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TOPICAL REVIEW

The rebound effect representation in climate and energy models

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Abstract

We review the state-of-the-art and common practice of climate and energy modeling vis-á-vis the rebound literature. In particular, we study how energy system and economy-wide models include and quantify rebound effects—the gap between actual and expected saving or the behavioral adjustment in response to an energy efficiency improvement, in terms of energy or greenhouse gas emissions. First, we explain the interaction between drivers of energy efficiency improvements, energy efficiency policies, and the rebound effect to provide a framework for a general theoretical revision from micro- to macro-economic levels. Using this classification, we analyze rebound effect representations in empirical models by four dimensions: actors (industry or the production side, and private households or the consumption side), the aggregation level (from micro- to macro-economic levels), income level (developed or developing countries), and time (short- and long-run). Furthermore, we review rebound effect studies whose models focus on three drivers of energy efficiency improvements: market-based policies, non-market-based policies, and a costless energy efficiency improvement that holds other attributes constant (zero-cost breakthrough). We find that a clear representation of one or simultaneous drivers of energy efficiency improvements is crucial to target the goals of energy savings, greenhouse gas mitigation, and welfare gains. Under this broader view, the rebound effect is one additional phenomenon to be taken into consideration. This perspective provokes and provides additional policy implications. Reporting rebound effects as a stand-alone percentage is not sufficiently informative for policy considerations and the distinction of the aggregation level is important to asses the scalability of energy efficiency policies. Finally, we identify some ideas and motivations for future research.

1. Introduction

Under the umbrella of the 17 Sustainable Development Goals of the United Nations (UN 2015), goals such as sustainable economic growth, responsible production and consumption, affordable clean energy, and climate action have promoted the implementation of a cluster of energy efficiency (EE) and climate policies as part of the global agenda. Some examples include the promotion of EE standards, energy savings, sufficiency strategies, greenhouse gas (GHG) emission reductions or renewable energy targets. In particular, due to the existence of the EE gap as a result of market failures (Jaffe and Stavins 1994, Gillingham and Palmer 2014), EE policies are often being implemented worldwide as seemingly win-win and cost-effective policies. However, the goals of these policies imply a complex web of non-linear interactions that are not yet well understood (Jenkins *et al* 2011). Borenstein (2013) and Schmitz and Madlener (2020) argue that a reduction in energy consumption is not the end goal, but reducing fossil fuel and GHG emissions is, while Freire-González (2017b) proposes that either one or both might be ultimate goals. Van den Bergh (2011) concludes that EE improvement (EEI) should not be a stand-alone policy goal, and

Azevedo (2014) and Pollitt (2017) introduce a multi-objective trade-off perspective between goals.

EEIs are desired results of an EE policy. Much of the controversy has focused around what level of efficiency we can obtain feasibly with energy efficiency policies, given the existence of rebound effects (REs), as illustrated in (Gillingham *et al* 2016), "*buy a more fuel-efficient car, drive more*". Thus, backfire, or the possibility that energy consumption increases by more than the energy saving levels expected from energy efficiency gains, would undermine the effectiveness of energy efficiency policies. However, very often the goal of an energy efficiency policy is not limited to reducing energy consumption, but more generally to producing less GHG (Borenstein 2013). Moreover, its effects on individual and social welfare are of utmost importance (Gillingham *et al* 2016). Hence, although the rebound effect impacts energy consumption and thereby energy savings, it would have implications for emission reductions and welfare gains as well. EEIs that might result in backfire could correlate or cause positive (or negative) effects with respect to welfare gains and GHG reduction goals, which is more evident at the macro-economic level. This ambiguity makes it difficult to assess the effectiveness of energy efficiency policies, because evaluating energy savings per se would result in an incomplete assessment of the effectiveness of an energy efficiency policy. Beyond the controversy, our paper extends the discussion on the inherent ambiguity.

At the micro-economic level, Borenstein (2013) states that backfire is unlikely, while Saunders (1992) and Saunders (2013)[6] find theoretical and historical empirical evidence of backfire on both, the micro- and macro-economic levels. Nonetheless, Gillingham *et al* (2013) calls into question the methodological validity of the previous two studies. Likewise, at the macro-economic level, Gillingham *et al* (2013) state that the RE has been overplayed because even at this level, it is highly probable that EE policies will not backfire. However, Rausch and Schwerin (2016) and Brockway *et al* (2017) find theoretical and empirical evidence of backfire. Moreover, Lemoine (2018) finds that backfire might occur, theoretically, from improvements in EE of the energy supply sector; however, empirically it might be dampened by increased consumption of non-energy inputs to production, and a size reduction of the supply sector. Gillingham *et al* (2013) address the possibility of ambiguous effects of EEIs by looking at social welfare effects. Although this view helps to extend the scope of the effectiveness of EE policies, it would still miss the important interaction with the goal of GHG reductions. Thus, in our review we include the interaction of EEIs with GHG emission reductions towards a more comprehensive assessment of EE policies and a better representation of this interaction in RE studies.

Hence, in response to the observed gaps between the micro- and macro-economic levels in the literature, we conduct a review to describe how drivers of EEIs shape the representation of REs by level of aggregation. We define the level of aggregation as the aggregation of consumers or firms going from local energy systems (micro-economic scale) to the overall level (macro-economic scale)[7]. Furthermore, we identify essential pieces necessary to build an RE model and describe methodologies found in the literature. We present findings in energy and climate models by four dimensions: level of aggregation, actors, income level, and time; taking into account heterogeneity (in terms of households, firms, energy services, goods, products, and attributes[8]). This allows us to discuss possible directions to extend the understanding of the energy rebound and the so-called "GHG rebound" effect[9]. To this end, we report on three important trade-offs between possible benefits and costs associated with drivers of EEIs: GHG reduction, welfare gains, and energy reduction. Additional impacts, such as energy security, health, labor, and other social impacts (Pollitt 2017), are beyond the scope of this review. To the best of our knowledge no empirical RE study has yet examined the interaction between energy consumption reduction, welfare impact, and GHG emission reduction.

Our article follows this structure. Section 2 defines drivers, dimensions, and effects of EEIs. In addition, it presents a summary of RE typologies and taxonomies. With these concepts at hand we aim to guide the understanding and comparison of empirical studies. Section 3 explains the methodologies and summarizes common results of empirical studies categorized by level of aggregation, actor, income level, and time. Section 4 concludes with a discussion on climate and energy modeling for policy decision making, and section 5 summarizes future research directions and perceived research needs.

2. From drivers to effects of EEIs

2.1. Drivers of EE

A first crucial step of modeling geared towards the representation and calculation of the rebound effect and its components is to clearly identify the driver that might potentially be causing the planned or observed EEI. The conceptualization of the driver might result in different ways to represent an EEI. The main three drivers of EEIs identified in our literature review are: market-based policies, non-market-based

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[6] See Cullenward and Koomey (2016) and Saunders (2017) for additional discussions.

[7] See Madlener and Turner (2016) for a distinction between economy-wide and macro-economic scales.

[8] See Gillingham *et al* (2016) for a definition of the concept.

[9] On the conversion of the energy rebound in terms of CO_2 emissions, see Birol and Keppler (2000) and Chitnis *et al* (2014).

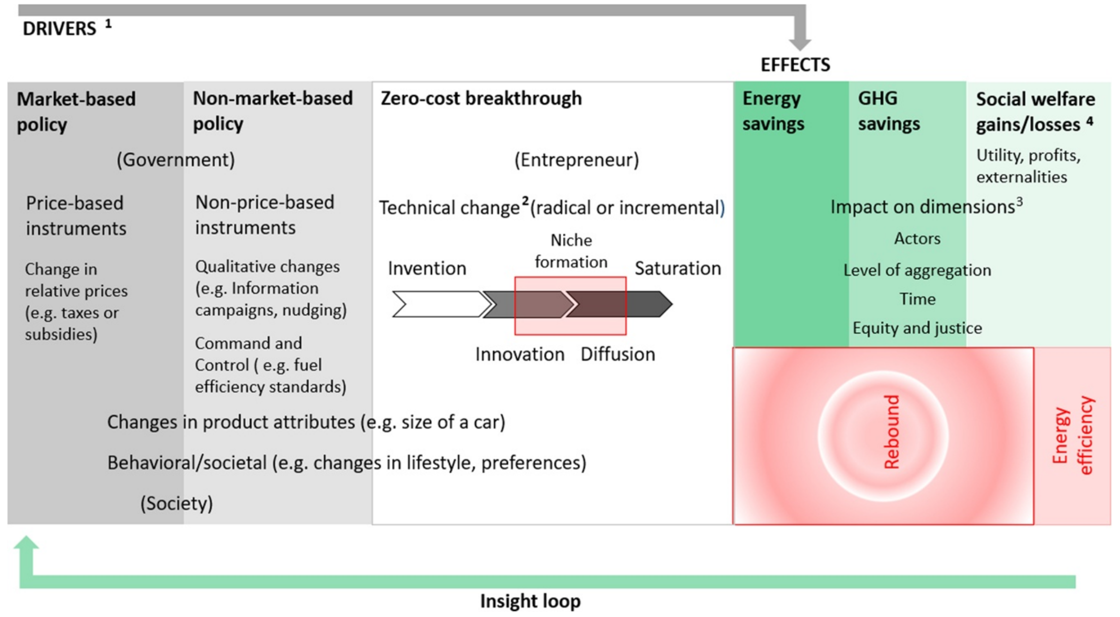

Figure 1. Possible drivers (or causes) and effects of an EEI.

policies and zero-cost breakthroughs[10], see figure 1. And although we isolate a driver or possible cause of an EEI, its causal relationship can be tested only on rare occasions. A second step would be to choose one or several dimensions in which an EEI might result in an effect. Throughout our paper, we distinguish between four dimensions for the study of an EEI: the level of aggregation (of each actor separately or jointly); actors (producers and consumers) income level (e.g. in developing and developed countries); and time (short- and long-run effects). A third step is to analyze correlations (or causal relationships) between relevant effects. The effects that we identify as the most relevant for current policy debate are: energy savings, GHG savings, and social welfare. Finally, after disentangling these concepts, one could estimate the energy or GHG RE. Figure 1 [11] illustrates a roadmap to walk the reader through drivers of EEIs, dimensions, and effects.

The way we think about EEIs is at the core of the energy RE representation. After identifying the drivers of EEIs, we now ask ourselves: What kind of energy improvement representation[12] would make our quantitative studies more reliable?

A clear definition of the term "energy service" in studies with explicit representations of EEIs is important for reproducibility and to contribute to objective debates on EE policies. To better identify drivers of EEIs in order to model REs, we explain the main three drivers: market-based policy, non-market-based policy, and zero-cost breakthrough (shown above in figure 1).

As a potential first driver of an EEI, **a market-based policy** is sometimes modeled by means of price-based instruments. It is important to notice that some types of EEIs could arise from market-based policies, non-market-based policies, or zero-cost breakthroughs. This could result in a different formulation of the EEI.

Price-based instruments.- These are instruments that produce a change in relative prices, such as taxes or subsidies for households or/and industries. Taxes imposed on the production side include energy and carbon taxes, whereas on the consumption side, they include taxes on energy-intensive goods (e.g. private transport fuels). Subsidies for the production side could come in the form of R&D investment to foster low-emission technologies and utility-sponsored rebate programs, while for the consumption side these might include subsidies for the adoption of low-pollutant emission devices, e.g. rooftop solar technologies, light bulbs, or electric cars. To the best of our knowledge, market-based policy EEIs including bundles of attributes have not been modeled yet on the production side. In particular, when a change in relative prices is introduced by a tax to promote energy savings, a rebound is no longer a possible effect of concern within the energy domain;

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[10] A zero-cost breakthrough energy efficiency improvement is a costless exogenous increase in energy efficiency holding other product attributes constant. A market-based policy change in energy efficiency is typically costly, a result of an energy efficiency policy, and bundled with changes in other product attributes (or including heterogeneity), see Gillingham *et al* (2016).

[11] We thank Ken Gillingham for comments on this representation.

[12] A summary of energy efficiency and rebound effect formulations at the micro- and macro-economic levels can be found in appendix 1.

however, a tax could still be a cause of rebound with respect to GHG savings and welfare gains or losses.

Change in product attributes.- When we represent EEI induced by a market-based policy, most often the energy service that a unit of energy provides is not only a function of useful work derived from a more energy-efficient device but is also a function of its attributes other than energy conversion efficiency. An attribute is a non-EEI in a characteristic of a product (or energy service), such as size (e.g. computer), comfort, reliability, speed, or acceleration (Sorrell and Dimitropoulos 2008). Examining a household vehicle portfolio, Archsmith *et al* (2017) found that complementarity and substitution effects between energy and non-energy inputs are not the only causes of lost energy savings; they found that bundles of attributes may also interact in a way that reduces energy savings, eroding as much as 60% of fuel savings from an increase in fuel efficiency, thus compromising the cost-effectiveness of EE policies. In another study, Galvin (2017) examined how average increases in the vehicle-speed attribute (acceleration) can be incorporated into calculations of energy rebounds, showing that the relationship between energy services and energy consumption levels might be non-linear. The main insight was that it is possible to completely expunge EE increases by interactions between both speed and acceleration. Studies in computing services, such as in Galvin and Gubernat (2016), also reveal the importance of representing attribute parameters in models.

Behavioral/societal.- Lifestyle and consumer change of preferences in time, or reprogramming of preference orderings to change a determined habitual behavior (i.e. shift to public transport, healthier diets) could also play a complementary role in meeting energy reduction and climate change targets. A change in consumer patterns might arise from self- or externally- (i.e. commonly attained by policies) imposed rules. In this scenario, a change in preferences is not seen as a potential source of undesirable outcomes (Elster 2000), but is consciously placed in order to achieve desired better outcomes and consistency in time. Using a computable general equilibrium (CGE) model, Duarte *et al* (2016) found that promoting public transport was a successful economic and environmental policy for Spain. Moreover, Bjelle *et al* (2018) examined a set of 34 possible behavioral actions to be undertaken in Norwegian households; they found that people could potentially reduce their carbon footprint by 58%. In Sweden, Grabs (2015) calculated that switching to a vegetarian diet can save 16% of energy use and lower GHG emissions by 20% related to their dietary consumption, with corresponding energy RE of 96% and GHG rebounds of 49%. However, this study only focused on income effects. Finally, Chitnis and Sorrell (2015) recommended including a lagged variable in studies to capture inertia in energy prices (habit formation), which can help to mitigate correlation problems and at the same time better reflect behavioral change/consumer behavior.

A second potential driver of EEIs is a **non-market-based policy** which could arise as qualitative changes, Command and Control instruments (CaC), change in product attributes, or behavioral/societal changes (the last two as explained previously, without government intervention).

Qualitative changes.- Without the use of a change in prices, the government could intervene by increasing quality or accessibility to information. Moreover, softer interventions include the use of nudges.

Command and Control instruments.- For the production side, these might include technology mandates (i.e. fixed input-output (IO) ratios restricting production flexibility) (Landis and Böhringer 2019), and performance standards on both the producer and consumer side (e.g. minimum EE standards, caps on residential energy use or residential energy intensity (Bye *et al* 2018).

As a third potential driver, we explore how EEIs are studied as a **zero-cost breakthrough**.

Technical change.- In general terms, an exogenous zero-cost breakthrough technical change can be modeled as neutral (also referred to as 'unbiased', i.e. equal reduction of all inputs), or non-neutral (also called "biased", i.e. some inputs are reduced more than others) (Broadstock *et al* 2007), where an EEI is given at a specific point in time, or as factor-augmenting (assuming a rate of growth of EEI over time). A clear distinction between a neutral technical change or a relative effect on inputs (affecting total factor productivity) or the effect on outputs, might reduce bias in estimations (Du and Lin 2015). Outputs might cause structural changes in the economy (e.g. growth of the share of services in the economy) via substitution of products between energy-intensive and non-energy-intensive sectors (Bibas *et al* 2015). In Frieling and Madlener (2016), Frieling and Madlener (2017a), and Frieling and Madlener (2017b) technical change is represented as an exogenous constant or linear time trend, while Schmitz and Madlener (2020) explore a quadratic trend. Technical change can be represented using a latent variable approach (market-based policy or zero-cost breakthrough EEI), depending on past energy prices (Hunt *et al* 2014). Moreover, it can be represented as energy source prices, relative prices, real prices, growth rates, or a reduction in discount rates. It is represented also as a reduction in the costs of technologies or price-diminishing (e.g. labeling and perceived costs) (Löschel 2002, Löschel and Schymura 2013). Representing energy improvements as induced or endogenous technical change might produce a more accurate representation of the overall RE (Löschel 2002, Witajewski-Baltvilks *et al* 2017). Endogenous technical change has been far less studied in energy system models (Gillingham *et al*

2016), but is more often considered in economy-wide studies and Integrated Assessment models. Otto *et al* (2007), Otto *et al* (2008) and Löschel and Otto (2009) develop and apply an endogenous model of energy-biased technical change with knowledge capital stocks and technology externalities in innovation and production. Therefore, an induced technical change as an EEI might be more accurate for the representation of REs on the producer side.

The increasing interest in climate policies leads to a more detailed analysis of energy REs in terms of GHG emissions, whereby the RE triggered by an increase in energy efficiency is converted into GHG emission units (the so-called "GHG rebound"). However, due to the lack of intrinsic value of carbon consumption, the incentive to increase the demand for carbon is quite weak. Thus, strictly speaking, as discussed in Birol and Keppler (2000), there exists to date no RE driven by a reduction of carbon consumption.

2.2. RE theory: typology and taxonomy

The analysis of the drivers of EEIs along the aggregation level results in the classification of types of RE through decomposition channels. To this aim, it is useful to systematically de-construct these effects into known components available in the literature. Further motivations to parse the RE involve linking the theoretical point of view to empirical calculations, and exploring causal effects whenever possible. Hence, tables 1 and 2 combine the typology and taxonomy of the RE from two perspectives: that of (1) a producer of energy services, and (2) an end-use consumer; and similarly from a combined perspective, along the aggregation level. These tables have gathered the contributions in the literature about the underpinnings of the RE, traditionally from Khazzoom (1980), Saunders (1992), Greening *et al* (2000), Berkhout *et al* (2000), and Birol and Keppler (2000), to more recent contributions from Van den Bergh (2011), Saunders (2013), Borenstein (2013), Azevedo (2014), Gillingham *et al* (2016), Madlener and Turner (2016), and Santarius (2016).

3. Modeling the RE

In a similar vein as in Varian (2016), in sections 1 and 2 we identified some essential pieces necessary to build an RE model. From possible causes or drivers of EE to existing rebound formulations, in this section we now turn to describe common methodologies found in the literature, used to model the RE.

In general, modelers seek to get a closer look at how energy is being consumed in real settings by collecting data to use in models, and/or studying treatment effects (i.e. of energy efficiency policies). They decide on (1) the representation of an EEI, (2) a mathematical representation of the RE, and in most cases (3) the economic theory, assuming a choice faced by a representative consumer (utility maximization), a producer (profit maximization), or a consumer-producer (”prosumer”, household-factory) that integrates production and consumption (a household produces energy services by minimizing costs in order to maximize utility derived from those energy services) (Becker 1965, Scott 1980), and (4) to include a degree of heterogeneity of actors (households or firms), energy services, goods, products, or attributes.

Our review has grouped energy- and economy-wide studies under the following categories: Structural models, Econometric studies, Simulation studies, and Integrated Assessment models. We present general assumptions for each type of model[13], report on EEIs as drivers for RE representations, and show results of empirical studies between 2016 and 2018. Using the tables depicted in appendix B, we categorize the EE driver or RE channel used in studies according to the discussion provided in section 2.

3.1. Structural models of neoclassical economic growth

Structural models have been the most common means to calculate direct REs as represented in appendix 1, equations (A1) to (A3). They include preferences and technology using observed past behavior (a characteristic of ex-post studies, often econometric studies) to estimate fundamental parameters.

3.1.1. Energy system structural models

The approach with these types of models is to adopt an industrial (or household) production functional form of first- or second-order of approximation or, alternatively, a derived cost function, such as, Leontief, generalized Leontief, Cobb-Douglas, CES (Solow), nested CES (Solow), generalized Barnett, generalized McFadden, Gallant, Fourier function (Saunders 2008, Saunders 2015), the Rotterdam model, or the translog function (Saunders 2013, Mishra 2011, Frieling and Madlener 2016, Frieling and Madlener 2017a, and Frieling and Madlener 2017b). To identify the substitution (output) effect and the income effect for consumption (production), it is common to use decomposition methods to calculate elasticities, such as the implicit function theorem. Other sets of structural models represent household demand, and allow to compute direct and indirect REs. Some examples include almost ideal demands (AIDs) (Deaton and Muellbauer 1980) or linearized AIDs with multi-stage budgets (Thomas and Azevedo 2013a, Schmitz and Madlener 2020), linear expenditure systems (Lin and Liu 2015), direct addilog, indirect addilog (Thomas 2012), double-log systems (Freire-González 2017a). Parameters are obtained

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[13] There might be some overlap between structural models and econometric studies; however, our criteria for categorization is based on the degree of flexibility allowed by each type.

Table 1. Rebound typology representation along the micro-economic level of aggregation.

Actor	Rebound typology[a]	Decomposition channel	Taxonomy
Consumer	(1) Direct rebound[b]	1.1 Substitution (+)	Own/price elasticity of demand, substitution to consume more of good 0 due to price reduction.
		1.2 Income[c] (+)	Free income used to consume more of good 0 due to price reduction.
	(2) Compensating cross-elasticies[b]	2.1 Fixed income (-)	Expenditure on good 0 takes away expenditure on other goods with energy content.
	(3) Indirect rebound	3.1. Substitution (-)	Cross-price elasticity of demand for other goods, substitution to consume less of other goods due to more consumption of good 0.
		3.2 Income[c] (+)	Consuming more of other goods due to savings on good 0 (re-spending effect).
		3.3 Embodied energy (+)	Energy or emissions associated with the lifecycle of an energy service.
		3.4 Behavioral (+)	Indirect rebounds not caused by EE improvement, but by changes in consumption behaviors.
	(4) Time savings	4.5 Time[d]	Available time that individuals have to spend on other activities that use energy.
Producer meso-level (sectoral)	(5) Direct rebound	5.1 Factor substitution (+)	Substitution to use more energy input 0 due to cost reduction (e.g. automation).
		5.2 Output (+)	Free expenditure (savings) to use more energy input 0 due to cost reduction resulting in increased production.
	(6) Indirect rebound	6.1 Factor substitution (-)	Substitution to use less of other inputs due to cost reduction.
		6.2 Output (+)	Free expenditure (savings) to use more of other inputs due to cost reduction resulting in increased production (Re-investment effect).
		6.3 Embodied energy (+)	Investments in energy efficiency technologies increase demand for energy (Grey energy).
	(7) Complementary rebound	7.1 Redesign(+)	Ex-ante expected cost savings for consumers lead producers to invest in redesigning the original product.

[a] There also exist the less-studied transformational rebound effects (Greening *et al* 2000), and motivational psychological rebound effects (Santarius 2016).

[b] Terms (1) and (2) are called the net direct rebound effect (Borenstein 2013).

[c] Both income effects (1.2 and 3.2) can be subsumed into the income effect rebound (Borenstein 2013).

[d] Introduced by Binswanger (2001), new studies such as Mizobuchi *et al* (2018) present theory and evidence of (small) time rebound effects of 1.4%, while Shao and Rodriguez-Labajos (2016) find evidence of time rebound effects in developed countries, in which a decrease in working time might lead to an increase in energy-intensive leisure activities with high carbon footprints.

Table 2. Rebound typology representation along the macro-economic level of aggregation.

Actor	Rebound typology[a]	Decomposition channel	Taxonomy
Producer and Consumer interaction[b]	(8) Interactive	8.1 Market price (+)	Increased aggregate energy demand due to reduction in the market price of energy services, leading to a decrease in the demand for a particular fuel. Reinforcing effect from market price on the consumer side income effect. Interplay from a firm, sector or numerous individual households up to the level of a sector or market.
		8.2 Disinvestment (-)	Direct and derived demands are not sufficiently elastic to prevent falling market prices of energy, leading to a decline in revenue, profitability and return on capital in domestic energy supply sectors.
		8.3 Composition (+)	Reduction in market price favors energy-intensive sectors of the economy, reducing the price of energy-intensive goods and services and thus causing the increase of their demand, altering the composition of the economy's portfolio of goods.
		8.4 Economies of scale (+)	Income and market effects causing an increase in demand for energy services or goods, leading to firm expansion that reinforces falling prices, whose impact reduces along the level of production.
		8.5 Rising labor income (+)	Firms using additional income from energy efficiency of production process to raise worker's wages.
	(9) Macroeconomic	9.1 Price	The adjustment of consumers and producers following a shift to the left of the market demand curve (Economy-wide).
		9.2 Growth: Sectoral allocation	Change in efficiency of energy inputs in an energy-intensive sector may lead to this sector's grow relative to others (Equal to the composition effect but causing economic growth).
		9.3 Growth: Induced innovation	Spillover effects of an energy improvement in one sector, attributable to an improvement in another one.
		9.4 Growth: Fiscal multiplier	Freed money previously spent on energy used in new economic activity that utilizes previously idle resources. Long-term debt associated with fiscal stimulus (Multiplier effect).
		9.5 Labor supply (-)[c]	Consumers adjust their labor supply to the extent that EE has an impact on real wages. It depends on the elasticity of substitution between leisure and consumption.

[a] Further, Saunders (2013) includes so-called "frontier effects", enabling new product applications or services. In the short term, RE models include changes in energy service demands while holding capital or investments constant; in the long term, they can incorporate laws of motion for capital costs, savings, scrappage, crowding-out effects, and/or increasing market saturation of appliances (Thomas and Azevedo 2013b) in order to capture consumer responses to price changes (Gillingham *et al* 2016).

[b] More recent cases include the use or purchase of heavy units or units with more functions/services and consequently using more energy (e.g. proof of work in block-chains for microgrids (Hittinger and Jaramillo 2019)).

[c] At the macro-economic level, REs are more ambiguous than at the micro-economic level. However, Böhringer and Rivers (2018) found that the elasticity of substitution between leisure and consumption is directly related to the labor supply elasticity, which is low across the economy as a whole; thus it is likely that the RE due to this channel is (-). It is closely related to the rising labor income effect channel (8.5).

using linear or non-linear econometric methodologies (i.e. ordinary least squares, dynamic ordinary least squares, feasible generalized least squares, non-linear least squares). Usual inputs are energy (or energy commodities, services), capital, labor, and materials. Recent studies have focused on the meso-economic RE to study production-side sectoral, and interactive REs (e.g. market effects) (Santarius 2016). Tables 5 and 6 in appendix B show in detail the review of selected structural models from the production and consumption sides, and their respective RE magnitudes as percentage figures.

3.1.2. Economy-wide structural models

Aggregated production functions (APFs) using Solow's residual can also be used to approximate total energy and GHG REs at national levels, as represented in appendix 1, equations (A4) and (A5). These models assume that parameters remain unchanged, in order to predict the responses to possible economic system changes, including those that have never happened before. Therefore, they can conveniently be used to conduct welfare calculations (Nevo and Whinston 2010). Nonetheless, the major concern is that the use of an "elaborate superstructure" will provide results driven by the model rather than the data (Angrist and Pischke 2010). Table 7 in appendix B shows a review of selected structural models.

3.2. Econometric studies

To avoid restrictions imposed by ex-post structural forms as in section 3.1, empirical modelers usually turn to reduced-form statistical ex-post estimations. Additionally, Nevo and Whinston (2010) argue that welfare calculations using this methodology would be less credible, due to the variety of economic environmental change parameters possible to be estimated. Econometric studies represent the RE in two broad categories, which vary according to the aggregation level of study. The first category includes energy systems that compute the direct RE, whereas the second category contains economy-wide contexts to calculate a total national or sectoral RE. However, Acemoglu (2010) and Lemoine (2018) argue that reduced-form models should not be used as stand-alone tools to evaluate the development of policies.

3.2.1. Energy system econometric estimations

Models in this section are categorized as ex-post estimations and calculated using regression analysis (e.g. at the less-studied meso-economic level; Wang *et al* (2016), e.g. uses a double-logarithmic model to study factors affecting electricity consumption; generalized linear models, ARIMA, vector autoregression, and cointegration models. Data used to solve these models include time-series data, cross-section analysis, panel data, and stochastic frontier functions. Less common are panel instrumental variable (IV) estimators, difference-in-difference estimators, and field quasi-experimental methods. More recently, machine learning (artificial intelligence algorithms) is being used in econometric estimations as well, see table 8 in appendix B. The advantage of these types of studies is that they might demonstrate causality and derive more robust results, but exogenous variables should be carefully controlled. Reducing the scope of the model to focus on a specific energy service could provide significant insights. Though Jacobsen and Van Benthem (2015) investigate the Gruenspecht effect[14], this study is a good example of the direction that RE studies might take. This is due to several reasons: they demonstrate causality using an IV estimator to calculate an elasticity of vehicle scrapping (i.e. using gasoline prices and vehicle prices), study the change in prices due to a fuel policy, and consider heterogeneity. Finally, quasi-experimental ex-post studies could provide more realistic insights about specific EE program performance and effectiveness.

3.2.2. Macro-econometric models

Despite of the difficulties in attaining a good degree of identification with reality, these post-Keynesian ex-ante models might perform useful forecasting and policy analysis (if an effective existing rule prevails, Sims 1980). Barker *et al* (2009) was the first to study the global RE using a macro-econometric model, the so-called E3ME. The E3ME (or E3ME variant) and non-equilibrium models have been used to assess co-benefits and trade-offs of policy scenarios in European economies using multiple sets of computable econometric equations. In the E3ME model, the RE is modeled in two parts: the direct RE (equation (A2) in appendix 1) is taken from the PRIMES bottom-up model (an energy system model), and this is then used to calculate the endogenous indirect RE and the economy-wide RE (equation (A4) in appendix 1), derived from the IO structure of the model (Pollitt 2017). Inputs of the model are shared with other models such as PROMETHEUS (fossil fuels and import prices) and GEM-E3 (macroeconomic and sectoral projections) (E3MLab and IIASA 2016). The main assumption with regard to EE is that rising fuel prices will stimulate technological innovation and boost growth of the world economy, thus the endogenous representation of technological change also has implications for the calculation of the RE. The model allows varying returns of scale and non-linear substitution, and it avoids the representative agent assumption. Nonetheless, it does not allow substitution between cheaper energy services and other inputs within production and embodied energy representation. The E3ME has focused on representing, from a macro-economic point of view, the price and growth effect (sectoral allocation channel). To see a comprehensive formulation on how

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[14] This effect occurs when prices of used vehicles increase; leaving their owners little or no incentive to scrap them.

the RE has been disentangled into partial and general effects (Barker *et al* 2009, Pollitt 2017), please refer to appendix A.1.

Main results highlight the importance of capital formation modeling to account for crowding out effects (Pollitt 2016). Table 9 in appendix B shows the review of macro-econometric studies.

3.3. Simulation models

3.3.1. Energy system simulation models: IO models and environmentally-extended input-output models (EEIO)

The most comprehensive studies applying this methodology use estimates of direct REs as inputs. These ex-post static models allow the calculation of indirect REs as cross-price elasticities for n goods (or n services). Following this estimation, total REs are computed as represented in equation (A4) in appendix 1. Most studies have focused on studying indirect REs on the consumption side. These models assume that constant returns to scale, sectors producing homogeneous goods and services, and outputs are created with constant and fixed proportions of inputs (linear representation, Miller and Blair 2009). Moreover, cross-price elasticities of other goods are modeled as constant, and re-spending to be proportional in each good and service. Widely used data inputs include Consumer Expenditure Surveys, Eora Global MRIO data, EXIOBASE, the Global Trade and Analysis Project (GTAP), and the World Input-Output Database (WIOD), see table 10 in appendix B for studies on the consumption side. Modeling RE with an EEIO model, Thomas and Azevedo (2013b) found that indirect rebound effects (IREs) are inversely proportional to direct rebound effects (DREs) and are bounded by consumers' budget constraints. Freire-González (2017b) developed risk and vulnerability indicators for REs.

3.3.2. Macro-economic simulation models: CGE models

Böhringer and Löschel (2006), Allan *et al* (2007) and Turner and Figus (2016) provide comprehensive reviews on these ex-ante "what-if" neo-classical models and their applicability to model energy-economy-environment interdependencies for exploring trade-offs and co-benefits. Known models used to parse the RE include GTAP-E, WARM, SCREEN, MSG-6, ENVI-UK, ORANI-G, REMES, SNOW-NO, CEPE, WIOD-CGE, and climate models such as GRACE which could potentially be used for rebound studies (Aaheim *et al* 2018). EEIs in this review are modeled as exogenous autonomous EEI and energy-augmenting, or as endogenous technical change using a latent variable approach of a market-based policy type (taxes or subsidies on production or consumption). However, induced technical change, as in Witajewski-Baltvilks *et al* (2017) and Lemoine (2018), and the implications of diffusion effects remain to be further studied. RE is calculated using equations (7) and (8). Advances in the analysis of RE tractability have also been applied, namely the decomposition of energy and GHG REs from partial to general equilibrium, as described in section 2.5. To parse the RE in direct and indirect partial equilibrium components, as described in tables 2–5 (i.e. substitution and income effects), modelers set all prices fixed except for the energy sector or service of interest in their analysis. To calculate the general equilibrium component, commonly used channels are: price, growth (sectoral allocation), labor supply (Böhringer and Rivers 2018, Chang *et al* 2018), and growth (fiscal stimulus) (Figus *et al* 2019). Finally, the total RE is obtained summing up the partial equilibrium components and general equilibrium component (or the economy-wide component, as discussed in section 3.2.2). Sensitivity analyses are more common, thus providing robust estimates mainly on the upper bound of the spectrum. Moreover, studies have investigated the influence of RE on macro-economic parameters such as GDP, employment, etc (Madlener and Turner 2016) and on welfare (Gillingham *et al* 2016). Birol and Keppler (2000) discuss the importance of modeling real world energy markets which are far from perfect competition; bridging the gap of theoretical and actual EE levels. Along these lines, we checked the adaptation and tailoring of models for relevant interactions (e.g. imperfect markets, substitution effects, reversibility or dynamic frameworks) that might potentially impact calculations of energy and GHG rebounds (Turner and Figus 2016): (1) balance of trade (imports/exports), (2) technological change vs. economic expansion, (3) imperfect competition, (4) unemployment (labor market representation), (5) capital formation, (6) dynamic adjustment of long time frames, (7) detailed treatment of energy supply, and (8) energy consumption. For each aspect, we find that (1) Armington's CES imperfect substitution was able to include an EEI representation. (2) Most models do not integrate adjustment of capital/labor growth (or decline) with regard to EEI. (3) Revised models assumed perfect competition, except Figus *et al* (2017), Figus *et al* (2018). For (4) and (5), capital that flows freely between national sectors, investments, and labor increases gradually. (6) Recent models are not only dynamic, but also capture consumer's responsiveness (Figus *et al* 2017, Figus *et al* 2018, Chang *et al* 2018, Bye *et al* 2018, Duarte *et al* 2018), including consumer response to price changes in time, but are often also regional-specific (or spatial CGE models) (Helgesen *et al* 2018). (7) To represent energy and non-energy goods, CES or Cobb douglas functions are commonly used, and inputs in the energy sector are modeled as Leontief composites, with no possibility of substitution. (8) While EEI in total factor productivity has not commonly been modeled, it has been included from one consumer aggregate with no possibility of substitution or CES/Klein-Rubin utility preferences, to bottom-up representations that capture consumer heterogeneity and distributional impacts (Bye *et al* 2018, Landis and Böhringer 2019). Tables 11–15 in appendix B show recent studies for production and consumption.

3.4. Integrated assessment models

There are two main types of ex-ante Integrated Assessment models (IAMs) for climate policy analysis. In a broad sense, these can be classified as detailed process (DP) IAMs and benefit-cost (BC) IAMs[15]. The main difference is the way they model climate change impacts. DP IAMs are more disaggregated models that use economic valuation or physical projections to provide forecasts of climate change impacts at detailed sectoral or regional levels. In contrast, BC IAMs represent sectoral (or regional) aggregation functions and climate change mitigation costs into a single economic metric, whose main goal is to analyze potentially optimal climate policies. For a detailed overview of IAMs and their applications, see Weyant (2017). Widely used models include DICE, RICE, FUND, PAGE, IWG (which has focused on EE), MESSAGEix-GLOBIOM, IMACLIM-R, IMAGE, AIM, GCAM4, REMIND-MAgPIE, WITCH, etc Allowing flexibility about the achievement of GHG emission reductions results in lower mitigation costs across all economic assumptions; however, too much flexibility can also be detrimental to the uselfulness of models (Pindyck 2017). Moreover, delays in implementing mitigation policies would result in increases in total discounted costs of meeting particular global GHG concentrations. DP IAMs identify and directly measure impacts on sectors, regions and ecosystems in more detail, providing insights on trade-offs between mitigation and adaptation strategies on global scales, which is useful for international negotiators, and national and/or regional decision makers. Aggregated BC IAMs might help to understand the cost-effectiveness of climate policies considering mitigation and adaptation strategies. These models highlight critical cost issues (i.e. including discount rates, risks, damages, social cost curve calculations), while incorporating new scientific findings into projections (Weyant 2017). Controversy around the use of physical or economic units is also found in these types of studies. On the current development of IAM models, Pindyck (2017) finds that these models are at an early stage of development, add much noise, and would require sensitivity analysis on key parameters. Moreover, considering the time pressure exerted by climate change, he concluded that simple models to calculate upper bounds would also be useful. Moreover, Riahi *et al* (2015) and Rogelj *et al* (2018) suggest that the proportion of successful IAM scenarios could be used as an indicator of infeasibility risk. Studies included in this overview, and summarized in tables 16 and 17 in appendix B, have included drivers of EEIs as zero-cost breakthrough, market-based policy, non-marked-based policy, or a combination of the previous ones. These drivers are represented as exogenous or endogenous shocks, through equations and (or) parameters that calibrate IAMs. After selecting drivers to study, models include channels that result in REs (e.g. substitution, income, price effects, etc). However, these studies do not show what would the impact of the RE channel's representation be (i.e. potentially how much energy consumption reduction will not be feasible due to these impacts). Though some studies have found increasing evidence of demand saturation in activity levels (Grubler *et al* 2018), RE magnitudes might also be used as parameters to run sensitivity scenario cases.

4. Conclusions

As far as the laws of mathematics refer to reality, they are not certain;
and as far as they are certain, they do not refer to reality.
(A. Einstein)

4.1. Model identification: a trade-off between theory and reality

Overall, the diverse nature of empirical models reviewed in this study contribute to the understanding of the RE from the production and consumption side. Moreover, given the tension between theory and reality, to reach 'reasonable' level of identification, we think it is good practice to have a clear picture about the motivation behind modeling, similar to what Blanchard (2018) presented. We can think of single models or combined models that cover theory without much emphasis on reality; policy (or zero-cost breakthrough) with emphasis in reality; toy models to add pedagogical insights; and forecasting models with emphasis on advanced statistical tools to reduce errors in projections. Other good practices include reporting standard deviations and robustness of results and performing sensitivity analyses on key parameters.

We carried out an extensive review of 118 studies on the RE along different aggregation levels, out of which 61 were empirical studies from the years 2016-2018 and the rest theoretical papers to develop sections 1 and 2. From this review, 25 studies computed and reported energy or GHG RE magnitudes which we summarize in table 3. From this sample of studies we can see that choosing a structural model might increase the uncertainty of RE calculations. Furthermore, there are fewer studies examining the RE on the production side. An important caveat to consider, when looking at this table, is the diverse nature of energy services under study. Combining previous,

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[15] There are other types of classification of IAMs in the literature which we do not cover here.

Table 3. Rebound effect magnitudes per methodology along the level of aggregation and actor.

Methodology	Level of aggregation	Actor	Rebound effect μ (mean)	σ (SE)
Structural models	Energy systems	Producer	120.6	139.1
		Consumer	−22 / −37.6[a]	– / 83.1
	Economy-wide	Producer	43.5	41.2
		Consumer	–	–
Econometric studies	Energy systems	Producer	–	–
		Consumer	44	1.4
	Economy-wide	Producer	–	–
		Consumer	58.5	12
Simulation studies	Energy systems	Producer	–	–
		Consumer	51.9	20.3
	Economy-wide	Producer	42.5	25.9
		Consumer	56.5	15.6

[a] Magnitudes at the right side are estimates of GHG rebound effects.

recent, and future studies on RE magnitudes could provide more data to increase the analytical power of RE estimates. A future meta-analysis study of the RE or the use of crowdsourcing data analysis strategies, as presented in Silberzahn *et al* (2018), could reveal further insights. We highlight the equal importance and complementarity of ex-ante and ex-post studies given the observed symmetry between models and the computation of REs, which requires the calculation of both expected and realized energy savings.

Although magnitudes presented in table 3 are informative, a main take-away is that depending on which EE driver is represented in models, including the study of environmental and welfare effects to the study of the energy RE (a specific phenomena of energy consumption reduction), results in a broader and different extent of policy implications. Therefore, reporting REs as a stand-alone percentage is not sufficiently informative for policy considerations. Additionally, it is important to perform a cost-benefit analysis to understand the effectiveness of legislations within the context of the introduction of EE policies.

4.2. Ex-post studies

We find that structural functions are the most often used methodology for modeling the production side in both energy systems and economy-wide models. Although there are clearly several limitations imposed by structural forms and assumptions (Gillingham *et al* 2016), and these types of models have been criticized for ignoring heterogenous capital at aggregate levels (Burmeister 2000); Saunders (2008) recommends the use of Gallant (Fourier) or the generalized Leontief/Symmetric generalized Barnett cost functions due to their flexibility to model REs. Moreover, on the consumption side, Schmitz and Madlener (2020) similarly found that the magnitude of the RE is sensitive to time and model specification, and they recommend modeling energy services in a system as an alternative to energy commodity models. The distinction between consumption and production direct REs is relevant, as the latter captures two thirds of total energy consumption (Santarius 2016). While recent econometric models on energy systems (section 3.2.1) have evolved to include data from field experiments, use randomized controlled trials, and study causal effects on the consumption side, there have been fewer studies on the production side (i.e. exploring technology choices and R&D investment) using these up-to-date methodologies. Although the aforementioned studies are computationally expensive, and their results are difficult to scale up due to their specific nature, they provide valuable insights on the effectiveness of EE policies and on the RE. Wang *et al* (2016) recommends studying final energy consumption habits across a plethora of household appliances.

Ex-post studies that put emphasis on reality depiction (policy and/or zero-cost breakthrough) are of high importance in providing empirical evidence. They serve as an input for ex-ante studies, in order to feed accurate parameters to ex-ante studies. Figures 2 and 3 show that ex-post studies in our review estimate either energy or GHG RE separately, while welfare effects are not computed. The circle shape indicates studies of developed countries (DE), while the triangle shape indicates studies of developing countries (DG). The colors red or blue distinguish ex-ante from ex-post studies, respectively. From 26 RE calculations performed in the studies we review, the magnitudes of the energy RE have a median of 31%, with a maximum of 334% and a minimum of -22%. GHG REs have a median of -30%, with a maximum of 78% and a minimum of -161%.

4.3. Ex-ante studies

Similar to ex-post studies, ex-ante studies also rely on structural forms or econometric estimates for the representation of consumer or producer choices. On the production side, Koesler *et al* (2016) and Brockway *et al* (2017) propose to review the adequacy of CES functions for representing the nested production function, and to better match the energy-augmenting technical progress paradigm. With regard to the elasticity parameter at macro-economic levels, Lemoine (2018) does not discard backfire

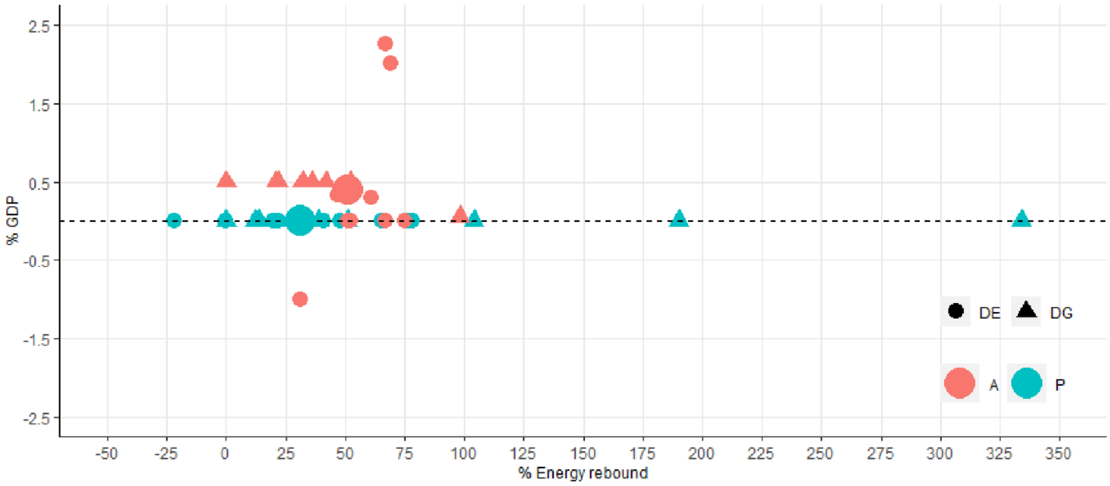

Figure 2. Results from studies on energy rebound effect versus welfare as % GDP.

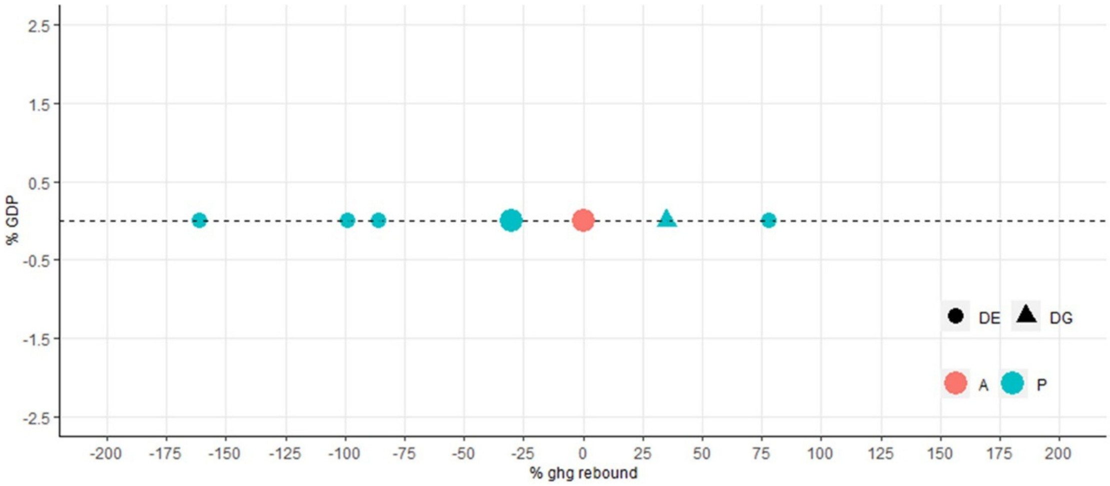

Figure 3. Results from studies on GHG rebound effect versus welfare as % GDP.

theoretically at the macro-economic level; however, empirically he finds that a 65 percent point reduction in energy savings occurs in the energy supply sector in the US. In addition, he finds that backfire can occur even for small elasticities between energy and non-energy goods occurring at the least efficient (or most energy-intensive) sectors. Nonetheless, there is a need for ex-post empirical evidence on fossil fuel supply elasticities at the micro-economic level (Böhringer and Rivers 2018). Moreover, Böhringer and Rivers (2018) also find that a large elasticity of substitution between capital and labor would reduce the magnitude of the energy RE. In addition, the larger size of the other sectors not affected by EEIs could also increase the RE magnitude (Böhringer and Rivers 2018), and the substitution effect would dominate (Zhou *et al* 2018). Another topic to examine more closely is the impact of EEIs on primary energy, which could benefit the expansion of energy services (intermediate energy) (Lu *et al* 2017). With regard to growth expansion, Ryan *et al* (2017) recommend examining trade-offs between economic expansion and EEI. Finally, investigating RE behavior over time is of importance, as it is theoretically possible that long-run elasticities are lower than short-run elasticities (Wei 2010), while on empirical grounds, Turner *et al* (2009) finds super-conservation and Lu *et al* (2017) finds a diminishing long-run energy RE. On the consumption side, studies find that large elasticity of substitution between energy and non-energy goods determines a larger partial equilibrium component (Gillingham *et al* 2016) which dominates the general equilibrium component (Böhringer and Rivers 2018). On the other hand, if the aforementioned parameter tends to have a low elasticity of substitution, it would result in low magnitudes of the energy RE due to consumer price unresponsiveness. More recently, heterogeneity has played an important role in studies disaggregating specific energy-intensive and less energy-intensive energy services (e.g. public vs. private transport or fossil fuel- vs. renewable-sourced heating), and including the representation of durable goods/investments within energy service sectors could provide more precise policy advice (Ryan *et al* 2017, Figus *et al* 2018).

Figure 2 above shows energy RE magnitudes obtained from the ex-ante studies examined in this review. Joint estimations of energy rebound and welfare effects have been carried out, while the GHG RE has not been computed, see figure 3. From 19 rebound effect calculations performed in studies shown in appendix B, the magnitudes of the energy RE have a median of 51%, with a maximum of 98% and a minimum of -0.1%. Welfare effects have a median of 0.4% of GDP, with a maximum of 2.25% and a minimum of -1%. Jointly, there can be high energy REs associated with high positive welfare effects (2.25%) but also low ones (0.05%). In our overview, REs from ex-ante studies show both lower median values. From 22 developed country studies along the level of aggregation, shown in the tables in in appendix B, the magnitudes of the energy RE have a median of 50%. Welfare effects have a median of 0.0% of GDP. Jointly, there can be high energy REs associated with high welfare effects (2.25%) but also moderate ones (0.32%). There is no clear link between the magnitude of rebound and welfare effects. For 16 developing country studies along the level of aggregation, joint estimations of energy rebound and welfare effects have been carried out, while the GHG RE has not been computed. The magnitudes of the energy RE have a median of 34%. Welfare effects have a median of 0% of GDP. Jointly, there can be high energy REs associated with moderate welfare effects (0.5%) but also low ones (0.05%). Similar to studies on developed countries, there is no clear link between the magnitude of rebound and welfare effects. In our review, RE studies (along the level of aggregation) from developed countries show both lower median magnitudes than studies from developing countries. Welfare effects from developed country studies show lower median magnitudes.

4.4. Combined insights

Taking both sides into account, studies validating elasticities with historical data and the use of more sophisticated methods (i.e. causal identification) and sensitivity analyses would improve the reliability of studies (Saunders 2013, Wei and Liu 2017, Saunders 2017). Explicit and endogenous representations of EEIs could also reduce bias in estimates (Hunt *et al* 2014, Witajewski-Baltvilks *et al* 2017). Looking at the general equilibrium component, supply and demand effects should be considered (Wei 2010), as should the interaction of EEIs on both sides. For example, some studies found that an inelastic supply combined with an elastic demand may induce a higher energy RE (Gillingham *et al* 2016, Ghoddusi and Roy 2017). The status quo of the data (year) should be checked against assumptions of the year when technical EEI is introduced, to take into account not only innovation phases but also diffusion and approximation to saturation. If policies are already in place, this should be modeled because high initial levels of EEIs in place could result in higher GHG rebounds. Furthermore, the dynamics of the incorporating of EEIs in primary and/or secondary energy would provide further insights (Zhou *et al* 2018). Another branch of the RE study includes the calculation of REs in terms of GHG emissions (e.g. pollution effects). Chang *et al* (2018) found that ignoring calculation in terms of GHG emissions (considering only energy REs) could result in underestimation of the energy RE magnitude, though bringing positive welfare effects. In general, models could include locational aspects (e.g. multi-area), temporal aspects (i.e. different consumption or production patterns in summer and winter; Wang *et al* (2016), and group targeting (low/high income households, owners/tenants (Madlener and Hauertmann 2011), high/low energy intensive and/or high/low GHG emission industries Madlener and Turner 2016, Wang *et al* 2016 to check distributional effects when price is endogenous (Ghoddusi and Roy 2017). Furthermore, we consider that the analysis of cyclical fluctuations in the energy industry for specific energy services or resources could improve the understanding of EEI adoption and RE in time, both using ex-post and ex-ante studies. Overall, the potential effect of EEIs and REs on the economy would be higher for industry than households; however, we find mixed results. Ex-ante studies can also be used to monitor REs in the economy, not just for forecasting (e.g. using now-casting or back-casting methods in CGE models). The calculation of REs has two components, one expected (or ex-ante), and another real (or ex-post). The expected component shows significant variability depending on how energy reductions are assumed to be realized. Thus, we suggest that GHG reductions and energy savings would be more direct quantitative indicators for policy assessment. Finally, all figures imply that there is a correlation between welfare, GHG reductions and energy savings.

5. Needs for future research

5.1. EEIs on consumption and production

Studies included in this review have shed light on the inclusion of EEIs as technical change and preferences on energy systems more often than on economy-wide models. Few IAM studies have been found to consider EEIs simultaneously on both sides. In particular, less common so far are studies that study the RE as described in section 2.2, complementary RE (7), composition REs (8.3), or effects of economies of scale (8.4). Transformational RE studies have not yet been found. For heterodox studies about the RE, see Santarius (2016) or Herring *et al* (2009).

5.2. Heterogeneity

On the production side, and considering the GHG emissions reduction goal, Lemoine (2018) indicates that EEI policies should target energy-efficient sectors with low elasticity of substitution between energy and non-energy inputs and less energy-intensive sectors; however, this study does not include the representation of inter-fuel substitution, long-run effects or impacts of heterogeneity on the consumption side. Likewise, in Norway, Helgesen *et al* (2018) found that a 50% reduction in GHG emissions through technology investments are achievable by 2030 but at a cost of 6.3% reduction of GDP; however, this study assumes that energy intensity remains constant. Moreover, in developing countries such as China, policies on the supply side should encourage resource-specific technological progress in energy-intensive sectors (e.g. industry and manufacturing) (Zhang *et al* 2017b). On the consumption side, similar to the production side, Ryan *et al* (2017) suggests that the policy focus should expand to consider not only improvements in EE in energy-intensive sectors, but also how these improvements interact with less energy-intensive sectors. For China, Wang *et al* (2016) found that in residential electricity consumption, investment should be promoted in energy-saving technologies. Moreover, it is common to consider heterogeneity in energy services and attributes in energy system approaches, Bye *et al* (2018) found that modeling EEI in a specific sector (i.e. the electricity sector), instead of considering EEIs on all energy uses in an economy, could result in economic distortions that may lead to welfare loss, even though the electricity supply in Norway is mainly produced from renewable energy sources. Thus, the question here would be to what degree and for what cases is heterogeneity relevant for policy analysis.

5.3. Long-run vs short-run

A clearer distinction of estimates in ex-post and ex-ante studies between the results obtained in the short and long run would improve the insights of the models. For example, Brockway *et al* (2017) concluded for China that the deployment of renewable energy sources should occur more rapidly than planned. However, Herring and Roy (2007) state that this would make little difference in the long term in order to reduce carbon emissions. Pui and Othman (2017) found that a double dividend in GHG emission reductions and welfare maximization is gained in the short-run with autonomous EEIs, but EEI policies should be accompanied by taxes to control and level-up price reductions. In contrast, Lu *et al* (2017) found that policies should target the efficiency of EEI policies in the long run, where REs diminish. In that vein, Frieling and Madlener (2017b) concluded from a comparison of production in a structural partial equilibrium model with factor-augmenting inputs for Germany, the US and the UK, that energy consumption is relatively immutable in the short run. It remains to be further analyzed how the RE affects GHG emissions, in scenario cases where the earth warms more than 1.5 degrees.

5.4. Uncertainty due to expectations and the counterfactual

Engineering estimates on energy savings found in actual EE policy programs are reported to be much higher than actual savings. Thus improving modeling on both sides, using ex-post and ex-ante studies (e.g. using machine learning to compute counterfactual scenarios), could help to reduce uncertainty in calculations. Furthermore, Frondel and Vance (2018) use an IV estimator to resolve endogeneity between EE and energy services thereby recovering causality. By using this method they find higher upper-bound RE estimates compared to estimations in studies that assume a linear relationship of efficiency between energy and energy services. Ghoddusi and Roy (2017) found that modeling stochastic demand and supply could also increase control for uncertainty in energy RE estimates.

5.5. EE up-front costs

More market-based policy studies including EE investment costs such as Burlig *et al* (2017) and Fowlie *et al* (2018), at the micro-economic level and Bye *et al* (2018) at the macro-economic level, could give a more complete picture regarding the cost-effectiveness of EE policies. With respect to CGE and IAM models on the producer side, it would be useful to track down how managers' behavior might impact the balance between investments and savings in the long run (the closing rule) and how this mirrors on their inter-temporal decisions (e.g. sunk costs, adjusted cost functions, etc). On the consumer side, CGE and IAM models that represent consumer behavior towards their investment in durables and non-durables and how this could impact different generations, considering their death probabilities, might also help to understand the reasons behind a particular result regarding the effectiveness of EE and climate policies (Conrad 2001).

5.6. Imperfect markets, externalities and imperfect regulations

Most of the studies reviewed in this survey propose local, national or global regulations to solve to externalities and imperfect markets. For cases where studies are informative to policy decision-making, we reflect on study insights in this section to raise awareness and promote discussion about how methodological considerations (and limitations) might shape conclusions and their applicability. For the production side in China, Yang and Li (2017) arrive at the conclusion that in power generation, ad valorem taxation on energy input prices (i.e. fossil fuels) could help to better reflect fossil fuel scarcity and environmental costs. Furthermore, they recommend a parallel lift of feed-in tariffs to promote clean energy. Meanwhile, in developed countries like Switzerland, Landis and Böhringer (2019) found that the economic costs of EE CaC policies (Promotion) are five times more expensive than the use of taxes (Steering) combined with per capita rebates. Moreover, there exist trade-offs between cost-effectiveness and distributional impacts of policies. However, this study did not take into account environmental benefits or externalities (which could reduce the gap between both instruments) resulting in an upper-bound estimate. On the consumption side, Bye *et al* (2018) found that EEI policies for dwellings (i.e. a cap on residential use and energy intensity) are highly costly even when including CO_2 taxes; therefore, these policies would be inefficient to abate CO_2 emissions. Whereas Pollitt (2017) found that EEIs for buildings in Europe would yield all three co-benefits: GHG reductions, welfare increase and energy savings on climate change models, Van den Bergh (2017) found cap-and-trade to be the best approach to manage global and international energy, and more importantly, the GHG RE. Furthermore, energy-saving policies are usually modeled in IAMs, as the common strategy in mitigation scenarios, but transition pathways that can meet such targets are less commonly studied. From six IAMs and five shared socio-economic pathways, Rogelj *et al* (2018) found that scenarios characterized by a rapid shift away from fossil fuels toward large-scale low-carbon energy supplies, reduced energy use and carbon removal successfully reached the target of a temperature rise below $+1.5^{\circ}$ C by 2100; while scenarios with scattered short-term climate policy, strong inequalities in socio-economic pathways, and high baseline fossil fuel use, missed it. Gidden *et al* (2018) analyzed 13 scenarios with open-access and reproducible higher gridding spatial resolution (aneris python library), comparing SSPs to representative concentration pathways, and recommended that the assessment of the role of uncertainty is carried out not only between scenarios, but also between model results for a certain scenario, such as fluorinated gases trajectories. Additionally, carbon dioxide and methane gases are well-known climate forcers that have a higher impact from a political rather than physical perspective, thus adding spatial detail would provide more meaningful insights for policy analysis.

5.7. Targeting and distributional concerns

For the case of the transport sector, studying the interaction between carbon taxes, equity effects and investments in infrastructure (i.e. public transport) could shed light on fuel efficiency policies. IAMs find mitigation efforts on the transportation, industry and buildings sectors of particular importance (Méjean *et al* 2018, Rogelj *et al* 2018). Taking into account that heterogeneity of attributes is also relevant for policies targeting the transport sector, as described in Galvin (2017), the interaction between speed and acceleration becomes crucial to investigate the efficiency of electric vehicles.

5.8. Understanding consumer preferences and changes

Another branch of research to inform policy development includes changes in behavior and lifestyle (Herring and Roy 2007), as well as field experiments and surveys to better approximate, in a more realistic manner, end-user discount rates and preferences. Understanding how to move from bad habits to good habits, in accordance with consumer's preferences, could contribute to reduce energy consumption in the short or medium run. We find that more studies that include heterogeneity of actors (household or firm) would help to shed light on the distributional impacts of EE policies.

5.9. Interactions between energy consumption, GHG emissions reductions and welfare

Chang *et al* (2018) found for the production side that pollution-minimizing policies are less costly than welfare-maximizing increases in EEIs on green technologies, describing a U-shaped environmental Kuznets curve. In general terms, to reduce global emissions and energy use in the long term, EEI policies on both the demand and supply side could help illustrate existing trade-offs/co-benefits between economic growth, social welfare, reduction of GHG emissions, and total energy use (Wei and Liu 2017). Brockway *et al* (2017) conclude that because EE and rebound may act as engines of economic growth (Ayres 2010), there might be a potential trade-off between climate and economic growth policies. Although carbon taxes would be better than command-and-control policies to reduce rebound while allowing for economic growth, distributional impacts have to be considered carefully to account for energy poverty and energy climate justice. This could improve the social acceptance of policies. Thus, a better understanding of interactions between energy consumption, energy savings, GHG emissions and economic growth would provide a more comprehensive understanding at macro-economic levels. This could be help identifying adequate policy strategies to target different dimensions, such as the level of aggregation, actors, income level, and time.

Policies that encourage EEIs should be clear about about the trade-offs and be more explicit about the required level of detail regarding the modeling of the most pressing issues to solve: securing economic growth, reducing GHG emissions, and (or) increasing fossil fuel energy savings. Within the study of these interactions, the RE is only one aspect to consider. Furthermore, BC analysis would be equally necessary to foster well-informed decisions. Future large shifts in policy will require answers and solutions to many open questions regarding complex interactions, to understand how EE and energy saving interacts with low-carbon economies, sustainability, socio-technical (Geels *et al* 2018) and psychological aspects. Moreover, better knowledge of social transitions is required (van Vuuren *et al* 2018, Rogelj *et al* 2018). Although policy strategies must identify clearly their targets among multiple dimensions; they should find common ground at the global level. Studies on spillover effects and strategic alliances between regions could also shed light on feasible futures. To reach national or sectoral policy objectives in a cost-effective fashion, we require a comprehensive understanding of the RE from both theoretical and empirical grounds. This has the potential to better guide policy decisions in the future.

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Appendix A

A.1. Energy efficiency improvement formulations

The easiest representations of energy efficiency improvements conceptualize the change as deriving exclusively from energy supply and use (Birol and Keppler 2000).

An explicit representation of EEIs at the microeconomic level, as specified by Hunt *et al* (2014), defines efficiency as the ratio of useful energy outputs to energy inputs of an energy system, or as units of the energy service (ES) produced per unit of the energy source (E) used,

$$\varepsilon = ES/E; \tag{A1}$$

the term energy service[16] in equation A1[17] is sometimes taken as a physical indicator (e.g. vehicle kilometers in transportation), or an explicit thermodynamic measure where heat content is represented (e.g. joules of heat in water heating inside a closed energy system). More recently energy service has been defined as exergy, the usable energy to perform physical work, or the effective energy available for end-use consumption (Brockway *et al* 2017). Fell (2017) finds 27 definitions of "energy service". A clear definition of the term energy service in studies where there are explicit representations of energy efficiency improvements is important for reproducibility and to contribute to objective debates on energy efficiency policies. Moreover, depending on the type of study, an energy efficiency improvement formulation might be influenced also by a utility or production function, which represents the choice made by the consumer or producer.

According to Hunt *et al* (2014), energy efficiency improvements should be explicitly modeled to avoid bias, but Frondel and Vance (2018) find similar results (though with high standard errors) when comparing an explicit representation of energy efficiency improvement with an implicit representation in their own study. Therefore, a simplified model might be preferred in cases where additional complexity in models leads to robust results. Along these lines, we recommend avoiding the following three representations of energy efficiency improvements; they would entangle increases in energy efficiency with other factors (e.g capital), and therefore be biased:

(a) Implicit representation of energy efficiency, not using equation (A1). In these cases, the own-price elasticity of energy demand is taken as a proxy for the rebound effect (i.e. historical studies of fuel consumption), see equation (A7).
(b) Energy intensity as an equivalent measure to energy efficiency (e.g. total energy consumption/GDP). This might be true for one unit of production under unbiased technical change, but not when the level of aggregation is scaled up (Birol and Keppler 2000).
(c) Considering energy efficiency improvements as the ratio of the price of an energy service to energy as equal or linear to the ratio of the demand for energy services to energy consumption.

More realistic representations such as in Adeyemi *et al* (2010) model historical trends of increases and decreases in price[18]. Other studies use energy efficiency improvement indices, where a past maximum price is followed by price recoveries and decreases (using price decomposition methods) (Ang *et al* 2010).

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[16] We thank an anonymous referee for drawing our attention to the ambiguity of this concept.

[17] Energy efficiency improvements and, more generally, changes in energy consumption in time, can also be measured as a difference instead of a ratio (Ang *et al* 2010).

[18] Also referred to as asymmetric price responses on the demand side (Dargay and Gately 1997, Frondel and Vance 2013). Though they use this method for energy demand, it could be used for energy services.

Table 4. Rebound cases from micro to macro, adapted.

	Super efficiency R<0	Engineering rebound $R = 0$	Partial rebound $0 < R < 1$	Full rebound $R = 1$	Backfire $R > 1$
Micro					
Short-term	$\eta_\varepsilon(ES) < -1$[a]	$\eta_\varepsilon(ES) = 1$	$-1 < \eta_\varepsilon(ES) < 0$	$\eta_\varepsilon(ES) = 0$	$\eta_\varepsilon(ES) > 0$
Macro					
Short-term	-[a]	$\sigma_e^e \to -\infty$ or $\sigma^d \to 0$ and $\sigma^s \to 0$	$\sigma_e^e < -1$ or $-1 < \sigma^d < 0$	$\sigma_e^e = -1$ or $-1 < \sigma^d = -1$	$-1 < \sigma_e^e < 0$ or $\sigma^d < -1$
Long-term	$1/\sigma^s - \theta < \sigma_e^e < 0$	$\sigma_e^e < -\infty$ and/or $\theta \to \infty$	$\sigma_e^e < -1 - \theta$	$\sigma_e^e = -1 - \theta$	$-1 - \theta < \sigma_e^e < \min\{0, 1/\sigma^s - \theta\}$

[a] Although in zero-cost breakthrough studies it is impossible for this condition to happen in the case of partial equilibrium (Lemoine 2018), it is theoretically possible for it to occur when large externalities are modeled (e.g. in studies that model market-based policy improvements). Moreover, depending on the functional form of the production function, this can cause a "disinvestment effect" in the long-run (Turner *et al* 2009).

Table 5. Review of selected production-side direct rebound effect studies.

Author (year)	Spatial focus	Sectoral focus	Typology	EE / RE channel	RE magnitude	Welfare	GHG red.	Insights
Yang and Li (2017)	Beijing China	Production Electricity	(7) RE Translog cost ZCB	AEEI implicit $\eta_{\varepsilon}(P_E) = 0$ RE: $-\eta_{P_E}(E)$ Data 1985 - 2010	SR - LR 12% fossil fuel Rejects H_0[1]	NA	NA	Pricing reform (coal) reduced RE effect.
Li and Lin (2017)	China	Production Industry Heavy Light	(4) DRE Cobb Douglas ZCB/PI	Augmented TLD RE: $\eta_{\epsilon}(E)$ Data 1994 - 2012	SR - LR HE 334% LR LI 190% Does not reject H_0	NA	NA	Output component accounts for 85% of the rebound effect.
Zhang *et al* (2017b)	China	Production	(4) DRE ZCB	EE as resource-specific, LMDI, LVA-Z RE: *AES*/*PES* Data 1995 - 2012	SR - LRI 39% av. LRM 28% av. Rejects H_0	NA	NA	Structural shift between sectors has lower effect on reduction of energy consumption. DRE shows a decreasing trend in time in both sectors
Frieling and Madlener (2016)	Germany	Production	ZCB	ETT constant, nested CES, fixed σ_{KL} Data 1991 - 2013	MR $\sigma_{(KL)E} = 0.18$	NA	NA	(KL) complement of E, E is a strong constraint on economic growth.
Frieling and Madlener (2017a)	USA	Production	ZCB	ETT linear, nested CES, fixed σ_{KL} Data 1929 - 2015	LR $\sigma_{(KL)E} = 0.6\text{-}0.7$	NA	NA	(KL) complement of E, labor augmenting (at same time labor saving).
Frieling and Madlener (2017b)	UK	Production	ZCB	ETT linear, nested CES, fixed σ_{KL} Data 1855 - 2015	LR $\sigma_{(KL)E} = 0.5\text{-}0.8$	NA	NA	(KL) complement of E, except in times of economic stress, evidence of subsitution.

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[1] H_0: Backfire exists. EE representation: AEEI: autonomous energy efficiency improvement. TLD: Technology learning (remembering/forgetting). LVA-Z: Latent variable approach, zero-cost breakthrough. ETT: Exogenous time trend.

Table 6. Selected review of consumption-side direct rebound effect studies.

Author (year)	Spatial focus	Sectoral focus	Typology	EE / RE channel	RE magnitude	Welfare	GHG rebound	Insights
Schmitz and Madlener (2020)	Germany	Household, Fuels, Electricity	(1)DRE (3) IRE LAIDS ZCB	ETT, past-price dependant DRE: $-\eta_{P_E}(E)$ IRE: $\eta_{P_{EI,NEI}}$ Data 1970–2014	NA	NA	SR - LR Gas -161%av. Liq f -86%av. Other f -0.1%av. Veh f 78%. SR Elc -99% Does not reject H_0	When EEI is not considered explicitly, RE is overestimated. Income effects are smaller in magnitude than substitution effects; *IRE* > *DRE* magnitude
Zhang *et al* (2017a)	China Regional	Household Private transport	(1)DRE, (3)IRE AIDS ZCB	AEEI implicit DRE: $-\eta_{P_E S}(ES)$ IRE: $1-\ \Delta\ Q/\Delta\ H$ Data 2001–2012	NA	NA	SR - LR -30 to 35% av. Does not reject H_0	*IRE* > *DRE* magnitude for expenditure, conversely for pop. density. Underdeveloped regions backfire, high regional fluctuation.
Heesen and Madlener (2018)[1]	Germany	Household, Heating, tenants	Household-factory ZCB	AEEI, Heat Energy consumption model (HEC) DRE: $-\eta_{P_E S}(ES)$ Field experiment data 2010–2014 (60 houses)	SR- MR -22% HEC [1]	NA	NA	Income effects are less sensitive to model specifications compared to substitution effects; IRE larger in magnitude than DRE 1-year time frame; consumer price responsiveness. Habits are not influenced by economic signals in the SR.

ETT: exogenous time trend. AEEI: autonomous energy efficiency improvement

[1] This study does not estimate the RE; we assume price elasticity of demand as a proxy for RE (upper bound estimate).

Table 7. Review of selected national production-side rebound effect studies.

Author (year)	Spatial focus	Sectoral focus	Typology	EE / RE channel	RE magnitude	Welfare	GHG red.	Insights
Brockway *et al* (2017)	UK US China	Production	(1) DRE (3) IRE APF CES Solow's residual ZCB	AEEI explicit DRE: M1: *AES*/*PES* M2: Exergy $\eta_\tau(E)$ Data 1980/81 - 2010	SR - LR [1]: UK 34%av. US 22%av. China 104%av. Does not reject H_0 in China	NA	NA	Producer side and developing economies exhibit larger RE. High substitution between KL and E produce high RE. RE is a key component of energy growth.
Zhang and Lawell (2017)	China	Production	(8) Price/-growth effect APF two-level nested CES ZCB	AEEI Decomposed $\eta_\tau(E)$ DRE: $1+\eta_\tau(E)$	SR high variation LR Price 14% av. Growth E 0% Does not reject H_0	NA	NA	High variation of RE in time and by location.

AEEI: autonomous energy efficiency improvement.

[1] Average values taken from methods 1 and 2.

Table 8. Review of selected consumption side RE econometric studies.

Author (year)	Spatial focus	Sectoral focus	Typology	EE / RE channel	RE magnitude	Welfare	GHG red.	Insights
Frondel and Vance (2018)	Germany	Households, Private Transport, single-vehicle	(1) DRE Instrumental variables estimator PI	EE: LVA-P (tax rate/100 cm^3) DRE: $\eta_\epsilon(ES)$ Data 1997 - 2015	SR 67% [1] Rejects H_0	NA	NA	Using an instrumental variables estimator results in RE to be 30% points higher than fuel $\eta_{P_E}(E)$. Higher fuel efficiency offsets the effectiveness of fuel taxation by at least the same degree. CaC (fuel efficiency standard) negatively affects welfare.
Fowlie *et al* (2018)	US Michigan	Low-income Households, Heating, Infiltration	(1) DRE PI	EEI: policy b/w treated and non-treated houses RE: *AES*/*PES* Field experiment data 2011 - 2014 (899/28,888 houses)	$10 - 20\%$ red. in monthly energy consumption. Cannot reject RE $= 0$ [2]	less than 1% energy expenditure savings	SCC \$38/*ton* at r $= 3\%$ [3]	Negative rates of return on EEI investments would suggest there is no energy efficiency gap, and EE investments are not a cost-effective approach to mitigate climate change. Projected engineering savings overvalued by more than three times the actual savings.
Burlig *et al* (2017)	US California	Buildings, K-12 Schools, HVAC[4] Lighting	(1) DRE Panel Data vs. Machine learning PI	EEI policy before/after RE: reduced-form *AES*/*PES*, non-treated projections vs. real data points (after EEI). Field experiment data 2008 - 2014 (2,094 schools)	SR Light/HVAC 54/76%[5] Rejects RE $= 0$ 3.7% reduced energy consumption	NA	NA	Even targeting policies might be challenging due to heterogeneity found in the results.

LVA-P: Latent variable approach, market-based policy. EEI: Energy efficiency improvement.

[1] Other results for the US show lower estimates, see Small *et al* (2007).

[2] This study did not find a significant increase in temperature, and it found a small RE.

[3] r: Discount rate.

[4] Heating, ventilation and air conditioning.

[5] This result is likely driven by overly optimistic ex ante predictions or rebound.

Table 9. Review of selected macro-econometric studies.

Author (year)	Spatial focus	Sectoral focus	Typology	EE / RE channel	RE magnitude	Welfare	GHG red.	Insight
Pollitt (2016)	EU	Household, Buildings	(1) DRE input (8) TRE output ZCB/PI	Potential energy savings as input Investment in EEI as KNK Data 1970 - 2013 / 2014 - 2030	SR - LR 50% Rejects H_0	$0.1 - 0.6\%$	SR - LR red. $-0.5/-7.8\%$	Quantification of main co-benefits identified by IEA[1]. Policies should target poor households.
Pollitt (2017)	EU	Household Sectors	(1) DRE input (8) TRE output ZCB/PI	Potential energy savings as input Investment in EEI as KNK Data 1970 - 2014/ 2015 - 2050	SR - LR econ 67% Rejects H_0	$0.4 - 4.1\%$	SR - LR -44% av. by 2030	Competitiveness and economic benefits might be maximized if EE equipment and materials are manufactured domestically, because EE policies increase consumption of materials. Crowding out effects are important in more ambitious scenarios.

KNK: Kaldor's neo-Keynesian.

[1] International Energy Agency (IEA 2014).

Table 10. Review of selected simulation studies.

Author (year)	Spatial focus	Sectoral focus	Typology	RE channel	RE magnitude	Welfare	GHG red.	Insights
Thomas and Azevedo (2013b)	US	Household, Electricity, Gasoline	(1) DRE input 10% (3) IRE output ZCB	AEEI, fixed K DRE: $-\eta_{p_E S}(ES)$ IRE: Cross-price elasticities of demand for other goods with respect to energy services Survey data 2004 IRE: Energy intensity of spending on other goods	SR E48% av. G20% av. Rejects H_0	NA	NA	RE changes with time and location and GHG type.
Chitnis and Sorrell (2015)	UK	Household, Gas, Electricity, Vehicle fuel	(1) DRE estimate G59%, E41%, V56% (3) IRE output ZCB	AEEI DRE: $-\eta_{p_E S}(ES)$ IRE: Cross-price elasticities of demand for other goods with respect to energy services IRE: Energy intensity of spending on other goods Data 1964-2013	LR G 41% av. E 48% av. VF 78% av. Does not reject H_0	NA	NA	Studies that neglect indirect substitution effects may underestimate the RE.
Wang *et al* (2016)	China Beijing	Household, Residential electricity	(1) DRE estimate 28% av. (3) IRE output ZCB	AEEI DRE: $-\eta_{p_E}(E)$ IRE: Energy intensity of other goods spending Data 1990-2013	SR DRE 31% LR TRE 51% Rejects H_0	NA	NA	
Freire-González (2017b)	EU 27 C	Household, Residential energy end-uses	(1) DRE input 30% and 50% (3) IRE output ZCB	AEEI, fixed K DRE:$-\eta_{p_E S}(ES)$ IRE: Cross-price elasticities of demand for other goods with respect to energy; services IRE: Energy intensity of spending on other goods Data 2007	SR 77% av. Does not reject H_0	NA	NA	High variation of RE between countries.

AEEI: autonomous energy efficiency improvement.

Table 11. Review of selected CGE models focused on production.

Author (year)	Spatial focus	Sectoral focus	Typology	EE / RE channel	RE magnitude	Welfare	GHG red.	Insights
Koesler *et al* (2016)	Germany & International	Industry and Manufacturing	(8.1) ZCB	AEEI Exogenous prod. shock, one, all sectors, RE Energy in economic units aggregate equation (8) $\Delta\varepsilon = 10\%$ 5ys. Data 2009, WIOD CGE, 8 sectors, 3 regions	SR 51% global, 47% Germany $\sigma_x = 0.234$ $\sigma^d = 0$. Rejects H_0	$0.13 - 0.51\%$	NA	Domestic RE is overestimated without considering spillover effects.
Lu *et al* (2017)	China	Coal crude oil/nat. gas reference petrol. Electricity/steam, Gas supply	(4), (8.1) ZCB	AEEI Exogenous energy augmenting,-specific prod. shock, RE equation (8) $\Delta\varepsilon = 5\%$ Data 2007, ORANI-G, 140 sectors, 56 regions. Allows inter-fuel substitution	SR/LR [1] C 23/21% COG,RP 32/36% av. E 31/$-$0.1% GS 51/42% $\sigma_E ng = 0.5$, Leontief non-energy. Rejects H_0, *RE* lt; 0	$0.02 - 0.9\%$	NA	Policy focus of RE in the LR, allowing inter-fuel substitutability, increases RE magnitude.
Pui and Othman (2017)	Malaysia National Sectoral	Transport	(8.1) ZCB/PI	AEEI Energy-augmenting, exogenous prod. shock one sector, PI endogenous R&D investment from subsidy savings, environmental tax, RE Energy in physical units resource-specific (gasoline and diesel) $\Delta\varepsilon = 5\%$ 1y. Data 2010, ORANI-G, 124 sectors, 56 regions	3 scenarios AEEI/PI SR 98/98% av., LR 98/97% av. $\sigma_E = 0.5$, Leontief E/NE, CES energy. Does not reject H_0	SR 0.04/0.05% LR 0.07/$-$0.05%	GHG red. SR $-0.1/-0.11\%$ LR $-0.11/-0.19\%$	$\varepsilon > 0$ could produce a double-dividend effect (benefits) on the economy and environmental quality.
Zhou *et al* (2018)	China	Coal Crude oil and nat. gas reference petrol. Electricity Gas supply	(4), (8.1) ZCB	5 AEEI exogenous energy-augmenting and -specific productivity shocks, RE Energy in economic units $\Delta\varepsilon = 5\%$ Data 2007, ORANI-G, 140 sectors, 56 regions	SR C 22% OG,PR,E 32% av. GS 52% $\sigma_E = 0.5$, Leontief E, NE, CES energy. Rejects H_0	$0.02 - 0.9\%$	NA	Decomposition of RE in production and consumption contributors.

AEEI: autonomous energy efficiency improvement.

[1] Reported only inter-fuel substitution scenario.

Table 12. Review of selected CGE models focused on production.

Author (year)	Spatial focus	Sectoral focus	Typology	EE / RE channel	RE magnitude	Welfare	GHG red.	Insights
Lemoine (2018)	Theory	Production	(4), (5), (8.1) ZCB	AEEI Exogenous productivity shock $\Delta\varepsilon = 1\%$. Theoretical	Does not reject H_0	NA	NA	General Equilibirum channels are likely to be significant when EE improvements occur in sectors with a large value share of energy.
Böhringer and Rivers (2018)	Theory US, China, EU	Production	(4), (5), (8.1) RE Decomposition ZCB	AEEI, aggregate $\Delta\varepsilon = 1\%$. Data 2011, model from Böhringer *et al* (2016)	SR US, China, EU 67% $\sigma_x = 0.5$, , Leontief fossil fuels Does not reject H_0	NA	NA	Partial Equilibrium RE > Gen. Equilibirum component, $-\eta_{P_E}(E)$ as major driver of Total RE in sector with $\Delta\varepsilon > 0$, higher sector energy intensity and small sizes increase RE. Composition, growth and energy channels are relevant, and not the labor channel.
Chang *et al* (2018)	Theory	Production Consumption	8.1,2,3, RE Decomposition PI	Demand-side subsidy/tax clean goods supply-side subsidy/tax clean technology, RE Energy in GHG emission reduction units, aggregate $\Delta\varepsilon = 10\%$. Data 2009, Own model, 2- sectors clean/dirty goods	NA	$0.13 - 0.51\%$	R 90% with initial subsidy of 30%, 53% when $\sigma_{C,D} = 0.5$ and equal level of promotion C/D. Does not reject H_0	Steady-state pollution stock (Environmental Kuznets Curve) shows a U-shaped relationship with production and consumption promotions, status quo at time of intervention is of much importance.
Helgesen *et al* (2018)	Norway	Production Transport	8.1 PI	L/K shock, energy input coefficients (not in energy production) adjusted to TIMES quantities, AEEI productivity shock input from TIMES. Data 2010, REMES CGE and TIMES BU, hard/full-link, full-form integration, Multi-sectors, -regions	NA	NA	NA	50% GHG reduction is possible by 2030 with technology investments, amounting to -6.5% income. Energy intensity is constant in projections, adaptable.

Table 13. Review of selected CGE models focused on consumption.

Author (year)	Spatial focus	Sectoral focus	Typology	EE / RE channel	RE magnitude	Welfare	GHG red.	Insights
Figus *et al* (2017)	Scotland	Household	8.1 ZCB	AEEI prod. shock. RE Energy in economic units aggregate equation (8). $\Delta\varepsilon = 5\%$. Fiscal stimulus (devolved taxes). Sensitivity analysis of CPI and migration (with respect to ε). AMOS ENVI CGE dynamic model, Imperfect competition. CES functions, Leontief Energy. Data 2009.	SR 46% av. LR with fiscal stimulus, without 50%, considering migration and CPI levels up to 79%, 61% av. , for a period of 50 years. Rejects H_0	SR 0.1%av. LR 0.3%av.	NA	Trade-off between increase in regional economic activity/GHG reduction and levels of CPI / Migration. Drivers of RE are also the drivers of economic stimulus. $\Delta\varepsilon$ reduces energy use. Household RE < Economy-wide RE.
Figus *et al* (2018)	UK	Household, privatetransport	Theory Simulation ZCB	Endogenous vehicle-augmenting, physical units (fuel/miles). $\Delta\varepsilon = 10\%$. Partial Equilibrium Consumption of multiple goods. Sensitivity analysis of wage parameter. AMOS ENVI CGE dynamic model, Imperfect competition. CES functions, Leontief private transport/ other goods. Data 2010, no new data generation.	NA	NA	NA	Might boost productivity-led expansion, employment and household income depending on key substitution elasticities.

AEEI: autonomous energy efficiency improvement.

Table 14. Review of selected CGE models focused on consumption.

Author (year)	Spatial focus	Sectoral focus	Typology	EE / RE channel	RE magnitude	Welfare	GHG red.	Insights
Landis and Böhringer (2019)	Switzerland	Household. Heterogeneity	ZCB/PI	AEEI, technological change in power sector $\Delta\varepsilon = 20\%$, Thermal, motor fuels and electricity taxes on Industry and Households. Subsidies on building programs, competitive bidding. Data 2008, 38 sectors, 3 final demands, CEPE TD-BU (Household survey) model, ES modeled as durable goods in combination with energy commodities.	NA	NA	NA	Energy taxes are 5 times more cost effective than promoting energy savings. 36% of the households gain under tax-based regulation, upper-bound estimates. Does not consider environmental benefits.
Bye *et al* (2018)	Norway	Households, Electricity	(8.1) PI	Endogenous EE from BU model costs inc., caps on residential energy use and intensity, investments in housing. $\Delta\varepsilon = 27\%$. Data 2011, SNOW-NO dynamic recursive model TD-BU (TIMES, EE investments and energy-savings potential), 41 prod. sectors, 18 final consumption, cross-border interactions, small open economy.	SR 31% $\sigma_{D,E} = 0.3$ $\sigma^d = 0$ IRE > DRE. Rejects H_0	-1%	GHG inc. 2.4%	High economic costs of EE policies increase if they interact with carbon pricing.

AEEI: autonomous energy efficiency improvement.

Table 15. Review of selected CGE models focused on consumption.

Author (year)	Spatial focus	Sectoral focus	Typology	EE / RE channel	RE magnitude	Welfare	GHG red.	Insights
Duarte *et al* (2018)	Spain	Household, Electricity, Transport	(8.1) ZCB	EEI Diffusion: Logistic schedule captures gradual EEI from real evolution. RE equation (8). Partial Equilibrium Consumption of multiple goods. Sensitivity analysis of wage parameter. Spanish dynamic recursive model, Imperfect competition. CES functions, Leontief private transport/ other goods. Data 2005, Proj. 2030.	SR/LR E 12%/51% T 26%/52% E+T 59%/75%	NA	NA	Changes in consumer patterns should take place gradually.
Wei and Liu (2017)	Global	Household	(8.1) ZCB	AEEI $\Delta\varepsilon = 10\%$. Endogenous regional GDP generation. K, L mobile. Data 1995-2009, Proj. 2040.	70% av. on energy use and GHG in 2040.	NA	NA	Leads to increase on K, L. Regional and global LR RE > SR. EEIs are more efficient in energy-intensive sectors (e.g. Transport, Cement). $\eta p_{EI,NEI}$ for production is a stronger determinant of RE than $\eta p_{EG,NEG}$ for consumption. Inelastic $\eta p_{EG,NEG}$ produce small RE.

AEEI: autonomous energy efficiency improvement.

Table 16. Review of selected IAM models focused on production.

Author (year)	Spatial focus	Sectoral focus	Typology	EE / RE channel	RE magnitude	Welfare	GHG red.	Insights
Van den Bergh (2017)	International Global	RE and Climate Change	ZCB PI	Technology Consumer patterns	NA	NA	NA	Cap-and-trade is possibly the best approach to tackle energy and GHG rebound effects, but it requires an international climate treaty.
Grubler *et al* (2018)	Global	Consumption	ZCB	Change in consumption patterns and technology improvements (LEDs), aggregate industrial process $\Delta\varepsilon = 20\%$, improved physical capital stock, 2-sector model, MESSAGEix-GLOBIOM model, bottom-up changes in activity levels, energy intensities and final energy demand	Energy red. N/S av. 43%	NA	NA	End-user LED scenario under electricity and hydrogen sourced energy could lead to $+1.5^{\circ}$ without relying on negative emission technologies; however, RE interaction would need to be added into the model.
Rogelj *et al* (2018)	Global	Production consumption	ZCB PI	Shared socio-economic pathways (SSPs), on consumer side: energy intensity red. rates of $2-4\%$ per year from 2020 to 2050, on supply side: renewable energy technologies, CO_2 removal, 6 IAMS, World induced technical change hybrid model	NA	NA	GHG red. %per year in 2050	To reach to the $+1.5^{\circ}$ goal in 2100, rapid shifts from fossil fuel towards large-scale renewables, reduced energy use and CO_2 removal are required. If SSPs are characterized by strong inequality, fossil fuel consumption or non-stringent climate policy, the goal is not reached.

Table 17. Review of selected IAM models focused on production.

Author (year)	Spatial focus	Sectoral focus	Typology	EE / RE channel	RE magnitude	Welfare	GHG red.	Insights
Méjean *et al* 2018)	Global	Electricity, Industry, Transportation, Residential, consumer patterns	ZCB PI	Economic growth, technology costs of electricity and transport decrease through LBD, parameter growth of motorization rate as EEI in transport, in residential sector EEI is the income elasticity of the building stock growth, in industry sector AEEI, in other sectors endogenous EEI through energy prices. Inertia of sectors is modeled by inflexible vintage capital. Data 2010-2016, hybrid dynamic CGE model, IMACLIM-R model, bottom-up changes in activity levels, uniform carbon price.	NA	NA	NA	$+1.5\ ^\circ$C objective is not possible to attain if emission peaks are delayed until 2030, and EEI policies in ndustry and transport sectors are of most relevance to reach the goal. Thus, it does not imply a proportional effect on all sectors. Demand patterns contribute to achieve the $+1.5\ ^\circ$C goal.
van Vuuren *et al* (2018)	Global	Consumption	ZCB PI	EEIs in transport, industry, buildings and materials. AEEI $\Delta\varepsilon = 25\%$, 46% renewable share in electricity in 2050, lifestyle changes low-meat diet, transport habits, less cooling and heating, low population, uniform carbon tax, IMAGE-3 model and MAGNET CGE land-use model.	NA	NA	GHG red. 50%av. in 2050	Alternatives such as life style change and rapid electrification of energy demand based on renewable energy to reach $+1.5^\circ$C help diversify strategies, and a rapid transformation in energy consumption and land use is needed, however RE would need to be added to the model. High reliance on CO_2 removal is still required, but can be reduced.

LBD: Learning by doing.

A.2. Rebound effect formulations

Conceptual clarity leads to more accurate formulations. After showing how possible causes of energy efficiency improvements might translate into rebound effect components, we now revise available rebound effect formulations in the literature. Thus, formulations that are less prone to bias include:

the direct energy rebound effect (DRE) (Berkhout *et al* 2000),

$$DRE = \eta_{\varepsilon}(ES) - 1; \tag{A2}$$

where $\eta_{\varepsilon}(ES)$ is the energy services elasticity of demand with respect to its energy efficiency. But data to calculate the DRE in this form is scant, thus an alternative formulation is;

$$R = 1 - \frac{AES}{PES}; \tag{A3}$$

where AES is actual energy savings and PES is potential or expected energy savings in the absence of rebound effects, holding prices constant (Berkhout *et al* 2000).

IREs can be computed using cross-price elasticities, income elasticities, and expenditure elasticities between energy and other goods or energy inputs or non-energy inputs ($\eta_{P_{EG,NEG}}$ or $\eta_{P_{EI,NEI}}$, respectively). IREs can also arise from behavioral changes, not just energy efficiency improvements (Druckman *et al* 2010).

In the case of a macro-economic rebound calculation, a household productivity shock is usually applied to the model for calculating the difference between AES and PES corresponding to general equilibrium measures (Guerra and Sancho 2010). Notice that for economic growth models, it is also common practice to obtain two scenarios, one assuming engineering savings, and the other represented with a law of motion of capital, to quantify the rebound effect, as in (Turner *et al* 2009):

$$RE = \left[1 + \frac{\dot{E}}{\alpha\gamma}\right]100; \tag{A4}$$

where γ is the efficiency elasticity of energy, usually represented as an autonomous (or exogenous zero-cost breakthrough) energy efficiency improvement, and $\alpha = 1$ for economy-wide rebound, or takes the value of $\alpha = E_i/E$, modeled for the production or consumption side (sector) of country i, and E is the value of energy in physical or economic units (value share).

The rebound effect can also be expressed in terms of GHG emissions:

$$R = 1 - \frac{\Delta Q}{\Delta H}; \tag{A5}$$

where ΔQ is the net change in GHG emissions and ΔH is the change in emissions without behavioral response (Chitnis and Sorrell 2015).

At the economy-wide level, when using a theoretical welfare maximization CGE model, as in Wei (2010), the rebound effect can be expressed as:

$$R^s = \frac{1 + 1/\sigma^s}{1/\sigma^s - 1/\sigma^d}; \tag{A6}$$

where R^s is global rebound in the short term, and

$$R^l = \frac{1 + 1/\sigma^s}{1/\sigma^s - \sigma_e^e - \theta}; \tag{A7}$$

where R^l is global rebound in the long term. σ^s is the price elasticity of energy supply, σ_e^e is the energy own elasticity of marginal product with respect to energy input in the welfare function, σ^d is the price elasticity of demand, and θ is the own-price elasticity of capital supply and demand, as cross-price elasticity of marginal product with respect to capital and energy inputs in the production of welfare. This theoretical framework is simplified to account for only one non-energy good, and the analysis of elasticities are only for comparison purposes between the micro- and macro-economic levels. Lemoine (2018) gives a word of caution about the reliability on magnitudes of elasticities of substitution to guide the likelihood of backfire at the macro-economic level, due to the existence of sectoral interactions that need to be taken into account.

Formulations from (i) to (vii) summarize additional formulations that link the micro-economic level to the macro-economic level. It can serve as a guide to further explore additional insightful interactions that are less intuitive due to the complexity of the RE phenomena.

(a) Macro-economic RE $\equiv$ 'indirect rebound effect' + 'economy-wide rebound effect'[19];
(b) Total rebound effect $\equiv$ 'macro-economic rebound effect' + 'direct rebound effect';
(c) Gross energy savings from IEA energy efficiency policies $\equiv$ 'net energy savings (taken as exogenous in E3MG)' + 'direct rebound energy use';
(d) Change in macro-economic energy use from energy efficiency policies from E3MG $\equiv$ 'energy use simulated from E3MG after the imposed exogenous net energy savings' - 'energy use simulated from E3MG before the imposed exogenous net energy savings';
(e) Total rebound effect as % $\equiv$ 100 times the 'change in macro-economic energy use from energy efficiency policies from E3MG'/'gross energy savings from IEA energy-efficiency policies';

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[19] Although Sorrell (2007) defines the economy-wide rebound effect as the sum of the direct and indirect rebound effect components. See Madlener and Turner (2016) on the distinction between economy-wide and macro-economic rebound effect.

(f) Direct rebound effect as % ≡ 100 times 'direct rebound energy use'/'gross energy savings from IEA energy-efficiency policies';
(g) Macro-economic rebound effect as % ≡ 'total rebound effect as %' - 'direct rebound effect as %'.

We used these mathematical representations to summarize and classify the existing rebound effect types we found in the literature. This is relevant to organize the rebound effect within the four dimensions discussed in section 2.1, 2.2, and tables in appendix B. Table 4 shows five types of rebound effects and their respective elasticity domains.

In contrast to formulations A2 to A8, the following might lead to upward-biased estimates. These relate to the representations of energy efficiency that we recommend to avoid, explained in section 2.1 Though these conceptions were helpful to study the rebound effect initially, we do not recommend them for future studies, because they do not disentangle changes in relative prices due to an energy efficiency policy from exogenous technical change:

$$DRE = \eta_{\varepsilon}(E) - 1; \tag{A8}$$

where $\eta_{\varepsilon}(E)$ is the energy elasticity of demand (of energy output for the consumer side, or input for the producer side e.g. fuel) with respect to efficiency;

$$DRE = -\eta_{P_E}(E); \tag{A9}$$

where $\eta_{P_E}(E)$ is the own-price elasticity of energy demand for the relevant energy service (of energy commodities on the consumer side, or fuel on the producer side). This only holds when the price of energy (in physical units) remains constant, so that any change in energy efficiency is reflected in the effective price of energy (Guerra and Sancho 2010) (meaning that efficiency is not influenced by other changes in energy prices), and when the reaction to a price decrease equals the reaction to an energy efficiency improvement (Madlener and Hauertmann 2011). Moreover, rebound effects can arise from marginal and non-marginal pricing (Borenstein 2013); and:

$$DRE = -\eta_{P_{ES}}(ES); \tag{A10}$$

where $\eta_{P_{ES}}(ES)$ is the own-price elasticity of the energy service. However, this formulation is also subject to bias unless an explicit formulation of efficiency improvement is introduced in the definition of the energy service, in demand or supply functions (or choices), since this approximation also assumes that one source of energy is exclusively used in the production of one energy service (Hunt et al 2014).

Appendix B

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