should be easy to estimate in each specific case, but its value varies considerably between different cases. For example the latest hybrid car technology is not necessarily cost effective (unless the buyer drives very long distances). Such consumption choices may rather be driven by environmental motives and the ratio q/q_{BE} may be larger than 1. On the other extreme, a household changing from a large to a small car may save both fuel and investment costs, i.e. q/q_{BE} may be below 0. For an energy service price elasticity of -0.25 (which appears to be a reasonable assumption, see Section 2.4), the rebound effect in the first case may be around 0.1 and in the second case as high as 0.5[5]. These together with three cases of residential energy efficiency improvements are compared in Table 4.

It can be noted that for a typical energy efficiency investment choice, such as whether to insulate the attic or not, a perfect market assumption gives $q/q_{BE} = 1$, while if there are market imperfections the investment may be profitable ($q/q_{BE} < 1$).

4. Conclusions

In this paper the rebound effects of energy efficiency and energy conserving behaviour in households have been analyzed in terms of price effects due to lowered price of energy services, and income effects due to the redirection of saved money to other consumption. Effects on the production side of the economy in response to changing demand have not been analyzed in this

[5] High rebound in itself does not mean that such measures are inferior to high-tech solutions. The goal must be to reduce total energy use or emissions.

paper. Such effects can be safely ignored for small changes in demand but as the aggregation level increases they become more important. For example a global improvement of energy efficiency may result in decreasing energy prices and thus rebounding demand.

Figure 1. The Rebound Effect of Energy Efficiency in Private Transports ($\sum\gamma_i e_i/e_A$ = 0.26) as a Function of Energy Service Price Elasticity (α) and Investment Costs (q/q_{BE}). These Results Are Calculated for An Initial Energy Saving of 30 % (β = 0.3) but the Results vary Only Marginally as a Function of β.

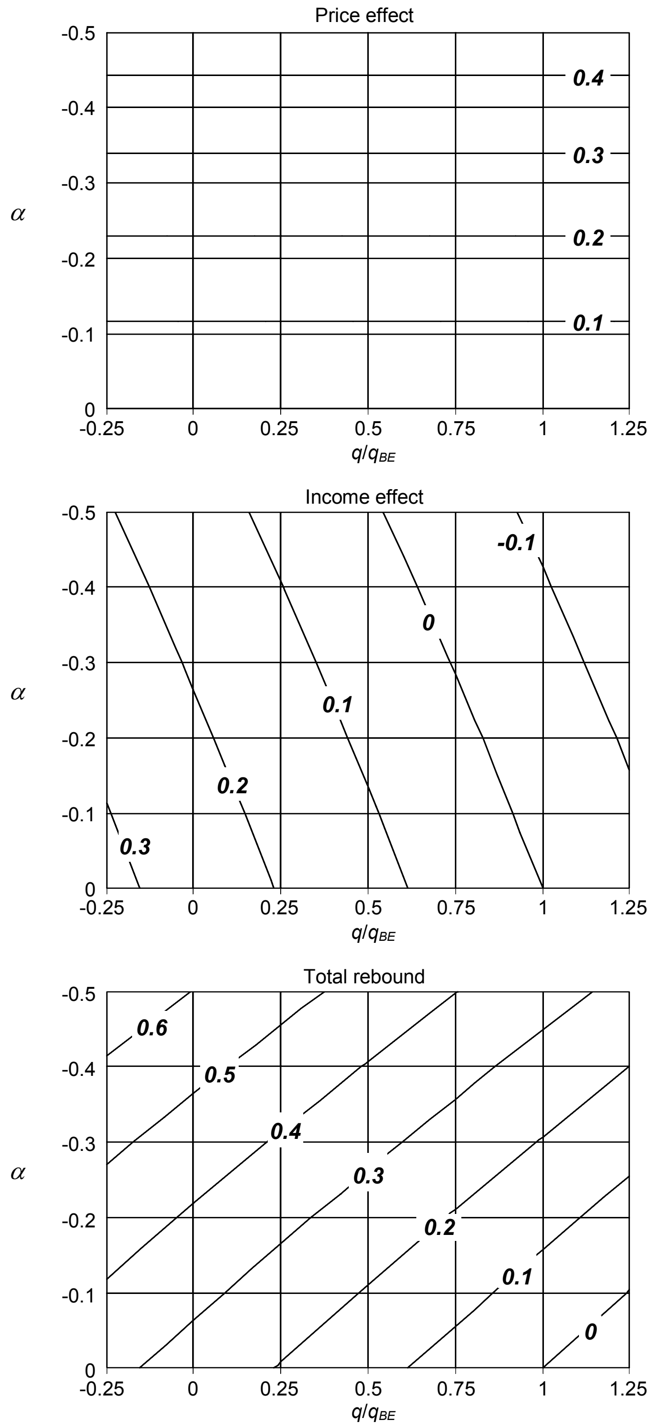

Table 4. Rebound Effects for Different Cases of Energy Efficiency Improvements. All Cases Are Calculated for an Initial Energy Saving of 30% ($\beta = 0.3$) and Energy Intensities from Table 3.

	q/q_{BE}	α	R_{Price}	R_{Income}	R_{Total}
Space heating					
Break-even investment in building shell energy efficiency	1	-0.1	0.09	-0.01	0.08
Profitable investment in building shell energy efficiency (corrected market imperfection)	0.5	-0.1	0.09	0.06	0.15
Electric appliances					
New energy efficient refrigerators at the same price as old ones (no-cost technological development)	0	0	0	0.11	0.11
Private transports					
Environmentally driven early adoption of new expensive technologies (e.g. hybrid cars)	1.2	-0.25	0.22	-0.11	0.11
Changing from big/expensive to small/cheap car	-0.2	-0.25	0.22	0.26	0.48

The price effect is essentially a matter of price elasticities and has been analyzed in several previous studies. An important distinction is that this refers to the price elasticities of the energy services (e.g. vehicle-km) which are lower than the more frequently published energy price elasticities.

The results of income-induced rebound effects are based on the assumption that any money saved from an energy efficiency investment (the annual energy cost saving after the price induced rebound minus the annuity of the capital cost) is redirected to consumption of other goods and services in proportion to the marginal consumption shares. This in turn is calculated using expenditure data for different income levels from the Swedish Household Budget Survey. This assumption is reasonable on average but not for specific households.

The income effect may be both positive and negative. Early adoption of new technologies may in fact be rather costly resulting in reduced consumption of other goods and services while the choice to buy a smaller car may save both fuel and investment costs which give room for increasing consumption in other sectors.

The total rebound effects (price and income effects) of energy efficiency appear to be in the range 5-15% in most cases, but these results are fairly sensitive to assumptions of energy service price elasticities. Cases with low or negative investment costs for energy efficiency, such as the choice to buy a smaller car, may also result in much higher total rebound effects as the income effect become more important.

Energy conserving behaviour (reduced energy service demand) affecting direct energy use such as heating and transport fuels gives rise to rebound effects in the order of 10-20%, depending on the household expenditure per primary energy for different fuels and energy carriers.

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