

The macroeconomic rebound effect and the world economy

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Abstract This paper examines the macroeconomic rebound effect for the global economy arising from energy-efficiency policies. Such policies are expected to be a leading component of climate policy portfolios being proposed and adopted in order to achieve climate stabilisation targets for 2020, 2030 and 2050, such as the G8 50% reduction target by 2050. We apply the global “New Economics” or Post Keynesian model E3MG, developing the version reported in IPCC AR4 WG3. The rebound effect refers to the idea that some or all of the expected reductions in energy consumption as a result of energy-efficiency improvements are offset by an increasing demand for energy services, arising from reductions in the effective price of energy services resulting from those improvements. As policies to stimulate energy-efficiency improvements are a key part of climate-change policies, the likely magnitude

of any rebound effect is of great importance to assessing the effectiveness of those policies. The literature distinguishes three types of rebound effect from energy-efficiency improvements: direct, indirect and economy-wide. The macroeconomic rebound effect, which is the focus of this paper, is the combination of the indirect and economy-wide effects. Estimates of the effects of no-regrets efficiency policies are reported by the International Energy Agency in World Energy Outlook, 2006, and synthesised in the IPCC AR4 WG3 report. We analyse policies for the transport, residential and services buildings and industrial sectors of the economy for the post-2012 period, 2013–2030. The estimated direct rebound effect, implicit in the IEA WEO/IPCC AR4 estimates, is treated as exogenous, based on estimates from the literature, globally about 10%. The total rebound effect, however, is 31% by 2020 rising to 52% by 2030. The total effect includes the direct effect and the effects of (1) the lower cost of energy on energy demand in the three broad sectors as well as of (2) the extra consumers’ expenditure from higher (implicit) real income and (3) the extra energy-efficiency investments. The rebound effects build up over time as the economic system adapts to the higher real incomes from the energy savings and the investments.

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Introduction

This paper explores the macroeconomic rebound effects for the global economy from climate policies based on energy-efficiency improvements and programmes reported by the International Energy Agency (IEA 2005) in the World Energy Outlook 2006 (IEA 2006), synthesised in the 2007 IPCC Report and discussed elsewhere in this volume. We use a global “New Economics”, Post Keynesian model with estimated energy demand equations to illustrate the potential scale of the rebound problem and suggest how policy portfolios and strategies can be developed to manage, monitor and counter the rebound effects.

The rebound effect refers to the idea that some or all of the expected reductions in energy consumption as a result of energy-efficiency improvements are offset by an increasing demand for energy services, arising from reductions in the effective price of energy services resulting from those improvements (Greening et al. 2000 for a survey). As policies to stimulate energy-efficiency improvements are a key part of climate-change policies (Geller et al. 2006), the likely magnitude of any rebound effect is of great importance to assessing the effectiveness of those policies. However, the magnitude, the definition and the scope of rebound effects are controversial (Brookes 1990; Grubb 1990).

The literature distinguishes between three types of rebound effect from energy-efficiency improvements: direct, indirect and economy-wide (Greening et al. 2000):

- *Direct rebound effects:* Improved energy efficiency for a particular energy service will decrease the effective price of that service and should therefore lead to an increase in consumption of that service. This will tend to offset the expected reduction in energy consumption provided by the efficiency improvement.
- *Indirect rebound effects:* For consumers, the lower effective price of the energy service will lead to changes in the demand for other goods and services. To the extent that these require energy for their provision, there will be indirect effects on aggregate energy consumption.
- *Economy wide rebound effects:* A fall in the real price of energy services will reduce the price of intermediate and final goods throughout the

economy, leading to a series of price and quantity adjustments, with energy-intensive goods and sectors gaining at the expense of less energy-intensive ones. Energy-efficiency improvements may also increase economic growth, which should itself increase energy consumption.

Of particular interest for global climate (and energy) policy is the magnitude of the macroeconomic rebound effect, which we take to cover the indirect and economy-wide rebound effects extended to include effects on consumption from the implicit higher real income and investment required for the energy-efficiency policies to be effective. The Khazzoom–Brookes postulate (Khazzoom 1980; Brookes 1990; Saunders 1992, 2000) is an interpretation of the rebound effect at the macroeconomic level suggesting that the aggregate energy saving from energy-efficiency measures might be offset by associated increases in energy demand. If the energy-efficiency measures lead eventually to even more energy being consumed than otherwise, the rebound effect has been termed a “backfire” effect (Saunders 2000, p. 440).

The underlying assumption in our analysis is that the no-regrets options can be identified by targeted policies and measures and that they pay for themselves assuming social discount rates. There will be an investment cost of the measures, but it is assumed that resources will be available so that the investment will not replace other investment or consumption, i.e. there are under-employed resources in the system sufficient to avoid inflation. This assumption is more plausible when the construction industry is working at less than full capacity as it is after 2008 in many countries as an outcome of the “credit crunch” of 2007 and 2008.

The macroeconomic rebound effect considered in this paper is the combination of the indirect and economy-wide effects. We start with the estimated effects of the no-regrets options for final demand for electricity and fossil fuels that are synthesised by the IEA in the World Energy Outlook 2006 (IEA 2006). This report in agreement with the IPCC AR4 considers that electricity savings are found at relatively low costs, and they are, therefore, expected to be implemented first. The assessed effects cover energy saving from energy-efficiency policies for Transport, residential-service Buildings (henceforth “Buildings”), and Industry broad sectors of the economy for the post-2012 period, 2013–2030.

The overall results are decomposed into effects assuming first that each of the three sectors undertake the policies unilaterally but implemented for both the OECD and non-OECD regions and second that the OECD regions and the non-OECD regions take unilateral action across the three sectors. Finally, we have assessed and reported below where the rebound effects originate by dividing them up into

1. direct rebound effects assumed to be implicit in the IEA estimates
2. effects from the energy savings per se, reducing costs and prices for households, businesses and governments
3. effects from the extra imputed real incomes accruing to consumers as a result of lower spending on traditional biomass, oil, gas and electricity
4. effects from the higher investment required to generate the energy savings.

“Literature review” of the paper provides a brief review of the debates on the macroeconomic rebound effect in relation to energy (and climate) policy. “Modelling” describes the approach taken here to modelling the macroeconomic rebound effect. “Description of policies and scenarios” describes the IEA WEO 2006 (IEA 2006) energy-efficiency policies incorporated into this modelling and the scenarios used. “Results” describes the results, including the overall impacts of energy-efficiency policies on energy demand, economic activity and CO₂ emissions and the sources and magnitude of the macroeconomic rebound effect. “Conclusions” provides some conclusions.

Literature review

The literature on the rebound effect has developed in recent years as climate mitigation has moved up the policy agenda (Herring and Sorrell 2009; Herring 2004; Schipper and Grubb 2000; Vikström, 2004; Grepperud and Rasmussen 2004; International Energy Agency 2005; Sorrell and Dimitropoulos 2007; Sorrell 2007). The topic has proved controversial, partly through differences between an energy-engineering approach, which identifies no-regrets options for energy efficiency and which is normally adopted in “bottom-up” energy systems models, and a traditional economics approach, which assumes that no-regrets options do not exist,

except in the case of market failures, and which is adopted in “top-down” equilibrium models assuming no market failures. However, the debate is also about the source of the energy-efficiency improvements, i.e. whether they come from the energy-efficiency policies or from a general improvement in productivity of energy-using equipment. The different assumptions about the source have different consequences because the policies require investment in energy-saving equipment such as more efficient vehicle engines, or home insulation, to be effective, whereas the energy saving from technological progress is treated as “manna from heaven” in the top-down models.

Brookes (1990) adopted the traditional economic argument that technological progress has led to significant increases in energy productivity but that this has been offset by faster growth in general productivity and output and so to higher energy use. Policies for improved energy efficiency may lead to higher energy use (“backfire” in the literature) and a rise in GHG emissions, depending on the source of energy, unless energy prices increased at the same time the energy-efficiency policies were introduced. Grubb (1990) opposed this interpretation, arguing that there are significant differences between ‘naturally-occurring’ energy-efficiency improvements from on-going technological change, and energy-efficiency improvements as a result of targeted policies and measures. The differences between the two sides reflect a different view of the efficiency of the market. If the market is perfectly efficient, then the traditional view holds and the efficiency improvements come from exogenous technological change. If there are market failures, then policies can address them, and efficiencies can be improved but require additional investment.

The issue was first raised in *The Coal Question* (Jevons 1865/1905). He argued: ‘It is a confusion of ideas to suppose that the economical use of fuel is equivalent to diminished consumption. The very contrary is the truth’ ... ‘The reduction of the consumption of coal, per ton of iron, to less than one third of its former amount, was followed, in Scotland, by a tenfold increase in total consumption, between the years 1830 and 1863, not to speak of the indirect effect of cheap iron in accelerating other coal-consuming branches of industry’. Jevons was one of the first neoclassical economists, and the issue here is one of rapid technological change in the whole

economy (the Industrial Revolution). He is not considering either energy-efficiency policies or market failures, so his analysis is less relevant to the effects of energy-efficiency policies today. However, the general issue of lower cost of energy services and rapid economic development is relevant in late twentieth century and in projections to 2030, with India and China transforming their economies.

One of the main reasons behind the debate is the lack of a rigorous theoretical framework that can describe the mechanisms and consequences of the rebound effect at the macro-economic level (Dimitropoulos 2007). There exist several models built on different economic framework, e.g. Post Keynesian models, neoclassical models of economic growth, computable general equilibrium models and alternative models for policy evaluation which were used to evaluate the rebound effect (Barker et al. 2007; Grepperud and Rasmussen 2004; Saunders 2008; Small and Van Dender 2007; Sorrell 2007; Sorrell et al. 2009; Wei 2006). The multi-disciplinary risk analysis carried out by the Stern Review team (Stern 2006) and the IPCC 4th Assessment Report (IPCC AR4 2007) has highlighted that important weaknesses of the traditional, neoclassical approach, especially as regards the treatment of uncertainty and risks challenges the validity or confidence that policy makers should place in policies that have long and (largely) irreversible consequences. The equilibrium-based models by themselves are not, in our view, appropriate for providing an adequate understanding of the climate change problem (Barker 2008), especially where energy-efficiency measures constitute basic climate policies. The rebound effect relevant in the study of climate change mitigation is essentially a behavioural response to an improvement in energy efficiency that comes not as “manna from heaven” but from detailed sectoral policies designed to identify and overcome market failures. Modelling approaches that fail to include the apparent market failures arising when consumer and business behaviours are assessed in detail (i.e. by assuming that such failures do not exist) may not properly estimate this effect.

Mandated efficiency improvements (appliance standards, residential and services building codes, fuel economy standards) and efficiency improvements from education or recognition of opportunities (better business practices) are basically different from price (tax) or quantity (emission allowances) policies.

Efficiency standards overcome two market failures: first social rates of return are generally lower than private rates of return, so more and stronger measures are justified; and second under conditions of risk aversion (a particular piece of capital may not deliver the expected return), society should be risk neutral with respect to capital improvements and can offset private risks by collective action, whereas private individual agents are likely to be more risk averse and hence less likely to take action. For example, first purchasers of private automobiles typically hold these capital purchases for 5 years. If the price of new automobiles increases due to fuel-economy technologies, the sales-weighted average value of automobiles, on average after 5 years discounting at 3%pa, provides an effective residual value of 32.8% (US DfT 2008, p. VII-42). This is far below the lifetime social benefits that accrue from the average new car vehicle lifetime of 15 years. Thus, there are significant market failures, including principal-agent failures (or a mismatch between social and private behaviour) that cause systemic inefficiencies in energy-capital-investment decisions. These principal agent problems, plus those ignored by a lack of widespread markets for climate change damages, are not reflected in market energy costs.

To allow for such market failures, a global “New Economics”, Post Keynesian model, namely the Energy-Environment-Economy Model at the Global level (E3MG) has been used to confirm the scale and importance of the macroeconomic rebound effect.

Modelling

The macroeconomic rebound effect arising from IEA WEO 2006 (IEA 2006) energy-efficiency policies and programmes is investigated here using E3MG, a sectoral dynamic macroeconomic model of the global economy, which has been designed to assess options for climate and energy policies and to allow for energy-environment-economy (E3) interactions (Barker *et al.* 2006; Barker 2008). The model contains 41 production sectors, which enables a more accurate representation of the effects of policies than is common in most macroeconomic modelling approaches. The model addresses the issues of energy security and climate stabilisation both in the medium and long terms, with particular emphasis on dynam-

ics, uncertainty and the design and use of economic instruments, such as emission allowance trading schemes. E3MG is a non-equilibrium model with an open structure such that labour, foreign exchange and public financial markets are not necessarily closed. It is very disaggregated, with 20 world regions, 12 energy carriers, 19 energy users, 28 energy technologies, 14 atmospheric emissions and 41 production sectors, with comparable detail for the rest of the economy. The model represents a novel long-term economic modelling approach in the treatment of technological change, since it is based on cross-section and time-series data analysis of the global system 1973-2002 (in the version used for this paper) using formal econometric techniques, and thus provides a different perspective on stabilisation costs.

The model is based upon a Post Keynesian economic view of the long-run. In other words, in modelling long-run economic growth and technological change we have adopted the “history” approach¹ of cumulative causation and demand-led growth² (Kaldor 1957, Kaldor 1972, Kaldor 1985; Setterfield 2002), focusing on gross investment (Scott 1989) and trade (McCombie and Thirlwall 1994, 2004), and incorporating technological progress in gross investment enhanced by R&D expenditures. Other Post Keynesian features of the model (see Holt 2007, for a discussion of such features) include: varying returns to scale (that are derived from estimation), non-

¹ This is in contrast to the mainstream equilibrium approach (see DeCanio, 2003 for a critique) adopted in most economic models of climate stabilisation costs. See (Weyant, 2004) for a discussion of technological change in this approach. Setterfield (1997) explicitly compares the approaches in modelling growth and Barker et al. (2006) compares them in modelling mitigation.

² The theoretical basis of the approach is that economic growth is demand-led and supply constrained. Growth is seen as a macroeconomic phenomenon arising out of increasing returns (Young, 1928), which engender technological change and diffusion, and which proceeds unevenly and indefinitely unless checked by imbalances. Clearly growth can increase only if labour and other resources in the world economy can be utilised in more productive ways, e.g. with new technologies and/or if they are otherwise underemployed in subsistence agriculture or unemployed. Palley (2003) discusses how long-run supply is affected by actual growth. In contrast, the modern theory of supply-side economic growth assumes full employment and representative agents, and optimises an intergenerational social welfare function (see Aghion and Howitt, 1998). It goes back to Solow (1956, 1957), with endogenous growth theory developed by Romer (1986, 1990).

equilibrium, not assuming full employment, varying degrees of competition, the feature that industries act as social groups and not as a group of individual firms (i.e. no optimisation is assumed but bounded rationality is implied), and the grouping of countries and regions has been based on political criteria. At the global level, accounting conventions are imposed so that the expenditure components of GDP add up to total GDP and total exports equal total imports at a sectoral level allowing for imbalances in the data.

For the representation of the electricity generation and supply sector E3MG incorporates a dynamic bottom-up simulation submodel, the Energy Technology Model (ETM), which implements a probabilistic theory for the penetration of the energy technologies in the market (Anderson and Winne 2004). The ETM submodel is designed to account for the fact that a large array of non-carbon options is emerging, though their costs are generally high relative to those of fossil fuels. However, costs are declining relatively with innovation, R&D investment and learning-by-doing. The ETM does not adopt a cost optimization technique for modelling the electric system expansion and the dispatch of the different technologies. But it combines a detailed representation of their economic, technical and environmental performance with historical data in order to assess their capability to substitute away from a “marker” technology. The implementation of different policies through time, such as incentives, regulation, and revenue recycling allow low or non-carbon options to meet a larger part of global energy demand. The process of substitution is also argued to be highly non-linear, involving threshold effects. ETM includes 28 representative energy technologies, described by 21 technology characteristics, being less detailed than bottom-up models such as the POLES (<http://upmf-grenoble.fr/iepe/Recherche/indexe.html>), MARKAL and TIMES (<http://www.etsap.org/applicationGlobal.asp>). However, such energy-systems models typically have no or limited representation of economy-wide interactions unless they are used as part of an integrated assessment model. These are captured in E3MG through the interactions between the different sectors in the model, with input-output and econometric modelling allowing for complex interactions between energy demand, output, investment, employment, incomes, consumption, trade, prices and wages, without assuming that resources are used at full economic efficiency.

For energy demand, a 2-level hierarchy is being adopted. A set of aggregate demand equations on annual data covering 19 fuel users/sectors and 20 regions is estimated and is then shared out among main fuel types (coal, heavy fuel oil, natural gas and electricity) assuming a hierarchy in fuel choice by users: electricity first for “premium” use (e.g. lighting, motive power), non-electric energy demand shared out between coal, oil products and gas. The energy demand for the rest of the 12 energy carriers is estimated based on historical relations with the main 4 energy carriers. All energy demand equations use co-integrating techniques, which allow the long-term relationship to be identified in addition to the short-term, dynamic one. A long-term behavioural relationship is identified from the data and embedded into a dynamic relationship allowing for short-term responses and gradual adjustment (with estimated lags) to the long-term outcome. The equations and identities are solved iteratively for each year, assuming adaptive expectations, until a consistent solution is obtained. The economy aggregates, such as GDP, are found by summation. This enables representation of the wider macroeconomic impacts of policies focused on particular sectors, including rebound effects.

These long-run energy demand equations are of the general form given in equation (1), where X is the demand, Y is an indicator of activity, P represents relative prices (relative to GDP deflators for energy), TPI is the Technological Progress Indicator, the β are parameters and the ε errors. TPI is measured by accumulating past gross investment enhanced by R&D expenditures (Lee et al. 1990) with declining weights for older investment. The indicators are included in many equations in the model, but only those for energy are analysed here. All the variables and parameters are defined for sector i and region j .

$$X_{i,j} = \beta_{0,i,j} + \beta_{1,i,j}Y_{i,j} + \beta_{2,i,j}P_{i,j} + \beta_{3,i,j}(TPI)_{i,j} + \varepsilon_{i,j} \quad (1)$$

In the equations, $\beta_{2,i,j}$ are restricted to be non-positive, i.e. increases in prices reduce the demand (for energy demand, see surveys in Atkinson and Manning, 1995 and Graham and Glaister, 2002). In the energy equations $\beta_{3,i,j}$ are estimated to be negative, i.e. more TPI is associated with energy saving. These parameters are constant across all scenarios.

This approach is in contrast with the treatment of energy users as representative agents in equilibrium models. In our approach, each sector in each region is assumed to follow a different pattern of behaviour within an overall theoretical structure, implying that the representative agent assumption is invalid (Barker and De Ramon, 2005). This means that the behaviour of each sector-region is not assumed to be the same as that of the average of the group.

The original energy demand equations are based on work by Barker et al. (1995) and Hunt and Manning (1989). The work of Serletis (1992) and Bentzen and Engsted (1993) has helped in the cointegrating estimation. Since there are substitutable inputs between fuels, the total energy demand in relation to the output of the fuel-using industries is likely to be more stable than the individual components. This total energy demand is also subject to considerable variation, which reflects both technical progress in conservation, and changes in the cost of energy relative to other inputs. Aggregate and disaggregate energy-demand equations' specifications follow similar lines including economic activity, technology, relative price effects, spending and R&D investment and are in the process of being respecified so as to also capture the temperature effect. As an activity measure, gross output is chosen for most sectors, but household energy demand is a function of total consumers' expenditure. The long-run price elasticity for road fuel is imposed at -0.7 for all regions, following the research on long-run demand (Franzén and Sterner 1995; Johansson and Schipper 1997, p. 289). The measures of research and development expenditure and investment capture the effect of new ways of decreasing energy demand (energy-saving technical progress) and the elimination of inefficient technologies, such as energy-saving techniques replacing the old inefficient use of energy.

Table 1 presents the weighted averages of short-term and long-term activity and prices elasticities of demand for aggregate energy, across global energy-using sectors, with the world average added as the final row. The equations are estimated from annual data over the period 1973-2002 and year 2000 weights are used to find the averages. The equations are estimated as specified above, with further details in (Barker et al. 2006). In the projections after 2012, these elasticities are modified to restrict outliers and to allow for reductions in activity elasticities due to

Table 1 Weighted averages (2000 weights) of the estimated elasticities of global aggregate energy demand from the energy-use equations

	Short-term		Long-term	
	activity	relative price	activity	relative price
Power own use and transformation	0.389	-0.113	0.604	-0.178
Other energy own use and transformation	0.806	-0.172	0.557	-0.283
Iron and steel	0.241	-0.288	0.457	-0.493
Non-ferrous metals	0.420	-0.101	0.489	-0.480
Chemicals	0.497	-0.205	0.569	-0.362
Non-metallics nes	0.621	-0.201	0.609	-0.247
Ore-extra (non-energy)	0.418	-0.092	0.683	-0.202
Food, drink and tobacco	0.824	-0.270	0.134	-0.262
Textiles, clothing and footwear	0.429	-0.163	0.435	-0.267
Paper and pulp	0.215	-0.246	0.429	-0.221
Engineering, etc.	0.762	-0.143	0.157	-0.207
Other industry	0.506	-0.142	0.618	-0.387
Rail transport	0.870	-0.311	0.754	-0.253
Road transport	0.691	-0.213	0.739	-0.700
Air transport	0.509	-0.128	0.402	-0.405
Other transportation services	0.933	-0.246	0.923	-0.839
Households	0.478	-0.244	0.648	-0.318
Other final use	0.392	-0.141	0.560	-0.269
Non-energy use	0.122	-0.168	0.001	-0.226
World average for all sectors	0.506	-0.178	0.591	-0.338

Source: E3MG 2.4 and 4CMR

saturation effects and higher responses to relative prices via emission trading schemes and *ad hoc* incentive schemes introduced to accelerate reductions in energy use.

The modelling undertaken in this study required the specification of scenarios to reflect the set of IEA WEO 2006 (IEA 2006) energy-efficiency policies and programmes for the Transport, Buildings and Industry sectors of the economy for the period 2013–2030. The estimated *direct rebound effects* on electricity and fuel saving from no-regrets policies were derived from the literature (Sorrell 2007; Sorrell et al. 2009; Schipper and Grubb 2000). The investment and other costs to governments, firms and individuals have been taken from IEA WEO 2006 (IEA 2006). These estimates are incorporated exogenously into the macroeconomic modelling. A set of initial reductions in net energy demand brought about by energy-efficiency policies is disaggregated in terms of the model's classifications and imposed on the selected final-demand, fuel-using sectors with a proportional disaggregation of the IEA WEO 2006 (IEA 2006) estimates. The effects of the policies are calculated by comparing model

solutions 2013–2030 with and without the policies. Scenarios are developed to allow the calculation of macroeconomic rebound effects by modelling final energy demand by 19 fuel-using sectors. The policy case for the modelling includes implicitly the present and committed energy-efficiency policies 2013–2030, including key assumptions (oil price, and a carbon price from the EU Emissions Trading Scheme (ETS)). The fuel price assumptions for the reference case were based on the ADAM projections from February 2008 (ADAM D-M2.1 2007), considering the outcomes from the World Energy Technology Outlook 2050 report (http://ec.europa.eu/research/energy/pdf/weto-h2_en.pdf) using the POLES model (<http://upmf-grenoble.fr/iepe/Recherche/indexe.html>).

The methodology of the assessment was developed in (Barker et al. 2007). The macroeconomic rebound effect is the response of the economy in terms of energy demand stimulated, through indirect and economy-wide effects, following the initial energy savings arising from energy-efficiency policies. In the model, the initial effects are treated as exogenous, from IEA WEO (IEA 2006) 2006 as energy savings

and imposed sector by sector. The impacts spread from the energy-using sectors throughout the rest of the economy via the input–output structure of the E3MG model to give the macroeconomic and indirect effects. The total rebound effects are calculated by taking the difference between the net energy saving projected by the model, i.e. taking into account the indirect and economy-wide effects throughout the economy, and the expected *gross* energy savings (after adding back the direct rebound effect) projected as the effects of energy-efficiency policies by the IEA in WEO 2006 (IEA 2006), with an additional calculation (since this is not provided by the IEA report) of the effects on power generation using E3MG. This difference is then expressed as a percentage of the expected *gross* energy saving from these studies to give the total rebound effect. The macroeconomic rebound effect is the difference between the direct effect, also calculated as the percentage of the expected gross energy saving, and the total effect.

These definitions and identities can be expressed as seven equations:

1. ‘macroeconomic rebound effect’≡‘indirect rebound effect’+‘economy-wide rebound effect’
2. ‘total rebound effect’≡‘macroeconomic rebound effect’+‘direct rebound effect’
3. ‘gross energy savings from IEA energy-efficiency policies’≡‘net energy savings (taken as exogenous in E3MG)’+‘direct rebound energy use’
4. ‘change in macroeconomic energy use from energy-efficiency policies from E3MG’≡‘energy use simulated from E3MG after the imposed exogenous net energy savings’–‘energy use simulated from E3MG before the imposed exogenous net energy savings’
5. ‘total rebound effect as %’≡100 times ‘change in macroeconomic energy use from energy-efficiency policies from E3MG’/‘gross energy savings from IEA energy-efficiency policies’
6. ‘direct rebound effect as %’≡100 times ‘direct rebound energy use’/‘gross energy savings from IEA energy-efficiency policies’

From 2, 5 and 6:

7. ‘macroeconomic rebound effect as %’≡‘total rebound effect as %’–‘direct rebound effect as %’

The effect of energy saving in production is to reduce the costs of industrial energy use, so leading to reductions in prices and increases in profits of the industries working more efficiently. These lower prices are then passed on to reduce costs for other industries. The process gives rise to a rebound effect in that the initial savings are (partially) offset by increases in energy demand due to higher demands for the exports and outputs of the industries that have improved their energy efficiency and so reduced their energy costs. The lower costs will also be passed on to final consumers, depending on the price behaviour of the industries. Consumers will substitute spending towards the lower-priced products. Higher consumer and labour demand will increase output (and GDP) more generally and, hence, lead to higher energy demand.

In the case of extra energy saving in the residential buildings sector, the reduction in expenditure on fuels (assuming that fuel prices are unchanged) implies an increase in the real income of consumers. This effect is modelled by assuming consumers initially maintain the level of energy services received from the fuels, i.e. cut actual spending to receive the same services; however, the further response is more complicated. We assume that they behave (1) *as if* fuel prices had fallen, so that they substitute back towards fuels, depending on their responses to lower effective prices and (2) *as if* they had an increase in real income so that they increase spending on energy and other activities, depending on estimated income elasticities. For (2), the saving ratio is changed so that real expenditures rise by the appropriate amount. The higher consumers’ expenditure on all goods and services, especially energy-intensive ones such as transport, then raise energy use more generally.

Description of policies and scenarios

Policies

The majority of the assumed no-regrets options appear to be aimed at incentivising energy-efficiency improvements. It is the macroeconomic rebound effect arising from all these energy-efficiency policy measures that it is assessed in this paper.

Scenarios

The Reference Case is constructed to establish a counterfactual history of the global economy for the period 2013–2030 without the impact of the no-regrets energy-efficiency policies implemented over this period. It is a fully dynamic solution of the model over the period, given the year-by-year profile of exogenous variables such as population, exchange rates, interest rates and fiscal policies in general. It includes the impact of policy measures which are not explicitly targeted at energy efficiency.

The Policy Case is an alternative fully dynamic solution but including the sectoral effects on energy use, year by year 2013–2030, of all the current and committed IEA WEO 2006 (IEA 2006) energy-efficiency policies for the transport, buildings and industry sectors. The difference between the policy case and the reference case, thus, gives a dynamic estimate of the impact of these policies on the global economy and will enable calculation of the amount by which the original estimated energy saving of the policies is reduced through the rebound effect.

Differences between the reference and policy scenarios are used to assess the impacts of energy-efficiency policies on energy demand and CO₂ emissions under the different scenario assumptions, taking into account the macroeconomic effects estimated using the model. By comparing these with the imposed estimates for energy and CO₂ saving from the earlier evaluation, which did not take the macroeconomic effects into account, estimates of the magnitude of the macroeconomic rebound effect on energy demand and CO₂ emissions are calculated.

Scenario assumptions

Within each scenario, the effects of the relevant policy measures are introduced into the model on an annual basis. This is done by including the projected direct energy saving resulting from actions taken as a result of that policy measure, taking into account any projected direct rebound effect. The projected electricity and non-electricity savings for OECD and non-OECD countries, presented in Table 2, are used as assumptions in E3MG model, so as to examine their macroeconomic and total rebound effect. According to IEA WEO 2006 (IEA 2006), 1.1 Gtoe of energy (both electricity and non-

electricity) are projected up to 2030, where one third is used in OECD countries and the other two thirds in the non-OECD countries. The projected net energy savings from the policies (net of the direct rebound effect) are about 10% by 2030 for both groups of countries. These savings come almost equally from the three main examined sectors (Transport, Buildings, and Industry). Almost two thirds of them concern savings in fossil-fuel use, while the rest concern electricity savings, with the exception of transport where all savings come from fossil fuels, as the electricity use in this sector is very small.

Table 2 shows the projected direct net energy savings by 2030 allowing for the direct rebound effects discussed below. The table also converts these projected savings to the percentage of the total sectoral energy use and total sectoral emissions, respectively, to enable an approximate comparison of the strength of each policy. It should also be noted that the paper focuses on the macroeconomic implications of energy-efficiency policies and measures for final users of energy and does not provide an evaluation of their likely effectiveness at a micro-level. The effect of the policies on the power sector is derived from the IEA final demand data using the E3MG model and not from IEA WEO 2006 (IEA 2006) or the synthesis tables in the IPCC AR4 so the results for energy supply and CO₂ emissions can be regarded as a check on the IPCC synthesis in Chapter 11.

The required cumulative investment for the post-2012 period 2013–2030, presented in Table 3, is based on the IEA WEO (IEA 2006, pp. 197), as the relevant information is not given explicitly in the IPCC AR4.

The direct rebound effects by sector in energy terms are derived by applying the assumed rebound percentages to the gross energy savings from the sector. There are three broad sectors for which these direct rebound effects have been empirically estimated in the evaluations of the IPCC AR4 energy-efficiency policies and reviewed in (Sorrell 2007; Sorrell et al. 2009). Given that we are applying them to many different countries and time periods, we have adopted a stylized treatment: the Transport sector are assumed at 10%, the residential Buildings sector at 25% and other sectors at low or zero rebound effects. In the case of energy-intensive processes, no direct rebound effects are assumed, and the extra efficiency mainly takes the form of lower unit costs and the

Table 2 Projected direct energy savings in 2030 for IEA WEO 2006 energy efficiency policies or measures used in this study as inputs to the modelling

Target sector	Projected electricity savings in 2030 (Mtoe)	% of total sectoral electricity use in 2030	Projected non-electricity energy savings in 2030 (Mtoe)	% of total sectoral non-electricity en electricity use in 2030	Projected electricity and non-electricity energy savings in 2030 (Mtoe)	% of total sectoral energy use in 2030
Residential services ^a	201	14.27	248	8.82	449	10.64
OECD	88	12.09	29	3.02	117	6.93
Non-OECD	113	16.59	219	11.83	332	13.11
Industry ^b	95	10.11	242	8.09	337	8.57
OECD	33	9.40	58	5.57	91	6.53
Non-OECD	61	10.37	185	9.48	246	9.69
Transport ^c			307	9.87	307	9.87
OECD			146	8.80	146	8.80
Non-OECD			162	11.16	162	11.16
Total	295	12.21	827	8.94	1,122	9.62
OECD	119	10.89	245	6.45	364	7.44
Non-OECD	174	13.16	584	10.72	758	11.19

^a Concerns policies/measures on heating, ventilation, air-conditioning, lighting, appliances, office appliances, hot water systems

^b Concerns policies/measures on motors, pumps, compressor systems, irrigation pumping systems

^c Concerns policies/measures on fuel economy, modal shift

Source: International Energy Agency 2006

Table 3 Projected cumulative investment costs in 2013–2030 for IEA WEO 2006 energy efficiency policies/measures used in this study as inputs to the modelling

Target sector	Cumulative investment costs for electricity saving measures in 2005–2030 (billion 2005US\$)	Cumulative investment costs for non-electricity saving measures in 2005–2030 (billion 2005US\$)	Total cumulative investment costs for electricity and non-electricity saving measures in 2005–2030 (billion 2005US\$)
Residential services	758	168	926
OECD	546	76	622
Non-OECD	212	92	304
Industry	195	167	362
OECD	121	89	210
Non-OECD	74	78	152
Transport		1076	1076
OECD		661	661
Non-OECD		415	415
Total	953	1411	2364
OECD	667	826	1493
Non-OECD	286	585	871

Source: International Energy Agency 2006

rebound effects are the indirect effects of the lower costs on sales to other industries and exports, which we capture in the modelling. Low values (5%) for the direct rebound are taken for services and other (e.g. waste, agriculture and forestry) sectors. There are good reasons for expecting the direct rebound effects to be small or negligible for these sectors. In the case of services buildings, indoor temperatures are both conventionally and legally within acceptable ranges, and these ranges seem unlikely to change in response to energy-efficiency measures. In case of the other sectors, estimated energy savings from no-regret measures are negligible.

The assumptions used in the modelling for carbon, oil, coal and gas prices are shown in Table 4.

The growth rates of GDP for the reference case are shown in Table 5.

To implement the scenarios in E3MG, the effects of the relevant energy-efficiency policy measures are introduced into the model by imposing a reduction in energy use on the estimated aggregate energy demand equations for the sectors affected (using the projected energy savings shown in Table 2).

Results

Macroeconomic effects of energy-efficiency policies

Table 6 shows the macroeconomic effects of the total of the energy-efficiency policies as modelled by E3MG (by comparing the energy-efficiency policy case to the reference case without policies). These effects include the macroeconomic rebound effect, which is

Table 4 EU ETS allowance (Carbon price) and fuel price assumptions, reference case, 2005–2030

		2005	2010	2015	2020	2025	2030
EU ETS allowance price	(2005\$/tC)	0	82.8	82.8	82.8	82.8	82.8
Crude oil	2005\$/bbl	50.62	57.50	55.00	55.00	57.50	60.00
Gas	2005\$/MMBTU	7.460	6.750	6.750	7.000	7.318	7.636
Coal	2005\$/tonne	60.48	55.00	55.00	57.04	59.63	62.22

Sources: BERR-EWP (2007), BERR-ER (2006), IEA WEO 2007 and International Energy Agency 2006

Table 5 Average annual growth of key macroeconomic variables, reference case

	2000–2010	2010–2020	2020–2030
OECD			
GDP (% pa)	2.39	2.16	1.90
Non-OECD			
GDP (% pa)	5.17	4.45	3.65
World			
GDP (% pa)	2.97	2.74	2.41

This table shows projections chosen to correspond closely with the actual outcome and represents a solution of the model adopted for the study. The projections are not intended to be forecasts.

Source: E3MG 2.4 and 4CMR.

distinguished in “[Calculation of macroeconomic rebound effect](#)” below. Overall the policies lead to a saving of about 4% of the energy which would otherwise have been used by 2030 and a reduction in CO₂ emissions of 5% (or 2.8GtCO₂) by 2030. The table also shows the effects on GDP, the general consumer price level and employment for 2020 and 2030. The energy saving shows up as macroeconomic benefits in two main forms: firstly, lower prices (by 2030), as the production system requires fewer inputs to produce the same output; and secondly, higher output, partly the consequence of the lower inflation, as households spend more in response to their higher imputed income when their energy bills are reduced for the same level of energy services provided. The changes are relatively very small.

Table 6 Effects of energy-efficiency policies on key macroeconomic variables

Difference in levels		2010	2020	2030
World	Final energy demand (%)	0	-3.78	-4.34
	CO ₂ emissions (%)	0	-4.60	-5.50
	GDP (%)	0	0.21	0.28
	Price index consumers' expenditure (%)	0	0.039	-0.003
	Employment (%)	0	0.28	0.20

Differences in levels are % difference from reference case. Final energy demand corresponds to Final Consumption, excl non-energy use. CO₂ emissions refer to whole-economy CO₂ emissions from all anthropogenic sources. In this and subsequent tables, a positive figure indicates an increase with respect to the reference case, and a negative figure a reduction with respect to the reference case, e.g. a reduction in final energy demand due to energy efficiency policies is shown as a negative figure

Sources: E3MG 2.4 and 4CMR

Impacts of energy-efficiency policies on energy demand and CO₂ emissions

Final energy demand

Table 7 shows the effect of energy-efficiency policies on final energy demand only in energy units (mtoe), grouped by six broad sectors of the economy, again incorporating macroeconomic rebound effects. Overall, the reduction is about 600 mtoe, 4.3% of total energy demand by 2030. The demand falls over the period as the energy-efficiency policies gradually strengthen and their effects accumulate. The table shows the substantial differences between the sectors, with Energy supply and Buildings showing the largest reduction in absolute terms.

Figure 1 shows the effects of energy-efficiency policies on total final energy use for the global economy 2010–2030, showing the net energy saving, after the (exogenously estimated) direct rebound and (calculated) indirect rebound effects are taken into account. The figure shows the scale of these effects and how they accumulate over the period. Figure 2 shows how the energy savings from the policies are distributed across the main sectors in which they are implemented.

Impacts on CO₂ emissions

The above reductions in final energy demand, together with small reductions in own use of energy in the power generation and other fuel sectors, arising from energy-efficiency policies, lead to a reduction in

Table 7 Effect of energy policies on final energy demand by sector difference in mtoe

World	2010	2020	2030
Energy supply industries	0	-138.3	-168.1
Transport	0	-83.6	-111.3
Residential/Services Buildings	0	-120.9	-166.2
Industry	0	-108.1	-138.2
Agriculture	0	-4.7	-5.3
Total	0	-455.5	-589.0

Figures are policy case less reference case. Final energy demand corresponds to Final Consumption, excl non-energy use

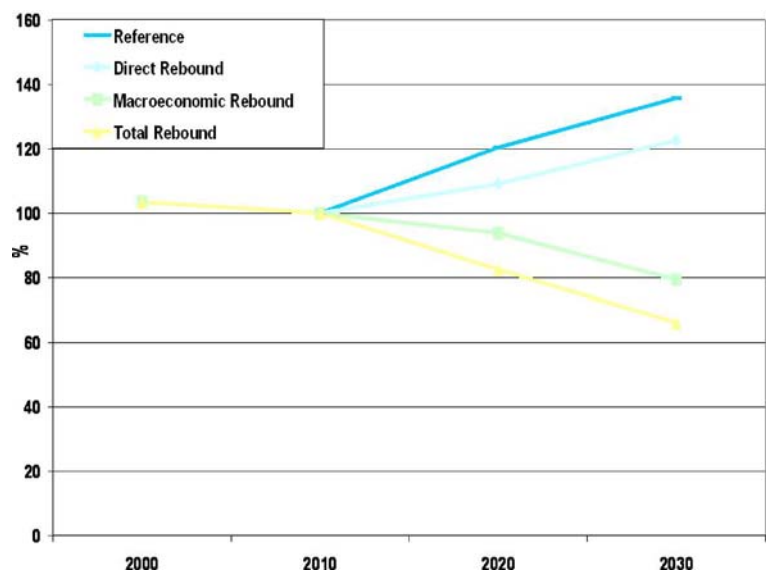
Sources: E3MG 2.4 and 4CMR

CO₂ emissions. Note that in the E3MG model, CO₂ emissions are allocated at the point of emission so that reductions in CO₂ emissions from power generation reflects both reductions in final electricity demand and reductions in own use of energy in power generation. Table 8 shows the effects of the energy-efficiency policies on global anthropogenic CO₂ emissions, grouped into power generation and the final-user sectors. The contribution from power generation to the overall reduction in CO₂ from the policies is substantial, about one third of the total 2.8GtCO₂ by 2030.

Calculation of macroeconomic rebound effect

Table 9 shows the magnitude of the direct, macroeconomic and total rebound effects on energy demand

Fig. 1 Effects of IEA WEO 2006 energy efficiency policies on final energy demand in the period 2000–2030

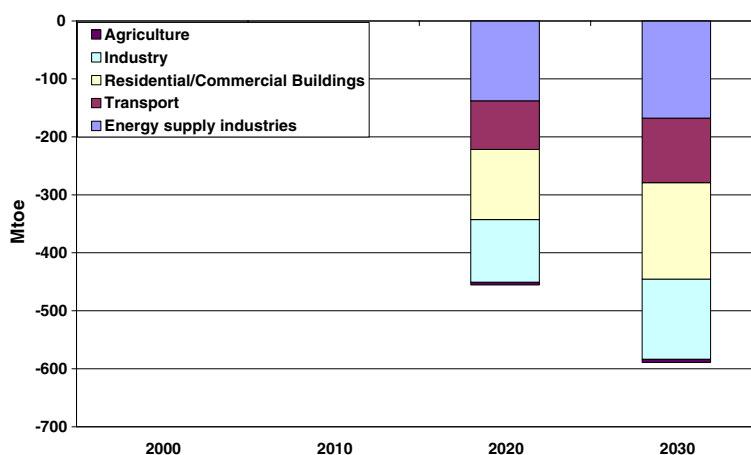


arising from all energy-efficiency policies, disaggregated by sector of the economy, with the assumed direct effects. The effects are calculated by taking the difference between the energy saving projected by the model and the expected *gross* energy saving (including the direct rebound effect) projected from IEA WEO 2006 (IEA 2006) energy-engineering studies of the policies (as set out in Table 2 above). This difference is then expressed as a percentage of the expected *gross* energy saving from these studies. The macroeconomic results show that the reduction in energy demand in 2030 is around 50% less than expected due to several indirect and economy-wide interactions discussed below, which are not covered in the IEA WEO 2006 (IEA 2006) or IPCC energy-engineering studies.

The highly disaggregated nature of the E3MG model gives detailed insights into the indirect and economy-wide interactions which give rise to the macroeconomic rebound effects in addition to the direct effects. Four potential sources of the total rebound effects arising from the introduction of energy-efficiency policies have been identified:

1. *Direct rebound effects.* These are comfort taking for residential buildings and increased vehicle use for transport and other effects as described above.
2. *Lowering of energy use and industrial costs.* The lower energy costs for energy consumers enable them to reallocate spending away from gas and electricity to a wide range of other goods and services, typically with very small energy and carbon

Fig. 2 Disaggregation of net energy savings from IEA WEO 2006 Energy Efficiency policies, in the period 2000–2030



content. In transport, industry and services, the targeted reductions in energy and carbon intensities lead to a reduction in industrial costs and, therefore, prices and consequently more output and exports.

3. *Higher imputed incomes for private consumers.* The reduction in energy costs implies an increase in consumer incomes. With the introduction of tighter building regulations and other policies to improve efficiency by the domestic sector, market energy prices are largely unchanged, but gross energy use falls if the volume of energy services remains the same. The higher real incomes must be imputed and allocated to consumers so that they increase their spending, as if they had an increase in actual income.
4. *Higher investment directly associated with the energy-efficiency policies.* Examples are the cost of extra insulation of houses or the extra cost of a fuel-efficient car over another with similar characteristics but lower efficiency. This extra investment, typically including the costs of the policies to consumers and business associated with the energy-efficiency measures, is added to industrial investment, investment in office buildings and dwellings and to the investment in road vehicles by consumers.

Table 10 shows the relative contributions of the three macroeconomic sources (items 2, 3 and 4 above) to the overall change in final energy demand, CO₂ emissions, GDP and prices. The table shows that the lowering of domestic and industrial energy costs is the main source of reduced CO₂ emissions and a major contributor to the reduction of prices. If

anything, the effect of the reduction in prices is an underestimate because the model has a simple treatment of cost inflation that does not allow for economies of scale. The extra spending, due to higher imputed income, leads to slightly higher energy use (a rebound effect) and emissions and slightly higher GDP and consumers' expenditure. This shows that the increased economic activity due to changes in consumer income mostly occurs in less energy-intensive areas, i.e. use of energy and carbon is inelastic to changes in consumer income. Similarly, the extra investment stimulated by energy-efficiency policies is itself concentrated on measures which reduce carbon emissions, whilst increasing economic activity.

Table 10, thus, shows that nearly all the indirect and economy-wide rebound effects on final energy use (which are contained within the figure of -4.3%) are due to the higher output resulting from greater energy efficiency.

Table 8 Effect of energy efficiency policies on CO₂ emissions by sector difference in Mt CO₂-eq

World	2010	2020	2030
Energy supply industries	0	-826.0	-1,121.5
Transport	0	-460.9	-621.4
Residential/Services Buildings	0	-348.5	-504.6
Industry	0	-437.4	-583.8
Agriculture	0	0	0
Total	0	-2,072.9	-2,831.2

Figures are policy case less reference case. Total CO₂ emissions include emissions from energy intensive industries' own use of energy, rail transport and water transport

Sources: E3MG 2.4 and 4CMR

Table 9 Direct, macroeconomic and total rebound effect of energy-efficiency policies (%), % difference between policy case and reference case

World	Direct			Macroeconomic			Total		
	2010	2020	2030	2010	2020	2030	2010	2020	2030
Energy supply industries	0	0	0	0	20.8	43.7	0	20.8	43.7
Transport	0	9.1	9.1	0	26.9	43.1	0	36.0	52.2
residential/services buildings	0	20.0	20.0	0	24.3	40.6	0	44.3	60.6
Industry	0	5	5	0	18.3	40.8	0	23.3	45.8
Agriculture	0	5	5	0	11.8	36.1	0	16.8	41.1
Total	0	9.4	9.7	0	22.1	41.6	0	31.5	51.3

Figures are total rebound effects, assumed direct rebound plus projected macroeconomic rebound effects

Sources: E3MG 2.4 and 4CMR

The rebound effects we find are consistent with the long-run parameters included in the aggregate energy equations for the response of energy demand to economic activity. All these activity elasticities are below one in the projections to 2030. Energy demand is, therefore, partly disengaged from activity in the long run. The low responses are interpreted as the outcome of several features in future energy use. Firstly, the activities within each broad sector are typically shifting over time towards more service-based and less material-energy-based activities as incomes rise and quality improves; energy demand will grow more slowly than activities as a result. Secondly, technological progress is taking the diffused form of more control in production and distribution and more precise use of energy in the form of electricity rather than fossil fuels directly; aggregate energy grows less, but the share of electricity rises. Thirdly, much of energy use for heating and cooling of buildings (residential and services' use of energy) is

largely an overhead cost once comfort levels are reached; in consequence, energy use will be associated more with employment and numbers of households rather than with output and incomes. Employment and numbers of households grow much less than GDP and incomes.

Conclusions

We find that the total rebound effect arising from the IEA WEO 2006 (IEA 2006) energy-efficiency policies for final energy users over the post-2012 period 2013–2030 is around 50% by 2030, averaged across sectors of the economy. Given the large magnitude of our estimated long-term rebound effects, a priority for future research should focus on the effectiveness of complementary policies such as broad-based energy taxes, educational and other behavioural changes that 'lock-in' first-order efficiency gains. There is also an

Table 10 Sources of macroeconomic effects of IEA WEO 2006 energy efficiency policies in 2030 % difference between policy case and reference case

World	Lower energy-use and industrial costs	Higher imputed income	Higher energy efficiency investments	Total
Final energy	-4.06	0.0002	-0.30	-4.34
CO ₂ emissions	-5.22	0.0001	-0.29	-5.50
GDP	0.007	0.0004	0.5	0.28
Price index consumers' expenditure	-0.029	0.0001	0.026	-0.003

The table shows contributions to % difference between policy case and reference case, from scenarios that decompose the total effects into three components

Sources: E3MG 2.4 and 4CMR

important role for the development of policies that are not focused on saving energy alone but on portfolios of policies that complement behavioural changes to ensure reductions in GHG emissions as living standards improve. For example, a sensible portfolio of policies for transport may combine (1) tighter engine efficiency and GHG standards with (2) a switch of fuel taxes to GHG taxes and (3) requirements that all new cars and trucks have CO₂ metres visible to drivers to provide real-time feedback on how driving behaviour affects fuel use.

The macroeconomic rebound effects arise from the reduction in energy costs for consumers and producers (particularly for energy-intensive industries). The lower energy costs for consumers lead them to substitute away from oil, gas and electricity to a wide range of other goods and services, typically with relatively small energy and carbon content; hence, the rebound effect is low. In industry, the targeted reductions in energy and carbon intensities lead to a reduction in their industrial costs and, therefore, prices and consequently more output and exports.

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