Energy Efficiency (2023) 16:65
https://doi.org/10.1007/s12053-023-10148-y

REVIEW ARTICLE

Rebound effects of energy efficiency improvement based on computable general equilibrium models: a systematic review

Weiwei Huang · Jianxu Miao · Taoyuan Wei

Received: 18 August 2022 / Accepted: 10 July 2023 / Published online: 22 July 2023

Abstract Energy efficiency improvement is expected to reduce energy consumption. However, actual energy savings can be lower than anticipated, called rebound effects. This article reviews previous studies that have used computable general equilibrium (CGE) models to study the rebound effects caused by energy efficiency improvements in the recent two decades until 2021. A systematic review approach has been adopted to select the focused studies, and keywords co-occurrence analysis has been used to explore the characteristics of the selected studies. We reported our findings on specific aspects of these CGE studies, including geographic location, time scale, and methodological features; how an energy efficiency improvement is introduced; and the levels of rebound effects estimated by these studies. These findings suggest specific potential research gaps. For example, few CGE studies have focused on Russia, India, and Africa; no production functional forms other than constant elasticity of substitution (CES) have been used in these CGE studies; and little attention has been paid to negative rebound effects in the short run and the cases of joint implementation of energy efficiency improvement and other policy measures that drive energy cost higher.

Keywords CGE model · Energy efficiency · Rebound effect · Climate policy · Global warming · Energy consumption

Introduction

Energy efficiency improvement (EEI) has effectively reduced energy consumption and promoted economic development (Nordhaus, 2019). However, the lower energy costs induced by improving energy efficiency will almost certainly stimulate new energy demand to offset a large part of the potential energy savings, particularly at the economy-wide scale (Wei and Liu, 2017; Lemoine, 2020; Brockway et al., 2021; Berner et al. 2022), known as rebound effects (Saunders, 2000). Sometimes, the rebound effect is called

---

W. Huang
Center for Energy and Environmental Policy Research, Beijing Institute of Technology, Beijing 100081, China
e-mail: weiweihuang@bit.edu.cn

W. Huang
School of Management and Economics, Beijing Institute of Technology, Beijing 100081, China

W. Huang
Beijing Key Lab of Energy Economics and Environmental Management, Beijing 100081, China

J. Miao
School of Economics, Shandong University of Technology, Zibo 255000, China
e-mail: 1712595279@qq.com

T. Wei (✉)
CICERO Center for International Climate Research, 0318 Oslo, Norway
e-mail: taoyuan.wei@cicero.uio.no

the Jevons paradox (Jevons, 1866) or backfire effects (Brookes, 1990; Khazzoom, 1980).

Rebound effects can be classified as direct, indirect, and macroeconomic (Brockway 2021). From an engineering perspective, a 1% EEI leads to a 1% reduction in energy use. However, the EEI can reduce the effective price of services provided by the energy, encouraging more demand for those services and, in turn, more energy use, which is classified as direct rebound effects on energy use. It is also possible that the energy users re-spend the saved energy cost on activities other than the activities where the EEI occurs. These additional activities will require more energy use, which is classified as indirect rebound effects (Freire-González, 2019). Direct and indirect rebound effects assume fixed prices of energy and other economic products. However, the direct and indirect rebound effects can lead to price and income changes in the market, further disturbing the economy and required energy use, which is classified as macroeconomic rebound effects.

The net effects of the three types of rebound effects above are economy-wide rebound effects. In a recent review of rebound effects studies in the past 40 years, Rajabi (2022) concluded that further studies are required to enhance our understanding of the economy-wide rebound effects. Among all the approaches reviewed by Rajabi (2022), computable general equilibrium (CGE) models have been typically used to estimate economy-wide rebound effects (Lemoine, 2020; Berner et al., 2022) and have provided the most reliable estimates of the economy-wide rebound effects (Turner, 2013; Gillingham et al., 2016).

A recent critical review on the economy-wide rebound effects of EEI (Brockway et al., 2021) concluded that global energy scenarios generated from many global energy and integrated assessment models may have underestimated the potential role of rebound effects and projected a low growth of global energy demand. In that review, Brockway et al. (2021) focused on long-run economy-wide rebound effects estimated by CGE models, among other methodologies, including macroeconomic models, econometric analysis, and growth accounting methods.

Built upon the summary of the key results from CGE studies in a subsection of Rajabi (2022) and the critical review on economy-wide rebound effects (Brockway et al., 2021), the present study will provide a supplementary review on the CGE studies focusing on the economy-wide rebound effects by using a systematic review approach (Davis et al. 2014). Our review differs from Rajabi (2022) and Brockway et al. (2021) by addressing certain specific aspects of these CGE studies, including focused regions, time scale, and methodological features besides how an EEI is introduced and the range of rebound effects estimated by these studies. In this sense, this review does not provide a critical review of the literature as Brockway et al. (2021).

The remainder of the paper is organized as follows. The "Rebound effects studied by a CGE modeling approach" section briefly explains how a CGE modeling approach typically estimates rebound effects. The "Method" section introduces the systematic review approach we used. The "Results and discussion" section presents and discusses our review results, and the "Conclusions" section concludes.

Rebound effects studied by a CGE modeling approach

A rebound effect (R), either direct, indirect, macroeconomic, or economy-wide, can be defined as the share of the unexpected energy consumption in the total expected (or potential) energy savings due to an EEI or other measures, i.e.,

$$R = \frac{\Delta E_{unexpected}}{\Delta E_{expected}} = 1 - \frac{\Delta E_{actual}}{\Delta E_{expected}} \quad (1)$$

where ΔE_{actual} denotes the actual change in energy consumption and $\Delta E_{expected}$ is the expected change in energy consumption caused by a change in energy efficiency or other measures. The definition is intuitive as the rebound effect is zero if the actual energy consumption is the same as expected. Following this definition, the rebound effect can appear to be the other four cases (Saunders, 2000; Wei, 2010): backfire if the rebound is greater than 100%; full rebound if the rebound is equal to 100%; partial rebound if the rebound is positive but less than 100%; and super-conservation if the rebound is negative.

While the definition seems plausible, there are different interpretations of an EEI and the expected change in energy consumption associated with the EEI (Brockway et al. 2021). In CGE studies focusing on rebound effects, the cause of rebound effects is typically an EEI rather than other measures such as carbon taxes and energy standards. In most CGE studies on rebound effects, an EEI is introduced explicitly as a change in the efficiency parameter(s) of energy used by producers and final consumers.

Figure 1 illustrates the mechanism of rebound effects typically simulated in a CGE model. In a typical CGE analysis, the initial economy is assumed to stay at an equilibrium. The introduced "shock" of an EEI leads to direct and indirect rebound effects burdened by the energy users who assume fixed prices of energy and other goods in the market. The changes in market demand, supply, and associated prices are crucial in modifying the direct and indirect rebound effects on energy use and other economic variables induced by the energy users who directly adopt the introduced energy efficiency improvement. The changes in the market conditions motivate all energy users and producers in the economy to adjust their activities until another equilibrium is achieved. In the new equilibrium, the economy-wide energy use differs from that in the initial equilibrium. The difference is taken as "the change in the actual energy use" to estimate economy-wide rebound effects as defined in Eq. (1). As the EEI is introduced as a change in efficiency parameter(s) of energy input, then "the expected change in energy use" naturally refers to the same percentage energy savings as the percentage change in the EEI introduced to the model, assuming all the other things being equal in the economic system.

Notice that the direct and indirect rebound effects in Fig. 1 are just illustrative since a CGE model cannot explicitly separate both rebound effects due to the impact of changes in market prices endogenously determined in the CGE model. The dashed arrows in Fig. 1 show the possible feedback effects on direct and indirect rebound effects in a CGE model.

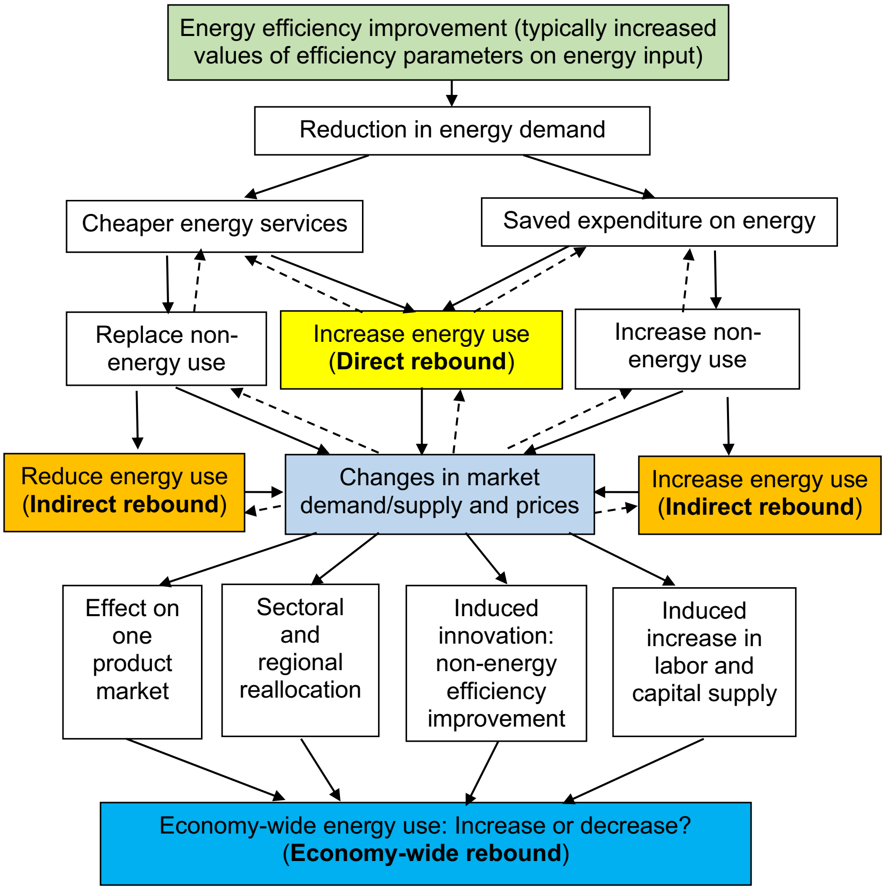


Fig. 1 An illustration of the mechanism of the economy-wide rebound effect typically simulated in a CGE model. Source: modified from Fig. 1 in Wei and Liu (2017)

The mechanism described above is typical if the introduced EEI is permanent. If the efficiency improvement is temporary, the economy can return to the original equilibrium in a dynamic CGE model once the efficiency improvement disappears.

Method

In this review, we aim to identify and analyze three specific questions in the existing studies:

(1) What has the literature covered and not covered regarding geographic location, time scale, and methodological features?
(2) How is an EEI introduced into a CGE model, and what is the range of rebound effects estimated by the existing studies?
(3) Which topics on the rebound effects require more CGE research based on the answers to the above two questions?

We adopt a systematic review approach following Rajabi (2022) to answer these questions rather than a traditional critical literature review approach. The systematic review approach offers advantages to identifying and including all available studies relevant to the pre-defined questions by using explicit criteria in a transparent and replicable process (Mulrow, 1994; Davis et al., 2014). This is suitable since our questions can be answered by directly extracting information from relevant studies.

Database of relevant studies

The relevant studies in the literature have to be selected from existing databases. Web of Science (WoS), Scopus, and Google Scholar are the three most used databases in bibliometric research, but with considerable differences in consistency and accuracy (Kulkarni et al., 2009). WoS is a good standard for bibliometric research, Scopus and Google Scholar can be treated as complementary sources (Meho and Yang, 2007). Hence, this article uses the WoS database to find and review the relevant literature.

Select relevant studies

Starting from the questions at the beginning of this subsection, we searched the literature in the WoS database, limiting the language to “English” and the document type to “Article.” In addition, this search covered many qualifiers related to CGE and energy, as shown in Table 1. We investigated the WoS database on December 13, 2021, and obtained 94 studies from 1999 to 2021.

Among the 94 retrieved studies, some articles were not closely related to the topic. Hence, we excluded studies on irrelevant research fields, such as medicine and biology, by refining research areas in the WoS database. Furthermore, we manually screen the remaining studies’ titles, keywords, and abstracts to exclude irrelevant studies. Finally, 56 studies were chosen for final review. We then downloaded the basic information of these 56 articles from the WoS database, including authors, titles, keywords, and references for further analysis.

Table 1 Retrieval function for literature on energy rebound effects estimated by CGE models

Retrieval type	Content
Formula	TS= (“energy” OR “fuel*” OR “oil” OR “coal” OR “petroleum” OR “natural gas” OR “fossil fuel*” OR “wind” OR “solar” OR “nuclear” OR “hydropower” OR “hydroelectricity” OR “biogas” OR “bio*energy” OR “renewable energy” OR “alternative energy” OR “electricity”) AND TS= (“general equilibrium” OR “CGE” OR “computable general equilibrium”) AND TS= (“rebound”)
Language	English
Document type	Article
Index	SCI-EXPANDED, SSCI
Year	2021

Analyze the selected studies

We classified the articles into different groups by reading the articles' titles and abstracts and combining a co-occurrence analysis, which regards the keywords of an article as comprehensive descriptors of its content. Thus, the links between articles can be identified by the keywords co-occurrence (Barberán et al., 2012). The keywords in a co-occurrence analysis can be either keywords, authors, or research regions in an article. To clarify which authors played a vital role in the reviewed studies, the keywords co-occurrence analysis was used to identify the co-authorship network of countries and authors.

In the end, we read the full articles to identify, extract, and analyze other specific issues, such as model types, how an EEI was introduced, and the estimated values of the rebound effects in these articles. For example, by reading the full text of the reviewed articles, we identify the causes that lead to rebound effects and the estimated values of economy-wide rebound effects in the focused studies. Several studies that did not report economy-wide rebound effects and were not representative were not considered in the "Introduction of increased energy efficiency" section. In addition, if a study did not explicitly involve EEI as at least one of the causes of rebound effects, it was excluded from consideration in the "Introduction of increased energy efficiency" section, although the measures it focused on were relevant to energy efficiency improvement. For instance, we excluded the following studies that focused on clean coal technology (Glosmrød and Wei, 2005), electric car subsidy (Vivanco et al., 2021), adoption of energy-efficient lighting by households (Barkhordar, 2019), shifts in spending among energy and other commodities by households (Freire-González and Ho, 2021), and changes in taxes paid by electricity generators (Langarita et al., 2021).

Results and discussion

Temporal and spatial analysis

Figure 2 shows the distribution of the articles published over time from 1999 to 2021. There were only two studies on rebound effects based on CGE models (Glomsrød and Wei, 2005; Grepperud and Rasmussen, 2004) before 2007, when the Intergovernmental Panel on Climate Change (IPCC) urged to reduce fossil fuel use in its fourth assessment report (IPCC, 2007). Since then, the number of studies has increased and remained stable at around ten every five years from 2007 to 2016. In the recent 5 years, the number of relevant articles has reached 34, 50% more than the previous studies combined. This is consistent with the temporal distribution of all 323 studies on energy rebound effects in the past 41 years that Rajabi (2022) found.

CGE studies on rebound effects appeared relatively late, although rebound effects have been discussed

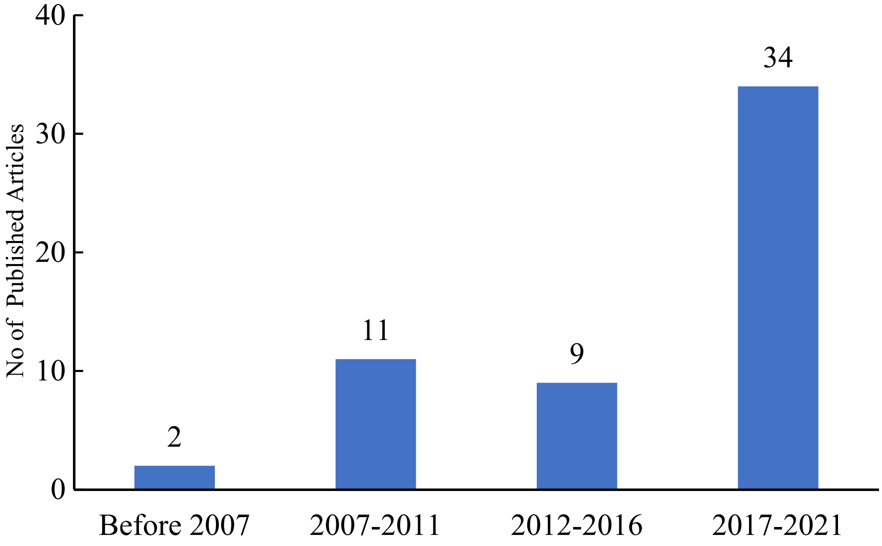


Fig. 2 Numbers of published articles during 1999–2021

in energy economics since 1980 (Khazzoom, 1980). This may relate to several factors. One is the communication of the knowledge on rebound effects. Although rebound effects had been discussed broadly in energy economics, it was not widely known by the CGE experts in mainstream economics. Even today, certain famous institutes with a long tradition of CGE work, such as the Centre of Policy Studies (CoPS), have not paid much attention to the rebound effects issue. Another factor can be related to the heavy demand for expertise and resources of CGE models in the early days, including computer programming, computing power availability, data availability, and knowledge of macroeconomics. The last but not most minor factor is related to limited policy concerns and research finance in the early days. All these factors in the coming decades tend to favor more research on rebound effects, and thus we would expect more CGE studies on rebound effects.

In terms of research regions (Fig. 3), over 50% of the studies have focused on three countries, including the UK (e.g., Font Vivanco et al., 2021), Spain (e.g., Guerra and Sancho, 2010), and China (e.g., Li et al., 2017; Wang and Wei, 2019), where China is the world's largest energy consumer and carbon emitter. Several articles have estimated Malaysia's energy rebound effects (e.g., Pui and Othman, 2017). In addition, more than 10% of the reviewed articles have studied rebound effects based on global CGE models (e.g., Wei, 2010; Wei and Liu, 2017). Our review shows fewer existing studies on specific regions such as Russia, India, and Africa.

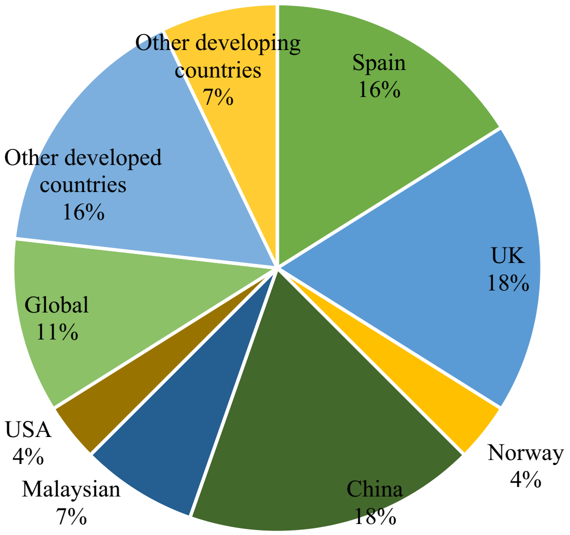


Fig. 3 Numbers of studies focusing on different geographic areas from 2003 to 2021

The UK studies on the topic are closely related to a key researcher, Karen Turner, as she was one of the co-authors in almost all the UK studies (9 of 10). On the contrary, we could not find such a key researcher in the China and Spain studies, where an author has been involved in a maximum of two studies. Still, many CGE researchers on energy and environmental economics have not paid attention to the rebound effects issue, even in these three countries.

Analysis of authors

Co-author networks explore collaboration patterns at the individual level (Geng et al., 2017) and the institutional or national levels (Li et al., 2019). The contribution of different countries/regions was studied by analyzing the postal addresses of the authors' affiliations shown in the reviewed articles. Figure 4 shows the network diagram of cooperation between countries where the authors are affiliated. Denser lines indicate closer collaboration and larger dots indicate more research articles in that country. It demonstrates that authors from UK, China, USA, and Spain contribute larger shares of studies in this field. The authors between the UK and Spain have collaborated the most frequently. The authors from China have collaborated more regularly with the authors from USA, UK, and Norway. Compared to Fig. 3, it is unsurprising that the research regions are highly overlapped with the located regions of the authors' affiliations. Overall, most studies on the topic are contributed by researchers affiliated with the USA, China, and EU rather than other regions such as India and Africa. For many African countries, this relates to the unavailability of input-output tables, the database required to build up a CGE model.

Figure 5 shows the collaborative network of the most productive authors. Combined with the author's country (Fig. 4), the studies of Turner, Hanley et al. (2009) and Lecca et al. (2014) have been cited the most frequently. They focused on energy and environmental issues in the UK, particularly Scotland. Duarte et al. (2018) used a CGE model to simulate scenarios and assess the impact

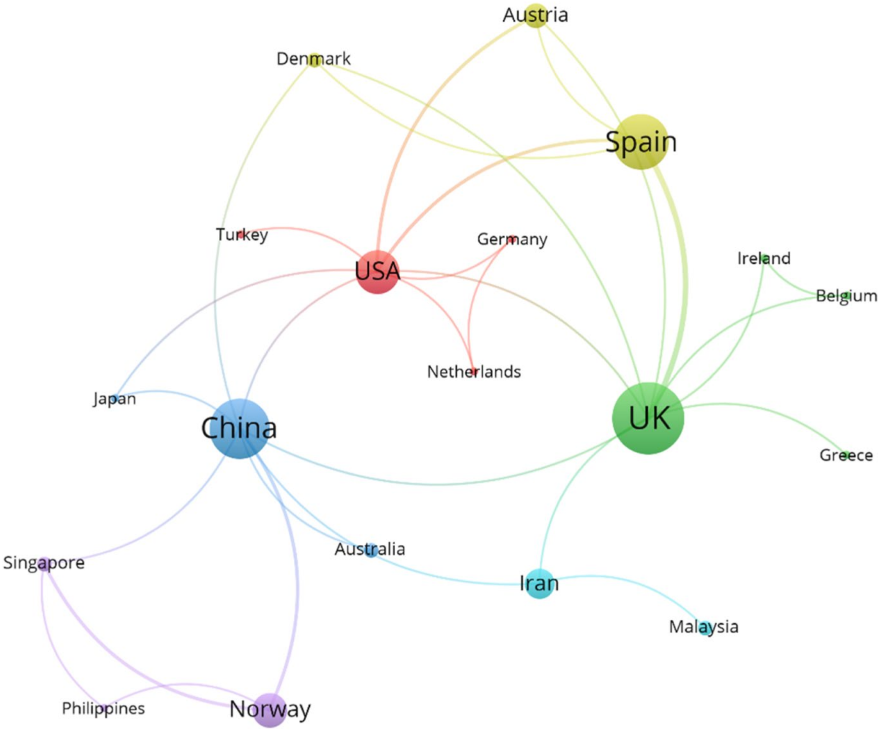


Fig. 4 The co-authorship network of countries where the authors' affiliations located

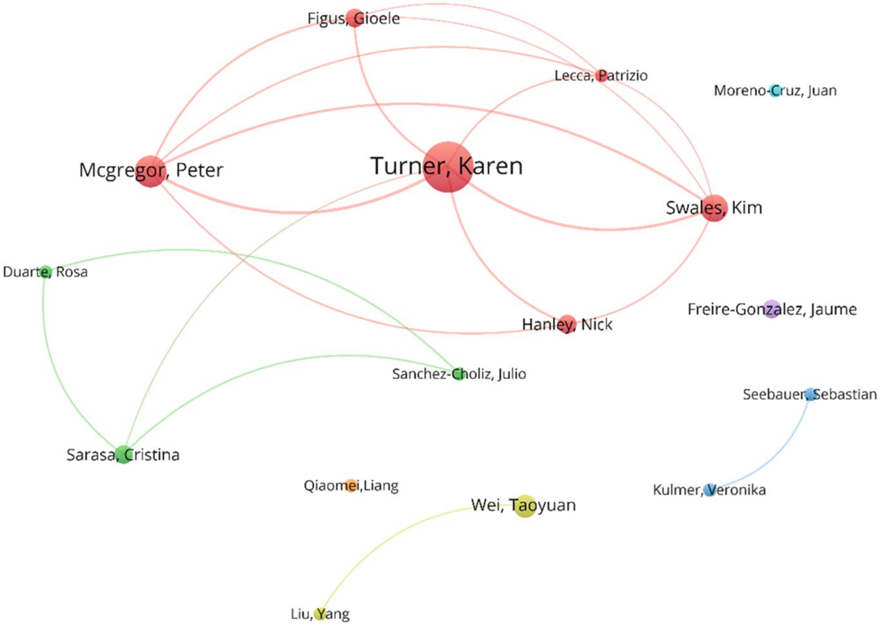


Fig. 5 The collaborative network of the most productive authors. Collaborations are represented by links between two authors, with more prominent points indicating more output

of adopting different policies on Spanish households (Duarte et al., 2014), electricity, and transportation (Sarasa and Turner, 2021). In the studies on China, Liang et al. (2009) used power industry data to simulate seven scenarios. They found that improvements in energy end-use efficiency would increase total energy consumption and CO_2 emissions. Glomsrød and Wei (2005) suggested that coal cleaning stimulates economic growth and reduces particle emissions, but coal use will increase.

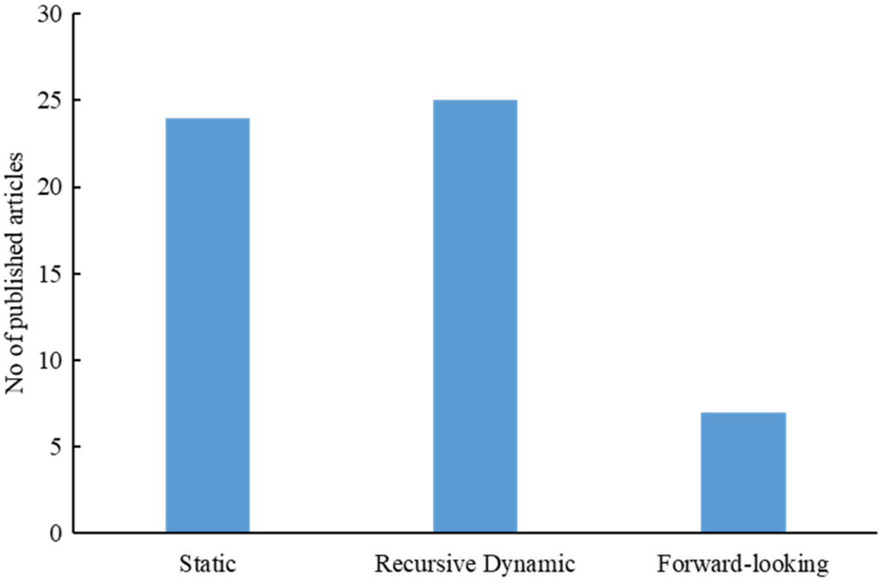
Static and dynamic CGE models

Static and dynamic CGE models differ in their treatment of time and how they simulate the adjustment process of an economy as a response to an exogenous shock like an energy efficiency improvement. Hence, the type of the CGE model used by a study may affect the estimated rebound effects. Static (e.g., Yu et al., 2015), Forward-looking (e.g., Barkhordar, 2019; Freire-González, 2020), and recursive-dynamic (e.g., Hanley et al., 2009; Skelton et al., 2020) models are the three most widely used model types, of which the latter two are also called dynamic models (Babiker et al., 2009). Static CGE models are concerned with comparing the initial state of an economy and the final equilibrium when a change in policy (such as an energy efficiency improvement) causes the economy to reallocate resources (Broberg et al., 2015). If, in a model, the initial state of an economy at equilibrium is associated with a steady state in a future period after considering a broad economic evolution over time, the model is classified as forward-looking rather than static. Static models can analyze changes in winners and losers after an economic shock, but it is challenging to capture the costs and benefits in the process of a change (Lu et al., 2017). Therefore, static models may overestimate or underestimate the costs and benefits caused by a shock.

Unlike static models, dynamic models assume that available capital stock in a period is influenced by the investments and capital stock in the previous period (Freire-González and Ho, 2021). Dynamic CGE models include recursive dynamic models and forward-looking models (Babiker et al., 2009). Recursive dynamic CGE models can perform multi-period analysis and use the equilibrium solution obtained in one year as the benchmark for the next year (Liu et al., 2019b). Hence, in recursive dynamic models, economic agents may face problems such as short-sightedness or expectation discrepancies (Barkhordar, 2019; Mahmood and Marpaung, 2014). On the contrary, forward-looking CGE models are suitable for a forward-looking problem, e.g., optimal intertemporal consumption, by making economic decisions in a period based on perfect information on parameters and variables for successive periods (Otto et al., 2008). Hence, a forward-looking CGE model may become too complicated to solve when considering sectoral and regional details, and exogenous investment shocks are one of the key advantages that a recursive dynamic CGE model can manage.

Figure 6 shows the frequency of the model types used by the reviewed articles. 24 reviewed articles used static models, 25 used recursive dynamic models, and only seven used forward-looking models. The relatively few articles based on forward-looking

Fig. 6 Distribution of articles by type of CGE models



models can be related to the much larger efforts required to build up a forward-looking model than the other two model types and the relative limitations of forward-looking models to address the issue.

Functional forms of production

As a given functional form of production can limit the possible values of rebound effects within a range (Saunders, 2008), we examine the functional forms of production adopted in these CGE studies. Regarding production functions, most models in the reviewed articles take the forms of Leontief, Cobb-Douglas, and CES (including nested CES). However, both Leontief and Cobb-Douglas functions can be taken as special cases of CES functions with substitution elasticity values of 0 and 1, respectively. Most studies (42) adopted CES production functions, while only four assumed Cobb-Douglas functions, and only five adopted combination forms of CES, Cobb-Douglas, and Leontief. Five articles adopted generic functional forms for theoretical analysis.

CES production functions are commonly used in CGE models due to their flexibility in capturing substitution possibilities between different inputs, including energy and non-energy inputs. However, other functional forms have been used in some studies, such as a translog production function (Kim, 2019) and a generalized Leotief cost function (Holmøy, 2016). The nested CES production function is a more complex version of the standard CES function, which allows for more detailed modeling of the production process by including multiple layers of production activities and intermediate inputs (Klump et al., 2012; Shen and Whalley, 2013). In some studies, the authors used a nested CES production function to capture the interdependencies between inputs, including energy, capital, and labor. The elasticity of substitution between energy and other inputs in the nested CES function may vary across sectors and over time, considerably affecting the estimated values of rebound effects.

However, CES production functions have excluded specific possible values of rebound effects, such as negative rebound effects or super-conservation (Saunders, 2008). Hence, it is valuable to examine whether alternative functional forms that do not exclude any possible values of rebound effects can modify the estimated rebound effects in CGE models. Such alternatives can be, e.g., Gallant (Fourier), the Generalized Leontief, and certain Translog functions suggested by Saunders (2008).

Introduction of increased energy efficiency

Table 2 lists the causes that lead to rebound effects and the estimated values of economy-wide rebound effects in the focused studies. There are three cases to introduce an EEI in a CGE study on rebound effects. In the most used case, an exogenous EEI is directly introduced to a CGE model, e.g., assuming a 5% efficiency improvement for all energy inputs in all production sectors. The exogenous EEI can be introduced simply by a change in the energy-augmented efficiency parameter in production and/or consumption functions. The efficiency improvement can apply to all the economic activities (e.g., Wei, 2010) and only part of the economic activities, e.g., only energy used in all production sectors (e.g., Allan et al., 2007) or specific production sectors (e.g., Broberg et al., 2015), and only energy used by households (e.g., Kulmer and Seebauer, 2019). The reported rebound effects can be economy-wide, as shown in Table 2 or decomposed into sectoral rebound effects (Yu et al., 2015).

Another case in the reviewed studies is introducing an EEI jointly with other measures, such as fossil subsidies (Li et al., 2017) and efficiency improvement in capital and labor used in production (Sarasa and Turner, 2021). In these studies, the synthetic rebound effects are reported and compared.

The last case is that an EEI is derived from other policy measures focused on by a CGE study, e.g., energy efficiency required to achieve a target of reduction in electricity consumption (e.g., Duarte et al., 2014), carbon emissions (e.g., Pereira and Pereira, 2016), electricity and petroleum used by households (Duarte et al., 2018), light vehicle fuel efficiency standards (Wang et al., 2019), and energy efficiency changes due to fluctuation in global oil prices (Sun et al., 2021). These studies link an EEI explicitly to other policy measures to provide plausible arguments for the EEI considered.

In almost all the reviewed CGE studies, EEI is assumed to be permanent without cost (Broberg et al., 2015; Freire-González, 2020). This kind of large-scale cost-free EEI is unlikely in the short term but may occur due to technological progress in the long

Table 2 Causes of rebound effects and estimated values of rebound effects in the focused studies

How EEI is introduced in a study	Estimated economy-wide rebound effects	Source
Exogenous EEI		
1% EEI in a generic form of production function	All range in theory	Wei (2010)
1% for one or more energy inputs in a generic form of production function	All range in theory	Rocha and de Almeida (2021)
5% efficiency in gasoline and diesel used by land transport	95–105%	Pui and Othman (2017)
EEI in all sectors follows historical trends	55–78%	Liu et al. (2019a)
5%, 7%, and 10% EEI at macro and sector levels	13.5–36.2%	Khosroshahi and Sayadi (2020)
5% EEI in all production sectors	30–50%	Allan et al. (2007)
5% uniform EEI in all sectors	about 10%	Liang et al. (2009)
5% EEI in all production. Disinvestment leads to a negative rebound	> 0 in short run, < 0 in long run	Turner (2009)
5% EEI in all production sectors	35–250%	Hanley et al. (2009)
5% EEI in all production sectors	15–230%	Guerra and Sancho (2010)
5% EEI in either all production sectors; non-energy sectors; or energy-intensive sectors	37–81%	Broberg et al. (2015)
5% EEI for each energy type in turn in all production sectors. Long run is lower	Between − 28.2 and 51.2%	Yu et al. (2015)
1.3–5% EEI of the use of coal, oil, gas, or electricity	40–100%	Wang and Wei (2019)
1, 3, or 5% EEI of the use of coal, oil, gas, or electricity in the construction industry	51.8–164.1%	Li et al. (2019)
5% efficiency of energy used by all industries	29.71–80.35%	Figus et al. (2020)
5% EEI in all production sectors	10–86%	Turner and Hanley (2011)
10% EEI in all production sectors; or individual production sectors	10–27%	Yu et al. (2015)
10% EEI in production	46.6–51.3%	Koesler et al. (2016)
10% EEI in all non-energy sectors	21–76%	Wei and Liu (2017)
Actual EEI compared to no such efficiency improvement in historical years	69%	Bataille and Melton (2017)
5% EEI for each energy type in turn in all production sectors	Between − 9.3 and 89.7%	Zhou et al. (2018)
10% efficiency improvement in fossil fuel consumed by households	60–73%	Kulmer and Seebauer (2019)
5% increase in household energy efficiency	38–72%	Lecca et al. (2014)
10% improvement in household residential energy efficiency	59.7–72.0%	Figus et al. (2017)
5% increase in household energy efficiency	29.01–70.61%	Figus et al. (2019)
Exogenous EEI together with other measures		
5% EEI when fossil subsidy reform considered	Between − 23.1 and 95.8%	Li et al. (2017)
5% EEI in production sectors with energy taxes.	Between − 21.4 and 142%	Peng et al. (2019)
5% EEI with carbon taxes.	From − 25 to 60%	Freire-González (2020)
10% efficiency in household nonrenewable electricity use and/or 10% efficiency in the use of capital and labor in the production of each renewable energy sector	Between − 52.0 and 62.4%	Sarasa and Turner (2021)
Derived EEI		
15.76% EEI to achieve a given reduction in electricity consumption	36.5%	Duarte et al. (2014)
EEI derived from achieving a given CO_2 reduction	67%	Pereira and Pereira (2016)

Table 2 (continued)

How EEI is introduced in a study	Estimated economy-wide rebound effects	Source
Achieve a 20% reduction in emissions by EEI	7–85%	Skelton et al. (2020)
A path of EEI to reduce 20% of electricity and/or petroleum used by households	12.1–75.4%	Duarte et al. (2018)
37–45% efficiency in automotive fuel use, implied by light vehicle fuel efficiency standards	49.99–50.63%	Wang et al. (2019)
Changes in energy efficiency due to fluctuations in global oil prices	95.26–104.57%	Sun et al. (2021)

run (Wei, 2010). In the reviewed studies, the cost of the introduced EEI has been considered by assuming a decline in labor and capital productivity in each sector (Allan et al., 2009; Peng et al., 2019) and assuming the efficiency improvement is financed by public expenditure (Figus et al. 2017, 2019). In these studies, the introduced EEI keeps exogenous rather than endogenously determined by its cost. This is reasonable as we focus on the rebound effects caused by energy efficiency improvement.

It might make a study on the rebound effects of an EEI more attractive if the costs to realize an EEI is considered jointly with the EEI when the rebound effects are estimated in the study. However, the rebound effects modified by the costs of an EEI may complicate and confuse the issue since it makes it harder to compare the estimated rebound effects across different studies. Hence, we suggest reporting the rebound effects of an EEI estimated without considering any of its costs, even in a study that introduces a costly EEI.

Estimates of rebound effects

Table 2 also shows the estimated values of economy-wide rebound effects reported in the reviewed articles. Notice that we have also included the estimates of short-run rebound effects in addition to the long-run rebound effects focused on by Brockway et al. (2021), as the short-run rebound effects can also be necessary for short-run policy assessment.

In our list, two theoretical studies (Wei, 2010; Rocha and de Almeida, 2021) have not excluded any possible values of rebound effects. Most of the numerical CGE studies reported positive rebounds even backfire. However, if a study reports backfire, generally low positive rebound effects are also reported, indicating the uncertainty associated with the estimates.

In all the reviewed studies assuming exogenous EEI only, only three studies (Turner, 2009; Yu et al., 2015; Zhou et al., 2018) have reported negative rebound effects due to reduced energy supply. Improved energy efficiency will reduce the energy supplier's profitability and energy supply, which discourages capital investment and reduces supply capacity in the long run, a phenomenon 'disinvestment' called by Turner (2009). Besides negative long-run rebound effects, the induced reduction in energy supply in short-run can also be strong enough to generate negative short-run rebound effects, as reported by Yu et al. (2015) in the case of no inter-fuel substitutability when an EEI is introduced to coal or electricity used by all production sectors in China.

On the contrary, all the studies introducing exogenous EEI together with other policy measures have reported negative rebound effects, as shown in Table 2. The additional policy measures in these studies include fossil subsidy reform, carbon and energy taxes, and efficiency improvement of capital and labor used by renewable energy production. All these additional measures discourage energy use instead of encouraging energy use by introducing higher energy use costs, thus, leading to negative rebound effects.

On the other hand, all the studies where the EEI was derived from other policy measures reported positive economy-wide rebound effects. These EEIs were derived to meet given targets to reduce energy use and CO_2 emissions, fuel efficiency standards, or responses to changes in global oil prices. This is broadly consistent with the largest group of studies assuming exogenous EEI only.

Even though the short-run economy-wide rebound effects are also included in the reviewed CGE studies in this review, we largely confirm that the economy-wide rebound effects may take back over half of the energy savings from improved energy efficiency, as concluded by Brockway et al. (2021). Furthermore, we emphasize that negative economy-wide rebound effects may appear even in the short run and become more likely if an EEI is jointly implemented with other policy measures that drive the costs of energy use higher.

Notice that in this review, we will not repeat the critical analysis provided by Brockway et al. (2021) on the various reasons behind the wide range of economy-wide rebound effects, such as regional sensitivity, the importance of elasticities of substitution between energy and other inputs, whether long-run rebound effects are larger, and the differences between the effects of an EEI by households and an EEI by producers.

Conclusions

This article reviewed the literature that used CGE models to study the rebound effect of energy efficiency improvements based on the relevant studies in the past two decades selected from the WoS database. Studies were selected and analyzed through machine screening and manual inspection by reading the articles' titles, abstracts, keywords, and in some cases, the full text.

We found that more CGE studies on rebound effects appeared over time, following the same trend as the literature on rebound effects. The UK, China, and Spain were the most studied countries, while little research has focused on regions like India and Africa. This might depend on a specific researcher interested in the topic in a country. Static and recursive dynamic CGE models are almost equally used in the literature and relatively few used forward-looking models. CES functional forms were typically used by the CGE models in these studies. The EEI was typically introduced exogenously either alone, derived from other policy measures, or jointly with other policy measures. The estimated economy-wide rebound effects are generally positive, with relatively a few showing backfire or negative. Negative rebound effects were occasionally reported in the short run and more frequently in joint implementation of exogenous EEI and other policy measures that drive energy use cost higher.

These findings suggest further research efforts to estimate rebound effects based on CGE models. For example, the study on India and Africa can be encouraged to fill in the regional gaps in the field. Production functional forms other than CES can be used in CGE studies to explore whether different functional forms affect the estimates of rebound effects. The conditions for negative rebound effects could be further explored to provide an attractive solution for decoupling energy use and carbon emissions from economic growth.

Acknowledgements We are grateful for constructive comments from three anonymous reviewers.

Funding This study was financially supported by the Research Council of Norway (grant no. 303486) and Diku–Norwegian Agency for International Cooperation and Quality Enhancement in Higher Education (Grant no. NGSC-CN-2021/0008).

Declarations

Conflict of interest The authors declare no competing interests.

References

Allan, G., Gilmartin, M., McGregor, P. G., Swales, J. K., & Turner, K. (2009). *Modeling the economy-wide rebound effect, Energy efficiency and sustainable consumption* (pp. 69–98). Springer.

Allan, G., Hanley, N., McGregor, P., Swales, K., & Turner, K. (2007). The impact of increased efficiency in the industrial use of energy: A computable general equilibrium analysis for the United Kingdom. *Energy Economics, 29*, 779–798.

Babiker, M., Gurgel, A., Paltsev, S., & Reilly, J. (2009). Forward-looking versus recursive-dynamic modeling in climate policy analysis: A comparison. *Economic Modelling, 26*, 1341–1354.

Barberán, A., Bates, S. T., Casamayor, E. O., & Fierer, N. (2012). Using network analysis to explore co-occurrence patterns in soil microbial communities. *The ISME journal, 6*, 343–351.

Barkhordar, Z. A. (2019). Evaluating the economy-wide effects of energy efficient lighting in the household sector of Iran. *Energy Policy, 127*, 125–133.

Bataille, C., & Melton, N. (2017). Energy efficiency and economic growth: A retrospective CGE analysis for Canada from 2002 to 2012. *Energy Economics, 64*, 118–130.

Berner, A., Bruns, S., Moneta, A., & Stern, D. I. (2022). Do energy efficiency improvements reduce energy use? Empirical evidence on the economy-wide rebound effect in Europe and the United States. *Energy Economics, 110*, 105939.

Broberg, T., Berg, C., & Samakovlis, E. (2015). The economy-wide rebound effect from improved energy efficiency in Swedish industries–A general equilibrium analysis. *Energy Policy, 83*, 26–37.

Brockway, P. E., Sorrell, S., Semieniuk, G., Heun, M. K., & Court, V. (2021). Energy efficiency and economy-wide rebound effects: A review of the evidence and its implications. *Renewable & Sustainable Energy Reviews, 141*, 110781.

Brookes, L. (1990). The greenhouse effect: the fallacies in the energy efficiency solution. *Energy policy, 18*, 199–201.

Davis, J., Mengersen, K., Bennett, S., & Mazerolle, L. (2014). Viewing systematic reviews and meta-analysis in social research through different lenses. *SpringerPlus, 3*, 1–9.

Duarte, R., Rebahi, S., Sánchez-Chóliz, J., & Sarasa, C. (2014). Households' behaviour and environmental emissions in a regional economy. *Economic Systems Research, 26*, 410–430.

Duarte, R., Sánchez-Chóliz, J., & Sarasa, C. (2018). Consumer-side actions in a low-carbon economy: A dynamic CGE analysis for Spain. *Energy Policy, 118*, 199–210.

Figus, G., Lecca, P., McGregor, P., & Turner, K. (2019). Energy efficiency as an instrument of regional development policy? The impact of regional fiscal autonomy. *Regional Studies, 53*, 815–825.

Figus, G., McGregor, P. G., Swales, J. K., & Turner, K. (2020). Do sticky energy prices impact the time paths of rebound effects associated with energy efficiency actions? *Energy Economics, 86*, 104657.

Figus, G., Turner, K., McGregor, P., & Katris, A. (2017). Making the case for supporting broad energy efficiency programmes: Impacts on household incomes and other economic benefits. *Energy Policy, 111*, 157–165.

Font Vivanco, D., Nechifor, V., Freire-González, J., & Calzadilla, A. (2021). Economy-wide rebound makes UK's electric car subsidy fall short of expectations. *Applied Energy, 297*, 117138.

Freire-González, J. (2019). Does water efficiency reduce water consumption? the economy-wide water rebound effect. *Water Resources Management, 33*, 2191–2202.

Freire-González, J. (2020). Energy taxation policies can counteract the rebound effect: analysis within a general equilibrium framework. *Energy Efficiency, 13*, 69–78.

Freire-González, J., & Ho, M. S. (2021). Voluntary actions in households and climate change mitigation. *Journal of Cleaner Production, 321*, 128930.

Geng, S., Wang, Y., Zuo, J., Zhou, Z., Du, H., & Mao, G. (2017). Building life cycle assessment research: A review by bibliometric analysis. *Renewable and Sustainable Energy Reviews, 76*, 176–184.

Gillingham, K., Rapson, D., & Wagner, G. (2016). The rebound effect and energy efficiency policy. *Review of Environmental Economics and Policy, 10*, 68–88.

Glomsrød, S., & Taoyuan, W. (2005). Coal cleaning: A viable strategy for reduced carbon emissions and improved environment in China? *Energy Policy, 33*, 525–542.

Grepperud, S., & Rasmussen, I. (2004). A general equilibrium assessment of rebound effects. *Energy economics*, 26(2), 261–282.

Guerra, A.-I., & Sancho, F. (2010). Rethinking economy-wide rebound measures: An unbiased proposal. *Energy Policy, 38*, 6684–6694.

Hanley, N., McGregor, P. G., Swales, J. K., & Turner, K. (2009). Do increases in energy efficiency improve environmental quality and sustainability? *Ecological Economics, 68*, 692–709.

Holmøy, E. (2016). The development and use of CGE models in Norway. *Journal of Policy Modeling, 38*(3), 448–474.

IPCC. (2007). In C. W. Team, R. K. Pachauri, & A. Reisinger (Eds.), *Climate Change 2007: Synthesis Report. Contribution of Working Groups I, II and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* (p. 104). IPCC.

Jevons, W.S., 1866. The coal question; an inquiry concerning the progress of the nation and the probable exhaustion of our coal-mines.

Khazzoom, J. D. (1980). Economic implications of mandated efficiency in standards for household appliances. *The energy journal, 1*(4).

Khoshkalam Khosroshahi, M., & Sayadi, M. (2020). Tracking the sources of rebound effect resulting from the efficiency improvement in petrol, diesel, natural gas and electricity consumption: A CGE analysis for Iran. *Energy, 197*, 117134.

Kim, K. I. (2019). Investigation of Japanese electricity industry using a CGE model of translog function. *Journal of Economic Structures, 8*(1), 20.

Klump, R., McAdam, P., & Willman, A. (2012). The normalized CES production function: theory and empirics. *Journal of Economic Surveys, 26*, 769–799.

Koesler, S., Swales, K., & Turner, K. (2016). International spillover and rebound effects from increased energy efficiency in Germany. *Energy Economics, 54*, 444–452.

Kulkarni, A. V., Aziz, B., Shams, I., & Busse, J. W. (2009). Comparisons of citations in Web of Science, Scopus, and Google Scholar for articles published in general medical journals. *Jama, 302*, 1092–1096.

Kulmer, V., & Seebauer, S. (2019). How robust are estimates of the rebound effect of energy efficiency improvements? A sensitivity analysis of consumer heterogeneity and elasticities. *Energy Policy, 132*, 1–14.

Langarita, R., Cazcarro, I., Sánchez-Chóliz, J., & Sarasa, C. (2021). The role of fiscal measures in promoting renewable electricity in Spain. *Energy Conversion and Management, 244*, 114480.

Lecca, P., McGregor, P. G., Swales, J. K., & Turner, K. (2014). The added value from a general equilibrium analysis of increased efficiency in household energy use. *Ecological Economics, 100*, 51–62.

Lemoine, D. (2020). General equilibrium rebound from energy efficiency innovation. *European Economic Review, 125*, 103431.

Li, H., Bao, Q., Ren, X., Xie, Y., Ren, J., & Yang, Y. (2017). Reducing rebound effect through fossil subsidies reform: A comprehensive evaluation in China. *Journal of Cleaner Production, 141*, 305–314.

Li, H., Jiang, H.-D., Yang, B., & Liao, H. (2019). An analysis of research hotspots and modeling techniques on carbon capture and storage. *Science of the total environment, 687*, 687–701.

Liang, Q.-M., Fan, Y., & Wei, Y.-M. (2009). The effect of energy end-use efficiency improvement on China's energy use and CO2 emissions: A CGE model-based analysis. *Energy Efficiency, 2*, 243–262.

Liu, H. X., Du, K. R., & Li, J. L. (2019a). An improved approach to estimate direct rebound effect by incorporating energy efficiency: A revisit of China's industrial energy demand. *Energy Economics, 80*, 720–730.

Liu, Y., Wei, T., & Park, D. (2019b). Macroeconomic impacts of energy productivity: a general equilibrium perspective. *Energy Efficiency, 12*, 1857–1872.

Lu, Y., Liu, Y., & Zhou, M. (2017). Rebound effect of improved energy efficiency for different energy types: A general equilibrium analysis for China. *Energy Economics, 62*, 248–256.

Mahmood, A., & Marpaung, C. O. P. (2014). Carbon pricing and energy efficiency improvement -- why to miss the interaction for developing economies? An illustrative CGE based application to the Pakistan case. *Energy Policy, 67*, 87–103.

Meho, L. I., & Yang, K. (2007). Impact of data sources on citation counts and rankings of LIS faculty: Web of Science versus Scopus and Google Scholar. *Journal of the american society for information science and technology, 58*, 2105–2125.

Mulrow, C. D. (1994). Systematic reviews - Rationale for systematic reviews. *British Medical Journal, 309*, 597–599.

Nordhaus, W. (2019). Climate change: the ultimate challenge for economics. *American Economic Review, 109*, 1991–2014.

Otto, V. M., Löschel, A., & Reilly, J. (2008). Directed technical change and differentiation of climate policy. *Energy Economics, 30*, 2855–2878.

Peng, J.-T., Wang, Y., Zhang, X., He, Y., Taketani, M., Shi, R., & Zhu, X.-D. (2019). Economic and welfare influences of an energy excise tax in Jiangsu province of China: A computable general equilibrium approach. *Journal of Cleaner Production, 211*, 1403–1411.

Pereira, A. M., & Pereira, R. M. (2016). Reducing carbon emissions in Portugal: the relative roles of fossil fuel prices, energy efficiency, and carbon taxation. *Journal of Environmental Planning and Management*, 60(10), 1825–1852.

Pui, K. L., & Othman, J. (2017). Economics and environmental implications of fuel efficiency improvement in Malaysia: A computable general equilibrium approach. *Journal of Cleaner Production, 156*, 459–469.

Rajabi, M. (2022). Dilemmas of energy efficiency: A systematic review of the rebound effect and attempts to curb energy consumption. *Energy Research & Social Science, 89*, 102661.

Rocha, F. F. D., & Almeida, E. L. F. D. (2021). A general equilibrium model of macroeconomic rebound effect: A broader view. *Energy Economics, 98*, 105232.

Sarasa, C., & Turner, K. (2021). Can a combination of efficiency initiatives give us "good" rebound effects? *Energy, 235*, 121335.

Saunders, H. D. (2000). A view from the macro side: rebound, backfire, and Khazzoom–Brookes. *Energy policy, 28*, 439–449.

Saunders, H. D. (2008). Fuel conserving (and using) production functions. *Energy Economics, 30*(5), 2184–2235. https://doi.org/10.1016/j.eneco.2007.11.006

Shen, K., & Whalley, J. (2013). *Capital-labor-energy substitution in nested CES production functions for China*. National Bureau of Economic Research.

Skelton, A. C. H., Paroussos, L., & Allwood, J. M. (2020). Comparing energy and material efficiency rebound effects: an exploration of scenarios in the GEM-E3 macroeconomic model. *Ecological Economics, 173*, 106544.

Sun, H., Lu, S., & Solaymani, S. (2021). Impacts of oil price uncertainty on energy efficiency, economy, and environment of Malaysia: stochastic approach and CGE model. *Energy Efficiency*, 14, 1–17.

Turner, K. (2009). Negative rebound and disinvestment effects in response to an improvement in energy efficiency in the UK economy. *Energy Economics, 31*, 648–666.

Turner, K. (2013). " Rebound" effects from increased energy efficiency: A time to pause and reflect. *The Energy Journal, 34*(4).

Turner, K., & Hanley, N. (2011). Energy efficiency, rebound effects and the environmental Kuznets Curve. *Energy Economics, 33*, 709–720.

Vivanco, D. F., Nechifor, V., Freire-González, J., & Calzadilla, A. (2021). Economy-wide rebound makes UK's electric car subsidy fall short of expectations. *Applied Energy*, 297, 117138.

Wang, J., Quiggin, J., & Wittwer, G. (2019). The rebound effect of the Australian proposed light vehicle fuel efficiency standards. *Economic Analysis and Policy, 61*, 73–84.

Wang, N., & Wei, W. (2019). China's regional rebound effect based on modelling multi-regional CGE. *Applied Economics, 51*, 5712–5726.

Wei, T. (2010). A general equilibrium view of global rebound effects. *Energy Economics, 32*, 661–672.

Wei, T., & Liu, Y. (2017). Estimation of global rebound effect caused by energy efficiency improvement. *Energy Economics, 66*, 27–34.

Yu, X., Moreno-Cruz, J., & Crittenden, J. C. (2015). Regional energy rebound effect: The impact of economy-wide and sector level energy efficiency improvement in Georgia, USA. *Energy Policy, 87*, 250–259.

Zhou, M., Liu, Y., Feng, S., Liu, Y., & Lu, Y. (2018). Decomposition of rebound effect: An energy-specific, general equilibrium analysis in the context of China. *Applied Energy, 221*, 280–298.