Available online at www.sciencedirect.com
SCIENCE DIRECT®
Energy Economics 26 (2004) 261–282
Energy Economics
www.elsevier.com/locate/eneco

A general equilibrium assessment of rebound effects

Sverre Grepperud[a,*], Ingeborg Rasmussen[b]

[a]Center for Health Administration, University of Oslo, NO-0027 Oslo, Norway
[b]ProSus, Norwegian Research Council, Sognsveien 70, N-0855 Oslo, Norway

Abstract

In this paper we use a general equilibrium model applied to a national economy (Norway) to explore the potential for energy efficiency improvements to trigger economic forces that offset potential savings from using more efficient technologies (rebound effects). Two types of energy efficiency improvements (electricity and oil) are introduced into various sectors of the economy. Our results suggest significant and surprising differences across sectors concerning both energy use and consequences for the build-up of greenhouse gases. Rebound effects are found to be quite significant for manufacturing sectors since long-term consumption of energy undergoes minor reductions or increases in response to efficiency improvements. In other sectors, rebound effects appear to be weak or almost absent.

JEL classifications: Q25; Q43; Q48

Keywords: Energy saving; Rebound effects; Macroeconomic implications; CO_2-emissions

1. Introduction

The application of efficiency improvements, in order to achieve reductions in pollution and resource consumption, has been on the political agenda since the early 1970s and is now frequently suggested as a measure towards the realisation of a sustainable development (see e.g. World Commission on Environment and Development, 1986; United Nations, 1995; Organisation for Economic Co-operation and Development, 1995, 1998). Recent advocates of efficiency improvements have also

*Corresponding author. Tel.: +47-23-07-53-11; fax: +47-23-07-53-10.
E-mail address: sverre.grepperud@samfunnsmed.uio.no (S. Grepperud).

0140-9883/04/$ - see front matter
doi:10.1016/j.eneco.2003.11.003

introduced new concepts. One example is Eco-efficiency, proposed by the World Business Council for Sustainable Development (1999), used about measures that reduce ecological impacts and resource intensity throughout the life cycle of goods and services. A second example is Factor 10, which appeared in 'The Carnoules Declaration' and called for an increase in current resource productivity by an average factor of 10 during the next 30–50 years, in order to reach sustainability (Wuppertal Institute, 1994).

While emphasising the importance of efficiency improvements, the above literature ignores the possibility of 'take-back' or rebound effects. Rebound effects can be defined as economic forces (demand side effects) that over time weaken the potential (technical) savings associated with efficiency improvements. One important cause of such effects is that higher efficiency reduces energy costs, which again increases demand. Khazzoom (1980, 1986, 1987, 1989) and Khazzoom et al. (1990) all discuss the significance of such effects. Khazzoom questions the adequacy of energy savings programs since greater efficiency could lead to increased, rather than decreased energy demand.[1] Khazzoom (1987) also presents a critique of Lovins (1985) for ignoring rebound effects when savings from more efficient mandated appliances were assessed. This again triggered a debate on the importance of rebound-effects (see e.g. Lovins, 1988; Henly et al., 1988; Khazzoom, 1989).

The controversy reappeared a few years later—now in the context of fossil fuel consumption and greenhouse gas abatement. A forerunner to this debate was a work by Manne and Richels (1990), which analysed the economic costs arising from CO_2-emission limits. This study showed that the autonomous energy efficiency index (AEEI) had a dramatic impact on the economic cost of reducing CO_2-emissions.[2] The same study found that a higher value on the AEEI (higher energy efficiency) would reduce both energy use and greenhouse gas emissions. Brookes (1990) and Greenhalgh (1990) nonetheless believe that widespread improvements in energy efficiency will not by themselves do anything to halt the build-up of greenhouse gases globally. Reductions in the energy intensity of output are associated with increases, rather than decreases in energy demand. Consequently, Brookes (1990) considers efficiency improvements to be an inappropriate way of combating the greenhouse effect. Grubb (1990), however, has challenged his arguments.

Saunders (1992) brought the debate a step further by applying Neo-classical theory in the analysis of the Khazzoom–Brookes' postulate which suggests that 'energy efficiency improvements might increase rather than decrease energy consumption'.[3] Calculations were undertaken in a one-sector growth model with three factors of production (labour, energy and capital) using Cobb-Douglas and nested CES production functions. Saunders (1992) conducted simulations under the assumption of a fixed real energy price and found that efficiency improvements increased the consumption of the resource that was exposed to higher efficiency

[1] Jevons, a 19th century economist, was the first to mention that efficiency gains would increase consumption (Jevons, 1865).

[2] By autonomous is meant a non-price induced efficiency improvement.

[3] Saunders (1992) is of the opinion that Khazzoom bases his arguments on price elasticity arguments while Brookes (1990) takes a more macroeconomic view.

rates as well as the two additional factors of production. The only exception concerned a nested CES technology given the elasticity of substitution being equal to 0.5. In this case, capital and labour combine in a Cobb-Douglas fashion, while the two together combines in a CES fashion with energy. As a consequence, Saunders (1992) concludes that the Khazzoom–Brookes' postulate holds regardless with Cobb-Douglas, and with nested CES it holds under most conditions.[4]

Demand studies using micro-data are also present in the literature. Studies on household electricity demand identify rebound effects ranging from 2 to 13% (e.g. Dubin et al., 1986). In a study using US data from a residential conservation program (electric household appliances) it was found that approximately 60–70% of the initial savings were eroded by the rebound effect (Khazzoom 1986). Similarly, Haugland (1996) refers to Norwegian survey data from 1990 describing the outcomes of programs launched to reduce oil consumption, which suggest rebound effects amounting to approximately 40% for households and 10% for commerce. Econometric analyses on the US transport sector have also been undertaken. Greene (1992) studies light-duty vehicle miles during the period of 1966–1989. His findings suggest a rather small rebound effect, approximately 5–15% or less. The short-run (1-year) adjustments accounted for essentially all of the change in journeys due to fuel price and fuel economy changes. This result is supported by previous studies by Mayo and Mathis (1988) and Gately (1990). Jones (1993) undertook an analysis using the same data as Greene (1992), but chose model specifications better able to capture long-term effects. The results showed somewhat more significant rebound effects ($\sim$30%).

The above discussion illuminates strong differences between the neo-classical growth approach and econometric analyses at sector level with respect to the magnitude of rebound effects. In this study an attempt is made to fill in some gaps between the two approaches by applying a macro-economic analysis of rebound effects at industry level. This is done by using an applied general equilibrium model that enables us to conduct analyses at sector level, while at the same time avoiding drawbacks usually associated with single-equation estimations. The consequences of efficiency improvements for various sectors can now be studied with complete sets of equations and without violating consistency demands for example with respect to budget constraints.

A general equilibrium framework also allows for an examination of the overall long-term effect of efficiency improvements. As pointed out in the literature, rebound effects do not only arise from substitution and income effects generated by changes in the effective price (implicit price) of a resource, but may follow from consumption ramifications extending economy-wide. Input–output relationships, cross-price effects and income elasticities are all important for sectoral complementarities and backward–forward linkages, and such effects may well be important. The analysis is undertaken in a multi-sectoral model describing the Norwegian

[4] Saunders (1992) refers to an econometric study by Hogan and Jorgenson (1991) which supports his findings. Hogan and Jorgenson identify an increasing value share of energy in 35 sectors in the US economy spanning 20 years. Such a development can be explained by an energy-augmenting technology progress with the energy substitution elasticity greater than unity.

economy, thus we go beyond aggregate data and a stronger empirical foundation is provided than is the case for Saunders (1992). Our approach to CGE modelling is econometric, which constitutes a sounder empirical basis than for example calibrated approaches. A general problem with analyses applying rich (complex) general equilibrium models is to provide precise explanations for the results arrived at.[5] However, by analysing efficiency improvements in one sector at a time it becomes easier to track down important causal factors.

We follow the literature on rebound effects by interpreting efficiency improvements as exogenous factor productivity changes. Consequently, efficiency improvements are not policy-driven, but can be interpreted as following general economic trends. Policy-driven efficiency improvements, however, should include an explicit modelling of relationships between public funding and/or public-induced price changes and innovation processes. Such relationships are indeed complex, but if introduced, would generate effects beyond those present in our analysis. Furthermore, we ignore any change in costs that are normally associated with changes in efficiency improvements, such as installation and operating costs.[6]

Our main focus is on the impacts of energy efficiency improvements. We study such effects for six different sectors of the Norwegian economy, and two different energy sources (electricity and oil). Our main concern is about changes in the demand for energy, however, as a reflection of the concern in the literature, we also report on CO_2-emissions. In contrast to Saunders (1992) we allow for efficiency improvements to influence all prices in the economy including energy prices. The first section of this paper contains a brief outline of the general equilibrium model. Thereafter, descriptions of the baseline scenario (BS) together with an explanation of how energy efficiency improvements are interpreted in our model are given. Finally the findings arrived at are presented and compared.

2. Model outline

The general equilibrium model applied in this analysis, MSG-6 (Multi-sectoral growth), is an applied general equilibrium model developed by Statistics Norway. MSG-6 is the latest version and a complete technical description of the model is still not available. However, a general overview is given by Holmøy (1992) and Holmøy and Strøm (1997), and detailed descriptions of producer behaviour are given by Holmøy (1997) and Holmøy and Hægeland (1997), while household behaviour is described by Bye and Holmøy (1997).[7] The MSG model is a tool in Norwegian long-term planning and has been applied to the analysis of issues such as welfare gains arising from trade liberalisation and tax reforms. The latest versions

[5] However, the purpose of general equilibrium models is precisely to reflect the complexity of an economy by incorporating relevant effects.

[6] Grubb (1990) denotes such effects as first-cost effects.

[7] Complete technical descriptions of former versions of the model are presented by Holmøy (1992) and Alfsen et al., (1996). Former applications of the MSG model, being available in journals, are Glomsrød et al. (1990), Brendemoen and Vennemo (1994), Holmøy and Vennemo (1995) and Larsen and Nesbakken (1997).

of the model include more advanced specifications of energy demand and economy–environment interlinkages, which makes it well suited for analysing environmental and energy policies.

The CGE model is made up of relations derived from competitive behaviour of agents combined with price clearing markets. The general absence of price rigidities and disequilibrium together with the mobility of capital makes the model relevant in a long-term perspective. Technologies in MSG-6 are in general more flexible (e.g. higher substitution possibilities) than is the case for short and medium term macro-economic models. MSG-6 consists of 41 private and 8 governmental production activities and 17 aggregated consumer goods. The behaviour of the economic agents is modelled in accordance with micro-economic theory and is based upon the assumption of rational behaviour given various constraints. Preference structure and technologies are in general organised in hierarchical systems by means of applying separability assumptions.

Producer behaviour in most sectors is specified at the firm level. Each firm allocates production between the domestic market and the world market. In general producers are price takers in the world market but have market power in the domestic market (monopolistic competition). Export volumes and import shares are endogenously determined by the ratio between domestic prices and the corresponding world market prices and a constant representing the elasticity of transformation.

The production technology is represented by a nested tree-structure of CES-aggregates,[8] which reduces the number of substitution possibilities since pair wise combinations of factors represent the substitution possibilities. The factors of production are labour, capital, energy, transport and materials, and the technology contains a detailed description of the use of energy and the demand for transport facilities. Energy is divided into electricity and fuels. It is worth noting that in Norway electricity is generated by hydropower, as a consequence electricity consumption has no direct effect on emissions to air. Transport is divided into polluting and non-polluting facilities where pollution mainly follows from the consumption of transport oils. Substitution possibilities exist between the two factors of the energy aggregate (electricity and fuels), between capital (machinery) and energy, capital/energy and labour, and capital/energy/labour and transport. Elasticities of substitution differ across factor combinations and sectors, and are estimated from national account data (Bye and Frenger 1985; Alfsen et al., 1996). In general, the elasticities of substitution range between 0 and 1, indicating moderate substitution possibilities at each step in the factor-tree. An industry consists of several firms with decreasing returns to scale at firm level. Firms differ with respect to total factor productivity and this heterogeneity assumption together with an endogenous entry–exit mechanism yield decreasing returns to scale at the industry level as well.

Consumption, labour supply and savings follow from maximising intertemporal utility with perfect foresight for a representative consumer. The preference structure is separable and nested, and multi-level budgeting solves the maximisation problem.

[8] At the 'top'-level of the production technology, services from structures (buildings) and the aggregate of all other variable inputs are combined in a Cobb–Douglas fashion.

Full consumption is a CES-composite of (utility from) material consumption and leisure. The intertemporal budget constraints for households equal the present value of consumption expenditure in the current and all future periods. Integrated in the model framework are submodels calculating emissions to air from nine pollutants—including SO_2, NO_X, CO and CO_2. Separate emission coefficients are estimated for stationary combustion, mobile combustion and industrial processes. Production in the public sector is exogenous and the government collects taxes, distribute transfers, and purchases goods and services from the industries and abroad. Overall government expenditure is exogenous and increases at a constant rate.

3. The baseline scenario

In this analysis we use a BS applied by the Norwegian Ministry of Finance in their latest green papers (Ministry of Finance, 1997a,b). The scenario builds upon projections of world economic growth, labour force growth, technological progress and net foreign debt and runs until 2050.[9] According to these projections, for the most important trade partners, gross domestic product (GDP) will grow by almost 2.0% on average during the next 50 years. For OECD countries the growth rate will slow down some decades into the next century. Projections of technological progress are based on historical estimates and equal the average rates of the last 15 years. The annual growth rate in total factor productivity for the private sector is approximately 1.0%.

An important assumption of the BS is a forthcoming international climate treaty. Such a treaty seeks to stabilise global emissions at 1990 levels by the year 2010. The emission target will be reached by the introduction of carbon taxes in all nations amounting to approximately $50 per ton (1997). The proceeds from carbon taxes will be kept by each individual country and will be offset by tax reductions in other sectors of the economy (mainly labour taxes). The presence of an international carbon tax will have a significant impact on the Norwegian economy compared to a situation without an agreement—Business as Usual (BAU). Figs. 1 and 2 compare developments over time in CO_2-emissions and electricity consumption in the BAU scenario with the BS scenario applied in this paper.

From Fig. 1 it follows that national CO_2-emissions will decrease to 1990 level by 2010–2015 according to the BS. CO_2-emissions in year 2050 will be cut by almost 50% according to the BS as compared to BAU. From Fig. 2 it is observed that the consumption of electricity is higher in BAU than that in BS. Furthermore, electricity consumption is growing in both scenarios. For BS this observation may seem surprising in view of Fig. 1 but follows from the fact that electricity in Norway is produced almost entirely by hydropower, an energy-source that does not lead to the emission of CO_2. As a consequence, carbon taxes are not levied upon electricity production.

A climate treaty will affect all nations; however, the consequences are expected to be particularly severe for the Norwegian economy due to its dependency on oil

[9] Most assumptions concerning the development in important variables are based upon projections made by a government commission (Ministry of Finance, 1988).

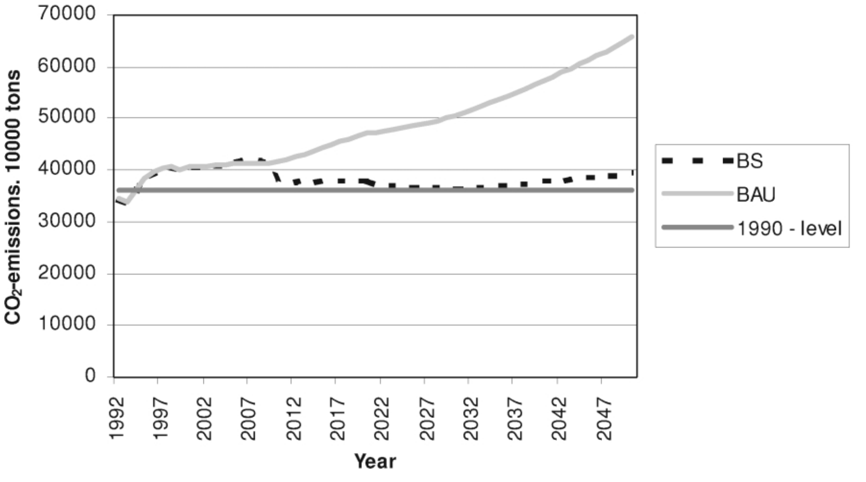

Fig. 1. CO_2-emissions (1000 tons). Baseline scenario (BS) and Business-as-Usual (BAU).

and gas production, which generates roughly 15–20% of GDP and 25–30% of total exports.[10] The introduction of an international carbon tax is assumed to lower the world market oil price by 20% compared to BAU. The treaty has further implications for energy markets. Norway has considerable natural gas resources in the North Sea and the Barents Sea, which represent a future potential for gas-based power generation. However, the presence of carbon taxes is assumed to hinder such a

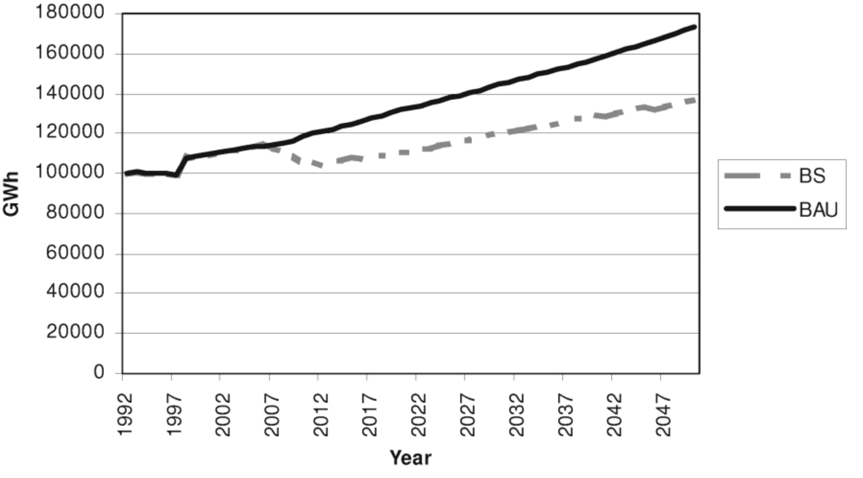

Fig. 2. Electricity consumption (6 Wh*). Baseline scenario (BS) and Business-as-Usual (BAU).

[10] According to the literature, oil-exporting countries will experience the greatest losses from a global carbon tax.

development and future electricity consumption will be produced almost entirely by hydropower.[11,12] Increases in the domestic demand for electricity over time are partly met by higher prices and partly by the use of renewable energy sources such as bio-energy, heat pumps and solar energy. The market price of electricity in BS will be approximately 30% higher than that in BAU in year 2010, which implies a relatively higher profitability of alternative renewable energy-sources in this scenario. An additional effect of the climate treaty would be a gradual removal of the present arrangements where energy intensive production sectors receive subsidised hydropower.[13] Thus, according to this scenario, the price of electricity will be determined entirely by market forces and become uniform for all sectors.

According to BS the annual GDP growth rate in mainland Norway (excluding oil and gas extraction) will be 1.9% the first 20 years and somewhat lower the next three decades (1.2%). Despite the introduction of a carbon tax, the future growth rate according to the BS will not be very different from the future growth in BAU. An important reason for this is the long-term perspective of the model that implies that costs associated with structural adjustments are being modified over time. In addition, the removal of electricity subsidies and the reduction of taxes on labour would have positive long-term impacts on the national economy. A higher world market price on electricity would partly compensate the loss in petroleum earnings following from an international carbon tax.

4. Description of sectors and the implementation of efficiency improvements

The intention of this section is to give a brief description of the six sectors for which efficiency improvements are being introduced. In addition, a precise description is given of how efficiency improvements are interpreted in the CGE-model. All six sectors are listed in Table 1 and include three manufacturing sectors (pulp and paper, metals, and chemical and mineral products), one service sector (finance and insurance), one transport sector (road transport) and one resource-based sector (fisheries). The selection of sectors was done according to several criteria. The most important consideration was to select sectors that are different with respect to input use, energy consumption and market structure. This was partly achieved by choosing sectors from different industries.[14] The manufacturing sectors together with fisheries are traditional exporting sectors while road transport and finance and insurance are more sheltered sectors of the Norwegian economy.

Table 1 reveals wide discrepancies across sectors with regard to energy consumption and CO_2-emissions in the base year of the model (year 1992). Metals and road

[11] However, two gas-fired power plants are already being planned in Norway and both of them are included in BS.

[12] In BAU, the increase in demand for electricity is met by a gradual introduction of electricity generated by gas. Approximately 30% of national CO_2-emissions in 2050 comes from gas power generation according to this scenario.

[13] Thirty percent of the Norwegian electricity production is still excluded from the market due to the existence of long-term contracts with regulated prices in some industries.

[14] Finance and insurance is believed to have a promising potential for energy savings (heating) and was included in our analysis for this reason.

Table 1
Energy consumption (intensities) and carbon emissions (intensities)—(1992)

Sectors (share of GDP[a] in 1992)	Electricity consumption (EC) million NKr. 1992 (electricity intensity = EC/GP_i[b])	Oil consumption (OC) million Nkr. 1992 (oil intensity = OC/GP_i)	Sectoral CO_2-emissions (tons) (CO_2-intensity = CO_2-emissions in tons (1992)/GP_i)
Manufacture of pulp and paper (2.4%)	818 (0.051)	95 (89 + 6)[c] (0.006)	224 371 (14.1)
Manufacture of metals (4.1%)	2 281 (0.084)	162 (146 + 16) (0.006)	4 562 208 (169.0)
Chemical and mineral products (5.4%)	671 (0.018)	251 (188 + 63) (0.007)	1 494 958 (41.7)
Finance and insurance (7.9%)	346 (0.006)	105 (2 + 103) (0.002)	59 698 (1.1)
Fisheries (1.0%)	0 (0)	612 (37 + 575) (0.100)	1 274 603 (208.2)
Road transport (5.2%)	34 (0.001)	2639 (155 + 2484) (0.076)	2 199 911 (63.5)

[a] Share of GDP for sector $i = (GP_i/GDP)100$.
[b] GP_i, gross production in sector i (million Norwegian kroner—1992).
[c] The terms in the parenthesis are heating oils and transport oils, respectively.

transport are the two sectors with the highest total energy consumption (electricity and oils) and CO_2-emissions in absolute terms. Finance and insurance, on the other hand, has the lowest energy consumption (electricity and oil) as well as the lowest CO_2-emissions.[15] The distribution of energy consumption across the two energy sources is also skewed across the sectors considered. Electricity is the most important source of energy in the three manufacturing sectors and finance and insurance, while oil consumption is the most important for the two remaining sectors. The variation in consumption between the two energy sources is least for chemical and mineral products and finance and insurance. For both sectors the consumption of electricity is approximately three times that of the consumption of oil. Furthermore, it follows that heating oils are more important than transport oils for the three manufacturing sectors while transport oils are more important than heating oils in both fisheries and road transport, due to the importance of mobile vehicles (vessels) in these sectors.

The sectors also differ with respect to intensities (see the parenthesis in Table 1). The three manufacturing sectors are the most important sectors with respect to electricity intensity. Road transport and fisheries, the two sectors with the highest oil consumption in absolute terms, are the two sectors with the highest oil-intensities. Sectoral CO_2-emissions in absolute terms are highest for metals, which is surprising since this sector is not the largest consumer of fossil oils. The reason lies with the fact that most emissions in this sector stem from process-related coal consumption. Road transport, chemical and mineral products, and fisheries are also important contributors to national CO_2-emissions, while pulp and paper and finance and insurance are less important. We also observe significant variations across sectors with respect to emission-intensities. Fisheries, together with metals, are the most polluting sectors relative to sectoral gross production (GP), while road transport, chemical and mineral products and pulp and paper are less important in this perspective. For finance and insurance the CO_2 emission-intensity is very low.

We have chosen to introduce efficiency improvements for the most important energy source in each sector. Accordingly, electricity efficiency improvements are introduced in four sectors (the three manufacturing sectors and finance and insurance) while transport oil efficiency improvements are introduced in road transport and fisheries. Efficiency improvements are interpreted along the lines of other economic analyses on this subject in that the quantity produced by a factor shall increase as a result of an efficiency improvement (see e.g. Saunders, 1992; Manne and Richels, 1990).

The production technology is represented by CES aggregates that are nested in order to reduce the number of substitution possibilities. Below we describe the specification of the CES energy aggregate, U. The energy aggregate production function is of the following type (Mysen, 1991 or Uzawa, 1962):

$$U=\left[S\left(\frac{1}{\alpha}E\right)^{(z-1)/z}+(1-S)\left(\frac{1}{\beta}F\right)^{(z-1)/z}\right]^{z/(z-1)} \tag{1}$$

[15] However, as seen from Table 1, finance and insurance uses more electricity than both road transport and fisheries and more oil than pulp and paper.

Table 2
Types of efficiency improvements and energy productivity growth rates

No.	Production sector	Type of energy efficiency improvements		Annual average growth rate in energy productivity (electricity or transport oil) (BS)
		Electricity	Transport oil	
27	Manufacture of pulp and paper	X		0.82
34	Manufacture of metals	X		0.82
43	Chemical and mineral products	X		0.82
63	Finance and insurance	X		0.82
13	Fisheries		X	3.31
81	Road transport		X	0.30

where E denotes electricity, F fossil fuels; z the elasticity of substitution between electricity and fuels; α and β are the productivity indices for E and F, respectively, while S is a coefficient representing electricity's share of total energy consumption.

The dual cost function $C(U)$ now equals UP_U where[16]

$$C(U)=UP_U=U\left[S^{1-\mathrm{CRU}}\left(\frac{\mathrm{PE}}{\alpha}\right)^{\mathrm{CRU}}+(1-S)^{1-\mathrm{CRU}}\left(\frac{\mathrm{PF}}{\beta}\right)^{\mathrm{CRU}}\right]^{1/\mathrm{CRU}} \tag{2}$$

where P_U is the implicit (effective) price of the energy aggregate (electricity and fuel), PE and PF are the market prices of electricity and fuels, respectively, and $\mathrm{CRU}=1-z$. The model includes specific assumptions about the annual average growth in factor indices (α and β) which can be said to reflect sectoral output changes that cannot be attributed to changes in factor quantities. The growth paths are calculated on the basis of historical observations of factor productivity changes across sectors. The actual growth rates in energy (electricity or fuel) productivity in the BS are presented in Table 2. It follows that the growth paths are similar for the three manufacturing sectors and finance and insurance (0.82%). However, the same rates differ for the two remaining sectors. In fisheries, the annual average growth in transport-oil productivity is quite high (3.31%) while the same rate for road transport is low (0.30%).

Factor productivity improvements will in the following be introduced by changing the value of α or β in Eq. (2). It follows from Eq. (2) that such a change will reduce the implicit price on energy (P_U) and the magnitude of this change will depend on energy shares as well as the elasticity of substitution. In this analysis we have chosen to double the growth rate in energy productivity (electricity or oil) in the BS. In other words, we introduce a continuous improvement of the energy factor productivity throughout the horizon of the model (until 2050). Another possibility would be to change the growth rate for a single year or a limited time period. However, since some sectors constitute relatively small parts of the national economy, we prefer significant improvements in order to trigger general equilibrium effects.

[16] The cost function is derived by inserting the marginal productivity of electricity and fuel from the first order conditions into the production function.

Accordingly, the technological changes undertaken are quite substantial. Since the growth rates differ somewhat across sectors, caution must be taken when comparing results.

5. Results

The main results together with important explanations for the observed changes are reported in this section. Efficiency improvements are introduced for each sector separately, and we report on changes in key variables, such as energy consumption, gross production and CO_2-emissions, compared to the BS.[17] Since we are concerned with long-term effects, the year 2050 acts as the benchmark for comparisons. In Table 3, the results for the first four sectors are presented; pulp and paper; metals; chemical and mineral products; and finance and insurance.

5.1. Manufacture of pulp and paper

A doubling of the annual average rate of electricity-specific factor productivity for pulp and paper causes a long-term decline in the demand for electricity by 2050 (-17.7%) compared to the BS. Thus, efficiency improvements in this sector induce a long-term reduction in the consumption of electricity. The initial effect from the introduction of efficiency improvements is that less electricity is needed to sustain the sectoral output path of the BS (technical savings). However, energy savings trigger several behavioural effects in the model.

The implicit price relationship between fuels and electricity can be said to change in favour of the latter, which again induces a change in demand for electricity at the expense of oil. The elasticity of substitution between electricity and fuel is high for this sector ($z=1.34$), suggesting a strong substitution effect.[18] It follows from Eq. (2) that the efficiency improvement causes the implicit price of the energy aggregate to decline and that this effect increases with z as well as electricity's share of total energy consumption ($S=0.89$). This again triggers substitution effects between energy and others factors of production in this sector. However, in this sector, such substitution possibilities only exist between energy and capital and are weak (0.33). As a consequence, the long-term demand for energy (electricity and fuel) increases only moderately at the expense of capital (machinery). The activity in the sector will also be stimulated by efficiency improvements, increasing the demand for all factors of production, including the two energy sources. This effect is a result of an efficiency improvement causing a decrease in the costs of production. This magnitude of this cost reduction will depend on (i) the substitution elasticity

[17] It follows that rebound effects in this analysis will be identified by comparison to the baseline scenario. However, reports about the magnitude of rebound effects could be more informative if related to the full engineering effect (without any rebound). However, such an approach is not chosen in this study since the full engineering effect in a particular sector can only be identified in the CGE model by introducing an efficiency improvement while on the same time disconnecting this sector from all endogenous forces in the model.

[18] The elasticity of substitution describes substitution between electricity and fuel for a given total energy input in the sector.

Table 3
Percentage deviation relative to BS (year 2050) electricity efficiency improvements

Sectors	Electricity consumption	Oil consumption	Gross production	CO_2-emissions (sectoral)	CO_2-emissions (national)[a]
Manufacture of pulp and paper	−17.7	−29.9	11.3	−28.6	−0.5
Manufacture of metals	17.8	87.5	31.9	39.7	3.7
Chemical and mineral products	−5.7	−1.2	4.1	0.1	0.0
Finance and insurance	−36.1	1.8	0.3	0.8	0.0

[a] National emissions, total emissions from all sectors of the Norwegian economy.

(z), (ii) the electricity share (S), (iii) substitution possibilities between the energy aggregate and the other factors of production, and (iv) the share of energy costs to total production costs. It follows from Table 3 that the activity in this sector, measured by gross production, increases by approximately 11%.[19] The increase is a result of a pulp and paper being a rather electricity intensive sector. High substitution possibilities between the two energy sources will also contribute to a significant reduction in production costs.

The consumption of oil is reduced by almost 30% compared to the BS. In fact, oil consumption does undergo a stronger relative reduction than the consumption of electricity, in spite of electricity being the energy source exposed to efficiency improvements. The reason lies with the rather strong substitution possibilities that exist between electricity and oil for a given total energy input, creating significant reductions in oil consumption in response to electricity efficiency improvements. The substitution effect away from capital and towards energy (electricity and oil) and the increase in the demand for all factors of production (including energy) due to lower production costs (activity effect) are not strong enough to offset the decline in the demand for oil.

The observed changes in factor demand that occur in this sector could have consequences for market prices. However, it turns out that the market price of electricity in 2050 is only 0.2% lower than the same price in the BS.[20] Finally, it follows from Table 3 that CO_2-emissions in this sector are reduced by almost 30% by the year 2050 compared to the BS, while national emissions are being reduced by 0.5%. The decline in emissions is proportional to the decline in the consumption of oil, which makes sense in view of the fact that changes in the consumption of electricity have no effects on CO_2-emissions.

5.2. Manufacture of metals

The results arrived at in this sector are quite different from those of pulp and paper. The demand for electricity increases now by almost 18%, suggesting strong rebound effects. Furthermore, the consumption of oil increases with 87.5% while the activity (gross production) in this sector increases with approximately 32%. The direction of change in demand for both energy sources is opposite of those identified for pulp and paper. In addition, the relative changes in the activity level of this sector are significantly higher than those observed for pulp and paper.

Two features distinguish metals from pulp and paper. First, substitution possibilities between electricity and oil are almost absent in this sector. Second, electricity is a relatively more important factor of production for this sector than for pulp and paper. The first property implies that electricity cannot substitute oil. However, this effect cannot alone explain the results arrived at since the absence of substitution possibilities, ceteris paribus, prevents rebound effects from occurring. The second

[19] This effect arises through the entry–exit mechanism in the model. Increased profitability in the sector raises the number of less productive firms joining the sector.

[20] This is a result that matters for all sectors analysed in this study. Efficiency improvements have no or very weak effects on the market price of energy.

feature, however, should trigger significant rebound effects in this sector since production costs are being reduced due to a strong reduction in the implicit price of energy. In addition, the rebound effect induced by a higher activity level is strengthened due to the existence of some substitution possibilities between energy and capital (0.62) and quite strong substitution possibilities between energy/capital and labour (1.09).[21]

National CO_2-emissions increase significantly in response to an electricity efficiency improvement (3.7%), since this sector is responsible for a large share of national emissions. An additional observation is that the sectoral increase in CO_2-emissions is not proportional to the increase in the demand for oil. This observation follows from the fact that industrial processes (coal-consumption) rather than stationary and mobile combustion are the important sources of CO_2-emissions in this sector. Consequently, a significant share of total CO_2-emissions is caused by other sources than oil consumption.

5.3. Chemical and mineral products

Electricity efficiency improvements in this sector induce moderate changes. The demand for electricity is reduced by 6%, the demand for oil by 1%, while gross production increases by 4%. Thus, the pattern of change is quite different from both sectors presented above. The results suggest that rebound effects appear to be more important for this sector than for pulp and paper (−17.7%), but less important if compared to metals (+17.8%).

Chemical and mineral products is characterised by quite strong substitution possibilities between oil and electricity (0.90) as well as between energy and other factors of production. As a consequence, strong forces are at play—all increasing the demand for electricity at the expense of both capital, labour, materials and oil. It follows from Table 3 that the activity in this sector, despite the existence of a flexible technology, does not increase much. Chemical and mineral products has a rather low electricity-intensity compared to the two sectors discussed above, as a consequence the costs of production are not affected to the same degree by an efficiency improvement. In total the characteristics of this sector produce changes, which yield a rather small reduction in electricity consumption. Both oil consumption and CO_2-emissions remain more or less unchanged for this sector. The combination of moderate reductions in costs and substitution effects that contradicts each other with respect to oil yields such an outcome.

5.4. Finance and insurance

A doubling of the annual growth rate in the factor productivity of electricity in finance and insurance yields a reduction in the demand for electricity in 2050 by

[21] A similar efficiency improvement was undertaken for this sector but now with BAU as the reference scenario. The choice of this scenario has important consequences for the results arrived at. The reason is that the absence of a climate treaty implies that both electricity consumption and the price of electricity become exogenous in this sector. As a consequence, the demand for electricity remains unchanged in response to efficiency improvements in this scenario, while oil consumption (+59%) undergo significant changes.

Table 4
Percentage deviation relative to BS (year 2050)

Sector	Electricity consumption	Oil consumption	Gross production	CO_2-emissions (sectoral)	CO_2-emissions (national)
Fisheries	–	−84.0	2.1	−81.8	−0.7
Road transport	0.8	−15.0	1.9	−14.8	−1.4

Oil efficiency improvements.

36%, an increase in the consumption of oil by 2%, while gross production remains more or less unchanged (0.3%). The results arrived at with regard to oil consumption and changes in the activity level share similarities with the ones arrived at for chemical and mineral products. However, the substantial reduction in the consumption of electricity distinguishes it from all three sectors commented upon so far.

One reason for the significant decline in long-term electricity consumption lies with weak substitution possibilities between all factors of production in this sector. In addition, energy costs constitute a small share of total factor costs. As already noted above, the impact on oil consumption in this sector is similar to the same impact for chemical and mineral products, but this sector was characterised by relatively strong substitution possibilities.[22] Consequently, weak substitution possibilities in finance and insurance seem to generate similar results as strong substitution possibilities did in chemical and mineral products.

The four sectors, for which electricity efficiency improvements are introduced, yield quite different results, both with regard to rebound effects, oil demand, the impacts on CO_2-emissions as well as gross production. The differences identified with respect to gross production for example do not follow from impacts on total factor costs only, but depend on assumptions made about the market structure. The three manufacturing sectors face an export market with a perfectly elastic demand function represented by an exogenous world price. A cost reduction in these sectors makes possible relatively larger increases in output from export deliveries than is the case for more sheltered sectors like finance and insurance relying on deliveries in domestic markets characterised by endogenous prices and downward sloping demand functions. Below we present the results for the two remaining sectors for which a transport-oil efficiency improvement is introduced (Table 4). Road transport is a sheltered sector with an endogenous domestic price while fisheries is a traditional export sector facing an exogenous world market price.

[22] Electricity efficiency improvements were also undertaken for another service sector (wholesale and retail services), but now with BAU as the reference scenario. The results for this sector turned out quite differently from those of finance and insurance. The demand for electricity declined by 22% while oil demand increased by 37%. The direction of the two effects in this sector is new compared to the sectors presented above, and follow from quite strong substitution possibilities between energy and others factors in this sector, combined with the moderate elasticity of substitution between electricity and oil (0.47).

5.5. Fisheries

Transport oil is the key source of energy in fisheries since fish vessels are main consumers of energy in this sector (see Fish farming and the manufacturing of fish products are separate sectors in MSG-6). Furthermore, substitution possibilities between transport oils and others factors of production are more or less absent. As seen from Table 4 the demand for transport oil is reduced substantially in 2050 compared to the BS (− 84%). Clearly, the dramatic reduction in oil consumption must be explained in view of the absence of substitution possibilities between energy sources, combined with the fact that a doubling of the factor productivity (3.31%) in this sector produces very strong changes compared to the other sectors.

An additional factor behind almost absent rebound effects in this sector is that output is not determined by market conditions, but is the outcome of negotiations between the government and the industry on annual catch quotas. As a consequence, output is exogenous and will not change in response to oil efficiency improvements despite the dramatic reductions in costs that follow from such improvements. The activity in this sector, measured by gross production, does change to some extent (2.1%). However, these changes are caused by changes in cross deliverances (input–output matrix) from other sectors. CO_2-emissions are reduced proportionally to the decrease in oil consumption (− 81.8%), while national CO_2-emissions undergo only minor changes (− 0.7%). The small decline in national CO_2-emissions follows from fisheries being responsible for only a small share of national emissions. Limited substitution possibilities combined with exogenous output make fisheries an adequate sector for oil-efficiency improvements, if oil savings and/or CO_2-reductions are the policy goals. Technology and regulation together eliminate rebound effects.

5.6. Road transport

Transport-oil efficiency improvements reduce oil consumption by approximately 15% in this sector. The decline in oil demand is less dramatic than was the case for fisheries partly because the efficiency improvement is significantly lower (0.30%). Road transport shares similarities with fisheries in that substitution possibilities between factors of production are very small. Furthermore, it can be seen from Table 4 that gross production increases with almost the same percentage points as fisheries (1.9%). However, this increase is relatively stronger when compared to the magnitude of the efficiency improvement undertaken. It also follows from Table 4 that the consumption of electricity (0.8%) increases somewhat despite absence of substitution possibilities, mainly due to the increase in the activity level that follows from a reduction in the costs of production. CO_2-emissions from this sector (− 14.8%) decrease proportionally to the reduction in oil consumption.

We have identified very different results across sectors with respect to the effects on energy consumption. Much explanation to the results arrived at is found from knowledge both about the dual cost function (Eq. (2)) and cost shares. The analysis of the Norwegian economy stresses the importance of being cautious in predicting the consequences of energy efficiency improvements. A general impression from the analysis is that significant rebound effects are triggered in manufacturing sectors, while the same effects are weaker in services, transport and the resource-based sectors (finance and insurance, road transport and fisheries). Furthermore, the analysis suggests that the existence of strong substitution possibilities (flexible technologies) is not sufficient to ensure that demand for a resource increases over time in response to efficiency improvements. Discrepancies across sectors become even more striking if we compare the effects on the energy-source that is not exposed to efficiency improvements. This is primarily a result of contradicting effects, arising from substitution possibilities between the two energy sources on the one hand, and between the energy aggregate and other factors of production on the other.

The analysis also produces some surprising conclusions concerning the relationship between energy efficiency improvements and CO_2. This is seen by comparing the results arrived at under electricity efficiency improvements for metals (40% sectoral increase in CO_2-emissions) with those of pulp and paper (30% sectoral reduction in CO_2-emissions). Electricity efficiency improvements can in principle both lead to a decrease and an increase in national CO_2-emissions irrespective of the magnitude of rebound effects. The reason for this is due to the lack of interdependence between electricity consumption and greenhouse gas emissions for Norway.[23] Our study has shown that efficiency improvements in some sectors of the Norwegian economy may produce quite significant reductions in CO_2-emissions. Examples here are transport-oil efficiency improvements in fisheries or electricity efficiency improvements in pulp and paper.

6. Conclusion

This paper examines the role of rebound effects for the Norwegian economy. The tool of analysis is a multisector computable general equilibrium model. Efficiency improvements at sectoral level are found to reduce the long-term consumption of the energy source that is being exposed to the improvements in five out of six sectors considered. Our findings contrast with those of Saunders (1992), where the demand for energy under most conditions was found to increase in response to energy improvements. Saunders (1992) conducted his analysis by undertaking numerical simulations in a one-sector Neo-classical growth model given fixed energy prices and a nested CES technology with substitution elasticities higher than one. One may argue that the explanation for the opposing results lies with the difference in aggregation level across the two studies. In MSG-6, substitution elasticities at the industry level are in general between 0 and 1, while Saunders (1992) derives his results from a one-sector model of the economy that makes assumptions about high substitution possibilities adequate.

However, the above explanation is a too simple one. Our analysis has shown that significant rebound effects are at work in industries with limited substitution

[23] In other words, Brookes (1990) and Greenhalgh (1990) were partly wrong when stating that an energy efficiency improvement is an inappropriate way of dealing with the greenhouse effect.

possibilities (metals) and that rebound effects can be weak in spite of a flexible technology (chemical and mineral products). The degree of substitutability among inputs (or aggregation level) is important but not essential for the results arrived at. An equally important factor is the degree to which the activity level in a sector is affected by efficiency improvements. The rebound that originates from this activity effect is not given sufficient attention in the literature. This 'effect' is a result of changes in costs which occur in response to efficiency improvements which again depend on factor-intensities, cost shares, and market structure—all factors which determine a sector's ability to take full advantage of a given efficiency improvement. Another important causal factor to our results is the treatment of energy as two substitutable sources of energy instead of as one aggregate production factor. The results show that there are substantial variations across sectors with respect to the energy source that is not exposed to energy efficiency improvements. In addition, a CGE model approach introduces other effects beyond those appearing in a one-sector model. The significance of such factors, however, is quite difficult both to trace and to quantify in rich CGE models.

The results show that efficiency gains have interesting, non-intuitive, and maybe provocative impacts on energy consumption and carbon emissions. Although the analysis is related to Norway which have an unusual character of energy supply, since electricity is virtually all produced by (non-carbon-emitting) hydropower, the analysis have wider relevance. Many economies base their energy consumption on several energy sources with different carbon content, examples are Sweden (hydropower, nuclear energy and oils), France (nuclear energy, oil, natural gas), Germany and Denmark (oil, gas and coal).

The results arrived at are partly determined by the role of inter-sectoral shifts in demand due to improvements in energy efficiency in one particular sector. An extension of our analysis would be to introduce efficiency improvements simultaneously in all sectors of the economy. As a consequence, consumption would not be shifted so much from one sector to the other—an effect that, ceteris paribus, could weaken rebound effects in each sector analysed. However, it is not obvious that such a policy would produce a long-term decline in total energy consumption. First, because an economy-wide electricity improvement will have a stronger effect on energy prices. This is an effect that pulls in favour of stronger rebound effects. In addition, we need to know how the remaining sectors will respond to efficiency improvements. The overall effect will depend on the importance of rebound effects in all sectors of the economy, as well as of their relative size of the national economy. A sector of particular interest is the household sector due to its considerable size. A Norwegian demand study suggests that rebound effects are stronger for households than for commerce (Haugland, 1996), if this is the case, economy-wide efficiency improvements in Norway may induce an increase in the long-term consumption of electricity.

It is important to be aware of the limitations associated with the approach chosen in this analysis. First, our study does not meet all of the criticism of macroeconomic approaches presented by Lovins (1988) and Grubb (1990). Our predictions are still based upon observed historical relationships. Nonetheless, our results do show that rebound effects may be absent or weak even if macroeconomic considerations are introduced. Second, we ignore any costs that may arise from efficiency improvements. In reality, efficiency improvements, either generated by institutional, organisational or technological changes, are outcomes of processes with cost implications. This applies also for innovations occurring in response to governmental programs. Funding of such initiatives must be raised either by taxation of the private sector or at the expense of other public activities. Third, efficiency improvements may themselves have an impact on future substitution possibilities. Fourth, technology improvements are not likely to be energy-specific. Fifth, innovation structure may be more important than the sector in which they occur.

The absence of rebound effects does not necessarily provide a rationale for governments to promote efficiency improvements. Whether policy induced innovations is desirable from a societal point of view will in general depend on the presence of market imperfections. If, however, such policies are implemented, it does not necessarily follow that they should be directed at sectors with weak rebound effects. In addition it is important to consider the costs associated with encouraging such policies. Cost–benefit analysis is a tool that can aid in identifying sectors with the highest net social returns. However, an understanding of the causal factors behind rebound effects is important and should be an integrated part of any cost–benefit analysis where resource savings is the policy goal.

Acknowledgments

The work related to this paper is sponsored by the Nowegian Authority of Pollution Control (Statens Forurensingstilsyn). Our paper benefitted greatly from discussions with B.M. Larsen. We also wish to thank H. Aasen, T. Bye and S. Hansen for valuable comments and M.I. Hansen for computable assistance. The paper was presented at the 20th USAEE Annual Conference, August 29 to September 1, 1999, Orlando, USA.

References

Alfsen, K.H., Bye, T., Holmøy, E. (Eds.), 1996. MSG-EE: An Applied General Equilibrium Model for Energy and Environmental Analyses. Statistics Norway, P.O.B 8131 Dep. N-0033 Oslo.

Brendemoen, A., Vennemo, H., 1994. A climate treaty and the Norwegian economy: a CGE assessment. Energy J. 15 (1), 77–93.

Bye, T., Frenger, P., 1985. Factor Substitution, Non-homotheticity and Technical Change in the Norwegian Production Sector. Mimeo, Statistics Norway, P.O.B. 8131 Dep. N-0033 Oslo.

Brookes, L., 1990. The Greenhouse effect: the fallacies in the energy efficiency solution. Energy Policy Vol. 18, 199–201.

Bye, B., Holmøy, E., 1997. Household Behaviour in the MSG-6 Model'. Documents 97/13, Statistics Norway, P.O.B. 8131 Dep. N-0033 Oslo.

Dubin, J.A., Miedama, A.K., Chandran, R.V., 1986. Price effects of energy-efficient technologies: a study of residential demand for heating and cooling. Rand J. 17 (3), 310–325.

Gately, D., 1990. The US demand for highway travel and motor fuel. Energy J. 11 (3), 59–73.

Glomsrød, S., Vennemo, H., Johnsen, T., 1990. Stabilisation of CO_2: a CGE assessment. Scand. J. Econ. 94 (1), 53–69.

Greene, L.D., 1992. Vehicle use and fuel economy: how big is the ‘Rebound’ effect? Energy J. 12 (1), 117–143.

Greenhalgh, G., 1990. Energy conservation policies. Energy Policy 293, 299.

Grubb, M.J., 1990. Energy efficiency and economic fallacies. Energy Policy 9, 783–785.

Haugland, T., 1996. Social benefits of financial investment support in energy conservation policy. Energy J. 17 (2), 79–102.

Henly, J., Ruderman, H., Levine, M.D., 1988. Energy saving resulting from the adoption of more efficient appliances: a follow-up. Energy J. 9 (2), 163–170.

Hogan, W.W., Jorgenson, D.W., 1991. Productivity trends and the cost of reducing CO_2-emissions. Energy J. 12 (1), 67–85.

Holmøy, E., 1992. The structure and working of MSG-5: an applied general equilibrium model of the Norwegian economy. In: Bergman, L., Olsen, Ø. (Eds.), Economic Modelling in the Nordic Countries. North-Holland.

Holmøy, E., 1997. The Modelling of Heterogeneous Industries in MSG-6. Mimeo, Statistics Norway, P.O.B. 8131 Dep. N-0033 Oslo.

Holmøy, E., Hægeland, T., 1997. Aggregate Productivity Effects of Technology Shocks in a Model of Heterogeneous Firms. The Importance of Equilibrium Adjustments. Discussion Papers 198, Statistics Norway, P.O.B. 8131 Dep. N-0033 Oslo.

Holmøy, E., Strøm, B., 1997. Samfunnsøkonomiske Kostnader av Offentlig Ressursbruk og Ulike Finansieringsformer—Beregninger Basert på en Disaggregert Generell Likevektsmodell. Rapporter 97/16, Statistics Norway, P.O.B. 8131 Dep. N-0033 Oslo.

Holmøy, E., Vennemo, H., 1995. A general equilibrium assessment of a suggested reform in capital income taxation. J. Policy Model. 17 (6), 531–556.

Jevons, W.S., 1865. The Coal Question—Can Britain Survive? First published in 1865. Reprinted by Macmillan in 1906.

Jones, T.C., 1993. Another look at US passenger vehicle use and the rebound effect from improved fuel efficiency. Energy J. 4 (14), 99–110.

Khazzoom, J.D., 1980. Economic implications of mandated efficiency standards for household appliances. Energy J. 1 (2), 21–40.

Khazzoom, J.D., 1986. An Econometric Model Integrating Conservation Measures in the Estimation of the Residential Demand for Electricity. JAI Press, Greenwich, CN.

Khazzoom, J.D., 1987. Energy saving resulting from more efficient appliances. Energy J. 8 (4), 85–89.

Khazzoom, J.D., 1989. Energy savings from more efficient appliances: a rejoinder. Energy J. 10 (1), 157–166.

Khazzoom, J.D., Shelby, M., Wolcott, R., 1990. The conflict between energy conservation and environmental policy in the US transportation sector. Energy Policy 18 (5), 456–458.

Larsen, B.M., Nesbakken, R., 1997. Norwegian emissions of CO_2 1987–1994. A study of some effects of the CO_2 tax. Environ. Res. Econ. 9, 275–290.

Lovins, A.B., 1985. ‘Least-Cost Electricity Strategies for Wisconsin’. September 9 Testimony to Wisconsin PSC, Vol. 33, WPSC #05-EP-4, RMI Publication #87-7.

Lovins, A.B., 1988. Energy saving resulting from the adoption of more efficient appliances: another view. Energy J. 9 (2), 155–162.

Mayo, J.W., Mathis, J.E., 1988. The effectiveness of mandatory fuel efficiency standards in reducing the demands for gasoline. Appl. Econ. 20, 211–219.

Manne, A.S., Richels, R.G., 1990. CO_2-emission limits: an economic cost analysis for the USA. Energy J. 11 (4), 51–74.

Ministry of Finance, 1997. Langtidsprogrammet 1998–2001. Stortingsmelding Nr 4 (1996–97), Oslo, Norway.

Ministry of Finance, 1997. Langtidsprogrammet 1998–2001. Særskilt vedlegg til Stortingsmelding Nr 4 (1996–97), Oslo, Norway.

Ministry of Finance, 1988. The Norwegian Economy in Transition (in Norwegian). NOU 1988:21, Oslo, Norway.

Mysen, H.T., 1991. Substitusjon Mellom Olje og Elektrisitet i Produksjonsektorene i en Makromodell. Rapporter 91/7, Statistics Norway, P.O.B. 8131 Dep. N-0033 Oslo.
Organisation for Economic Co-operation and Development, 1995. OECD Workshop on Sustainable Consumption and Production: Clarifying the Concepts. Final Report, Rosendal, Norway 2–4 July 1995. 75775 Paris Cedex 16, France.
Organisation for Economic Co-operation and Development, 1998. Eco-Efficiency. Group on Pollution Prevention and Control. Environmental Policy Committee. Draft report. 75775 Paris Cedex 16, France.
Saunders, D.H., 1992. The Khazzoom–Brookes postulate and neoclassical growth. Energy J. 13 (4), 131–148.
United Nations, 1995. Earth Summit Agenda 21. The United Nations Programme of Action from Rio: The Final Text of Agreements Negotiated by Governments at the United Nations Conference on Environment and Development (UNCED), 3–14 June 1992, Rio de Janeiro, Brazil, United Nations, New York, USA.
Uzawa, H., 1962. Production functions with constant elasticity of substitution. Rev. Econ. Stud. Vol. XXIX (4), 293–312.
World Business Council for Sustainable Development, 1999. Available from: http://www.wbcsd.ch/ecoeff1.htm.
World Commission on Environment and Development, 1986. Our Common Future. Oxford University Press, Oxford.
Wuppertal Institute, 1994. Factor 10 Club: Carnoules Declaration. Wuppertal Institute for Climate, Environment and Energy, Westphalian Science Centre, D-42103 Wuppertal, Germany.