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A general equilibrium analysis

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Abstract

The objective of this paper is to analyze the rebound effect from increased efficiency in industrial use of energy in Sweden. Energy efficiency improvements can have significant micro- and macroeconomic effects that hampers the positive effect on real energy savings. To assess the size of the overall rebound effect in the Swedish economy we apply a computable general equilibrium model. The results show that the economy-wide rebound effect in Sweden depends on a number of factors, e.g. the extent of the energy efficiency improvement, how the labour market is modeled as well as if the increase in energy efficiency is combined with a cost or not. We find that the rebound effect following a 5 percent increase of energy efficiency in the Swedish industry lies in the range of 40-70 percent. When energy efficiency only is improved in energy-intensive production, the rebound effect becomes even higher. These findings are in line with the results in the literature.

JEL classification: C68, D24, D58, Q43, Q55, Q58

Keywords: rebound effect, energy efficiency, energy use, industry, computable general equilibrium.

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1 Introduction

Energy efficiency has become a keyword in climate, environmental and energy policies. Often, the term is used synonymously with reduced energy use and is expected to lead to reduced environmental impacts and improved security of energy supply. However, it is not given that improved energy efficiency will fulfill such expectations. Increased energy efficiency can stimulate new demand for energy that counteracts the energy-saving potential. The so-called rebound effect can partially or wholly offset, or in worst case even outweigh, the energy-saving effect of energy efficiency measures. The extreme outcome of increased energy use has been labeled as Jevons paradox (Jevons, 1865 and Alcott, 2005), the Khazzoom/Brookes postulate (Khazzoom, 1980; Brookes, 1990 and Saunders, 1992) and most recently as "backfire" (Saunders, 2000).

Despite that the rebound effect is generally accepted in the literature and most relevant for evaluations of climate, environmental and energy policies it is seldom taken into account or even discussed in policy analyses. There are several reasons to why the rebound effect is ignored. The rebound effect is by its nature abstract and dynamic, and therefore difficult to measure. It has been evaluated using a variety of methods, at the micro-and macroeconomic level, with different time perspectives. The many approaches have contributed to a wide spread in the empirical estimates, which in turn have contributed to divergent conclusions about the size and relevance of the rebound effect (Greening et al., 2000; Sorrell, 2007 and van den Bergh, 2011).

The rebound effect can broadly be defined in terms of direct and indirect effects adding up to the overall rebound effect (Sorrell and Dimitropoulos, 2008). The direct rebound effect is evaluated within tight analytical frames and applies to the demand for individual energy services, e.g., car transports. The indirect rebound effect consists of a number of indirect effects that follow from increased energy efficiency. The indirect effects may be categorized as: (*i*) income and substitution effects; (*ii*) general equilibrium effects in terms of long run structural change following from changes in relative prices and (*iii*) radical changes in the social structure relating to technological development, preferences and institutions (Greening et al., 2000). When the overall rebound effect concerns the whole economy (a region, a country or the global economy) it is called the economy-wide rebound effect.

In this paper we use a computable general equilibrium (CGE) model for the Swedish economy to evaluate the economy-wide rebound effect that follows from a five percent increase in efficiency of industrial energy use in Sweden. Any cost-effective improvement in energy efficiency will lower production costs and thereby enhance competitiveness, especially in energy-intensive industries. Improved efficiency will change relative prices and potentially affect consumption and production levels in the whole economy. By applying a CGE approach we hope to capture as much as possible of these dynamic effects.

We contribute to the literature by adding to the existing evidence on the magnitude of the rebound effect. Our results are directly comparable to studies carried out for the UK as a whole and regionally for Scotland (Allan et al., 2007 and Hanley et al., 2009). Furthermore, Sweden is an interesting economy to study in the rebound effect context as it is relatively energy-intensive. The rebound effect is expected to be higher in energy-intensive economies as energy costs constitute a larger share of total production costs. Sweden is also a forerunner in climate and energy policies, e.g. a carbon tax was introduced in 1990 and a target for energy efficiency in 2008. In 2004 a program for increased energy efficiency in energy-intensive industries (PFE) was introduced. Furthermore, the Swedish government recently increased its funding of energy related research to enhance technological progress. These political decisions were mainly driven by concerns about climate change and energy security. The success of this type of policy measures is partly dependent on the rebound effect.

The paper is structured as follows. Section 2 provides an overview of the literature focusing mainly on the overall rebound effect and the CGE approach. Section 3 presents the method and data used in assessing the rebound effect in Sweden. Section 4 presents the scenario assumptions. The results are presented in Section 5. Finally, Section 6 concludes the paper.

2 Previous literature

There exist a number of papers that explicitly discuss the rebound effect in general and overviews the existing literature (Greening et al., 2000; Berkhout et al., 2000; Binswanger, 2001; Sorrell, 2007; Sorrell and Dimitropoulos, 2008; Sorrell et al., 2009; Herring and Sorrell, 2009; Madlener and Alcott, 2010 and van den Bergh, 2011). In this paper we focus on the economy-wide rebound effect from increased efficiency in industrial energy use (see Dimitropoulos, 2007 and Allan et al., 2009 for throughout discussions and literature overviews on the economy-wide rebound effect).

2.1 The economy-wide rebound effect

The overall rebound effect has been estimated using microeconometric models on household data that capture income- and substitution effects among households (see e.g. Brännlund et al., 2007) and macroeconomic models, both econometric models (see e.g., Barker et al., 2009) and CGE models (see e.g. Allan et al., 2009), also capturing effects on the production side of the economy and structural change. The CGE approach is most common in analyses of the rebound effect following from energy efficiency improvements in industries. As the CGE models differ in structure and assumptions it is difficult to compare these studies and also difficult to draw any general conclusion about the size of the rebound effect (Allan et al., 2009).

Grepperud and Rasmussen (2004) use a CGE model for Norway to analyze the effects of doubling the energy productivity in six energy-intensive sectors. The study focuses on energy use in individual sectors and not on energy use in the whole economy. Increased energy efficiency results in backfire only in the most energy-intensive sector ('Manufacture of metals'). They conclude that high energy intensity in itself does not cause backfire, good substitution possibilities are also required. In the energy-intensive pulp and paper sector backfire does not occur because substitutability between energy and other input factors are assumed to be poor.[1] Vikström (2008) uses a CGE model for Sweden and studies a scenario where energy efficiency is improved

[1] In their model energy and capital is nested to an intermediate factor of production, which implies that energy cannot be directly substitued for labour.

by 15 percent in the manufacturing industry and 12 percent in the energy sector. The results show a rebound effect of approximately 60 percent. As the model is calibrated to the year of 1957 and only simulates five years (to 1962) little can be said about the current state of the Swedish economy. Washida (2004) simulates the effects of a one percent improvement in the end use of energy in both industries and households in Japan. The results show a rebound effect of 53 percent.

Allan et al. (2007) apply a CGE model for the UK economy to analyze a five percent increase in energy efficiency in all sectors of production (including five energy sectors). They find a long run rebound effect of 27 percent for electricity and 31 percent for other energy. They also unexpectedly find that the rebound effects are higher in the short run, 62 percent for electricity and 55 percent for other energy. A crucial difference between the short and long-term is that some production factors, especially capital, are assumed to be rigid in the short-term. Therefore it is not possible for businesses to fully adjust to energy efficiency improvements in the short-term. Improvements in energy efficiency will increase the returns from investments in energy-intensive sectors relative to investments in other sectors. In the long-term resources will be redistributed benefitting energy-intensive sectors. Thus, it is reasonable to expect that the rebound effect is higher in the long-term (Wei, 2007 and Saunders, 2008). The lower long-term rebound effect in Allan et al. (2007) can be explained by a negative investment effect in the electricity sector (Turner, 2009). The UK has poor abilities to transmit electricity to the rest of Europe. Hence, when energy efficiency is improved the electricity price falls sharply in the short-term and lowers profits in the electricity sector which is negative for investments. In the long-term the installed capacity is reduced which causes a lower demand for coal and gas (which are energy-intensive sectors).

Hanley et al. (2009) use a CGE model for the Scottish economy to analyze a five percent increase in energy efficiency in all production sectors (including five energy sectors). They find backfire in the long run for both electricity and other energy. In section 2.2 we will discuss this study in more detail as it is most relevant to our analysis.

The economy-wide rebound effect from increased efficiency of industrial use of energy has also been estimated with post-Keynesian macroeconomic models. In this approach econometric methods are applied on historical data to estimate macroeconomic parameters. Using a post Keynesian model for the U.K. economy (MDM-E3), Barker et al. (2007) estimate the economy-wide rebound effect from measures to increase energy efficiency in energy-intensive industries. They estimate a base case scenario for the period 2000-2010 and compare it to a reference case to isolate the effects of the energy efficiency policies. They find rebound effects in the order of 19-26 percent depending on assumptions regarding the EU ETS price. Using a model for the global economy (E3MG), Barker et al. (2009) estimate global economy-wide rebound effects for the period 2013-2030 'of all the current and committed IEA WEO 2006 (IEA 2006) energy efficiency policies for the transport, buildings and industry sectors'. The results show global rebound effects of about 30 percent by 2020 and 50 percent by 2030.

2.2 Sensitivity analyses in CGE studies

The studies carried out for the UK as a whole (Allan et al., 2007; Allan et al., 2009; Turner, 2009 and Turner and Hanley, 2011) and regionally for Scotland (Hanley et al., 2009; Anson and Turner, 2009; and Turner and Hanley, 2011) constitute a good basis for a discussion on how the rebound effect is modeled in a CGE framework and which assumptions and circumstances that are important to the size of the rebound effect. These studies simulate the same scenarios and are based on two models (AMOSENVI and UKENVI) that are similar in structure and assumptions. A number of sensitivity analyses are carried out with respect to key assumptions. The results from these analyses show rebound effects ranging from minus to 174 percent. Below we review model features concerning: (*i*) the electricity sector; (*ii*) the elasticities of substitution; (*iii*) the labour market; (*iv*) the introduction of energy efficiency; and (*v*) the trade elasticities and how tax revenues are modeled.

The electricity sector

Improved energy efficiency is expected to result in lower price on electricity for two reasons: (*i*) the demand for electricity drops and (*ii*) production costs in the electricity sector decrease. In the model for Scotland it is assumed that cheap electricity can be exported to the rest of UK, where the price of electricity is higher. This is beneficial to the Scottish electricity sector, which will attract capital and the installed capacity will therefore increase. More coal and gas will be demanded and, as these sectors are energy-intensive, the rebound effect will be higher in the long-term (Anson and Turner, 2009). When energy efficiency only is improved in the manufacturing industry and not in the energy sectors the long-run rebound effect in Scotland turns out to be much lower, 41 percent for electricity and 35 percent for other energy (Hanley et al., 2009). Thus, the modeling of the electricity sector is of crucial importance for the result that increased energy efficiency in Scotland backfires, but is significantly below 100 percent when the same scenario is analyzed for the UK as a whole (as described above).

Elasticities of substitution

The substitutability between energy, labour, capital and materials is crucial to the demand for energy and other inputs. In CGE models substitutability is determined by assumptions about the production structure and the elasticities of substitution. Inputs are nested together to make models manageable and transparent. However, by nesting inputs substitutability is being restricted. In AMOSENVI and UKENVI labour and capital forms a composite factor of production (value added) and energy and materials form a composite intermediate good. The composites can be substituted for one another. In this structure energy can be directly substituted for materials but not for capital or labour (see appendix for an illustration of this type of production structure).

When inputs are aggregated to intermediate factors and later to production it is common to assume constant elasticities of substitution (CES). The values of the elasticities are as far as possible based on econometric estimates, but in general ”guesstimated” (Bergman, 2005). This since estimated elasticities from partial studies might not be suited for a general equilibrium framework, so there must always be some kind of judgement considering the accuracy of the model results.

Both Allan et al. (2007) and Hanley et al. (2009) use 0.3 as the default value of elasticities of substitution in all sectors and in both steps of the production structure concerning energy. Both studies analyze the effects of varying the size of these elasticities. The results from the sensitivity analyses are presented in Table 1. As can be seen, the higher the elasticities the larger the rebound effect. The impact of varying the substitution elasticity between energy and materials is significantly larger than the impact of varying the elasticity between value added and the intermediate good. The UK model is more sensitive to the size of the elasticities of substitution, this since greater substitutability reduces the pressure on the price of electricity and thus mitigates the negative effect on investments in the electricity sector. In Scotland increased energy efficiency leads to backfire even at the lowest elasticities.

Turner and Hanley (2011) finds backfire in both the short and long run in the UK when the elasticities of substitution concerning energy are assumed to be above unity.[2]

Table 1: Summary of sensitivity analyses for the long run economy-wide rebound effect with respect to elasticities of substitution. Two levels of the production structure are treated separately: substitution between energy and materials and substitution between value added and the intermediate composite good. The rebound effect is presented in percent.

Elasticity of substitution	Level in the production structure	Rebound effect: Electricity (Other energy)	
		Scotland (Hanley et al. 2009)	UK (Allan et al. 2007)
0.1	Energy and materials	113 (114)	12 (13)
0.1	Intermediate good and value added	128 (129)	14 (22)
0.3	Both levels of production structure	*132 (134)*	*27 (31)*
0.7	Energy and materials	169 (174)	58 (67)
0.7	Intermediate good and value added	139 (144)	53 (49)

Previous sensitivity analyses only concerns the long-run elasticities of substitution (Turner and Hanley, 2011). Different production structures could also have significant impacts on the rebound effect.[3]

The labour market

Assumptions concerning the labour market may also determine the economy-wide rebound effect. In AMOSENVI and UKENVI labour supply and the real wage rate is determined endogenously. The real wage rate is assumed to be a function of the workers negotiation power, which is inversely related to the unemployment rate. The model for the Scottish economy includes a migration function that makes labour supply more flexible compared to what is assumed for the UK economy.

[2] Note that Turner and Hanley (2011) assume 0,8 in their central case and 0,4 and 1,1 in their sensitivity analysis, which is significantly higher compared to earlier studies for the UK and the Scottish economies.

[3] One alternative to the above structure is to nest energy and capital as done in Grepperud and Rasmusen (2004).

An alternative is to model labour supply as an exogenous fixed factor. As a result of any disturbance, e.g. increased energy efficiency, the real wage needs to change in order to restore equilibrium in the labour market. Increased energy efficiency means that energy services can be consumed at lower cost and cost-efficient firms will therefore demand more energy services and thereby increase labour productivity and the real wage. As the costs for labour increases the effects of increased energy efficiency on total production costs and GDP will be hampered. Thus, the rebound effect becomes lower with fixed labour supply compared to the case where labour supply is endogenous (Allan et al., 2007 and Turner and Hanley, 2011). A third alternative is to assume that the labour force is mobile and that the real wage is fixed. Under this assumption increased energy efficiency will have a relatively large effect on economic activity which causes a higher rebound effect (Allan et al., 2007; Hanley et al., 2009).

Introduction of increased energy efficiency

Increased energy efficiency usually comes at a cost. In all CGE studies mentioned, energy efficiency improvements are assumed to be permanent and without any costs. It is unlikely that large costless improvements in energy efficiency will occur in the short run, although they may occur in the long run as a result of technological progress. Costless scenarios should be seen as extremes in analyses of the rebound effect. Allan et al. (2009) model another extreme, assuming that the production costs in each sector remains unchanged due to decreased labour productivity. Under this assumption they find a negative rebound effect. We contribute to previous analyses by introducing a cost for increased energy efficiency in terms of lower productivity in value added, as improved energy efficiency often is the result of new technology.

Increased tax revenues and international trade elasticities

Different assumptions regarding the treatment of increased tax revenues may have impacts on the rebound effect. Compared to the modeling features discussed above it is of minor importance to the rebound effect whether income taxes are lowered or public spending increased when tax revenues increases due to economic growth. Lowering income taxes, however, results in a higher rebound effect (Allan et al., 2007).

As improved energy efficiency changes the relative prices between domestically produced and imported commodities, trade flows will be affected and, therefore, also the rebound effect. To what degree energy efficiency improvements affect trade flows is partly determined by assumptions regarding export and import elasticities. Previous research has found that the rebound effect is relatively insensitive to different assumptions regarding global trade (Allan et al., 2007; Hanley et al., 2009).

2.3 The rebound effect in Sweden

There is no CGE analysis of the overall rebound effect in Sweden, besides the Vikstöm (2008) historical study. Brännlund et al. (2007) estimate an econometric model on household expenditures and simulate a 20 percent improvement in energy efficiency in transports and residential heating. They find rebound effects, defined in terms of carbon emissions from households' combustion of fossil fuels, exceeding 100 percent. They conclude that costless improvements in energy efficiency are counterproductive in climate policy and needs to be complemented by an increase in the carbon tax to avoid increased carbon emissions. Nässén and Holmberg (2009) also study household expenditures and find more modest rebound effects (5-15 percent), in terms of primary energy use in the household sector, compared to Brännlund et al.

3 Method and Data

We apply the environmental medium term economic model (EMEC) developed and maintained by the National Institute of Economic Research (NIER), which is a public authority and one of the leading economic forecasters in Sweden. The EMEC model is a static CGE model that has been applied in a vast number of policy analyses in Sweden mostly analyzing climate and energy policies. We will here only briefly describe the model and mainly focus on the features that were highlighted in Section 2. A detailed presentation of the model can be found in Östblom and Berg (2006).

The EMEC model specifies 27 sectors and 33 composite commodities. The goods and services produced are consumed domestically, exported or used together with imports to create composite commodities for domestic use. The model includes a public sector equal to a single government agent that produces public goods and services. Tax revenues is either transferred back to households or used as public consumption. The size of the public sector is exogenously determined. The model also specifies a foreign sector. The small country assumption is adopted and the problem of overspecialization is handled by the Armington assumption. The exogenous current account ratio (in relation to GDP) is used as closure rule.

Firms are assumed to maximize profits subject to resources restrictions. All markets are characterized by perfect competition and no economies of scale in production. Technological change is exogenous. Output *(Y)* is produced by means of labour *(L)*, capital *(C)*, energy *(E)*, materials *(M)* and transports *(T)*. Inputs are demanded as a function of relative prices *(PK*, *PL*, *PE*, *PM* and *PT)* and factor productivity (MP_g), which is specific to individual production factors. The production function for sector *i* is:

$$Y_i = f_i(C_i, L_i, E_i, M_i, T_i) \qquad i = 1, \ldots, n. \tag{1}$$

The demand for production factors C, L, E, M, T per unit of production is:

$$X_g = MP_g \varphi_g(PK, PL, PE, PM, PT) \qquad g = C, L, E, M, T. \tag{2}$$

The representative consumer maximise the utility of consumption. The households' demand for various goods and services *(HC)*, is a function of relative prices *(PHC)* and total expenditures *(X)*. The households' demand function is:

$$HC_{pr} = \varphi_{pr}\left(PHC_{pr}, X\right) \qquad pr = 1, \ldots, n. \tag{3}$$

Firms' production functions and the representative household's utility function are specified as nested CES functions. Elasticity values are specific to individual sectors and have been picked by surveying econometric studies. The elasticities of the model are presented in Table A1 in the appendix. The elasticities concerning substitution between energy and materials varies from 0.1 to 0.9 and has an unweighted mean of 0.46. The elasticities concerning substitution between value added (labour and capital) and the composite good of energy and materials varies from 0.1 to 0.7 and has an unweighted mean of 0.34.

Capital and labour can move freely between domestic sectors. Capital is supplied to the economy at a given price and thus the model runs with an exogenous interest rate. The total amount of workers in the economy is fixed but the number of working hours is assumed to be a function of the real wage. When the real wage increases leisure becomes more expensive and the individual chooses to work more. Thus, labour supply is flexible but restricted by the total number of working hours. In the numerical analysis we will also present analyses based on other assumptions regarding labour supply and the real wage.

The model is calibrated to base year data from the National Accounts and the Environmental Accounts, compiled by Statistics Sweden. The household data from the National Accounts is divided into six different household groups according to information from the household expenditure survey and income distribution survey compiled by Statistics Sweden. The tax system and tax rates are equal to current fiscal policy rules.

4 Definition of the rebound effect and scenario assumptions

4.1 Introduction of increased energy efficiency and the rebound effect

We examine the economy-wide rebound effect in the Swedish economy by initially improving energy efficiency. A common assumption in all scenarios is a permanent improvement in efficiency of industrial energy use equivalent of five percent. We broadly follow the analysis in Allan et al. (2007) and Hanley et al. (2009). We start by defining energy in physical terms and energy expressed in efficiency units. If a change in energy in physical terms is identified as $\dot{E}$ *and* ρ *is* a technology energy-augmenting process, then an effective change in energy can be defined as:

$$\dot{\varepsilon} = (1 + \rho) \cdot \dot{E} \quad (4)$$

Eq. (4) implies that due to technological progress energy use can be decreased without a corresponding change in the consumption of energy services and thus without any effect on output levels. We increase energy efficiency in the model by assuming that ρ=0,05 for the composite product energy (see Figure A1 in the appendix) and for propellant (one of the 17 material goods) used in private and public production. This means that energy use initially decreases with five percent and that firms' energy costs are lowered with 5 percent, ceteris paribus. While the potential energy savings is five percent we expect that the actual energy savings will be lower due to economic feedback effects, such as output, income and substitution effects.

We define the economy-wide rebound effect in percent as[4]:

$$\text{Rebound effect} = \left(1 - \frac{\Delta EA_{actual}}{\Delta EA_{potential}}\right) \cdot 100 \quad (5)$$

Where ΔEA_{actual} is the actual percentage change in energy use that the model results in and $\Delta EA_{potential}$ is the percentage change in energy use given by the initial five

[4] The same definition as in Allan et al. (2007).

percent increase in energy efficiency. That is, if the whole economy improves energy efficiency by 5 percent and this leads to a reduction in energy use by 3 percent then the rebound effect is 40 percent.

4.2 Scenario assumptions

The size of the rebound effect depends on how and in which sectors energy efficiency is increased. This is because energy efficiency affects other key variables such as the real wage. Generally we expect that the effect on the real wage will be larger when the increase in energy efficiency applies to the whole rather than parts of the economy. Previous analyses have shown that energy-producing industries have a vital role for the size of the rebound effect (Hanley et al., 2009). To see if this also applies to the Swedish economy we study a scenario in which energy efficiency is improved in all sectors, as well as a scenario where the improvement only applies to non-energy producing industries. Finally, to see if it is wise to target energy-intensive production in energy efficiency policies we run a third scenario where the efficiency improvement only applies to energy-intensive sectors.

The three scenarios are:

- A five percent increase in energy efficiency in all goods and services-producing industries in the Swedish economy
- A five percent increase in energy efficiency in all goods and services-producing industries in the Swedish economy except for the energy-producing industries: electricity, gas and district heating plants and refineries
- A five percent increase in energy efficiency in energy-intensive sectors: mining, mineral products, pulp and paper, chemicals, iron and steel and metals.

In the three scenarios, the increase in energy efficiency is assumed to be permanent and without any cost. In alternative scenarios, we introduce a notional cost of the same size as the reduced production cost that follows from the five percent increase in energy efficiency. We also perform a sensitivity analysis with respect to assumptions regarding the labour market.

The analysis is based on the macroeconomic reference scenario described in the National Institute of Economic Research (2012). The three scenarios are compared with the outcome from a benchmark scenario with unchanged energy efficiency. Since the EMEC model is a static general equilibrium model we are analysing the long-term effects of increased energy efficiency. When relative prices change it will take several years before the economy adjusts to a new equilibrium. The end year is 2035.

5 Results

5.1 Scenario results

In Table 2 we present the macroeconomic impacts of a five percent improvement in energy efficiency in line with the three scenarios described in section 4.2. The increase in energy efficiency lowers marginal production costs and stimulates economic activity, hence, GDP increases in the long run compared to the benchmark scenario. As the competitiveness of Swedish firms is strengthen exports increase. When the effective price of energy decreases, more energy is demanded, meaning more energy services per worker. Thus, labour productivity and the real wage increases and households supply more working hours. Private consumption increases in the long run as household income increases. The capital stock increases. The macroeconomic effects are smaller in the third scenario as efficiency is improved only in a subset of the production sectors accounting for approximately 5 percent of GDP in 2035.

From the results in Table 2 it is clear that whether or not energy efficiency is increased in the energy producing sectors has little impact on the macroeconomic indicators.

Table 2: Impacts on macroeconomic indicators following a five percent increase in efficiency of the industrial use of energy. Percentage difference in year 2035 compared to benchmark scenario (without the increase in energy efficiency).

	Scenario 1 All sectors of production	Scenario 2 All sectors of production excl. energy sectors	Scenario 3 Only energy-intensive sectors
GDP	0,3	0,3	0,1
Exports	0,3	0,3	0,1
Imports	0,2	0,2	0,1
Private consumption	0,3	0,3	0,1
Investment	0,4	0,4	0,1
Working hours	0,05	0,04	0,01
Real wage	0,2	0,2	0,1

Note: Public consumption is exogenous in the EMEC model.

Energy efficiency improvements will affect the structure of the economy as it benefits energy-intensive sectors relatively more than others, not only because these sectors have a higher energy cost per output unit but also because they use relatively few working-hours per output unit. Given the general equilibrium effects the output prices of the energy-intensive sectors will decrease. At the same time the marginal cost in the service sector will increase since they use relatively little energy but relatively much labour. Strengthened competitiveness of energy-intensive industries stimulates exports since the price of Swedish goods decreases relatively to foreign goods. Thus, there is a structural transformation towards energy-intensive production.

The structural change induced by the increase in energy efficiency has a profound effect on the outcome of the rebound effect. Table 3 presents both the economy-wide and the industry-specific rebound effects for the three scenarios analyzed. Rebound effects are calculated in line with Eq. (5). This means for example that when only the energy-intensive industry is subject to the improved energy efficiency the potential energy savings in the whole economy (including the households) amounts to 0.8 percent since the energy-intensive industry is only a subset of the total energy use in Sweden. The change in energy use given by the increase in efficiency is then compared to the actual long-term change in energy use for the entire economy after all sectors have adjusted to the new conditions. The sector-specific rebound effect is calculated from the potential and the actual change in energy use in each sector.

Table 3: Economy-wide and sector-specific rebound effects (in percent) following a five percent increase in efficiency of industrial use of energy.

	Scenario 1 All sectors of production	Scenario 2 All sectors of production excl. energy sectors	Scenario 3 Only energy-intensive sectors
Agriculture	35	33	
Fishery	24	24	
Forestry	24	24	
Mining	50	47	47
Other industry	51	46	
Mineral products	99	94	92
Pulp and paper mills	109	102	101
Drug industries	48	41	
Chemical industries	95	86	87
Iron & Steel industries	71	70	70
Non-iron metal ind.	53	51	50
Engineering	75	67	
Petroleum refineries	34		
Electricity supply	5		
District heating	37		
Gas distribution	-52		
Water and sewage	33	34	
Construction	24	23	
Rail road transports	37	36	
Road passenger transports	18	18	
Road goods transports	15	15	
Sea transports	60	60	
Air transports	72	72	
Other transports	54	52	
Services	81	76	
Real estate	99	81	
Public services	76	65	
Whole economy	**73**	**69**	**78**
Whole economy excl. household energy use.	**68**	**66**	**75**

As can be seen in Table 3 the economy-wide rebound effect in Scenario 1-3 becomes: 73, 69 and 78 percent. The largest rebound effect occurs when only energy-intensive sectors are subject to the increase in energy efficiency. Although households are not directly affected by energy efficiency, households' income and energy use increase. If the household's energy use is excluded, the economy-wide rebound effect becomes lower amounting to 68, 66 and 75 percent in each scenario. Hence, the effect among households' has a significant impact on the rebound effect.

The sector-specific results in Table 3 show that the rebound effect exceeds 100 percent only in the pulp and paper sector, but in all three scenarios. The large rebound effect is explained by the sector's relatively high energy intensity and good substitution possibilities. It can also be seen in Table 3 (Scenario 1) that the rebound effect is relatively low in the energy sectors (electricity, heat and gas and refinery). Unlike most other industries the demand for their output will fall significantly as they produce goods that most sectors now use more efficiently and demand less of. Producers in the energy sectors use less energy as input due to both decreased production and increased energy efficiency in their own production. However, the reduction in demand for energy goods is greater than the energy sectors' income effect from increased energy efficiency.[5]

In Scenario 3 where energy efficiency is improved only in energy-intensive sectors the rebound effect for almost all sectors[6] is slightly lower than in other scenarios. The reasons for this are a less pronounced increase in the real wage and a relatively small income effect on the whole economy, which hampers demand for all goods and services. As highlighted above energy-intensive sectors generally demand relatively little labour and therefore benefits in relative terms when the real wage increases.

5.2 Reducing the elasticity of substitution with 50 percent

In our case the elasticities of substitution are assumed to be relatively high in the energy intensive sectors, 0.7-0.9. These elasticities are applied in sectoral production functions allowing for structural change in the long run, e.g. more production of a certain steel or paper quality. Although the elasticities applied have been carefully picked from the empirical literature, lower elasticities are possible. To test how sensitive the estimated rebound effect is to assumptions about substitution possibilities we reduce the elasticities of substitution with 50 percent and rerun the second and third scenarios. The corresponding results are presented in Table 4. A comparison of the first and second column in Table 4 reveals that the relationship between the rebound effect and the elasticities of substitution is strong as the rebound effect drops by 40 percent. The third column shows that assumptions regarding the energy intensive sectors are important as altering the substitution possibilities only in those sectors reduce the rebound effect with 13 percent. The forth column illustrate how the rebound effect following a 5 percent improvement in energy efficiency only in energy intensive sectors (Scenario 3) is affected by a 50 percent reduction in substitution possibilities in those same sectors. As can be seen by studying the results for the third scenario in Table 2, decreased substitution possibilities reduce the macroeconomic impact from increased energy efficiency and, thus, the rebound effect by almost 50 percent.

The sensitivity of the results is somewhat lower, but still in line with the findings in Allan et al. (2007), but more significant than that found in Hanley et al. (2009).[7]

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[5] Note that the increase in energy efficiency only applies to the fuels modelled in the EMEC model. Therefore electricity and district heating production is only affected by the energy efficiency improvements in their use of oil, bio, coal, gas and electricity. Hence, nuclear, hydro, and wind power will not be affected directly.

[6] With the chemical industry as an exception.

[7] We also have tested different assumptions regerding the substitution between value added and the energy-material composite. We find that the rebound effect is relatively insensitive to these assumtions, which is in line with findings in Hanley et al. (2009).

Table 4: Sensitivity analysis with respect to elasticities of substitution. Impacts on macroeconomic indicators and the rebound effect on energy use following a five percent increase in efficiency of the industrial use of energy.

Percentage difference in year 2035 compared to benchmark scenario (without the increase in energy efficiency).

	Scen 2	Scen 2 Elasticity between material and energy reduced by 50% in all sectors	Scen 2 Elasticity between material and energy reduced by 50% only in energy intensive sectors	Scen 3 Elasticity between material and energy reduced by 50% only in energy intensive sectors
GDP	0,3	0,2	0,3	0,1
Exports	0,3	0,2	0,2	0,1
Imports	0,2	0,2	0,2	0,1
Private consumption	0,3	0,2	0,3	0,1
Investment	0,4	0,3	0,3	0,1
Working hours	0,04	0,04	0,04	0,01
Real wage	0,2	0,2	0,2	0,1
Rebound effect	69	41	60	37
Rebound effect excl. household energy use	66	39	58	34

5.3 Altering the assumptions for the labour market

The results show that changes in the real wage have significant effects on the size of the rebound effect. In previous analyzes for the UK and Scotland (see e.g., Allan et al., 2007; Hanley et al., 2009; and Turner and Hanley, 2011) various assumptions about the labour market have been found to have significant effects on the size of the rebound effect. The conclusion from these studies is that the more flexible labour supply the higher is the rebound effect. In our analysis we assume that the total amount of workers in the economy is fixed but that the workers, based on how the real wage is changing, adjust their number of hours worked. Another possibility is to allow the labour supply to be completely inelastic and fixed at the same level as in the reference case. Under this assumption the supply of hours worked is constant regardless of how the real wage evolves. We label this labour market assumption *fixed*. A third alternative is to assume that labour supply is completely elastic so that the real wage is not affected at all. We label this assumption *flex*.

Table 5 presents the macroeconomic effects and the economy-wide rebound effect for different assumptions concerning the labour market in Scenario 2, where the efficiency of energy use is improved by five percent in all non-energy sectors. The results confirm the finding in the literature: the more flexible labour supply the higher is the rebound effect. If labour supply can increase without any change in the real wage then energy efficiency improvements will result in a much higher rebound effect (81 percent) compared to scenarios where the real wage increase due to higher productivity. It can be seen that the flex-scenario results in a substantial increase in GDP, which is due to lower marginal costs of production. The difference between letting the labour supply depend on the elasticity of substitution between labour and leisure (base scenario) and a scenario where the labour supply is completely inelastic (fixed) is not as sharp. When labour supply is assumed to be completely fixed the real wage increases slightly more than in the base scenario and thus dampens the rebound effect.

Table 5: Sensitivity analysis with respect to labour market assumptions. Impacts on macroeconomic indicators and economy-wide rebound effect following a five percent increase in efficiency of the industrial use of energy (Scenario 2 excl. energy sectors). Percentage difference in year 2035 compared to the benchmark scenario (without the increase in energy efficiency). Rebound effect in percent. Scen 2 = fixed labour force, working hours flexible; Fixed = Fixed labour supply; and Flex = Elastic labour supply.

	Scen 2	Scen 2 Fixed	Scen 2 Flex
GDP	0,3	0,2	0,7
Exports	0,3	0,2	0,6
Imports	0,2	0,2	0,5
Private consumption	0,3	0,2	0,6
Investment	0,4	0,3	0,8
Working hours	0,04	0,0	0,4
Real wage	0,2	0,3	0,0
Rebound effect	69	68	81
Rebound effect excl. household energy use.	66	65	72

5.4 Notional cost for the increase in energy efficiency

Until this section, all improvements in efficiency have been introduced without any costs to firms or to the economy as a whole. This is not very realistic in the short-term, but can be seen as an approximation of a continuous exchange of old machines for new and more energy efficient machines. The costless scenario should be seen as an extreme in the rebound debate. Another extreme is to assume that the effect, of energy efficiency improvements on production costs, is offset by a change in the productivity of any other production factor. Since it is not obvious what kind of costs energy efficiency incurs we test three different assumptions. In the first case, increased energy efficiency incurs a cost in terms of lower labour productivity in sector *i* ($\beta_{i,L}$) and is equal to:

$$\beta_{i,L} = 0{,}05 \cdot \left(\frac{Ec_i}{Ac_i}\right) \tag{3}$$

where Ec_i is the energy expenditure of sector *i* in the reference scenario and Ac_i is the labour costs in the reference case for sector *i*.

In the second case, the cost incurs in terms of lower capital productivity in sector *i* ($\beta_{i,C}$) and is equal to:

$$\beta_{i,C} = 0{,}05 \cdot \left(\frac{Ec_i}{Cc_i}\right) \tag{4}$$

where Cc_i is the capital cost in the reference case for sector *i*.

Finally, the cost incurs in terms of lower productivity in value added to reflect that the cost of energy efficiency can involve a mix of capital and labour costs. The decrease in productivity of value added in sector i ($\beta_{i,FV}$) is equal to:

$$\beta_{i,FV} = 0{,}05 \cdot \left(\frac{Ec_i}{FV_i}\right) \quad (5)$$

where FV_i is value added in the reference case for sector *i*.

The results in Table 6 show that when a notional cost for the increase in energy efficiency is introduced the output effect as well as the rebound effect is greatly reduced. The rebound effect drops by approximately 17 percentage points. As we have "turned off" the output (income) effect the results remain the same whether or not the households are included in the analysis.

These results are not fully in line with Allan et al. (2007), who find that the rebound effect is negative when energy efficiency is combined with reduced labour productivity ($\beta_{i,L}$). A negative rebound effect implies that a negative scale effect out-weights the substitution effect. As it is assumed in our scenarios that the economic benefits of increased energy efficiency are approximately neutralized in such a way that the total production costs remain unchanged, we do not find any substantial negative effect on GDP.

Table 6: Impacts on macroeconomic indicators and economy-wide rebound effect following a five percent increase in efficiency of the industrial use of energy (Scenario 2 excl. energy sectors) given a notional cost keeping the production costs constant initially. Percentage difference in year 2035 compared to the benchmark scenario (without the increase in energy efficiency). Rebound effect in percent.

Scenario 2	Energy efficiency without cost	Energy efficiency with cost - lower labour productivity	Energy efficiency with cost – lower capital productivity	Energy efficiency with cost – lower productivity in value added
GDP	0,3	-0,1	0,0	-0,1
Exports	0,3	-0,2	-0,1	-0,2
Imports	0,2	-0,1	0,0	-0,1
Private consumption	0,3	0,0	0,0	0,0
Investment	0,4	-0,2	0,3	0,1
Working hours	0,04	0,0	0,0	0,0
Real wage	0,2	0,1	0,0	0,1
Rebound effect	69	50	53	52
Rebound effect excl. household energy use	66	50	53	52

As a final sensitivity analysis we add up the effects of all the conservative assumptions to provide a lower benchmark for the rebound effect given Scenario 2 (excl. energy sectors). As can be seen in Table 7 the rebound effect shrinks to 44 percent if we turn off the output effect and reduce the elasticities of substitution for the energy-intensive sectors with 50 percent.

Table 7: Impacts on macroeconomic indicators and economy-wide rebound effect following a five percent increase in efficiency of the industrial use of energy (scenario 2 excl. energy sectors) given a notional cost keeping the production costs constant initially and that the elasticities between material and energy are reduced by 50% in energy intensive sectors. Percentage difference in year 2035 compared to the benchmark scenario (without the increase in energy efficiency). Rebound effect in percent.

	Scen 2	Scen 2 Notional cost in terms of lower productivity of value added	Scen 2 Notional cost in terms of lower productivity of value added when elasticities between material and energy are reduced by 50% in energy intensive sector
Rebound effect	69	52	44
Rebound effect excl. household energy use.	66	52	44

6 Discussion and conclusions

From an economic perspective the rebound effect is a natural and unproblematic effect that follows from technological progress. Cost-effective improvements of energy efficiency create economic growth. The rebound effect becomes a problem when there are restrictions to economic growth, e.g. targets for carbon emissions or energy use. The question for policy makers then becomes whether measures to improve energy efficiency contribute to a cost-efficient fulfillment of the targets set out for the environmental and energy policies. Whether or not energy efficiency improvements are part of a cost-efficient policy mix depends on costs and actual effects, the latter being determined by the rebound effect. It is absolutely essential to ensure that backfire is not a likely outcome of any energy efficiency measure. Even cases where the rebound effect is high but do not exceed 100 percent are problematic because environmental or energy policy measures could become exorbitantly expensive as the energy saving potential is eroded by economic and behavioral adjustments.

In this paper we have applied a CGE model for the Swedish economy to assess the economy-wide rebound from a five percent increase in efficiency of industrial energy use. The scenarios studied are similar to those analyzed for the UK economy as a whole (e.g., Allan et al., 2007) and regionally for the Scottish economy (e.g., Hanley et al., 2009). Our results point at an economy-wide rebound effect in the range of 40-70 percent depending on the size of the substitution elasticities and whether energy efficiency improvements are combined with a cost. In contrary to the studies for the UK and the Scottish economies we find that it is of minor importance to the rebound effect whether the energy sectors are part of the initial improvement of energy efficiency. The rebound effect is somewhat higher when the improvement in energy efficiency includes all sectors.

We conclude that assumptions regarding the electricity sector are of great importance to the size of the economy-wide rebound effect. In the Scottish case electricity could be exported without restrictions and the electricity production was dependent on coal and gas, which are energy-intensive sectors. In the case for UK the electricity production was also dependent on coal and gas, but the export of electricity was restricted.

Extraction of coal and gas do not take place in Sweden and the use of fossil fuels in electricity production is minimal. Swedish electricity production is mainly (around 90 percent) based on nuclear and hydro power, which are not affected by our energy efficiency simulations. Sweden are somewhere in between the extremes of Scotland and the UK when it comes to interregional electricity trade. Sweden is part of the Nordic electricity market (*Nord pool spot*), but the international transmission capacity is constrained, which causes the price of electricity to decrease as a result of lower domestic consumption. The characteristics of the electricity market are one of the reasons why the rebound effect in Sweden is significantly lower than in Scotland when energy sectors are included in the analysis.

Sweden has a relatively energy-intensive production and an increase in energy efficiency is therefore expected to stimulate economic activity to a larger extent compared to economies with lower energy intensity, ceteris paribus. This expectation is supported in our analysis. We find a rebound effect of 69 percent when energy efficiency is only improved in non-energy sectors, which is higher than the corresponding value for Scotland (35-41 percent). The rebound effect from energy efficiency improvements in energy-intensive manufacturing sectors, such as the pulp and paper sector, is expectedly larger compared to when energy efficiency is improved in all production sectors. Our results indicate a rebound effect of 78 percent when energy efficiency is improved only in energy-intensive sectors. We conclude that policy measures to improve energy efficiency in energy-intensive sectors are likely to be ineffective and possibly counterproductive in the long run if the objective is to lower energy use.

Our results are sensitive to the assumptions concerning the labour market and confirm the findings in the literature that the rebound effect becomes higher when labour supply is flexible. In the EMEC model labour supply is semi-flexible as the labour force is fixed but the working hours flexible and a function of the real wage rate. We find that the rebound effect increases (to 81 percent) when we introduce a completely flexible labour supply and a fixed wage rate, which is similar to the central case in the analysis of the Scottish economy. Under the assumption of a fixed labour supply the rebound effect becomes somewhat lower compared to our central case. We conclude that the assumptions made for the labour market may be one of the main drivers behind the finding of backfire in the Scottish economy.

Finally, our analysis shows that if energy efficiency improvements is introduced at a cost, the size of the rebound effect becomes significantly lower than if efficiency comes free of charge, like 'manna from heaven'. It is reasonable to assume that energy efficiency improvements involves a combination of new technology and adjustments of existing technologies that require higher input of both capital and labour. Our results indicate that when energy efficiency improvements are combined with lower efficiency in value added, such that the production costs remains unchanged (before the general equilibrium effects), the rebound effect drops to 52 percent. When costs are introduced solely on labour it creates a negative output effect and the rebound effect becomes somewhat lower. It seems more appropriate to introduce costs in terms of value added, which includes both labour and capital, than in terms of only labour. These results are not in line with the negative rebound effects in Allan et al. (2007). It is not clear what drives their significantly larger negative output effect since total production costs were held approximately constant.

The literature on the economy-wide rebound effect frequently emphasizes that measures to increase energy efficiency needs to be complemented by changes in economic policy instruments, such as carbon and energy taxes (Brännlund et al., 2007; Hanley et al., 2009; van den Bergh, 2011; Turner and Hanley, 2011). Our results to some extent contest that complementary policy measures are needed in general. We conclude that improved energy efficiency, as a result of technological progress, probably will have significant impacts on energy use without complementary changes in taxes. If measures to improve energy efficiency are costly to start with, complementary policy measures are even less needed as the rebound effect is lower in such cases.

The focus of CGE studies on the rebound effect has been regional or national. We study energy use in Sweden and efficiency improvements taking place only in Sweden. However, technological progress is likely to be global. Future research should extend the analytical frames to address new scenarios. If industrial efficiency is improved globally world market prices would change which would create other macroeconomic effects then studied this far. The studies for the UK as a whole and regionally for Scotland may give a hint on how extended frames of the analysis may affect the results. In these studies the same scenario of improved energy efficiency generates completely different results on the size of the rebound effect.

Although CGE models have many attractable features their use is restricted. In most CGE models it is assumed that all markets are in equilibrium where firms and households act rationally based on complete information. Thus, CGE models may not be suitable for analysis of certain types of market failures, e.g., incomplete information or rigidities on the labour market (Sanstad et al., 2006). As the current debate on energy efficiency is focused on elimination of market failures, CGE models need to be complemented by econometric modeling, especially when effects in the short- or medium-term are analyzed.

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8 Appendix

Table A1: Elasticities of substitution in production sectors

Production sector	Elasticity of substitution between value added and material-energy aggregate	Elasticity of substitution between material and energy	Elasticity of substitution between capital and labour
1. Agriculture	0,3	0,5	0,5
2. Fishery	0,2	0,3	0,3
3. Forestry	0,3	0,4	0,5
4. Mining	0,3	0,4	0,8
5. Other industries	0,3	0,4	0,8
6. Mineral products	0,7	0,9	0,8
7. Pulp and paper mills	0,7	0,9	0,8
8. Drug industries	0,3	0,4	0,8
9. Chemical industries	0,7	0,8	0,8
10. Iron & Steel industries	0,4	0,5	0,8
11. Non-iron metal ind.	0,3	0,4	0,8
12. Engineering	0,6	0,7	0,8
13. Petroleum refineries	0,1	0,3	0,2
14. Electricity supply	0,1	0,1	0,3
15. Hot water supply	0,1	0,1	0,3
16. Gas distribution	0,1	0,1	0,3
17. Water and sewage	0,2	0,3	0,3
18. Construction	0,2	0,3	0,3
19. Rail road transports	0,2	0,3	0,2
20 Road goods transports	0,2	0,3	0,2
21. Road passenger transports	0,2	0,3	0,2
22. Sea transports	0,2	0,2	0,2
23. Air transports	0,2	0,3	0,2
24. Other transports	0,6	0,7	0,8
25. Services	0,7	0,9	0,8
26. Real estate	0,5	0,8	0,6
27. Public services	0,1	0,7	0,7

Figure A1: The input-activity specification in the *EMEC* model