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# Energy efficiency and economy-wide rebound effects: A review of the evidence and its implications

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ABSTRACT

The majority of global energy scenarios anticipate a structural break in the relationship between energy consumption and gross domestic product (GDP), with several scenarios projecting absolute decoupling, where energy use falls while GDP continues to grow. However, there are few precedents for absolute decoupling, and current global trends are in the opposite direction. This paper explores one possible explanation for the historical close relationship between energy consumption and GDP, namely that the *economy-wide rebound effects* from improved energy efficiency are larger than is commonly assumed. We review the evidence on the size of economy-wide rebound effects and explore whether and how such effects are taken into account within the models used to produce global energy scenarios. We find the evidence base to be growing in size and quality, but remarkably diverse in terms of the methodologies employed, assumptions used, and rebound mechanisms included. Despite this diversity, the results are broadly consistent and suggest that economy-wide rebound effects may erode more than half of the expected energy savings from improved energy efficiency. We also find that many of the mechanisms driving rebound effects are overlooked by integrated assessment and global energy models. We therefore conclude that global energy scenarios may underestimate the future rate of growth of global energy demand.

## 1. Introduction

### *1.1. Background: the important role of energy efficiency, and the threat of rebound*

Improved energy efficiency is expected to play a central role in meeting both the goals of the Paris Agreement [1] and the Sustainable Development Goals [2], contributing up to 40% of the envisaged reductions in global greenhouse gas (GHG) emissions over the next two decades [3,4]. However, whilst energy efficiency is firmly embedded as a key mitigation strategy within Integrated Assessment Models (IAMs) [5], there are few signs that the rate of growth of global energy demand is slowing. Indeed, after nine years of slower global economic growth following the 2008 global recession, global primary energy consumption increased by 2.1%/year in 2017 and 2.3%/year in 2018 [6], close to the average of ~2.4%/year over the last 250 years [7]. Between 1971 and 2018, global GDP (in US$2010 constant prices) grew by an average of 3.1%/year [8] while global primary and final energy consumption increased by an average of 2.0%/year and 1.8%/year, respectively [9]. This is *relative* decoupling, since energy consumption grew more slowly than GDP, but there is no historical global experience of *absolute* decoupling, where energy use falls while GDP continues to grow.

There is some experience of absolute decoupling at the national level, but only for a limited number of countries (e.g., the UK and Denmark) for relatively short periods of time [10,11]. These examples of absolute decoupling have been partly achieved by 'offshoring' domestic manufacturing to other countries [12,13]. In their analysis of 99

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**Nomenclature**

*Abbreviations/Acronyms*

| | |
|---|---|
| AEEI | autonomous energy efficiency improvements |
| AIM | Asia-Pacific Integrated Model |
| CES | Constant Elasticity of Substitution |
| CGE | Computable General Equilibrium |
| GCAM | Global Change Analysis Model |
| GDP | gross domestic product |
| GHG | Greenhouse Gas |
| GLOBIOM | Global Biosphere Management Model |
| IAM | Integrated Assessment Model |
| IEA | International Energy Agency |
| IMAGE | Integrated Model to Assess the Global Environment |
| IPCC | Intergovernmental Panel on Climate Change |
| IRENA | International Renewable Energy Agency |
| MAgPIE | Model of Agricultural Production and its Impact on the Environment |
| MER | Market Exchange Rate |
| MESSAGE | Model of Energy Supply Systems And their General Environmental Impact |
| PIEEI | Price Induced Energy Efficiency Improvements |
| PPP | Purchasing Power Parity |
| REMIND | Regional Model of Investments and Development |
| SSP | Shared Socioeconomic Pathway |
| USEIA | US Energy Information Administration |
| WEM | World Energy Model |
| WEO | World Energy Outlook |

*Symbols (and Units)*

| | |
|---|---|
| $E_P$ | Primary energy use (measured in e.g., Joules/year) |
| E/Y | Energy intensity (measured in e.g., $Joule/US) |
| Y | Gross Domestic Product (GDP), Gross Output (measured in e.g., $US/year) |
| $\theta_E$ | Energy efficiency (Y/E) in economic terms (measured in e.g., $US/Joule) |
| K | Capital stock (measured in e.g., $US/year) |
| L | Labour inputs (measured in e.g., work hours/year or number of workers/year) |
| E | Energy inputs (measured in e.g., Joules/year) |
| M | Materials inputs (measured in e.g., tonnes/year) |
| U | useful exergy output (measured in e.g., Joules/year) |
| X | primary exergy input (measured in e.g., Joules/year) |
| $I_t$ | Aggregate energy intensity ($E_t/Y_t$) at time t (measured in e.g., $US/Joule) |
| $A_t$ | total factor productivity, at time t (dimensionless) |
| $\lambda$ | 'factor neutral' technical change (dimensionless) |
| $\pi$ | 'capital-augmenting' technical change (dimensionless) |
| ρ | 'labour–augmenting' technical change (dimensionless) |
| $\tau$ | Energy-augmenting technical change (dimensionless) |
| $\upsilon$ | 'materials-augmenting' technical change (dimensionless) |
| $\varepsilon$ | primary-to-useful exergy efficiency (ratio, dimensionless) |
| $t_0$ | time at initial period, 0 |
| $t_1$ | time at subsequent period, 1 |

countries over the period 1971–2010, Csereklyei *et al.* [10,14] find relatively stable cross-sectional relationships between per-capita primary energy use ($E_P$) and per-capita constant GDP ($Y$) exchanged at purchasing power parity (PPP) basis, with an elasticity (of $E_P$ with respect to Y) of ~0.7. This relationship implies that richer countries are less energy intensive and that, on average, a 1% increase in per-capita income is associated with a 0.3% decrease in per-capita primary energy intensity ($E_P/Y$). Semieniuk *et al.* [15] analysed 185 countries over the period 1950–2014 and found an even stronger correlation (Spearman's rank coefficient of 0.86) between per-capita primary energy use and per-capita (PPP) GDP, with an elasticity of 0.89 for most of the sample.

In this context, the global energy scenarios from the International Energy Agency (IEA) [4], the Intergovernmental Panel on Climate Change (IPCC) [16], and other organisations represent a significant departure from the historical trend. These scenarios commonly project low or no growth in energy demand over the next few decades, due to a combination of structural change and the more rapid uptake of energy efficient technologies [15]. Energy demand in lower-income regions is projected to grow slowly, despite the need for large-scale investment in infrastructure and heavy industry [17,18], and in many scenarios this increase is more than offset by reductions in energy demand in high-income regions. For example, a review of 2 °C scenarios from three IAMs (TIAM-Grantham, MESSAGE-GLOBIOM, and WITCH) found average changes in global final energy demand of between +0.2%/year and −0.9%/year in the period from 2020 to 2050 [5]. The top end of this range (+0.2%/year) is only a tenth of the average rate of increase since 1971, while (given the assumption of economic growth continuing at 2–3%/year [19]) the bottom end of the range (−0.9%/year) represents significant levels of absolute decoupling.

Most scenarios also project an immediate acceleration in the rate of decoupling, but there is little evidence that such an acceleration is underway. Indeed, global primary energy intensity fell by only 1.3%/year in 2018, the lowest annual fall for a decade, and the fourth year in a row that the rate of improvement has declined [20]. The common response to this slow rate of progress is to call for rapid implementation of more ambitious energy efficiency policies [20]. However, given that mandatory energy efficiency polices already cover 35% of global final energy use in 2018 [20], it is not certain that a step change in energy efficiency policies would deliver the envisaged reduction in energy consumption.

A failure to achieve the anticipated structural break in the rate of growth of global energy demand could have important consequences. If greater decoupling of energy consumption from GDP is not achieved, it will be necessary to rely more heavily on low-carbon energy supply, carbon capture and storage, and negative emission technologies to meet the Paris Agreement goals. These strategies require ambitious policies, large-scale investment, extensive land use, and significant lead-times – so expanding them further will be politically challenging and will take time to have an effect. Hence, further investigation of the prospects for absolute decoupling, and the possible obstacles to that decoupling, is warranted.

This paper explores **one possible explanation** for the historical close coupling between energy consumption and GDP, namely that *economy-wide rebound effects* from improved energy efficiency are larger than is commonly assumed. We use the term 'rebound effects' to refer to a variety of behavioural and economic responses to improved energy efficiency, whose net result is to reduce energy savings relative to a counterfactual scenario in which those responses do not occur [21]. If rebound effects are large, absolute decoupling will be more difficult to achieve [22]. Whilst energy rebound research was historically driven by a focus on the energy supply and economic implications of improved energy efficiency [23–25], added recent impetus has been given by the implications for climate change and climate policies [26,27]. We review the evidence on the size of economy-wide rebound effects and explore whether and how such effects are taken into account within the models used to produce global energy scenarios. We argue that: first, the evidence suggests economy-wide rebound effects may erode more than half of the potential energy savings from improved energy efficiency; second, the models used by the IPCC and others take insufficient account of these rebound effects; and third, the resulting scenarios may therefore underestimate the future rate of growth of global energy demand.

### 1.2. Review outline

There are five elements to this Review (Sections 2–6), leading to the Discussion and Conclusions (Sections 7 and 8). The starting point is Section 2, which compares the historical trend (1971–2018) in global final energy consumption with those projected by 17 selected global energy scenarios (2018–2050). The aim is to establish the historical relationship between final energy consumption and GDP and to identify how this is projected to change in the selected scenarios. We find that many scenarios project a significant break in the relationship between energy use and GDP - thereby raising questions about their plausibility [15]. The remaining sections investigate whether large, economy-wide rebound effects could help explain the historical linkage between energy use and GDP and hence whether these effects could obstruct any future decoupling. Section 3 presents the different definitions of improved energy efficiency, and describes how different types of rebound effects may erode the anticipated energy savings. We clarify the mechanisms contributing to direct, indirect, and macroeconomic rebound effects and show how these combine to create an overall economy-wide rebound effect.

Sections 4 and 5 review the empirical evidence on the size of these economy-wide rebound effects. Section 4 summarises the results from 21 studies that use computable general equilibrium (CGE) models to estimate rebound effects, while Section 5 summarises the results from 12 studies that use a range of other methods. The selected studies were identified from keyword searches in Google Scholar, using the criteria that: a) they estimate rebound effects at the economy-wide level; and b) they explicitly or implicitly include one or more macroeconomic rebound effects. While this is a narrative review rather than a systematic review of the type by Sorrell [21], we include a broad selection of studies in this area,[1] which serves to give a representative sample of reported rebound magnitudes, from studies with a broad range of methods and assumptions.

Sections 4 and 5 demonstrate that the majority of empirical studies estimate economy wide rebound effects of 50% or more, suggesting that at least half of the potential energy savings from improved energy efficiency may be 'taken back' by various economic and behavioural responses. Section 6 then examines whether and how the mechanisms contributing to these rebound effects are included in the integrated assessment and global energy models used to produce global energy scenarios (seen in Section 2). We demonstrate that the majority of models only include a subset of these mechanisms, thereby creating the risk that they underestimate the size and importance of economy-wide rebound effects.

Section 7 discusses the extent to which the omission of some or all of these mechanisms could lead to over-optimistic projections of the future decoupling of energy consumption from GDP. Finally, Section 8 concludes by highlighting some of the implications for research and energy modelling.

## 2. Structural breaks in global final energy demand

To establish the nature and scale of the anticipated structural break between historical trends and future projections of global final energy consumption, we collate and compare data from a range of sources. We focus upon final rather than primary energy consumption since this avoids the difficulties created by different conventions for measuring primary energy – which become more important as non-fossil sources form a larger share of the global energy mix [28,29].[2]

For historical trends over the period 1971–2018, we take global final energy consumption data (in TJ/year) from the IEA's Extended World Energy Balances [9], and historical GDP data (Market Exchange Rate [MER] in US$2010 constant prices) from the World Bank [8]. For projections over the period 2018 to 2050, we take eight scenarios from the IPCC and nine scenarios from other authoritative sources (some scenarios have an end year of 2040).

From the IPCC, we take four scenarios that limit warming to 1.5 °C by 2100 with a >50% probability, and four that meet the 2.0 °C target with >66% probability [30–32]. These scenarios are derived from a number of IAMs and assume different levels of population [33] and different patterns of demographic, political, and economic development -via alternative Shared Socioeconomic Pathways (SSPs) [34].[3] They also lead to different atmospheric concentrations of GHGs - the IPCC's Representative Concentration Pathways (RCPs). In addition, we take global energy scenarios from the IEA [4,35,36], the International Renewable Energy Agency (IRENA) [37], Greenpeace [38], the US Energy Information Administration (USEIA) [39], bp [40], and Shell [41]. These scenarios are derived from a variety of *global energy models* and represent a range of outcomes for global average temperature.

We align the GDP projections in these scenarios to our historical data via constant MER values in $US2010 prices[4] and the final energy consumption projections to our historical data in TJ. Table 1 summarises the different scenarios, Fig. 1 presents the historical and projected trends in global final energy consumption and GDP, and Fig. 2 indicates the corresponding changes in global final energy intensity.

The structural break in energy-GDP relationships in many of the model scenarios can be seen in Fig. 1 (final energy demand) and Fig. 2 (annual change of final energy intensity). In 9 of the 15 scenarios, final energy intensity ($E_F/Y$) falls by more than 2.4%/year every year between 2020 and 2030 (Table 1) - more than double the average rate of decline since 1971 (1.2%/year). Nearly all the scenarios imply a structural break in energy-GDP relationships, but the size of this break depends upon the level of ambition of the scenario, the structure of the model, and the assumptions for key parameters and variables.

Three other notable features are apparent. First, as climate targets tighten, the scenarios tend towards absolute decoupling of final energy consumption from GDP. For example, the mean rate of growth of final energy consumption in the IPCC 1.5 °C scenarios is +0.0%/year, while that in the 2.0 °C scenarios is +0.9%/year – which is still only half the average rate of growth since 1971 (+1.8%/year). Second, the annual reductions in global final energy intensity (Table 1) vary from −1.1%/year to −5.2%/year. The IPCC scenarios exhibit the largest reductions (−3.1%/year) versus the other scenarios (−2.0%/year) in the 2020–2030 decade, and these are 2–3 times the average rate of decline in the preceding decade (−0.8%/year). Third, in the period 2020–2030,

[1] The evidence base is currently both too small (n = 33) and too methodologically diverse for a meta-analysis to be applied, but this remains a possibility for the future.

[2] Appendix A repeats the analysis for primary energy use and GDP, and finds very similar patterns.

[3] The baseline scenarios for the five SSPs describes future developments in the absence of new climate policy. These broadly correspond to: a) sustainability focused growth and equity (SSP1); b) continuation of historical trends (SSP2); c) fragmented world of resurgent nationalism (SSP3); d) increasing inequality (SSP4); and d) rapid and unconstrained growth in economic output and energy use (SSP5).

[4] Conversion of PPP growth rates to MER growth rates via factor of 0.78, i.e. MER growth rate = 0.78 x PPP growth rate. 0.78 factor chosen based on two sources: 1. World Bank 2010$US constant MER growth rate 2000-2018 = 2.86% / IEA PPP 2018$US constant PPP growth rate 2000-2018 = 3.70% (Table B2, WEO 2019); and 2. World gross domestic product (GDP) annual growth rates calculated from EIA International Energy Outlook 2019 for 2018-2050 on MER basis (2.40%) and PPP basis (3.00%), https://www.eia.gov/outlooks/aeo/data/browser/#/?id=4-IEO2019&cases=Reference&sourcekey=0

**Table 1**
Projected change in global final energy intensity in a selection of global energy scenarios.

| Scenario type | Climate outcome | Model and documentation | Model Scenario | Average annual change in final energy intensity (%) | | |
|---|---|---|---|---|---|---|
| | | | | 2020–2030 | 2030–2040 | 2040–2050 |
| IPCC scenarios | ~1.5 °C | IMAGE [42] | SSP1-1.9 (sustainability) [31] | −5.3% | −2.6% | −1.2% |
| | | MESSAGE-GLOBIOM [19] | SSP2-1.9 (middle-of-the-road) [31] | −2.8% | −2.1% | −1.3% |
| | | REMIND-MAgPIE [43] | SSP5-1.9 (fossil fuel) [31] | −2.6% | −3.4% | −1.9% |
| | | MESSAGE-GLOBIOM [19] | IIASA Low Energy Demand [31] | −5.2% | −3.7% | −2.6% |
| | ~2.0 °C | IMAGE [42] | SSP1-2.6 (sustainability) [31] | −2.9% | −2.4% | −1.8% |
| | | MESSAGE-GLOBIOM [19] | SSP2-2.6 (middle-of-the-road) [31] | −1.8% | −1.5% | −1.3% |
| | | GCAM [44] | SSP4-2.6 (regional rivalry) [31] | −2.1% | −1.4% | −1.1% |
| | | REMIND-MAgPIE [43] | SSP5-2.6 (fossil fuel) [31] | −1.9% | −2.6% | −1.9% |
| | **IPCC model average** | | | **−3.1%** | **−2.5%** | **−1.6%** |
| Other scenarios | ~1.5 °C | IEA World Energy Model [45] | Sustainable Development Scenario (SDS) [35] | −2.5% | −2.7% | −2.7% |
| | ~2.0 °C | IEA World Energy Model [45] | Efficient World Scenario (EWS) [20] | −2.5% | −2.2% | −2.2% |
| | | IRENA – N/A | Renewable Energy Roadmap [37] | −2.6% | −2.2% | −2.6% |
| | | Shell World Energy Model [46] | Shell Sky Scenario [41] | −1.6% | −1.3% | −1.1% |
| | | BP Energy Outlook model [47] | Rapid transition scenario [40] | N/a | N/a | N/a |
| | | Mesap PLaNet model [48] | Greenpeace World Energy [r]evolution [38] | −2.8% | −3.5% | −2.8% |
| | >2.0 °C | IEA World Energy Model [45] | Stated Policies Scenario (STEPS) [35] | −1.2% | −1.5% | −1.5% |
| | | IEA World Energy Model [45] | Current Policies Scenario (CPS) [4] | −1.2% | −1.2% | −1.2% |
| | | EIA World Energy Projection System Plus [49]. | EIA Mid GDP, mid oil price scenario [39] | N/a | N/a | N/a |
| **Other scenarios average** | | | | **−2.0%** | **−2.1%** | **−2.0%** |

Notes.
1. Global final energy intensity fell by an average of −1.2%/year over the period 1971–2018, and by −0.9%year over the period 2008–2018.
2. The IPCC 1.5 °C Special report [50] uses the AIM model scenario for SSP1-1.9. However, we take the IMAGE SSP1-1.9 scenario for consistency with the previous IMAGE SSP1-2.6 scenario, and to better enable comparison of energy projections moving from RCP-2.6 to RCP-1.9.
3. GCAM is the marker model for SSP4-2.6 scenario, but does not have a SSP4-1.9 scenario. In its place, for our fourth 1.5 °C scenario, we choose to include the MESSAGE-GLOBIOM IIASA Low Energy Demand scenario.

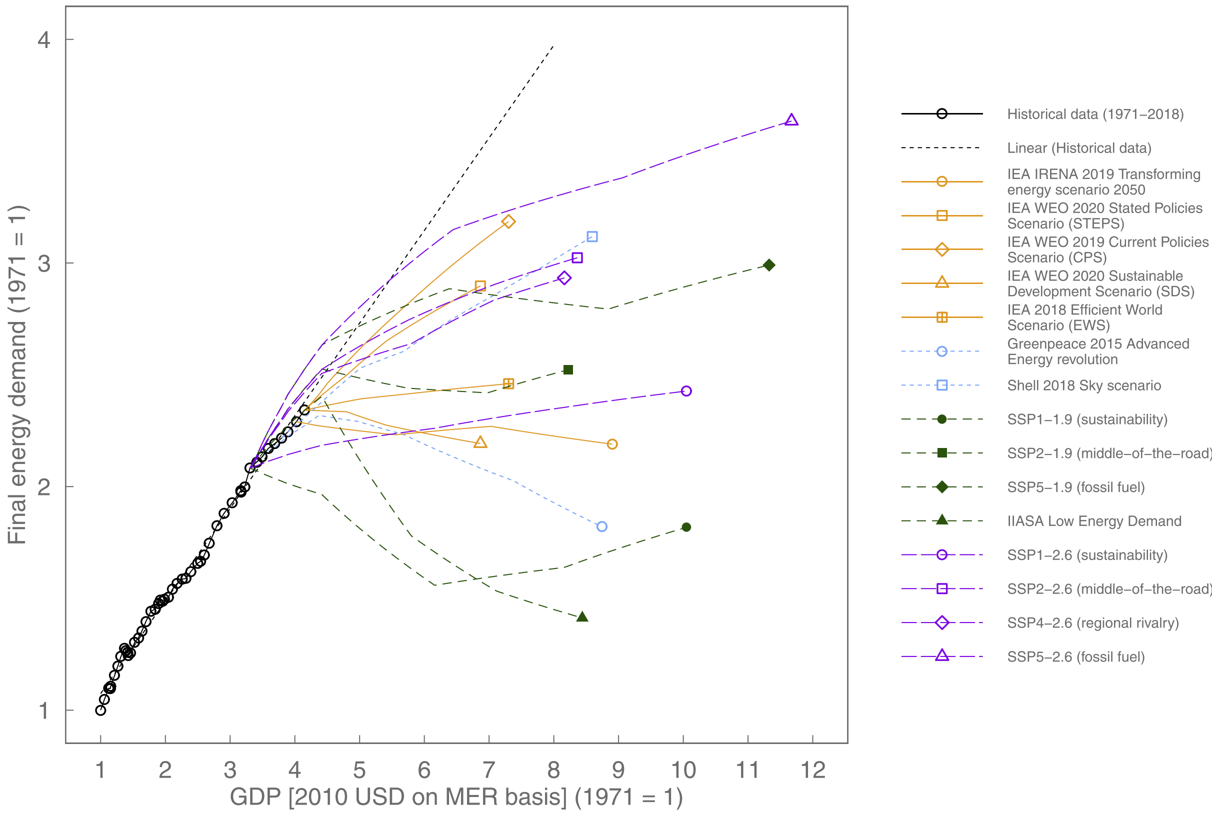


**Fig. 1.** Historical trends and future scenarios for global final energy use and GDP (1971–2050). *Notes*: Scenario plots are in four groups: orange (IEA models); green (1.5 °C IAMs); purple (2.0 °C IAMs) and blue (other models). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

the rate of decline in energy intensity in the IPCC 1.5 °C scenarios (−4.0%/year) is nearly twice that observed in the 2.0 °C scenarios (−2.2%/year).[5]

In summary, the structural break observed in many of these scenarios represents a radical departure from the historical trend, both in the rate of growth of final energy consumption and the rate of decline of final energy intensity. The plausibility of this structural break therefore deserves closer attention.

## 3. Improved energy efficiency and economy-wide rebound effects

The decoupling in the above scenarios is largely the projected result of improved energy efficiency throughout all sectors of the global economy. The scenarios include different types, sources, sizes, and costs of energy efficiency improvement, but these improvements may lead to variety of rebound effects, which may not always be captured by the relevant models. Hence, it is first necessary to define what ‘improved energy efficiency’ means and how it is commonly modelled, and then to clarify how rebound effects can erode the associated energy savings.

[5] The same relationship would hold between per capita energy consumption and per capita GDP – as demonstrated by Semieniuk *et al*. [15]. The largest disconnect is observed in the near term (2020–2030), when the rate of population growth should be close to that during the last decade.

### 3.1. Defining and modelling improved energy efficiency

Energy efficiency is simply the ratio of useful outputs to energy inputs for a specified system – such as a motor, a machine tool, an industrial process, a firm, a sector, or an entire economy. Depending upon the system and the purpose at hand, inputs and outputs may be measured in energy terms, such as heat content or physical work; physical terms, such as vehicle kilometres or tonnes of steel; or economic terms such as value-added or GDP [51]. Energy intensity is the inverse of energy efficiency and is most commonly measured in *economic* terms. Different energy efficiency measures may be more or less appropriate for different systems and purposes.

Empirical and modelling studies relating to energy efficiency improvements vary in terms of:

1. how they *define* the numerator and denominator of relevant energy efficiency measures (e.g. first law thermodynamic, second law thermodynamic, physical, economic);
2. the *system boundaries* to which these definitions apply (e.g. devices, households, firms, sectors, national economies);
3. the methods used to *aggregate* different energy types (i.e. whether and how differences in energy quality are accounted for [52];
4. the *source* of improvements in energy efficiency (e.g. exogenous technical change, price-induced substitution, mandatory standards);
5. the *cost* of achieving those improvements (e.g. zero-cost technical change, high-cost regulatory standards [53]; and
6. whether those improvements control for (or are assumed to be independent of) improvements in the productivity of other inputs, or increases in the utility obtained from other commodities.

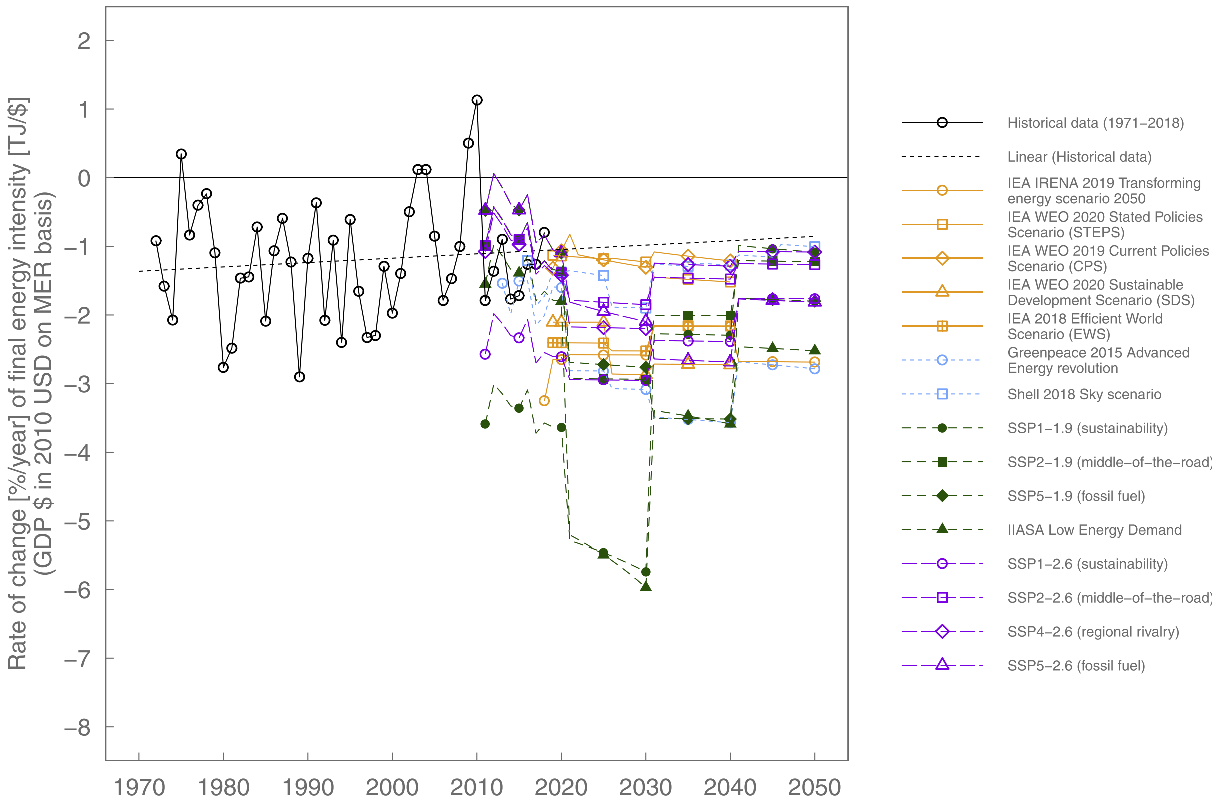


**Fig. 2.** Historical trends and future scenarios for annual change in final energy intensity (1971–2050). *Notes*: Annual percentage change in global final energy intensity (plotted annually for the historical trend, and as a decadal average for each scenario). Black dotted line is linear regression/projection of historical trends. The scenario plots are in four groups: orange (IEA models); green (1.5 °C IAMs); purple (2.0 °C IAMs) and blue (other models). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Many aggregate economic models simulate the behaviour of an economy by a production function of the form: $Y = \lambda f(\pi K, \rho L, \tau E, \upsilon M)$; where $Y$ is gross output, $K$ is capital inputs, $L$ is labour inputs, $E$ is energy inputs, $M$ is material inputs, and $\lambda, \pi, \rho, \tau$ and $\upsilon$ are exogenous, time-dependent multipliers representing 'factor neutral', 'capital-augmenting', 'labour–augmenting', 'energy-augmenting' and 'materials-augmenting' technical change respectively. Technical change is assumed to improve the productivity[6] of individual inputs over time (e.g.,$\tau_{t_1} > \tau_{t_0}$ for $t_1 > t_0$) independently of changes in relative prices. Hence, energy-augmenting technical change should improve aggregate economic-based energy efficiency ($\theta_E = Y/E$), because less energy is required to produce the same level of economic output. Increases in the relative price of energy should also improve aggregate energy efficiency, because this encourages producers to substitute other inputs for energy – but since costs have increased, output may fall. In contrast, technical change improves energy productivity independently of changes in relative prices and without reducing output.[7]

Energy-augmenting technical change ($\tau$) is one way of simulating improved energy efficiency, but this is not directly observed and hence is difficult to measure empirically [54]. In contrast, it is straightforward to measure the aggregate economic-based energy efficiency of a sector ($\theta_E = Y/E$), but this depends upon the level and price of each input, the current state of technology, and the level of output, as well as upon how individual inputs are measured and aggregated. In addition, a one-off or ongoing improvement in the productivity of energy inputs ($\tau$) will lower the price of 'effective energy' ($\tau E$) and hence encourage producers to substitute (effective) energy for other inputs – which is one of the mechanisms contributing to the rebound effect [55]. As a result, a 1% improvement in the productivity of energy inputs ($\tau$) within a firm, sector or economy may not translate to a 1% improvement in the aggregate energy efficiency ($\theta_E$) of that firm, sector, or economy [56]. Also, changes in aggregate energy efficiency may result from changes in the level, price, and productivity of non-energy inputs, even in the absence of energy-augmenting technical change [56]. Similarly, improvements in energy efficiency at one level of aggregation (e.g., an industrial sector) may not translate to improvements in energy efficiency at a higher level of aggregation (e.g., a national economy) owing to a variety of macroeconomic adjustments – for example, a shift towards more energy intensive goods and services as a consequence of a fall in their relative price. More generally there is no necessary link between improvements in one measure of energy efficiency (e.g., $\tau$) and improvements in another measure (e.g., $\theta_E$) at either the same or different levels of aggregation. Since different studies define and measure energy efficiency improvements in different ways and for different levels of aggregation, great care must be taken when comparing and interpreting their results.

[6] We define 'productivity' in this context as the level of economic output per unit of energy (or labour, capital or materials) input.

[7] Substitution is represented in neoclassical economic theory as movement along an isoquant of a production function and technical change as a shift of the isoquant [55]. However, the distinction between the two is less clear from an engineering perspective: changes in prices may themselves induce technical change; and both technical change and substitution may reflect a complex mix of investment, operational changes and shifts in the composition of output. Classical economic growth theory does not distinguish substitution movements from technical change [130].

### *3.2. Economy-wide rebound effects*

Cost-effective energy efficiency improvements reduce the effective price of energy services, such as heating and lighting, and hence encourage increased consumption of those services, which in turn will partly offset the energy savings per unit of the energy service. This *direct* rebound effect is well established and is now the subject of a large and growing empirical literature [21,57–59], especially for efficiency improvements by consumers. However, energy efficiency improvements can also trigger *indirect* and *macroeconomic* responses and associated rebound effects [59], with consequent impacts on energy consumption throughout the economy (see Appendix B for a summary of the different components of the direct, indirect and macroeconomic rebound effects).

For example, the savings in gasoline consumption from using fuel-efficient cars may be spent on other goods and services that also require energy to manufacture and use (indirect rebound). Similarly, the widespread adoption of energy efficient cars may reduce gasoline demand and hence gasoline prices, that will in turn encourage increased consumption of gasoline and other energy (macroeconomic rebound) and have secondary impacts in other markets. Both direct and indirect rebound effects are *partial equilibrium,* since the methodologies employed to estimate them (e.g., input-output models) hold input and commodity prices fixed throughout the economy, and only consider variations in the effective price of the energy service itself. In contrast, the macroeconomic rebound effects are *general equilibrium,* since the methodologies employed to estimate them (e.g., computable general equilibrium models) allow input and commodity prices to vary throughout the economy. In practice, these different effects occur simultaneously and their net result - the *economy-wide rebound effect* – is normally expressed as a percentage of the expected economy-wide energy savings, as estimated from a counterfactual scenario where none of these adjustments occur [60,61].

Economy-wide rebound effects are challenging to estimate, but there is growing evidence to suggest they may be *large*. For example, Saunders [26] uses data over the period 1850–2000 to estimate economy-wide rebound effects in excess of 60% for Sweden, whilst Bruns *et al.* [62] uses data over the period 1973–2016 to estimate rebound effects of ~100% for the US (both of these studies are reviewed below). Suggestive evidence is also provided by van Benthem [22] who finds that economic growth in developing countries is as energy-intensive as past growth in industrialized countries, despite dramatic improvements in the energy efficiency of individual technologies. The equality in energy intensity suggests that the energy savings from improvements in individual technologies have been offset by other trends, such as a shift toward more energy-intensive patterns of consumption [10,22]. Similarly, Csereklyei *et al.* [10] show that the long-term decline in regional and global energy intensity is due to countries getting richer, rather from them producing particular levels of wealth with less energy.

The following two sections review some recent estimates of the magnitude of economy-wide rebound effects, including both *ex-ante* estimates from macroeconomic models and *ex-post* estimates from historical data. The selected studies were identified from keyword searches in Google Scholar, using the criteria that: a) the studies estimate rebound effects at the economy-wide level; and b) they explicitly or implicitly include one or more of the macroeconomic effects listed in Appendix B. Thus, for example, we exclude studies that focus upon individual energy services [63], or upon individual economic sectors [64], as well as those that rely solely upon input-output models (e.g., [65–69]), because the latter neglect macroeconomic rebound effects. While the resulting sample is not fully comprehensive, it provides a representative coverage of the available evidence and includes the most highly cited studies in this area.

We split the evidence into two groups: estimates from computable general equilibrium (CGE) models (Section 4) and estimates from other methodologies (Section 5).

## 4. Estimates of economy-wide rebound effects from computable general equilibrium (CGE) models

The most common approach to estimating economy-wide rebound effects is to use CGE models of regional or national economies. CGE models are widely used for energy-economic analysis and are based upon social accounting matrices for the relevant economies. They consist of a set of simultaneous equations describing the behaviour of producers, consumers and other economic actors, together with the interdependencies and feedback between different sectors. Multi-regional or global CGE models do this for a number of regions and simulate the trading links between those regions. CGE models are parameterised to reflect the structural and behavioural characteristics of the relevant economies and may be used to estimate the impact of ‘disturbances’ such as improvements in the productivity of energy inputs ($\tau$) within one or more sectors – which is the most common way of representing improved energy efficiency in such models. Here, the counterfactual is simply a model run without any energy efficiency improvement [60].

CGE models have only recently been used to investigate rebound effects, but the literature has grown substantially since the publication of an earlier review in 2007 [70]. CGE models have a number of well-established limitations (Appendix C), but these must be set against the insights they provide into the complex adjustments that follow specific disturbances – including the changes in input and commodity prices, industrial structure, consumption patterns and trade patterns. CGE models allow both the short-run and long-run magnitude of rebound effects to be estimated and the relative contribution of different mechanisms to be identified. The latter is much harder to achieve through econometric analysis, owing to the need to control for multiple conflicting variables [59].

Table 2 summarises the estimates of long-run, economy-wide rebound effects from 21 CGE studies, while the Supplementary Information provides more detailed information on each study. Seven of the studies model energy efficiency improvements by households, while the remainder model improvements by producers. Three of the studies [71–73] use multi-regional models to estimate global rebound effects, while the remainder use regional (national or subnational) models to estimate regional rebound effects. The modelled regions vary widely in size, economic structure, openness to trade, aggregate energy intensity and other relevant variables - all of which influence the size of the estimated effects. All the CGE studies estimate rebound effects for energy consumption (either in the aggregate, or for different fuels), with the associated rebound effects for carbon (or GHG) emissions being either larger or smaller depending upon the carbon (or GHG) intensity of energy use in different sectors. For example, Bye, *et al.* [74] estimate that energy efficiency improvements in Swedish households *reduce* economy-wide energy use (with a rebound of ~40%) but *increase* economy-wide carbon emissions (with a rebound of >100%), owing to the low carbon intensity of Swedish electricity generation.

All of the studies simulate producer (consumer) behaviour through ‘nested’ constant elasticity of substitution (CES) production (utility) functions (see Appendix C), although the level of aggregation, the nesting structure, and the assumed parameter values vary widely from one model to another. Most CGE models represent energy efficiency improvements as a costless, one-off increase in the productivity of energy inputs to producers ($\tau$) or in the utility obtained from energy commodities by consumers. Notable exceptions are Wei *et al.* [73] and Duarte *et al.* [89], who model annual improvements in these variables. The productivity improvements may affect all energy commodities or a subset of those commodities (e.g., only electricity); and may apply to all producers/households or to individual sectors/household groups. Bye *et al.* [74] is the only study to allow for the capital costs of energy efficiency improvements, although Broberg *et al.* [80] include these in their sensitivity tests. All of the studies model ‘pure’ energy efficiency improvements that leave the productivity of other inputs (or the utility obtained from other commodities) unchanged. In practice, energy

**Table 2**
Estimates of long-run, economy-wide rebound effects from 21 CGE modelling studies.

| Source | Region | Model Type | Modelled energy efficiency improvement(s) | Baseline estimate of long-run, economy-wide rebound effect | Range of estimates in sensitivity tests |
|---|---|---|---|---|---|
| Vikström [75] | Sweden | Dynamic | 15% (12%) in non-energy (energy) sectors. | 60% | 60% |
| Grepperud *et al.* [76]; | Norway | Dynamic | Doubling growth rate of electricity productivity in paper, metals, chemicals & finance (in turn), and growth rate of oil productivity in fisheries and road transport (in turn) | Not quantified but modest in fisheries and road transport, larger in paper and chemicals, and >100% in metals | |
| Allan *et al.* [77] | UK | Dynamic | 5% in all production sectors | Elec = 27%; Non-elec = 31% | Elec = 12%–58%; Non-elec = 13%–67% |
| Hanley *et al.* [78] | Scotland | Dynamic | 5% in all production sectors | Elec = 131%; Non-elec = 134% | Elec = 41%–250% Non-Elec = 35%–244% |
| Anson *et al.* [79] | UK | Dynamic | 5% in commercial transport sector | 39% | 37%–105% |
| Guerra *et al.* [60] | Spain | Static | 5% in all production sectors | 87% | 15%–230% |
| Broberg *et al.* [80] | Sweden | Dynamic | 5% in: 1) all production sectors; 2) non-energy sectors; 3) energy-intensive sectors | 1) All sectors = 73% 2) Non-energy = 69% 3) Energy-intensive = 78% | 41%–81% |
| Yu *et al.* [81] | Georgia (US) | Static | 10% in: a) all production sectors; b) individual production sectors | All sectors: Elec = 12% Non-Elec = 25% By sector: 309%–728% | Elec = 10%–13% Non-Elec = 22–27% |
| Garau *et al.* [82] | Italy | Static | 1% in all production sectors | 21% | 5%–210% |
| Lu *et al.* [83] | China | Static | 5% for each energy type in turn in all production sectors | Coal = 21%; ‘ Oil-Gas’ = 42%; Petroleum = 30%; Electricity = 0.1%; | |
| Wei *et al.* [73] | Global | Dynamic | 10% in non-energy production sectors | 76% | 21%–76% |
| Koesler *et al.* [72] | Global | Static | 10% in German: a) manufacturing sectors; b) production sectors | a) 48% b) 47% | |
| Böhringer *et al.* [71] | Global | Static | 1% in manufacturing, agriculture and services sectors in China, the EU and the US (investigated in turn) | Manufacturing = 65%–75% Agriculture = 70%–90% Services = 70–75% | 60%–110% |
| Du *et al.* [84] | China | Static | 1%, 3% and 5% in construction sector | Gas 99%; Coal 91% Oil 89%; Elec 84% | |
| Koesler [85] | Germany | Static | 10% in household transport energy use | 49% | −5%–49% |
| Lecca *et al.* [86] | UK | Dynamic | 5% in household energy use | 64% | |
| Figus *et al.* [87] | Scotland | Dynamic | 5% in household energy use | 50% | 50%–78% |
| Kulmer *et al.* [88] | Austria | Static | 10% in household fossil fuel use | 65% | 59%–73% |
| Duarte *et al.* [89] | Spain | Dynamic | 20% reduction in household electricity and vehicle fuel use by 2030, relative to 2005 | 75% | 51%–75% |
| Bye *et al.* [74] | Sweden | Dynamic | 27% reduction in household energy use by 2030, relative to baseline scenario | 40% | 17%–62% |
| Barkhordar [90] | Iran | Dynamic | Adoption of energy efficient lighting by households | 44% | 35%–52% |

efficiency improvements may derive from technologies that also improve the productivity of other inputs – which in turn could lead to larger rebound effects owing to the greater boost to economic output.

We make several observations from this review. First, the estimated size of economy-wide rebound effects in the studies is highly sensitive to various features of the relevant economy, as reflected in the assumed or calibrated values of parameters such as, the elasticity of supply of capital and labour, the elasticity of output demand in different sectors, the energy intensity of those sectors, the potential for substitution between different energy types, the potential for substitution between energy and other inputs, the potential for substitution between energy and other consumption goods, the expenditure elasticity of those goods, the elasticities of import and export demand, and the manner in which increased tax revenue is used. For example, the contrasting economy-wide estimates from Hanley *et al.* [91] for Scotland (>100%) and Allan *et al.* [77] for the UK (~30%) are largely explained by differences in the elasticity of electricity exports in the modelled regions. Scotland is a major electricity exporter to England and Wales, but the UK is only a minor electricity exporter to the EU. Similarly, Allan *et al.* [77] estimate an economy-wide rebound effect of 21% for electricity when assuming an inelastic labour supply, but 47% when assuming an elastic labour supply.

Second, the estimates of economy-wide rebound effects are particularly sensitive to the assumed elasticities of substitution between energy and other inputs, which indicate how easy it is for producers to adjust to a change in relative prices – with easier substitution being associated with larger rebound. There is a large empirical literature on this topic [92], but the results are contradictory and difficult to interpret, and there is only a tenuous link between empirical estimates of substitution elasticities and the assumptions used within CGE models [55]. As a result, there is considerable uncertainty about the appropriate values for these parameters and hence of the magnitude of the associated rebound effects.

Third, the long-run rebound effect may either be larger or smaller than the short-run effect. Although long-term adjustments generally increase rebound effects, there are also countervailing forces. For example, lower energy demand leads to lower energy prices, and if energy demand is inelastic, this will reduce profitability and the return on capital in energy supply sectors. Lower profitability, in turn, may cause energy sector firms to reduce capital investment ('disinvestment'), leading to a long-term reduction in the capital stock, which will drive up energy prices and dampen the economy-wide rebound effect [93]. Shale oil provides an example of such investment and disinvestment cycles within the energy sector, triggered in part by fluctuations in global oil prices.

Fourth, the global rebound effect may be smaller or larger than the regional rebound effect (i.e. global energy savings may be larger or smaller than regional energy savings), depending upon the model construction and assumptions. For example, Koesler, *et al.* [72] found that energy efficiency improvements in German industry improve the competitiveness of German producers, encourage increased exports and thereby *reduce* production and energy use in other regions. At the same time, energy efficiency improvements increase German GDP and wages, increase domestic demand and imports, and thereby *increase* production and energy use in other regions. The net result is that (in this case) the global rebound effect is smaller than the rebound effect within Germany alone.

Fifth, the rebound effects following energy efficiency improvements by households may be comparable in size to those following energy efficiency improvements by producers. While the latter increase productivity, stimulate economic growth, and improve national competitiveness; the former increase demand, put upward pressure on input and product prices, and potentially reduce national competitiveness. But despite these contrasting impacts, the modelling estimates suggest rebound effects of comparable size. For producers, the studies suggest that rebound effects tend to be larger following efficiency improvements in energy-intensive sectors (including the energy sectors themselves) and in sectors with a high output elasticity with respect to energy and/or greater scope for substitution between energy and other inputs.

Finally, and most importantly, the CGE studies consistently estimate **large** economy-wide rebound effects. Specifically, 13 of the 21 studies provide baseline estimates of **~50% or more**, and several estimate almost 100% rebound. As a crude indicator, the mean (median), baseline estimate of economy-wide rebound effects from the 21 studies is **58%** (55%) – with a mean of **65%** (60%) from the 14 producer studies and **55%** (50%) from the 7 consumer studies. The associated sensitivity tests suggest a remarkably wide range of possible outcomes, with the lowest estimate of ~12% and the highest estimates exceeding 200%. This wide range of estimates, together with the limitations of the modelling approach (see Appendix C), limit the confidence we can have in these results. Nevertheless, the evidence from CGE studies broadly suggests that **economy-wide rebound effects may erode more than half of the energy savings from improved energy efficiency**.

## 5. Estimates of economy-wide rebound effects from other methods

Researchers have explored a variety of other (non-CGE) methods for estimating economy-wide rebound effects which vary in their specification of energy efficiency improvements (Section 3) and their inclusion of different rebound mechanisms (Appendix B). Table 3 classifies 12 selected studies within this category into three broad groups – *macroeconomic models, econometric analysis*, and *growth accounting* – and summarises the key features of each study, together with their estimates of economy-wide rebound effects. We briefly review these studies below.

### 5.1. Macroeconomic models

The macroeconomic models in Table 3 differ in important ways from the CGE models discussed in Section 4 but incorporate parameters estimated from empirical data. Rebound effects are typically estimated by comparing model runs with and without energy efficiency improvements.

Saunders [26] employs a Solow-Swan growth model with a CES production function that includes a *(KL)E* nesting structure and energy-augmenting technical change. Parameter values are taken from Stern and Kander [103], who investigate the contribution of energy to Swedish economic growth since 1850. By running scenarios with different assumptions for technical change, Saunders estimates an economy-wide rebound effect of **50–60%** holding energy prices fixed. These results are sensitive to the elasticity of substitution between energy and other inputs (easier substitution leads to larger rebound), but the magnitude of this elasticity is uncertain [55,92].

Barker *et al.* [94] employ a disaggregated, macro-econometric model of the global economy (41 production sectors, 20 regions, 12 energy carriers). They estimate the investment cost and energy savings from the energy efficiency policies included in the 2006 IEA World Energy Outlook (making explicit allowance for direct rebound effects) and incorporate these exogenously into the model. They then estimate the indirect and macroeconomic rebound effects by comparing scenarios with and without these policies, leading to an estimated economy-wide rebound effect of ~**50%** by 2030, most of which derives from increased output.

Lemoine [95] develops a general equilibrium model and derives analytical expressions for partial and general equilibrium rebound effects following energy efficiency improvements by producers. The expressions isolate the contribution of individual mechanisms to rebound effects, such as changes in labour supply and the expansion and contraction of the energy sector. The model is not calibrated to a particular economy, but Lemoine estimates a rebound effect of **38%** by setting input cost shares and substitution elasticities in line with US data, with a **28%** rebound for improvements in non-energy sectors, and **80%** for improvements in the energy sector. The results are sensitive to the assumed elasticity of substitution between different consumption goods, as well as between different production inputs.

Rausch and Schwerin [96] develop a two-sector (production and consumption good-producing) general equilibrium model, where both business equipment and consumption goods are produced by a combination of non-energy capital, labour and energy services – and where the latter is produced by a combination of energy-using capital and energy. They model investment in different vintages of energy-using capital, where the efficiency of each vintage depends upon energy-augmenting technical change and energy prices. Both lower-priced capital and higher-priced energy lead to more energy efficient capital, but these mechanisms have different macroeconomic effects. Rausch and Schwerin calibrate the model to US data over the period 1960–2011 and estimate rebound effects by comparing the historical trend with a scenario in which energy service prices are fixed. They estimate a rebound of **102%,** suggesting all expected energy savings were taken back by different rebound mechanisms.

**Table 3**
Estimates of economy-wide rebound effects from a selection of non-CGE studies.

| Category | Source | Region, Period | Model structure | Specification of energy efficiency | Method of estimating economy-wide rebound effect | Baseline estimate of economy-wide rebound effect |
|---|---|---|---|---|---|---|
| Macroeconomic models | Saunders [26] | Sweden, 1850–2000 | Solow growth model with a (*KL*, *E*), CES aggregate production function incorporating energy-augmenting technical change | Energy-augmenting technical change ($\tau$) | Ratio of modelled actual energy savings to modelled potential energy savings | 50–60% |
| | Barker *et al.* [94] | Global 2010–2030 | 41-sector, 20-region macro-econometric model of the global economy (E3MG) | Energy efficiency policies included in the 2006 IEA World Energy Outlook | Direct rebound effect assumed. Indirect and macroeconomic effects estimated from ratio of modelled actual energy savings to modelled potential energy savings | 52% |
| | Lemoine [95] | Non-specific, but cost share and elasticity data from US | General equilibrium model with *N* production sectors and an energy sector | Energy-augmenting technical change ($\tau$) | Analytical expressions decomposing the rebound into a number of partial and general equilibrium effects | 38%<br>80% energy sector<br>28% other sectors |
| | Rausch and Schwerin [96] | US 1960–2011 | Two sector (production and consumption) general equilibrium model with different vintages of energy-using capital | Energy-augmenting technical change ($\tau$) | Ratio of modelled actual energy savings to modelled potential energy savings | 102% |
| Econometric analysis | Adetutu *et al.* [97] | 55 countries 1980–2010 | Stochastic frontier analysis to estimate energy efficiency. Autoregressive, dynamic panel model to estimate efficiency elasticity of energy demand | Distance to frontier in a panel of 55 countries | Efficiency elasticity of energy demand | 90% (short term)<br>−36% (long term) |
| | Brockway *et al.* [98] | China, US, UK 1980–2010 | (*KL,U*) CES aggregate production function ($U$ = useful exergy), with neutral technical change | Aggregate primary to useful exergy efficiency of national economy ($U/X$) | Elasticity of primary exergy with respect to primary to useful exergy efficiency | US 13% (12–16%)<br>UK 13% (13-∞%)<br>China 208% (55-∞%) |
| | Wei [99] | 40 regions 1995–2009 | Cobb Douglas aggregate production function with input-augmenting technical change | Aggregate primary energy efficiency of national economy ($Y/E$) | Decomposed change in output caused by change in energy intensity | Mean 150%<br>Median 120%<br>(−2716% to +636%) |
| | Bruns *et al.* [62] | US 1973–2016 | Structural vector auto-regression for aggregate GDP, energy use and energy prices - used to identify energy efficiency shocks | Energy-augmenting technical change | Estimated impulse response function for energy use following energy efficiency shock | ~100% |
| Growth accounting | Lin & Liu [100] | China, 1981–2009 | Historical data for energy intensity and output changes. Malmquist index to estimate total factor productivity | Aggregate energy efficiency index derived from log mean divisia analysis of sectoral final energy efficiencies | Ratio of the change in energy consumption from the output growth attributed to technical change, to the change in energy consumption attributed to changes in aggregate energy efficiency | 53% |
| | Shao *et al.* [101] | China 1954–2010 | Historical data for energy intensity and output changes. Latent variable analysis to estimate total factor productivity | Aggregate primary energy efficiency ($Y/E$) | Ratio of the change in energy consumption from the output growth attributed to technical change, to the change in energy consumption attributed to changes in aggregate energy efficiency | 40%<br>(47% before 2000<br>37% after 2000) |
| | Lin and Du [102] | China 1981–2011 | Historical data for energy intensity and output changes. Translog aggregate production function to estimate total factor productivity | Aggregate energy efficiency index, derived from log mean divisia analysis of sectoral final energy efficiencies | Ratio of the change in energy consumption from the output growth attributed to technical change, to the change in energy consumption attributed to changes in aggregate energy efficiency | 30–40% |
| | Brockway *et al.* [98] | China, US, UK 1980–2010 | Historical data for energy intensity and output changes. (*KL,U*) CES aggregate production function ($U$ = useful exergy) to estimate total factor productivity | Aggregate primary energy efficiency ($Y/E$) | Ratio of the change in energy consumption from the output growth attributed to technical change, to the change in energy consumption attributed to changes in aggregate energy efficiency | US 40% (15–47%)<br>UK 54% (50–57%)<br>China 77% (64–83%) |

### 5.2. Econometric analysis

These studies estimate rebound effects directly from the econometric analysis of secondary data.

Adetutu *et al.* [97] combine a stochastic frontier analysis with a two-stage dynamic panel data approach for 55 countries over the period 1980–2010. Taking the whole sample together, Adetutu *et al.* [97] estimate a **90%** rebound in the short run, but a *negative* rebound (−36%) in the long run.

Brockway *et al.* [98] estimate aggregate, three-input CES production functions for the US, UK and China over the period 1980–2010, including neutral technical change. They follow Saunders [26] in using a *(KL)E* nesting structure, but replace primary energy ($E$) with 'useful exergy' ($U$) which is the product of primary exergy inputs ($X$) and the estimated primary-to-useful exergy efficiency ($\varepsilon$) of the economy (i.e. $U = \varepsilon X$). Their measure of useful exergy therefore partly incorporates the effect of energy-augmenting technical change [104,105]. Using an iterative, non-linear estimation procedure combined with a 'bootstrapping' technique, they find large error bounds on their estimated parameters. Following Saunders [106], they estimate the economy-wide rebound effect from the elasticity of primary exergy consumption with respect to primary-to-useful exergy efficiency [105]. Their estimated rebound effect is **13%** for the US and UK and **>100%** for China – suggesting that rebound effects may be higher in energy-intensive, export-oriented economies.

Wei and Liu [107] estimate Cobb-Douglas aggregate production functions with input-augmenting technical change for 40 countries between 1995 and 2009. By deriving and parameterising an expression for the change in output following a change in aggregate energy intensity, Wei *et al.* [99] estimate a mean rebound effect of **150%** for the sample as a whole**,** with estimates for individual countries ranging (rather implausibly) from −2716% (Brazil) to +636% (Indonesia).

Lastly, Bruns *et al.* [62] estimate US energy consumption, GDP, and energy prices as a function of the lags of these variables and a vector of contemporaneous exogenous shocks. They identify the latter through Independent Component Analysis, which applies machine learning techniques to identify independent linear combinations of the residuals. They interpret the energy efficiency shocks as energy-augmenting technical change, since they are independent of changes in GDP and energy prices. They estimate rebound effects by constructing the impulse response function of energy with respect to the identified energy efficiency shocks. Using monthly and quarterly data from the US over the period 1973–2016, Bruns *et al.* [62] estimate a rebound effect of **100%** after four years.

### 5.3. Growth accounting

These studies employ growth accounting techniques, which specify the rate of growth of output as the weighted sum of the rate of growth of each input, plus the rate of total factor productivity growth ($A_t$) – which is commonly estimated as a residual [108]. Letting $Y_t$ represent aggregate economic output in period $t$, $E_t$ primary energy consumption and $I_t$ aggregate energy intensity ($E_t/Y_t$), the studies estimate economy-wide rebound effects from variants of Eqn. (1) [98]:

$$R_t = \frac{A_{t+1}(Y_{t+1} - Y_t)I_{t+1}}{Y_{t+1}(I_t - I_{t+1})} \quad (1)$$

Here the denominator is interpreted as the potential energy savings and the numerator is interpreted as the change in energy consumption resulting from the output increase attributed to technical change.

Studies using this approach vary in how they define and estimate aggregate energy intensity ($I_t$). Both Shao *et al.* [101] and Brockway [98] use aggregate primary energy intensity ($Y/E_P$), while both Lin and Liu [100] and Lin and Du [102] use an energy efficiency index – which separates the effect of final energy intensity reductions within individual sectors from structural change between those sectors [109]. Studies also vary in how they define and estimate total factor productivity ($A_t$). For example, Brockway *et al.* [98] estimate an aggregate CES production function, Lin and Liu [100] estimate a Malmquist index [110], Lin and Du [102] estimate an aggregate translog production function and Shao *et al.* [101] use latent variable analysis. These four studies estimate economy-wide rebound effects in the range **30–77%.**

### 5.4. Summary

Each of the studies in Table 3 provides useful insights, but each also has important limitations. For example, Saunders [26], Wei *et al.* [99], Brockway *et al.* [98] Lin and Du [102] employ aggregate production functions which some economists consider invalid [111,112]. Lemoine [95] and Rausch and Schwerin [96] develop simplified general equilibrium models that have similar drawbacks to CGE models, but with an even weaker foundation in empirically measured parameters. The study by Adetutu *et al.* [97] is difficult to interpret and finds a negative long-run rebound effect which contradicts the findings of all other studies in this area. The growth accounting studies almost certainly underestimate rebound effects, owing to their choice of aggregate energy efficiency as the independent variable (which neglects rebound effects from efficiency improvements at lower levels of aggregation) and their assumption that increases in output are the primary driver of rebound (which neglects other rebound mechanisms). Overall, particular weight can be placed upon the study by Barker *et al.* [94], since their macro-econometric model overcomes many of the limitations of CGE models and their measure of energy efficiency improvements is most relevant to public policy by virtue of implementing the anticipated energy reductions of energy efficiency policies. The study by Bruns *et al.* [62] is also significant, since it opens up a promising new approach to estimating rebound effects that relies upon few *a-priori* assumptions. Barker *et al.* [94] estimate an economy-wide rebound of **50%**, while Bruns *et al.* [62] estimate a rebound of ~**100%**.

However, the most notable finding from this review of other methods is that the studies consistently estimate **large** economy-wide rebound effects. Specifically, 10 of the 12 studies in Table 3 provide baseline estimates of ~50% or more, and three estimate >100% rebound. As a crude indicator, the mean estimate of economy-wide rebound effects from the 12 studies is **71%** – with a mean of 62% from the macroeconomic models, 104% from the econometric studies, and 46% from the growth accounting studies. This consistency is all the more surprising given the widely different measures of energy efficiency (e.g., aggregate energy intensity, primary to useful exergy efficiency, energy-augmented technical change), the range of methodologies employed (e.g., growth accounting, stochastic frontier analysis), the variations in model structure (e.g., aggregate production functions, general equilibrium models, macro-econometric models), and the differences in the number and type of rebound mechanisms included (e.g., growth effect only versus most of the mechanisms in Appendix B). These differences demonstrate that there is much to learn about the determinants and magnitude of economy-wide rebound effects and much work to do in reconciling the definitions, approaches and conclusions of different studies. Nevertheless, the results broadly reinforce the conclusion from the review of CGE studies, namely that **economy-wide rebound effects may erode more than half of the energy savings from improved energy efficiency**.

Having reviewed the evidence on the size of economy-wide rebound effects, we now examine the treatment of these effects in energy-economy models.

## 6. Rebound effects in energy-economy models

The scenarios summarised in Section 2 derive from a variety of models with widely differing structures, methodologies, levels of complexity, and assumptions for key variables. Here we investigate the extent to which these models capture the various mechanisms contributing to rebound effects and hence whether they may potentially underestimate the size of those effects. We first review the *integrated assessment models* (IAMs) used by the IPCC and then the *global energy models* used by other organisations. We base the review upon model documentation and email responses from modelling teams. However, some of our judgments are uncertain since there is only limited information in the public domain for many of the IAMs, and even less for most of the global energy models.

### 6.1. Integrated assessment models (IAMs)

IAMs capture the interactions and feedbacks between the economy, energy system, and climate system. They typically combine simplified economic and climate models with more detailed modelling of regional and global energy systems, but they vary widely in the level of detail within each component. Most IAMs model energy supply in great detail, but treat the determinants of energy demand in a simpler manner [113]. Similarly, for some IAMs key economic variables are exogenous. Both of these features limit their ability to endogenously model rebound effects.

Table 4 summarises some key features of the four IAMs used for the scenarios reviewed in Section 2, including their representation of the macro-economy, their specification of energy efficiency, and our assessment of their ability to capture rebound effects. Each of these IAMs is a 'marker model' for one of the Shared Socio-economic Pathways (SSPs) used in the IPCC's sixth assessment report – which means that each model provides a preferred implementation of the relevant SSP [34,114].

We make four observations from this review. First, the IAM documentation contains practically no reference to rebound effects and no study to date has used these IAMs to explore or quantify rebound effects – suggesting that the IAM community has largely overlooked this topic. Although IAM modelling teams regularly carry out model comparisons to establish patterns of model behaviour and to explain differences in results [119], the relevance of rebound effects to these results remains unexplored. One exception is the "Low Energy Demand" Scenario [32] – see also Table 1 - that discusses a 50% rebound effect. However, this is an exogenous adjustment of energy demand, rather than one generated within the model.

Second, IMAGE and GCAM are *partial equilibrium* models and therefore use exogenous assumptions for economic growth and the development of the macro-economy. By construction, such models can only include a limited number of rebound mechanisms: specifically in GCAM a direct rebound effect from a negative price elasticity for energy service demand, potentially combined with an energy market rebound effect from a negative price elasticity for aggregate energy demand. Whilst more rebound channels were identified in IMAGE, the extent to which both IMAGE and GCAM actually capture their mechanisms, together with the relative magnitude of each effect, is difficult to discern from the model documentation.

Third, MESSAGE-GLOBIOM and REMIND are *general equilibrium* in the sense that they include endogenous modelling of the macro-economy, although with a single-sector growth model, not a multi-sectoral one, like CGE models.[8] Both models employ aggregate CES production functions incorporating energy-augmenting technical change, and both are able to capture substitution between energy and other inputs and energy price and growth effects – three of the mechanisms contributing to rebound effects (Appendix B). However, since they assume a single representative producer, they cannot capture composition effects or variations in rebound effects between sectors. Similarly, since they assume a single representative final good, they cannot capture substitution effects for consumers. Both IAMs model multiple types of final energy demand (an input into the aggregate production function), so have the potential to model income (consumer) and output (producer) effects for other energy input services, together with energy market effects.

Fourth, the general equilibrium IAMs treat energy-augmenting technical change in a different manner to the CGE studies reviewed in Section 4. The latter simulate improved energy efficiency as a costless, one-off increase in the productivity of energy inputs ($\tau$) and investigate the impacts on aggregate energy intensity ($\theta_E$) and other macroeconomic variables. They then estimate rebound effects by comparing the results with those from a scenario with no technical change. In contrast, the IAMs begin with exogenous baseline scenarios for energy demand or energy intensity ($\theta_E$) and use these to *calibrate* the energy-augmenting technical change parameters. The latter remain fixed in the policy scenarios, which instead model price-induced substitution of capital for energy in response to changes in energy and carbon prices – supplemented in some cases with bottom-up modelling of fuel switching and technology improvements in individual sectors [120], and in others with top-down modeling of price-, learning-, or R&D-induced technological changes [121]. Hence, from the perspective of capturing rebound effects, the IAMs work backwards - they calibrate energy-augmenting technical change *to* an assumed outcome, rather than modelling the outcomes *from* energy-augmenting technical change.[9]

In sum, partial equilibrium IAMs exclude the majority of mechanisms contributing to rebound effects, while general equilibrium IAMs incorporate more of these mechanisms but in a highly simplified manner. Moreover, the process of calibrating baseline scenarios to exogenous assumptions for energy demand and energy intensity *precludes* the investigation of rebound effects from energy-augmenting technical change within a model run. Instead, the energy efficiency improvements within IAM policy scenarios reflect a mix of substitution, endogenous technological change and bottom-up modelling of technology choices within individual sectors. Given that assumptions about energy intensity and economic growth appear the most important determinants of future emissions [122], this relatively crude modelling of the determinants of energy intensity appears an important limitation of current IAMs and **creates a risk that IAM scenarios will overestimate the potential for energy intensity reductions and/or underestimate the impact of rebound effects on energy demand**.

### 6.2. Global energy models

In contrast to IAMs, the global energy models from bp, Shell, the EIA, and the IEA focus solely upon projecting the evolution of the global energy system and the balance between energy supply and demand. These are all bottom-up simulation models, but they differ in structure, level of disaggregation (by regions, sectors, fuels and technologies), and key assumptions. A common feature is their reliance upon exogenous assumptions for GDP, population, and other key variables.

The most detailed and best documented model is the IEA World

[8] The AIM/CGE model, another SSP marker model, is an exception and does provide a CGE structure.

[9] Different baseline-policy scenario combinations assume different energy intensity improvements so in principle pairs of these could be compared to each other for rebounds. The authors are grateful to Joeri Rogelj for this observation.

**Table 4**
Modelling of rebound effects in four Integrated Assessment Models.

| Integrated Assessment Model | Type | Regions | Modelling of the macro-economy | Modelling of energy demand and improved energy efficiency | Modelling of rebound effects |
|---|---|---|---|---|---|
| IMAGE | Partial equilibrium Recursive dynamic | 26 | Limited economic modelling.<br>Exogenous assumptions for population, per-capita GDP and other variables | IMAGE model energy demand for a range of end-use functions in six sectors, including industry [115], transport [116], and residential [117]. The end-use functions (such as lighting, heating, cooling, hot water and appliances in the residential sector) are represented on the basis of relationships with economic activity levels that physical activity indicators (such as tonnes of steel, passenger kilometers per transport mode), structural change and both autonomous energy efficiency improvements (AEEI) and price induced energy efficiency improvements (PIEEI). Subsequently, different energy carriers and associated technologies compete for market share on the basis of costs and preferences. The latter also include options for electrification.<br>AEEI for new capital increases as a fraction (0.3–0.45) of the economic growth rate. PIEEI estimated from cost curves for energy conservation (specified for each sector and energy carrier) using current energy prices.<br>Some sectors modelled in greater detail, including competing technologies with different energy efficiencies. | **Direct:** several. Decreasing costs of energy supply in response to efficiency measures can lead to increases in activity levels (such as transport activity) or reduction of investments in efficiency.<br>**Indirect:** Several. Decreasing costs of energy supply in response to efficiency measures in one sector, can significantly impact measures in other sectors. Similar holds for measures to reduce costs of energy supply.<br>**Macroeconomic:** Energy market effect (lower price of energy induces greater demand). |
| MESSAGE-GLOBIOM | General equilibrium Intertemporal optimisation | 11 | MACRO model maximises intertemporal utility function of a single representative consumer in each region.<br>Production allocated to current consumption, non-energy capital investment and energy system costs – with the latter estimated by an energy model (MESSAGE).<br>Employs nested *(KL)E* CES aggregate production function. | Modelling begins with assumptions about energy intensity and GDP. Macro model (MACRO) then runs iteratively with the energy supply model (MESSAGE), adjusting GDP, energy demand and energy prices until a consistent solution is found [118].<br>Improved energy efficiency is modelled in three ways:<br>• Substitution of capital for energy in the aggregate production function, assuming an elasticity of substitution of between 0.2 and 0.3.<br>• Energy augmenting technical change. The calibration process adjusts these parameters to ensure consistency with exogenous assumptions for regional energy intensity.<br>• Fuel switching in response to relative prices, which can also lead to efficiency improvements - for example through electrification. | **Direct**: positive elasticity of substitution in CES production function.<br>**Indirect**: none, since single sector model, though income effects possible between different energy types<br>**Macroeconomic**: Energy market and growth effects |
| GCAM | Partial equilibrium Recursive dynamic | 32 | Limited economic modelling.<br>Exogenous assumptions for population, per-capita GDP and other variables | Detailed bottom up modelling of energy demand in key sectors (e.g. transport), including assumptions about technical efficiency and price elasticity | **Direct:** negative price elasticities of energy service demand.<br>**Indirect:** none<br>**Macroeconomic:** energy market effect. |
| REMIND-MAgPIE | General equilibrium Intertemporal optimisation | 11 | Maximises intertemporal utility function of a single representative consumer in each region, accounting for inter-regional trade in goods, energy and carbon allowances.<br>Production allocated to consumption, exports, investment, R&D, and energy costs (investment, fuel & O&M) – with the latter estimated by an energy system module.<br>Output simulated by non-nested (*KLE*) CES production function, with final energy (*E*) produced by nested CES production function - both incorporating input-augmenting technical change. | Energy-augmenting parameter ($\tau$) assumed to change at the same rate as labour augmenting parameter ($\rho$), modified by an adjustment factor that is specific to each region and energy carrier. Calibration process adjusts the former to ensure consistency with exogenous scenarios for energy demand. Latter, in turn, are based upon historical relationships between per-capita GDP and energy demand, combined with assumptions about long-term convergence [119].<br>Improved energy efficiency is modelled in three ways: | **Direct:** positive elasticity of substitution in CES production function.<br>**Indirect** none since single sector model, though income effects possible among different energy types<br>**Macroeconomic**: energy market and growth effects. |

(*continued on next page*)

**Table 4** (*continued*)

| Integrated Assessment Model | Type | Regions | Modelling of the macro-economy | Modelling of energy demand and improved energy efficiency | Modelling of rebound effects |
|---|---|---|---|---|---|
| | | | GDP is endogenous, but calibrated to an exogenous baseline scenario by adjusting parameters for labour-augmenting technical change. | • Substitution of capital for energy in the aggregate production function, assuming an elasticity of substitution of between 0.25 and 0.5.<br>• Energy augmenting technical change. The calibration process adjusts these parameters to ensure consistency with exogenous assumptions for regional energy intensity.<br>• Fuel switching in response to relative prices. This can also lead to efficiency improvements - for example through electrification. | |

*Source*: Model documentation [19,42–44] and contacts with the modelling teams.

**Table 5**
Inclusion of rebound effects in a selection of global energy models.

| Global energy model | Modelling of the macro-economy | Modelling of rebound effects |
|---|---|---|
| Global modelling for BP Energy Outlook | Exogenous, via regional projections of population, per-capita GDP, energy intensity and other variables | **Direct:** included via assumptions for the own-price elasticity of some energy services.<br>**Indirect** none<br>**Macroeconomic**: energy market effect. |
| Shell World Energy Model | Exogenous, via regional projections of population and per-capita GDP | **Direct**: included via assumptions for the own-price elasticity of energy services, together with an 'energy ladder' effect for energy services in developing countries.<br>**Indirect**: none.<br>**Macroeconomic:** energy market effect |
| IEA World Energy Model | Exogenous, via regional projections of population, per-capita GDP, energy service demand and other variables. GDP assumptions based on OECD, IMF and World Bank projections, combined with assumptions about long-term convergence of growth rates between regions. | **Direct**: included via assumptions for the own-price elasticity of some energy services<br>**Indirect**: none.<br>**Macroeconomic:** energy market effect |
| EIA World Energy Projection System Plus (WEPS+) | Exogenous, via regional projections of population, per-capita GDP, energy service demand and other variables. GDP assumptions from the Oxford Economics Global Economic Model (GEM) and Global Industry Model (GIM) | **Direct**: included via assumptions for the own-price elasticity of some energy services<br>**Indirect**: none.<br>**Macroeconomic:** energy market effect |

*Source*: Model documentation [45,46,49,47] and contacts with the modelling teams.

Energy Model (WEM), which is used to produce the annual IEA World Energy Outlook reports (WEOs).[10] The WEM distinguishes between six industrial sectors, six types of energy service in buildings (e.g., water heating, cooking, space cooling), five transport sub-models (e.g. road, air, rail), and multiple energy carriers (e.g., gasoline, diesel, liquefied natural gas) [45]. A simulation begins with exogenous assumptions for the growth in energy service demand, derived by combining econometric analysis of historical trends with assumptions for key scenario drivers. The model then calculates the mix of technologies used to meet these demands, based upon the age and structure of the existing capital stock, energy and carbon prices, and the assumed cost and performance of new technologies [45]. Iterations between the energy supply and energy demand modules leads to energy prices that match available supply with projected demand for each energy carrier. This approach allows for the detailed exploration of individual technology choices, but provides only limited feedback between the price of energy services and the macro-economy – which restricts the ability of the model to capture macroeconomic rebounds.

The WEM does capture energy market effects, however, since lower energy demand leads to lower energy prices, which in turn encourages increased energy demand. To counteract this rebound, the IEA increase transport fuel duty in their 2019 Sustainable Development Scenario "to keep end-user prices at the same level as in the Stated Policies Scenario" [p.18, 45]. However, they make no mention of comparable adjustments to the price of other fuels.

The approach of the other global energy models with regard to rebound is broadly comparable to that of the WEM, but less detail is provided in Table 5, as there is less information on the bp, Shell and EIA models in the public domain.[11] Direct rebound effects are modelled for some (but not all) energy services through the use of price elasticities for those services, but the relevant assumptions are not transparent. The energy market effect is captured via price elasticities, but indirect rebounds and other types of macroeconomic rebound are excluded since they cannot be simulated within a bottom-up structure. The documentation for each model makes little or no reference to rebound effects and contacts with the modelling teams suggest only limited consideration of the topic. The 2012 edition of the IEA WEO [123] stated that an economy-wide rebound effect of 10% was assumed, but subsequent editions of the Outlook make no reference to this assumption. A 10% rebound is relatively small, even considering direct effects alone, and is

[10] The World Energy Outlook is published each year by the IEA, and examines how the global energy system could develop in the future, usually to 2030/2040/2050. For the WEO-2020 see https://www.iea.org/reports/world-energy-outlook-2020.

[11] Available documentation [45-47,49,] was supplemented by contact with modelling teams.

inconsistent with the evidence reviewed in Section 4 and 5. For comparison, Barker *et al.* [94] estimate a 50% rebound for the energy efficiency measures included in the 2006 WEO.

In sum, the structure of the global energy models largely preclude the simulation of rebound effects, **creating the risk that global energy scenarios will overestimate the potential for energy intensity reductions and/or underestimate the impact of rebound effects on energy demand**.

## 7. Discussion

We now summarise the lessons learned from the preceding sections. First, the majority of global energy scenarios include a structural break in energy demand trends, beginning around 2020 and moving towards absolute decoupling of energy consumption from GDP as climate targets tighten. Scenario projections of annual changes in aggregate final energy intensity in the period 2020–2030 (−2.5%/year) is twice the mean annual change since 1971 (−1.2%/year), and has been observed in only 4 of 47 years in the 1971–2018 period. As Stern observes "*this does not mean that such a rate of decline is impossible*" [p.538, 124], but it does raise legitimate queries over the mechanisms and policies that will enable this to be achieved.

Second, the evidence on the size of economy-wide rebound effects has grown rapidly over the last few years and has led to broadly consistent conclusions. For example, 13 of the 21 CGE modelling studies reviewed above estimated an economy-wide rebound effect of 50% or more, as did 10 of the 12 studies that used other methodologies. Hence, it seems reasonable to conclude that **economy-wide rebound effects erode more than half of the energy savings from improved energy efficiency**. This is a larger figure than is commonly found in studies of direct rebound effects for consumers [27,125], and the focus on the latter within the rebound literature may have diverted attention away from the possibility of larger rebound effects at the economy-wide level. In addition, there is growing evidence that rebound effects are larger for energy efficiency improvements by producers, particularly in energy-intensive sectors. Stern [126] also finds growing support for large, economy-wide rebound.

Third, it is challenging to compare the results of the empirical studies and to draw overall conclusions, owing to the different definitions of the relevant independent variable (improved energy efficiency), together with the varying coverage of rebound mechanisms, the differing methodologies employed, and the sensitivity of results to key assumptions. Such variability in parameters is particularly evident in CGE models, whose results are highly sensitive to assumed values for substitution elasticities that lack a firm empirical grounding [55]. However, these uncertainties have not prevented the widespread use of CGE models in other areas of research, and these methodological differences and limitations have not prevented a growing consensus that economy-wide rebound effects are larger than typically assumed.

Fourth, integrated assessment and global energy models only capture a subset of the mechanisms contributing to economy-wide rebound effects, partly because these models either include a relatively crude representation of the macro-economy (e.g., a single representative producer and consumer), or rely upon exogenous assumptions for key macroeconomic variables, which in turn means there is only limited feedback between energy efficiency improvements and broader changes in economic structure and energy demand. In addition, rebound effects have not been a priority for the modelling teams. The IAM community has focused upon other areas of model development, while the global energy model community has focused upon updating parameter assumptions and re-estimating scenarios for the next publication. A systematic review of the IAM and global energy model structures and their inclusion (or not) of different rebound mechanisms would be of benefit to all modelling teams. Colmenares *et al.* [127] provide some suggestions in this regard.

Finally, the representation of energy efficiency improvements within empirical studies frequently differs from the simulation of such improvements within the integrated assessment and global energy models. More than 70% of the reviewed studies simulate energy efficiency improvements as a costless, one-off increase in the productivity of energy inputs (energy-augmenting technical change). In contrast, the integrated assessment and global energy models tend to start from historical correlations between aggregate output and energy demand, and then increase the rate at which energy intensity falls by possibly price-induced energy-augmenting technical change, without accounting for the majority of channels via which rebound operates. As a result, the energy efficiency improvements simulated in these scenarios may potentially lead to smaller rebound effects than the energy-augmenting technical change investigated by the empirical studies. Although depicted in current IAMs as a 'deviation' from an optimal baseline trajectory and hence growth-retarding by construction, price or policy-induced energy-augmenting technical change could also accelerate the growth of the economy whilst reducing energy demand, but only if the associated rebound effects are relatively modest. Our concern is that the opposite may be the case, and that large, economy-wide rebound effects could undermine the effectiveness of global climate policy focussed on energy efficiency.

## 8. Conclusions

Many climate and energy scenarios project a significant departure from the historical close relationship between global energy consumption and GDP and a move towards absolute decoupling. These scenarios assume rapid improvements in energy efficiency through all sectors of the global economy and a shift towards less energy-intensive consumption patterns. However, the evidence reviewed in this paper suggests that economy-wide rebound effects could erode more than half of the anticipated energy savings. Since the mechanisms contributing to these effects are only poorly captured by the relevant models, global energy scenarios may overestimate the potential for decoupling energy consumption from GDP. Large rebound effects may therefore provide one explanation for the historical close relationship between energy consumption and GDP and at the same time may make it more difficult to decouple energy consumption from GDP the future.

The review has highlighted multiple limitations in the available evidence, which limits the degree of confidence that we can have in the results. However, the review also demonstrates that the evidence base is growing in quality, quantity, and diversity, and that widely different studies provide broadly similar conclusions. Importantly, the implications of this evidence appears to have been largely neglected by the integrated assessment and global energy modelling communities, and the current generation of energy-economy models lacks the capacity to capture these rebound effects effectively. The inclusion of broader, economy-wide rebound effects within energy and IAM models are vital if we are to have confidence in global energy scenarios, and if policymakers are to effectively anticipate and address the possibility of large rebounds.

We suggest that a research priorities should be to (a) include more comprehensive and disaggregated modelling of the macro-economy within energy-economy models and (b) to find ways to endogenously incorporate a broader range of rebound mechanisms. Efforts are also required to (a) reconcile the divergent representations of energy efficiency within both empirical studies in energy-economy models and (b) to further explore the implications of different types, sources, and locations of energy efficiency improvement. Moving towards more robustly reported analytical frameworks within rebound studies would allow better comparisons, and eventually meta reviews, such as is common in the energy-GDP causality literature [128]. Meantime, if large, economy-wide rebound is a possibility, it would be prudent to explore scenarios with more limited decoupling of energy consumption from GDP and to assess their implications – presumably implying greater urgency in decarbonising energy supply. Modelling efforts should also extend to estimating and including rebound effects, in conjunction with sensitivity testing, and to assessing strategies to offset those effects while minimising the impact on welfare.

In sum, radical departures from the historical energy-GDP trends raise important questions about their feasibility. Much greater attention should therefore be placed on understanding the determinants of energy demand and on assessing the risk of unanticipated outcomes.

## Data statement

The University of Leeds data repository for this study can be found at https://doi.org/10.5518/956. Data included within this depository includes: summary statistics, model projection data for energy and GDP. The IEA World Energy Statistics and Balances can be downloaded with institutional or other user licence from https://doi.org/10.1787/enestats-data-en.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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## Supplementary information

Supplementary information to this article can be found online at https://doi.org/10.1016/j.rser.2021.110781.

## Appendix A. Primary Energy plots

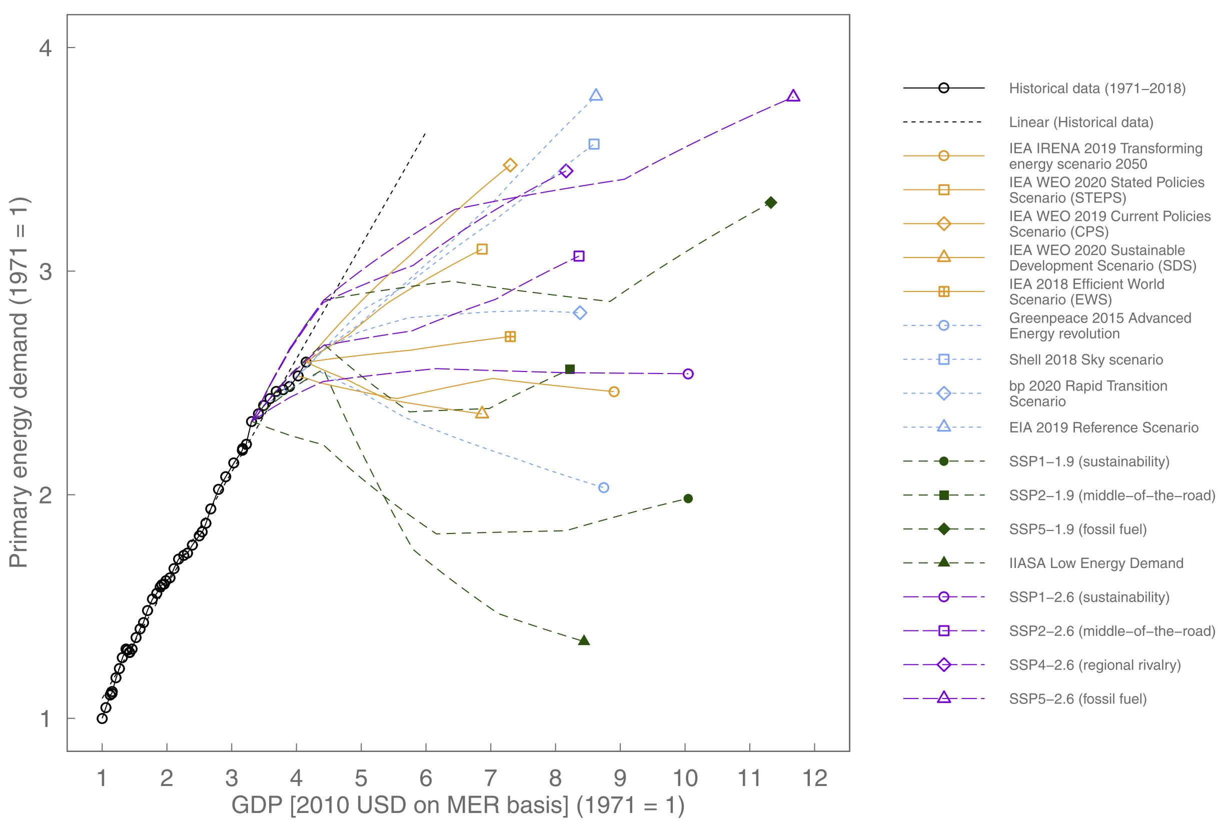


**Fig. A1.** Historical trends and future scenarios for global primary energy use and GDP (1971–2050). Notes: Scenario plots are in four groups: orange (IEA models); green (1.5 °C IAMs); purple (2.0 °C IAMs) and blue (other models). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

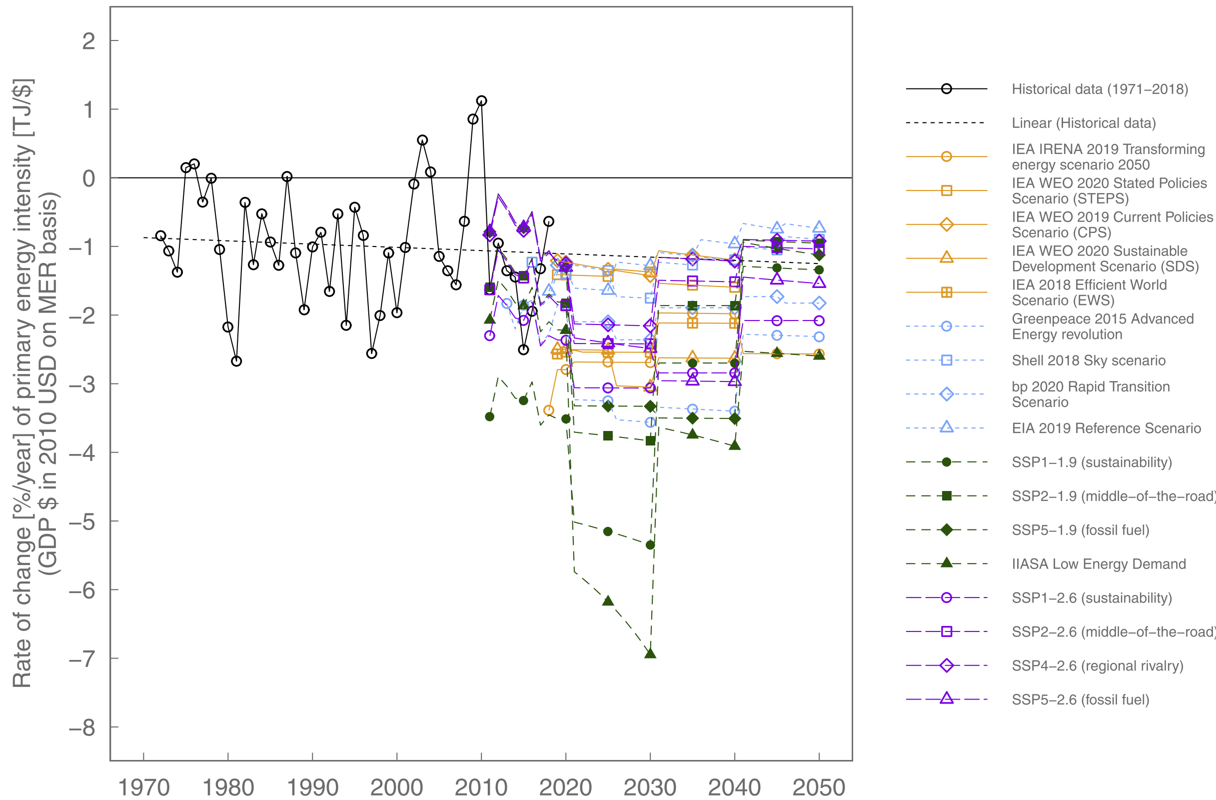


**Fig. A2.** Historical trends and future scenarios for annual change in primary energy intensity (1971–2050) Notes: Annual percentage change in global final energy intensity (plotted annually for the historical trend, and as a decadal average for each scenario). Black dotted line is linear regression/projection of historical trends. The scenario plots are in four groups: orange (IEA models); green (1.5 °C IAMs); purple (2.0 °C IAMs) and blue (other models). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

## Appendix B. Mechanisms contributing to economy-wide rebound effects

| Category | Mechanism | Source |
|---|---|---|
| Direct rebound effect (partial equilibrium) | Income effect (consumers) | Changes in the consumption of the energy service, owing to the increase in real income stimulated by the energy efficiency improvement |
| | Substitution effect (consumers) | Changes in the consumption of the energy service, owing to a fall in its effective price relative to other commodities (holding utility constant) |
| | Output effect (producers) | Changes in the consumption of the energy service owing to the increase in output stimulated by the energy efficiency improvement |
| | Substitution effect (producers) | Changes in the consumption of the energy service, owing to a fall in its effective price relative to other inputs (holding output constant) |
| Indirect rebound effect (partial equilibrium) | Income effect (consumers) | Changes in the consumption of other commodities, owing to the increase in real income stimulated by the energy efficiency improvement |
| | Substitution effect (consumers) | Changes in the consumption of other commodities, owing to an increase in their effective price relative to the energy service (holding utility constant) |
| | Output effect (producers) | Changes in the consumption of other inputs owing to the increase in output stimulated by the energy efficiency improvement |
| | Substitution effect (producers) | Changes in the consumption of other inputs, owing to an increase in their effective price relative to the energy service (holding output constant) |
| Macroeconomic rebound effect (general equilibrium) | Energy market effect | Changes in energy consumption following changes in energy prices (leftward shift of the demand curve for energy) |
| | Composition effect | Changes in energy consumption following structural change in the economy - with energy-intensive sectors and goods benefiting more |
| | Growth effect | Changes in energy consumption following investment and increased output stimulated by the energy efficiency improvement |
| | Scale effect | Changes in energy consumption following reductions in the price of goods and services stimulated by increased output of those goods and services |
| | Labour supply effect | Changes in energy consumption following increases in real wages stimulated by the energy efficiency improvement |
| | Disinvestment effect | Changes in energy consumption following disinvestment in the energy supply sectors in response to lower energy prices |

*Sources*: Own elaboration based upon [21,71,93].

*Note:* This list is not exhaustive, the mechanisms are not necessarily additive; and each mechanism may either increase or reduce economy-wide energy consumption depending upon the particular situation. The relative importance of these mechanisms will also vary from one context to another and from one type of energy efficiency improvement to another.

## Appendix C. Limitations of Computable General Equilibrium (CGE) models

- *Market and behavioural assumptions*: CGE models rely upon standard but frequently unrealistic assumptions about economic behaviour, such as market equilibrium, utility maximization, perfect competition and constant returns to scale.
- *Functional Forms*: CGE models simulate producer (consumer) behaviour through 'nested' constant elasticity of substitution (CES) production (utility) functions. These are chosen for their computational convenience, but rely on the assumption that inputs (commodities) are 'separable': that is, the elasticity of substitution between inputs (commodities) within a nest is unaffected by the level or price of inputs (commodities) outside the nest [55]. This assumption typically lacks empirical support. Model results are sensitive to the assumed nesting structure, but this varies from one model to another and there is no consensus on where energy inputs should be located within this structure [129]. For example, capital (*K*), labour (*L*) and energy (*E*) inputs could be nested as: *(KL)E, (KE)L or (LE)K.*
- *Calibration*: CGE models are calibrated to a social accounting matrix for the base year, with adjustments being made to the data to ensure equilibrium. But since markets are not in equilibrium, the choice of base year can influence the results. For example, if a particular sector is depressed in the base year, the share of profits in the output of the sector would be low.
- *Parameters*: CGE parameter values are either determined through calibration, taken from the empirical literature or assumed. But the process of compiling parameter values lacks transparency, and the cited empirical studies may use different functional forms and parameter definitions to those used in CGE models, as well as applying to different sectors, time-periods and/or levels of aggregation [55]. Model results are sensitive to these parameter values, but they vary widely from one model to another. Sensitivity tests are increasingly used, but are typically confined to only a small number of relevant parameters.
- *Static versus dynamic*: Static CGE models simulate equilibrium states of the economy and compare the initial and final equilibrium after some exogenous shock, such as an improvement in energy efficiency. This approach neglects the costs and time taken for the economy to adjust. For example, transport and building infrastructures take longer to adjust than other types of capital equipment. Dynamic CGE models explicitly model the adjustment process, with the capital stock in any year being dependent upon investment in the previous year. This overcomes some of the limitations of static models, but dynamic models are more complex and computationally intensive. Also, both types of model have difficulties simulating structural change and the emergence of new technologies and sectors.
- *Model closure*: The choice of which variables to set exogenously is termed the model closure. For example, some CGE modellers hold employment and the trade balance fixed while others allow these to vary. Of particular importance is whether capital is fixed or adjustable within individual sectors and regions, and how wages and labour supply adjust to changes in economic activity. These assumptions can have a major influence on the results.

## References


[1] United Nations Framework Convention on Climate Change (UNFCCC). Adoption of the Paris Agreement FCCC/CP/2015/L.9. Available at: https://unfccc.int/resource/docs/2015/cop21/eng/l09.pdf; 2015.
[2] United Nations. Sustainable Development Goal #7: ensure access to affordable, reliable, sustainable and modern energy for all. Available from: https://sustainabledevelopment.un.org/sdg7; 2015.
[3] International Energy Agency (IEA). Energy technology perspectives 2014. Energy Technology Perspectives 2014;2014. Available from: https://www.iea.org/reports/energy-technology-perspectives-2014.
[4] International Energy Agency (IEA). World energy Outlook 2019. 2019. Available from: https://www.iea.org/reports/world-energy-outlook-2019.
[5] Gambhir A, Drouet L, McCollum D, Napp T, Bernie D, Hawkes A, et al. Assessing the feasibility of global long-term mitigation scenarios. Energies 2017;10(1).
[6] International Energy Agency (IEA). Global energy and CO2 status report - 2019. Paris: IEA; 2019.
[7] Jarvis AJ, Leedal DT, Hewitt CN. Climate-society feedbacks and the avoidance of dangerous climate change. Nat Clim Change 2012;2:668–71.
[8] World Bank. GDP (constant 2010 US$). Available from: http://data.worldbank.org/indicator/NY.GDP.MKTP.KD; 2019.
[9] International Energy Agency (IEA). Extended world energy balances (database). IEA World Energy Statistics and Balances; 2019. Available from: http://www.oecd-ilibrary.org/energy/data/iea-world-energy-statistics-and-balances/extended-world-energy-balances_data-00513-en.
[10] Csereklyei Z, Rubio-Varas MdM, Stern DI. Energy and economic growth: the stylized facts. Energy J 2016;37(2):223–55.
[11] Haberl H, Wiedenhofer D, Virág D, Kalt G, Plank B, Brockway P, et al. A systematic review of the evidence on decoupling of GDP, resource use and GHG emissions, part II: synthesizing the insights. Environ Res Lett 2020:1–50.
[12] Hardt L, Owen A, Brockway P, Heun MK, Barrett J, Taylor PG, et al. Untangling the drivers of energy reduction in the UK productive sectors: efficiency or offshoring? Appl Energy 2018;223(March):124–33.
[13] Moreau V, Vuille F. Decoupling energy use and economic growth: counter evidence from structural effects and embodied energy in trade. Appl Energy 2018;215:54–62.
[14] Csereklyei Z, Stern DI. Global energy use: decoupling or convergence? Energy Econ 2015;51:633–41. 2015.
[15] Semieniuk G, Taylor L, Rezai A, Foley DK. Plausible energy demand patterns in a growing global economy with climate policy. Nat Clim Change 2021;(Jan 25):1–14. https://doi.org/10.1038/s41558-020-00975-7.
[16] The Intergovernmental Panel on Climate Change (IPCC). Climate change 2014: mitigation of climate change. In: Working group III contribution to the fifth assessment report of the intergovernmental panel on climate change; 2014. p. 1454.
[17] Krausmann F, Wiedenhofer D, Haberl H. Growing stocks of buildings, infrastructures and machinery as key challenge for compliance with climate targets. Global Environ Change 2020;61(May 2019):102034.
[18] Steckel JC, Brecha RJ, Jakob M, Strefler J, Luderer G. Development without energy? Assessing future scenarios of energy consumption in developing countries. Ecol Econ 2013;90:53–67.
[19] Fricko O, Havlik P, Rogelj J, Klimont Z, Gusti M, Johnson N, et al. The marker quantification of the Shared Socioeconomic Pathway 2: a middle-of-the-road scenario for the 21st century. Global Environ Change 2017;42:251–67.
[20] International Energy Agency (IEA). Energy efficiency 2019. Paris: International Energy Agency; 2019. 2019.
[21] Sorrell S. The Rebound Effect: an assessment of the evidence for economy-wide energy savings from improved energy efficiency. UK Energy Research Centre (UKERC) Technology Policy Assessment Report. London: UKERC; 2007. p. 1–123.
[22] van Benthem AA. Energy leapfrogging. J Assoc Environ Resour Econ 2015;2(1):93–132.
[23] Jevons WS. In: Flux AW, editor. The coal question: an inquiry concerning the progress of the nation, and the probable exhaustion of our coal-mines. New York: Augustus M. Kelley; 1905. 1865.
[24] Khazzoom DJ. Economic implications of mandated efficiency in standards or household appliances. Energy J 1980;1(4):21–40.
[25] Grubb M. Energy efficiency and economic fallacies – a reply. Energy Pol 1990;18:783–5.
[26] Saunders HD. Recent evidence for large rebound: elucidating the drivers and their implications for climate change models. Energy J 2015;36(1):23–48.
[27] Azevedo IL, Sonnberger M, Thomas B, Morgan MG, Renn O. The rebound effect: implications of consumer behaviour for robust energy policies. In: A review of the literature on the rebound effect in energy efficiency and report from expert workshops. Report. Lausanne: International Risk Governance Council (IRGC); 2013.
[28] Kraan O, Chappin E, Kramer GJ, Nikolic I. The influence of the energy transition on the significance of key energy metrics. Renew Sustain Energy Rev 2019;111(May):215–23.
[29] Semieniuk G, Weber IM. Inequality in energy consumption: statistical equilibrium or a question of accounting conventions? Eur Phys J Spec Top 2020;229:1705–14.
[30] International Institute for Applied Systems Analysis (IIASA). SSP database (shared socioeconomic pathways) - version 2.0. Available from: https://tntcat.iiasa.ac.at/SspDb/dsd?Action=htmlpage&page=10; 2018.
[31] Huppmann D, Kriegler E, Krey V, Riahi K, Rogelj J, Rose SK, et al. IAMC 1.5°C scenario explorer and data hosted by IIASA. Integrated Assessment Modeling Consortium & International Institute for Applied Systems Analysis; 2018. . 2018. Available from: data.ene.iiasa.ac.at/iamc-1.5c-explorer.
[32] Grubler A, Wilson C, Bento N, Boza-kiss B, Krey V, McCollum DL, et al. A low energy demand scenario for meeting the 1.5 °C target and sustainable

development goals without negative emission technologies. Nat Energy 2018;3 (June):515–27.
[33] KC S, Lutz W. The human core of the shared socioeconomic pathways: population scenarios by age, sex and level of education for all countries to 2100. Global Environ Change 2017;42:181–92.
[34] Riahi K, Vuuren DP van, Kriegler E, Edmonds J, O'Neill BC, Fujimori S, et al. The Shared Socioeconomic Pathways and their energy, land use, and greenhouse gas emissions implications: an overview. Global Environ Change 2017;42:153–68.
[35] International Energy Agency (IEA). World Energy Outlook. Available from: https://www.iea.org/reports/world-energy-outlook-2020; 2020.
[36] International Energy Agency (IEA). Energy efficiency 2018: analysis and outlooks to 2040. Market report series. Paris, FR: OECD/IEA; 2018.
[37] International Renewable Energy Agency (IRENA). Global energy transformation: a roadmap to 2050: 2019 edition. Available from: https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2019/Apr/IRENA_Global_Energy_Transformation_2019.pdf; 2019.
[38] Greenpeace International. World energy [r]evolution: sustainable world energy Outlook 2015 5th edition. Available from: https://www.greenpeace.org/canada/en/publication/1572/energy-revolution-2015-the-latest-documentation-2/; 2015.
[39] US Energy Information Administration (US EIA). International energy Outlook 2019. Available from: https://www.eia.gov/outlooks/ieo/pdf/ieo2019.pdf; 2019.
[40] bp plc. BP energy Outlook 2020 edition - data tables. Available from: https://www.bp.com/en/global/corporate/energy-economics/energy-outlook/energy-outlook-downloads.html; 2020.
[41] Shell International BV. Sky scenario. Available from: https://www.shell.com/energy-and-innovation/the-energy-future/scenarios/shell-scenario-sky.html; 2018.
[42] van Vuuren DP, Stehfest E, Gernaat DEHJ, Doelman JC, van den Berg M, Harmsen M, et al. Energy, land-use and greenhouse gas emissions trajectories under a green growth paradigm. Global Environ Change 2017;42:237–50.
[43] Kriegler E, Bauer N, Popp A, Humpenöder F, Leimbach M, Strefler J, et al. Fossil-fueled development (SSP5): an energy and resource intensive scenario for the 21st century. Global Environ Change 2017;42:297–315.
[44] Calvin K, Bond-Lamberty B, Clarke L, Edmonds J, Eom J, Hartin C, et al. The SSP4: a world of deepening inequality. Global Environ Change 2017;42:284–96.
[45] IEA. World Energy Model Documentation - 2019 Version. Paris: International Energy Agency; 2019. p. 1–88.
[46] Shell International BV. Shell world energy model: a view to 2100. Available from: https://www.shell.com/energy-and-innovation/the-energy-future/scenarios/shell-scenarios-energy-models/world-energy-model.html; 2017.
[47] bp plc. BP energy Outlook 2020, statistical review. London: bp plc; 2020. Available from: https://www.bp.com/content/dam/bp/business-sites/en/global/corporate/pdfs/energy-economics/energy-outlook/bp-energy-outlook-2020.pdf.
[48] Aalborg University Denmark. Mesap PlaNet global energy system model. Available from: https://www.energyplan.eu/othertools/national/mesap-planet/.
[49] US Department of Energy (DoE). World energy projection system plus: overview. 2017. December 2017.
[50] Masson-Delmotte V, Zhai P, Pörtner HO, Roberts D, Skea J, Shukla PR, et al. IPCC, 2018: summary for policymakers. In: Global warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways. the context of strengthening the global; 2018.
[51] Patterson MG. What is energy efficiency? Energy Pol 1996;24(5):377–90.
[52] Cleveland CJ, Kaufmann RK, Stern DI. Aggregation and the role of energy in the economy. Ecol Econ 2000 Feb;32(2):301–17.
[53] Fullerton D, Ta CL. Costs of energy efficiency mandates can reverse the sign of rebound: CESifo Working Paper no. 7550. CESifo Work Pap 2019;(April):1–34.
[54] Saunders HD. Historical evidence for energy efficiency rebound in 30 US sectors and a toolkit for rebound analysts. Technol Forecast Soc Change 2013 Sep;80(7):1317–30.
[55] Sorrell S. Energy substitution, technical change and rebound effects. Energies 2014 Apr 29;7(5):2850–73.
[56] Berndt ER. Aggregate energy, efficiency, and productivity measurement. Annu Rev Energy 1978;3:225–73.
[57] Sorrell S, Dimitropoulos J, Sommerville M. Empirical estimates of the direct rebound effect: a review. Energy Pol 2009 Apr;37(4):1356–71.
[58] Dimitropoulos A, Oueslati W, Sintek C. The rebound effect in road transport: a meta-analysis of empirical studies. Energy Econ 2018;75:163–79.
[59] Gillingham K, Rapson D, Wagner G. The rebound effect and energy efficiency policy. Rev Environ Econ Pol 2016;10(1):68–88.
[60] Guerra AI, Sancho F. Rethinking economy-wide rebound measures: an unbiased proposal. Energy Pol 2010;38(11):6684–94.
[61] Turner K, Hanley N. Energy efficiency, rebound effects and the environmental Kuznets Curve. Energy Econ 2011 Sep;33(5):709–20.
[62] Bruns SB, Moneta A, Stern DI. Macroeconomic time-series evidence that energy efficiency improvements do not save energy. 2019. CAMA Working Paper 21/2019 February 2019.
[63] Tsao JY, Saunders HD, Creighton JR, Coltrin ME, Simmons JA. Solid-state lighting: an energy-economics perspective. J Phys D Appl Phys 2010 Sep 8;43 (35):354001.
[64] Orea L, Llorca M, Filippini M. A new approach to measuring the rebound effect associated to energy efficiency improvements: an application to the US residential energy demand. Energy Econ 2015;49:599–609.
[65] Chitnis M, Sorrell S. Living up to expectations: estimating direct and indirect rebound effects for UK households. Energy Econ 2015;52:S100–16.
[66] Chitnis M, Sorrell S, Druckman A, Firth SK, Jackson T. Turning lights into flights : estimating direct and indirect rebound effects for UK households. Energy Pol 2013;55:234–50.
[67] Chitnis M, Sorrell S, Druckman A, Firth SK, Jackson T. Who rebounds most? Estimating direct and indirect rebound effects for different UK socioeconomic groups. Ecol Econ 2014;106:12–32.
[68] Thomas BA, Azevedo IL. Estimating direct and indirect rebound effects for U.S. households with input–output analysis Part 1: theoretical framework. Ecol Econ 2013;86:199–210.
[69] Freire-González J. Evidence of direct and indirect rebound effect in households in EU-27 countries. Energy Pol 2017;102(November 2016):270–6.
[70] Allan G, Gilmartin M, Turner K, McGregor P, Swales K. Review of evidence for the rebound effect technical report 4: computable general equilibrium modelling studies. 2007. UKERC Work Pap UKERC/WP/TPA/2007/012.
[71] Böhringer C, Rivers N. The energy efficiency rebound effect in general equilibrium. CESifo Working Paper Series No. 7116 2018;54.
[72] Koesler S, Swales K, Turner K. International spillover and rebound effects from increased energy efficiency in Germany. Energy Econ 2016;54:444–52.
[73] Wei T, Liu Y. Estimation of global rebound effect caused by energy efficiency improvement. Energy Econ 2017;66:27–34.
[74] Bye B, Fæhn T, Rosnes O. Residential energy efficiency policies: costs, emissions and rebound effects. Energy 2018;143:191–201.
[75] Vikström P. Energy efficiency and energy demand: a historical CGE investigation on the rebound effect in the Swedish economy 1957. Umeå Papers in Economic History 2008;35(35):1–27. 2008.
[76] Grepperud S, Rasmussen I. A general equilibrium assessment of rebound effects. Energy Econ 2004;26(2):261–82.
[77] Allan G, Hanley N, McGregor P, Swales K, Turner K. The impact of increased efficiency in the industrial use of energy: a computable general equilibrium analysis for the United Kingdom. Energy Econ 2007;29(4):779–98.
[78] Hanley N, McGregor PG, Swales JK, Turner K. Do increases in energy efficiency improve environmental quality and sustainability? Ecol Econ 2009;68(3):692–709.
[79] Anson S, Turner K. Rebound and disinvestment effects in refined oil consumption and supply resulting from an increase in energy efficiency in the Scottish commercial transport sector. Energy Pol 2009;37(9):3608–20.
[80] Broberg T, Berg C, Samakovlis E. The economy-wide rebound effect from improved energy efficiency in Swedish industries-A general equilibrium analysis. Energy Pol 2015;83:26–37.
[81] Yu X, Moreno-Cruz J, Crittenden JC. Regional energy rebound effect: the impact of economy-wide and sector level energy efficiency improvement in Georgia , USA. Energy Pol 2015;87:250–9.
[82] Garau G, Mandras G. Economy-wide rebound effects from an increase in efficiency in the use of energy:the Italian case. Centro ricerche economiche nord sud working paper. Sardinia: Universita di C Agliari; 2015. 2015.
[83] Lu Y, Liu Y, Zhou M. Rebound effect of improved energy efficiency for different energy types: a general equilibrium analysis for China. Energy Econ 2017;62:248–56.
[84] Du Q, Li Y, Bai L. The energy rebound effect for the construction industry: empirical evidence from China. Sustainability 2017;9(5):1–11.
[85] Koesler S. Catching the rebound: economy-wide implications of an efficiency shock in the provision of transport services by households. ZEW-Centre for European Economic Research; 2013. Discussion Paper 2013.
[86] Lecca P, McGregor PG, Swales JK, Turner K. The added value from a general equilibrium analysis of increased efficiency in household energy use. Ecol Econ 2014;100:51–62.
[87] Figus G, Lecca P, Turner K, McGregor PG. Increased energy efficiency in scottish households: trading-off economic benefits and energy rebound effects? (April 13, 2016). 2016. USAEE working paper No. 16-270.
[88] Kulmer V, Seebauer S. How robust are estimates of the rebound effect of energy efficiency improvements? A sensitivity analysis of consumer heterogeneity and elasticities. Energy Pol 2019;132(April):1–14.
[89] Duarte R, Sánchez-Chóliz J, Sarasa C. Consumer-side actions in a low-carbon economy: a dynamic CGE analysis for Spain. Energy Pol 2018;118(March):199–210.
[90] Barkhordar ZA. Evaluating the economy-wide effects of energy efficient lighting in the household sector of Iran. Energy Pol 2019;127(November 2018):125–33.
[91] Hanley N, McGregor PG, Swales JK, Turner K. Do increases in resource productivity improve environmental quality? Theory and evidence on rebound and backfire effects from an energy-economy-environment regional computable general equilibrium model of Scotland. Department of Economics, University of S; 2005.
[92] Koetse MJ, de Groot HLF, Florax RJGM. Capital-energy substitution and shifts in factor demand: a meta-analysis. Energy Econ 2008;30:2236–51.
[93] Turner K. Negative rebound and disinvestment effects in response to an improvement in energy efficiency in the UK economy. Energy Econ 2009 Sep;31 (5):648–66.
[94] Barker T, Dagoumas A, Rubin J. The macroeconomic rebound effect and the world economy. Energy Effic 2009;2:411–27.
[95] Lemoine D. General equilibrium rebound from improved energy efficiency. University of Arizona; 2019. Working Paper 14-02.
[96] Rausch S, Schwerin H. Long-run energy use and the efficiency paradox. Zurich: ETH Zurich, CER-ETH - Center of Economic Research; 2016. Economics working paper series, No. 16/227.

[97] Adetutu MO, Glass AJ, Weyman-Jones TG. Economy-wide estimates of rebound effects: Evidence from panel data. The Energy Journal 2016;37(3).
[98] Brockway PE, Saunders H, Heun MK, Foxon TJ, Steinberger JK, Barrett JR, et al. Energy rebound as a potential threat to a low-carbon future: findings from a new exergy-based national-level rebound approach. Energies 2017;10(51):1–24.
[99] Wei T, Zhou J, Zhang H. Rebound effect of energy intensity reduction on energy consumption. Resour Conserv Recycl 2019;144(December 2018):233–9.
[100] Lin B, Liu X. Dilemma between economic development and energy conservation: energy rebound effect in China. Energy 2012;45(1):867–73.
[101] Shao S, Huang T, Yang L. Using latent variable approach to estimate China's economy-wide energy rebound effect over 1954-2010. Energy Pol 2014;72:235–48.
[102] Lin B, Du K. Measuring energy rebound effect in the Chinese economy: an economic accounting approach. Energy Econ 2015;50:96–104.
[103] Stern D, Kander A. The role of energy in the industrial revolution and modern economic growth. Energy J 2012;33(3):125–52.
[104] Brockway PE, Barrett JR, Foxon TJ, Steinberger JK. Divergence of trends in US and UK aggregate exergy efficiencies 1960-2010. Environ Sci Technol 2014;48:9874–81.
[105] Brockway P, Sorrell S, Foxon T, Miller J. 'Chapter 8: exergy economics - new insights into energy consumption and economic growth' in Jenkins. In: K E H, Hopkins D, editors. Transitions in energy efficiency and demand: the emergence, diffusion and impact of low-carbon innovation. UK: Routledge; 2019. p. 133–54.
[106] Saunders HD. Fuel conserving (and using) production functions. Energy Econ 2008;30:2184–235.
[107] Wei T, Liu Y. Estimation of resource-specific technological change. Technol Forecast Soc Change 2019;138(August 2018):29–33.
[108] Schreyer P, Pilat D. Measuring productivity. OECD Econ Stud 2001;33:127–70.
[109] Ang BW. Monitoring changes in economy-wide energy efficiency: from energy–GDP ratio to composite efficiency index. Energy Pol 2006 Mar;34:574–82.
[110] Fare R, Grosskopf S, Norris M, Zhang Z. Productivity growth , technical progress , and efficiency change in industrialized countries. Am Econ Rev 1994;84(1):66–83.
[111] Felipe J, McCombie JSL. What is wrong with aggregate production functions. On Temple's "aggregate production functions and growth economics. Int Rev Appl Econ 2010;24(6):665–84.
[112] Temple J. Aggregate production functions and growth economics. Int Rev Appl Econ 2006:301–17.
[113] Napp TA, Few S, Sood A, Bernie D, Hawkes A, Gambhir A. The role of advanced demand-sector technologies and energy demand reduction in achieving ambitious carbon budgets. Appl Energy 2019;238(April 2018):351–67.
[114] Bauer N, Calvin K, Emmerling J, Fricko O, Mouratiadou I, Sytze H, et al. Shared socio-economic pathways of the energy sector – quantifying the narratives. Global Environ Change 2017;42:316–30.
[115] Ruijven BJ Van, Vuuren DP Van, Boskaljon W, Neelis ML, Saygin D, Patel MK. Long-term model-based projections of energy use and CO 2 emissions from the global steel and cement industries. Resour Conserv Recycl 2016;112:15–36.
[116] Girod B, Vuuren DP Van, Deetman S. Global travel within the 2°C climate target. Energy Pol 2012;45:152–66.
[117] Daioglou V, Ruijven BJ Van, Vuuren DP Van. Model projections for household energy use in developing countries. Energy 2012;37(1):601–15.
[118] Messner S, Schrattenholzer L. Message – macro: linking an energy supply model with a macroeconomic module and solving it iteratively. Energy 2000;25:267–82.
[119] ADVANCE. Report on improved representation of energy demand in models. ADVANCE project: advanced model development and validation for improved analysis of costs and impacts of mitigation policies. 2015.
[120] Kriegler E, Petermann N, Krey V, Schwanitz VJ, Luderer G, Ashina S, et al. Diagnostic indicators for integrated assessment models of climate policy. Technol Forecast Soc Change 2015;90(PA):45–61.
[121] Krey V. Global energy-climate scenarios and models: A review. Wiley Interdisciplinary Reviews: Energy and Environment 2014;3(4):363–83. https://doi.org/10.1002/wene.98.
[122] Marangoni G, Tavoni M, Bosetti V, Borgonovo E, Capros P, Fricko O, et al. Sensitivity of projected long-term CO2 emissions across the shared socioeconomic pathways. Nat Clim Change 2017;7:113–7.
[123] International Energy Agency (IEA). World energy Outlook 2012. 2012. Paris.
[124] Stern DI. How accurate are energy intensity projections? Climatic Change 2017;143(3–4):537–45.
[125] Sorrell S, Dimitropoulos J. Review of evidence for the rebound effect technical report 2: econometric studies. 2007. UKERC Work Pap UKERC/WP/TPA/2007/010.
[126] Stern DI. How large is the economy-wide rebound effect? Energy Pol 2020;147:111870.
[127] Colmenares G, Löschel A, Madlener R. The rebound effect representation in climate and energy models. Environ Res Lett 2020;15:1–35. 123010.
[128] Kalimeris P, Richardson C, Bithas K. A meta-analysis investigation of the direction of the energy-GDP causal relationship: implications for the growth-degrowth dialogue. J Clean Prod 2014;67:1–13.
[129] Turner K, Lange I, Lecca P, Soo JH. Econometric estimation of nested production functions and testing in a computable general equilibrium analysis of economy-wide rebound effects. 2012. http//www.management.stir.ac.uk/research/economics/working-Pap-1-26. Stirling econ discuss pap 2012-08 available.
[130] Foley DK, Michl TR, Tavani D. Growth and distribution. second ed. Harvard University Press; 2019.