The Rebound Effect and its representation in Climate and Energy models

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Abstract

In this paper, we review the state-of-the-art and common practice of energy and climate modeling visá-vis the rebound literature, in particular regarding how macroeconomic energy and climate models quantify and include energy and greenhouse gas rebound effects. First, we focus on rebound effects in models of costless energy efficiency improvement that hold other attributes constant (zero-cost breakthrough), and an energy efficiency policy that may be bundled with other product changes that affect energy use (policy-induced efficiency improvement) (Gillingham et al. 2015). Second, we examine macroeconomic studies focusing on energy efficiency both in industry and in private households. Third, we go through a general theoretical revision from micro- to macroeconomic levels (the aggregation level) to include a review of the so-called meso-level studies (focused on the analysis of the production side). From 118 recent studies along the aggregation level, out of which 25 compute rebound calculations, we find that the average energy rebound effect is 58% with a standard deviation of 58%, and when we include green house gas rebound calculations, the magnitude is of the order of 43% with a standard deviation of 55%. Finally, we argue that the rebound effect is a phenomenon that requires a sound understanding of the complex interactions from different dimensions (e.g. aggregation level, heterogeneity, climate, energy conservation and economic growth), and we provide some ideas and motivations for future research.

JEL Classification

E13, Q410, Q430, Q48, Q540, R13

Keywords

Rebound effect, Macroeconomic models, Energy efficiency, Energy policy;

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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, etc., have promoted the implementation of a cluster of energy and climate policies as part of the global agenda. Some examples include the promotion of energy efficiency standards, energy conservation, sufficiency strategies, greenhouse gas (GHG) emission reductions or renewable energy targets. In particular, due to the existence of the energy efficiency gap as a result of market failures [Jaffe and Stavins, 1994], [Gillingham and Palmer, 2014], energy efficiency policies are often being implemented worldwide as seemingly win-win cost-effective policies. However, the goals of these policies imply a complex web of nonlinear interactions that are not yet well understood [Jenkins et al., 2011]. Borenstein [2013] and Schmitz and Madlener [2017] 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 energy efficiency improvement should not be a stand-alone policy, and Azevedo [2014] and Pollitt [2017] introduce a multi-objective trade-off perspective between goals.

Much of the controversy has focused around what level of efficiency is feasible to obtain with energy efficiency policies, given the existence of rebound effects, as illustrated in [Gillingham et al., 2016], "*buy a more fuel-efficient car, drive more*". The possibility of backfire at the microeconomic level [Saunders, 1992], [Saunders, 2017], and more recently at the macroeconomic level [Brockway et al., 2017], [Rausch and Schwerin, 2016], has motivated a plethora of studies. Nonetheless, Borenstein [2013] finds backfire is unlikely at the microeconomic level. Furthermore, Gillingham et al. [2013] states that the rebound effect has been overplayed because even at the macroeconomic level, it is highly probable that energy efficiency policies will not backfire; therefore, efforts should be placed on carbon-pricing policies, or as proposed by [Belaïd et al., 2018] and [Landis et al., 2018] on carbon taxes. Looking specifically on energy efficiency and energy rebound effects, Gillingham et al. [2016] find that rebound effects should actually be promoted due to highly probable potential welfare gains overall of both energy efficiency and rebound. Moreover, Bjelle et al. [2018] claim that ignoring the rebound effect would compromise economic activity, because that would be equivalent to assuming decreased total expenditure. Pollitt [2017] indicates that rebound effects are one of the key factors to take into account for policy implications, since they may be beneficial for economic and social outcomes but might lead to detrimental environmental outcomes. Finally, Chitnis and Sorrell [2015] show that although all rebound effects contribute to GHG emissions, different studies estimate rebound effects in energy, carbon and GHG emissions, but no study has yet examined all three together.

In response to the observed micro- to macro-economic level gaps in the literature, as stated in Madlener and Turner [2016] and resumed by Santarius [2016] as: "*The volatility of rebound effects increases with the level of economic action and aggregation*", we conduct a systematic review to describe how rebound effects are treated in economic simulations at each level of aggregation: the microeconomic, meso-economic (energy systems), and macroeconomic (economy-wide) levels. We present findings for how energy and climate models at each level of aggregation and degree of heterogeneity (i.e. energy services, goods, attributes, economic actors) deal with the rebound effect, and we discuss possible directions to extend the understanding of the energy and GHG rebound effect phenomenon. To this end, we report on three important trade-offs between possible benefits/costs associated with energy efficiency improvements: Energy savings, GHG emission reductions and welfare. Other types of collateral impacts, such as energy security, health, labour, and other social impacts [Pollitt, 2017], are outside the scope of this review. A main take-away is that the aforementioned trifecta of interactions show that it is important to include environmental welfare considerations when studying the energy rebound effect, because when these rebound effects are reported as a stand-alone percentage, it is not sufficiently informative for policy considerations. Finally, in the case of policy-induced improvements, it is important to both perform a cost-benefit analysis and understand the effectiveness of legislations in a comprehensive manner.

The article follows this structure. First, we summarize mathematical forms used to calculate the rebound effect. Then, to guide the understanding and comparison of empirical studies, we develop a taxonomy of rebound effects along each level of aggregation. Using these concepts, we proceed to explain the underlying mechanics and methodologies used in empirical studies at each level of aggregation and summarize common results. We conclude with a discussion on energy/climate modeling, future research directions and perceived needs.

2 Energy efficiency improvement (EEI) and rebound effect (RE) representations

Modeling energy efficiency improvement (ε or in some studies referred as τ) on the producer or consumer side is at the core of the energy rebound effect representation. The energy efficiency improvement is defined as the ratio[1] 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 [Hunt et al., 2014]:

$$\Delta\varepsilon = ES/E > 0; \tag{1}$$

Energy efficiency improvement depends on the choice made by the consumer or producer (represented by the utility or production function chosen) and the RE formulation.

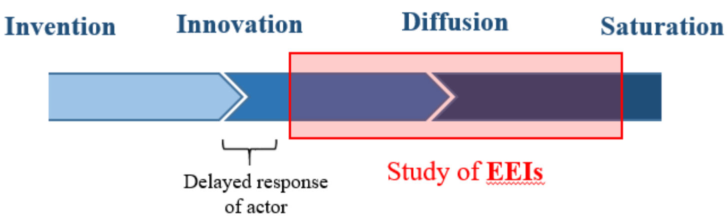
The main drivers of energy efficiency improvement are technical change and preference. The technical change driver is divided in zero-cost breakthrough (ZCB) and policy-induced (PI) interventions, where PI interventions can adopt the form of price-induced market based instruments (MBIs), command-and-control (CaC) instruments [Landis et al., 2018]), and program-based energy efficiency improvement [Gillingham et al., 2016]. The second driver, preference, is represented through consumption patterns [Azevedo, 2014].

2.1 Energy efficiency improvement as technical change

Technological progress encompasses not only more efficient technical choices for the use of inputs (e.g. automation for industries, or more efficient devices, such as, heating systems for households), but also structural changes in the economy caused by outputs (e.g. sectoral growth, economic growth) [Bibas et al., 2015].

Following [Löschel, 2002], energy efficiency improvement would be situated inside the process of technological change:

Figure 1: Process of technological change



In general terms, technical change can be modeled as neutral (equal reduction of all inputs), or biased (some inputs are reduced more than others) [Broadstock et al., 2007], where energy efficiency improvement is given at a specific point in time, or as factor augmenting (assuming a rate of growth of EEI over time). [Otto et al., 2007], [Otto et al., 2008] and [Löschel and Otto, 2009] develop and apply

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[1] Energy efficiency improvements could also be measured as a difference [Ang et al., 2010]; however, the reviewed studies have not taken this form.

an endogenous model of energy biased technical change with knowledge capital stocks and technology externalities in innovation and production. 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 [2017] explores a quadratic trend. Technical change can be represented using a latent variable approach (policy induced or zero-cost breakthrough), which could depend on past energy prices [Hunt et al., 2014], reflected as energy source price terms, relative prices, real prices, growth rates, or reduction of discount rates. Another representation is as price diminishing, which is a reduction in the costs of technologies [Löschel, 2002] (e.g. labeling and perceived costs). Furthermore, in the case of asymmetric price responses or energy efficiency improvement indexes [Ang et al., 2010], EEI could be represented as a past maximum price followed by price recoveries and decreases (using price decomposition methods). Other types of technical change representations found in our review are shown in Fig. 2.

Energy efficiency improvement as zero-cost breakthrough

In this context, a costless energy efficiency improvement with zero-cost breakthrough is introduced in models to study its direct impacts, holding other attributes constant [Gillingham et al., 2016].

Energy efficiency improvement as heterogeneous policy-induced improvement (Het-PI)

Following the concept of policy-induced improvements as introduced by Gillingham et al. [2016], we now expand the definition of policy-induced improvements to include (1) price-induced instruments and (2) Command and control instruments as part of energy efficiency improvement policy interventions; together we call this (3) Heterogeneous policy-induced improvements.

- **Price-induced instruments**. It is defined as market based instruments such as taxes or subsidies for households or/and industries. Taxes imposed on the production side include emissions 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, utility-sponsored rebate programs, etc., while for the consumption side these might include subsidies for adoption of low-pollutant emission devices, e.g. rooftop solar technologies, light bulbs, electric cars.

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

- **Policy-induced improvement**. For the consumer side, this is the policy-induced improvement as explained in [Gillingham et al., 2016]. In this context, an energy efficiency policy that, when introduced, also changes a device's attributes. To the best of our knowledge, these have not been implemented yet in models on the production side.

The attribute parameter

In some cases, the service a unit of energy provides is not only a function of useful work derived from a more efficient device but is also a function of its attributes (e.g size, comfort, reliability, speed, 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 energy efficiency policies. In another study, Galvin [2017] examined how average increases in the vehicle-speed attribute (acceleration) can be incorporated into calculations of rebound effects, showing that the relationship between energy services and energy consumption levels might be nonlinear. The main insight was that it is possible to completely expunge energy efficiency 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.

2.2 Energy efficiency improvement as preference: change in consumer patterns

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, use of energy-efficient appliances) 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, 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 greenhouse gas 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] recommend 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.

2.3 Rebound effect formulation

Physical or economic channels and aggregation (or indicators) [Broadstock et al., 2007] to represent energy to parse the rebound effect include:

1. Energy as the explicit thermodynamic representation of energy efficiency improvement, where heat content is represented by a physical indicator as the numerator (e.g. vehicle kilometers per liter of fuel), or by energy efficiency units (i.e energy services), exergy as effective end-use consumption energy [Brockway et al., 2017].
2. Energy as an explicit representation of an economic indicator, where an economic output is the numerator (e.g. from energy commodity or energy service prices, adding to value added/GWh or GDP/Total energy consumption).
3. Implicit energy efficiency, using the own-price elasticity of energy as a proxy for the rebound effect.

In the short term, rebound effect 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 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].

According to Hunt et al. [2014], energy efficiency improvement should be explicitly modelled 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. Although upper-bound studies are also important, induced or endogenous RE might produce a more accurate representation of overall RE [Löschel, 2002], [Witajewski-Baltvilks et al., 2017]. The distinction between total technical progress and energy-resource technical progress should also reduce bias in estimations [Du and Lin, 2015].

It is important to note that, GHG rebound effects and drivers have been less studied. Used models typically assume that there is a linear relationship between energy consumption and GHG emissions. We specifically address this difference when possible.

2.4 Mathematical rebound effect representations

There exist many different representations of energy and GHG rebound effects depending on the modeling approach, from microeconomic to macroeconomic level. Therefore, we classify mathematical rebound representations first.

The most common representations of the direct energy rebound effect (DRE) include [Berkhout et al., 2000]:

$$DRE = \eta_{\epsilon}(ES); \tag{2}$$

where $\eta_{\epsilon}(ES)$ is the efficiency elasticity of energy services;

or as own-price elasticities:

$$DRE = 1 + \eta_{\epsilon}(E); \tag{3}$$

where $\eta_{\epsilon}(E)$ is the efficiency elasticity of energy demand;

alternatively as:

$$DRE = -\eta_{P_E}(E); \tag{4}$$

where $\eta_{P_E}(E)$ is the own-price elasticity of energy demand (of energy commodities). This holds when the price of energy (in physical units) remains constant, so that any change in energy efficiency reflects in the effective price of energy [Guerra and Sancho, 2010] (meaning that efficiency is not influenced by changes in energy prices), and when the reaction to a price decrease equals the reaction to an energy efficiency improvement [Madlener and Hauertmann, 2011]. Rebound effects can arise from marginal and non-marginal pricing [Borenstein, 2013]; and:

$$DRE = -\eta_{P_{ES}}(ES); \tag{5}$$

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]. For a more complete representation of DREs see [Sorrell and Dimitropoulos, 2008].

Indirect rebound effects (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].

The total microeconomic energy rebound effects and macroeconomic energy rebound effects, are usually defined as:

$$RE = 1 + \eta_{\tau}(E); \tag{6}$$

where $\eta_{\tau}(E)$ is the efficiency elasticity of fuel (energy)[Saunders, 2008], [Wei, 2010];
or;

$$R = 1 - \frac{AES}{PES}; \tag{7}$$

where AES is actual energy savings and PES is potential or expected energy savings in the absence of rebound effects [Berkhout et al., 2000]. In the case of a macroeconomic rebound calculation, a household productivity shock is usually applied to the model to calculate the difference between AES and PES corresponding to general equilibrium measures [Guerra and Sancho, 2010]. Notice that for economic growth models, it is also a 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]:

$$RE = [1 + \frac{\dot{E}}{\alpha\gamma}].100; \tag{8}$$

where γ is the efficiency elasticity of energy, represented as an autonomous energy efficiency improvement, and α=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 total microeconomic GHG rebound effect is similarly defined as:

$$R = 1 - \frac{\Delta Q}{\Delta H}; \tag{9}$$

where ΔQ is the net change in GHG emissions and ΔH is the change in emissions without behavioral response .

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

$$R^s = \frac{1 + 1/\sigma^s}{1/\sigma^s - 1//\sigma^d}; \tag{10}$$

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

$$R^l = \frac{1 + 1/\sigma^s}{1/\sigma^s - \sigma^e_e - \theta}; \tag{11}$$

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.

We use the mathematical representations described above, to summarize and classify the existing rebound effect types in the literature, according to its magnitude. This is important in order to quantify the rebound effect within the aggregation level and time. Table 1 shows 5 types of rebound effects and their respective elasticity domains.

Table 1: 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	$\eta_{P_E}(E) < -1$[a]	$\eta_{P_E}(E) = -1$	$-1 < \eta_{P_E}(E) < 0$	$\eta_{P_E}(E) = 0$	$\eta_{P_E}(E) > 0$
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, 2017], it is theoretically possible for it to occur when large externalities are corrected (e.g. in policy induced studies). Moreover, depending on the functional form of the production function, this can cause a “Disinvestment effect” [Turner et al., 2009].

2.5 Rebound effect theory: Taxonomy and Typology

Due to the complexity of the rebound effect phenomena, and to better understand its mechanisms and possible causes, it is useful to systematically de-construct it into known effects available in the literature. Further motivations to parse the RE, involve linking the theoretical point of view to empirical calculations, and exploring causality effects.

Hence, Tables 2 to 5 combine the typology and taxonomy of the rebound effect, from two consumers' perspectives: that of (1) a producer of energy services, and (2) an end-use consumer; and similarly from producer's perspectives, along the aggregation level. This table has been elaborated with the contributions in the literature about the underpinnings of the rebound effect, 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].

Table 2: Rebound typology representation along the level of aggregation, as partial equil. (PE), part I

		Rebound Typology[1]	**Decomposition Channel**	**Taxonomy**	**Other names**
PE	**Consumer side**	(1) Direct rebound effect[2]	1.1 Substitution effect (+)	Own/price elasticity of demand, substitution to consume more of good 0 due to price reduction.	Price effect
			1.2 Income effect[3] (+)	Free income used to consume more of good 0 due to price reduction.	
		(2) Compensating cross-elasticicies[2]	Fixed income (-)	Expenditure on good 0 takes away expenditure on other goods with energy content.	
		(3) Indirect rebound effect	3.1. Substitution effect (-)	Cross-price elasticity of demand of other goods, substitution to consume less of other goods due to more consumption of good 0.	Analogous to the variation of energy intensity in the economy as a whole.
			3.2 Income effect[2] (+)	Consuming more of other goods due to savings on good 0.	Re-spending effect
			3.3 Embodied energy (+)	Energy or emissions associated with the life cycle of an energy service.	
			3.4 Behavioral effect (+)	Indirect rebounds not caused by EE improvement, but by changes in consumption behaviors.	

[1] There also exists the less studied "transformational" rebound effects [Greening et al., 2000],"motivational psychological" rebound effects [Santarius, 2016], and "time" rebound effects [Binswanger, 2001].

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

[3] Both income effects (1.2 and 3.2) can be grouped into the "income effect rebound" [Borenstein, 2013].

Table 3: Rebound typology representation along the level of aggregation, as partial equil. (PE), part II

	Rebound Typology[3]	**Decomposition Channel**	**Taxonomy**	**Other names**
Producer side and Meso-level (sectoral)	(4) Direct rebound effect	4.1 Factor substitution (+)	Substitution to use more energy input 0 due to cost reduction (e.g. automatization).	Analogous to the substitution effect on the consumer side.
		4.2 Output effect (+)	Free expenditure (savings) to use more energy input 0 due to cost reduction resulting in increased production.	Analogous to the income effect on the consumer side.
	(5) Indirect rebound effect	5.1 Factor substitution (-)	Substitution to use less of other inputs due to cost reduction.	
		5.2 Output effect (+)	Free expenditure (savings) to use more of other inputs due to cost reduction resulting in increased production.	Re-investment effect
		5.3 Embodied energy effect (+)	Investments in energy efficiency technologies increase demand for energy.	Grey energy
	(6) Complementary rebound effect	Redesign effect (+)	Ex-ante expected cost savings for consumers lead producers to invest in redesigning of the original product.	

Table 4: Rebound typology representation along the level of aggregation, as general equil. (GE), part I

		Rebound typology	**Decomposition Channel**	**Taxonomy**	**Other names**
GE	**Producer and Consumer interaction**	(7) Interactive rebound effect	7.1 Market price effect (+)	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.	
			7.2 Disinvestment effect (-)	Direct and derived demands are not sufficiently elastic to prevent falling market prices of energy, leading to decline in revenue, profitability and return on capital in domestic energy supply sectors.	
			7.3 Composition effect (+)	Reduction in market price favors energy-intensive sectors of the economy, reducing the price of energy-intensive goods and services causing the increase of their demand, altering the composition of the economy's portfolio of goods.	
			7.4 Effect of economies scale (+)	Income and market effects causing increase in demand for energy services or goods, leading to firm expansion that reinforces falling prices, whose impact reduces along the level of production.	
			7.5 Rising labor income effect (+)	Firms using additional income from energy efficiency of production process to raise worker's wages.	

Table 5: Rebound typology representation along the level of aggregation, as general equil. (GE), part II

	Rebound typology	**Decomposition Channel**	**Taxonomy**	**Other names**
GE	(8) Macro-economic rebound	8.1 Price effect	The adjustment of consumers and producers following a shift to the left of the market demand curve.	Economy-wide. Analogous to consumer price effect.
		8.2 Growth effect: 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.
		8.3 Growth effect: Induced innovation	Spillover effects of an energy improvement in one sector, attributable to improvement in another one.	
		8.4 Growth effect: 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.
		8.5 Labor supply (-)[1]	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.	

[1] At the macro-economic level, rebound effects 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 (7.5) in table 4.

Additionally, Van den Bergh [2011] identifies the following mechanisms:

1. Time savings (time rebound effect);
2. Technological innovation and diffusion effects; and
3. Purchase of larger (heavier) units or units with more functions/services and consequently using more energy (e.g., cars with air-conditioning).

Further, Saunders [2013] includes a so-called "frontier effects", enabling new product applications or services.

3 Modeling the rebound effect

In similar vein as in Varian [2016], in sections 1 and 2 we identified some essential pieces necessary to build a rebound effect model. From primitive possible characteristics of energy efficiency (technology improvements or consumer patterns), to its existing RE mathematical formulations, and economic effect components, we now turn in this section to describe common methodologies found in the literature, used to model the rebound effect.

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 energy efficiency improvement, (2) a mathematical representation of the rebound effect, and in most cases, (3) the economic theory, assuming a choice faced by a representative consumer (utility maximization), by a producer (profit maximization), or a consumer-producer ("prosumer", household-factory) that integrates production and consumption (a household produces energy services minimizing costs in order to maximize utility derived from those energy services) [Becker, 1965] [Scott, 1980], and (4) to include a degree of heterogeneity (for energy or energy services) of a representative consumer and firms.

Our review has grouped energy and macroeconomic studies under the following categories: Structural models, Econometric studies, Simulation studies and Integrated Assessment models. We present general assumptions for each type of model, and report on the EEI and RE representation and results in recent studies. [2]

3.1 Structural models of neoclassical economic growth

Structural models have been the most common means to calculate direct rebound effects as represented in equations (1) to (3). They include preferences and technology, using observed past behavior (characteristic of ex-post, often econometric studies) to calculate 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 et al., 2015], the Rotterdam model, or the translog function [Saunders, 2013], [Mishra, 2007], [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, such as the implicit function theorem, for calculating elasticities.

Other sets of structural models represent household demand consumption, and allow to compute direct and indirect rebound effects. 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, 2017], linear expenditure systems (LES) [Lin and Liu, 2015], direct addilog (DA), indirect addilog (IA) [Thomas, 2012], double-log (DL) system [Freire-González, 2017a], etc. Parameters are obtained using linear or non-linear econometric methodologies (i.e. ordinary least squares, dynamic ordinary least squares, feasible generalized least squares, nonlinear least squares, etc.). Usual inputs are energy (or energy commodities, services), capital, labor, and materials.

Recent studies have focused on the meso-economic rebound effect to study production-side sectoral, and interactive rebound effects (e.g. market effects) [Santarius, 2016].

Table 6 and 7 show a review of selected structural models from the production and consumption sides, and their respective RE magnitudes as percentage (%):

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

Table 6: Selected review of Production-side direct rebound effect studies

Author (year)	**Spatial focus**	**Sectoral focus**	**Typology**	**EE / RE channel**	**RE magnitude**	**Welfare**	**GHG red./ rebound**	**Insights**
Yang and Li [**2017**]	Bejing 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 less 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 $\sigma_{(KL)E}$=0.6-0.7	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 $\sigma_{(KL)E}$=0.5-0.8	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 7: Selected review of consumption-side direct rebound effect studies

Author (year)	Spatial focus	Sectoral focus	Typology	EE / RE channel	RE magnitude	Welfare	GHG red./ rebound	Insights
Schmitz and Madlener [**2017**]	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 $IRE > DRE$ mag.
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	$IRE > DRE$ mag. 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 frame consumer price responsiveness. Habits are not influenced by economic signals in the SR.

EE representation: 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).

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 rebound effects at national levels, as represented in eqs. (4) to (5). These models assume that parameters remain unchanged, 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 8 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 estimations that could be possible to estimate.

Econometric studies represent the rebound effect in two broad categories, which vary according to the aggregation level of study. The first category includes energy systems that compute the direct rebound effect, whereas the second category contains economy-wide contexts to calculate a total national or sectoral rebound effect. However, Acemoglu [2010] and Lemoine [2017] 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. 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.

The advantage of these types of studies is that they can take into account causality effects 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 [Jacobsen and Van Benthem, 2015]. Quasi-experimental ex-post studies could provide more realistic insights about specific energy efficiency program performance and effectiveness.

Table 8: Review of selected National Production-side rebound effect studies

Author (year)	**Spatial focus**	**Sectoral focus**	**Typology**	**EE / RE channel**	**RE magnitude**	**Welfare**	**GHG red./ rebound**	**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.

EE representation: AEEI: autonomous energy efficiency improvement.

[1] Averages taken from methods 1 and 2.

Table 9: Review selected of consumption side RE econometric studies

Author (year)	**Spatial focus**	**Sectoral focus**	**Typology**	**EE / RE channel**	**RE magnitude**	**Welfare**	**GHG red./ rebound**	**Insights**
[**Frondel and Vance, 2018**]	Germany	Households Private Transport single-vehicle	(1)DRE IV estimator PI	EE: LVA-P (tax rate/100 cm^3) DRE: $\eta_\epsilon(ES)$ Data 1997 - 2015	SR 67% Rejects H_0	NA	NA	Using IV estimator results in RE 30% points > 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)	15% red. energy consumption [1]	less than 1% energy expenditure savings	SCC \$38/ton at r=3% [2]	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[3] 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% Rejects RE=0 3.7% reduced energy consumption	NA	NA	Even targeting policies might be challenging due to heterogeneity found in the results.

EE representation: LVA-P: Latent variable approach, policy-induced. EEI: Energy efficiency improvement.

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

[2] r: Discount rate.

[3] Heating, ventilation and air conditioning. .

3.2.2 Macro-econometric models

Despite the difficulties in attaining a good degree of identification with reality, these post-Keynesian ex-ante models might perform useful forecasting and policy analysis (when an effective existing rule prevails) [Sims, 1980].

After Barker et al. [2009], macro-econometric and non-equilibrium models, such as the global dynamic E3ME (or E3MG variant) and NEMESIS, have been used to asses co-benefits and trade-offs of policy scenarios in European economies using multiple sets of computable econometric equations. In the E3ME model, the rebound effect is modeled in two parts: the direct rebound effect (eq. (2) in section 2.1) is taken from the PRIMES bottom-up model (an energy system model), and this is then used to calculate the endogenous indirect rebound effect and the economy-wide rebound effect using eq. (4), derived from the input-output structure of the model [Pollitt, 2017]. Inputs of the model are shared with other models such as the PROMETHEUS (fossil fuels and import prices) and GEM-E3 (macroeconomic and sectoral projections) [E3MLab and IIASA, 2016]. The main assumption with regard to energy efficiency 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 rebound effect. The model allows varying returns of scale and nonlinear 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.

Following our description in section 2.5, the E3ME has focused to represent, from the macro-economic point of view, the price and growth effect (sectoral allocation channel). Overall, taking into account partial and general effects, the RE has been computed as follows [Barker et al., 2009], [Pollitt, 2017]:

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

Main results highlight the importance of capital formation modeling to account for crowding out effects [Pollitt, 2016].

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[3] Although, Sorrell et al. [2007] defines the economy-wide rebound effect as the sum of the direct and indirect rebound effect components.

Table 10: Review selected of macro-econometric studies

Author (year)	**Spatial focus**	**Sectoral focus**	**Typology**	**EE / RE channel**	**RE magnitude**	**Welfare**	**GHG red./ rebound**	**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.

EE representation: KNK: Kaldor's neo-Keynesian.

[1] International Energy Agency [IEA, 2014].

3.3 Simulation models

3.3.1 Energy system simulation models

Input-output (IO) models and environmentally-extended input-output models (EEIO)

The most comprehensive studies using this methodology, use estimates of direct rebound effects as inputs. These ex-post static models allow the calculation of indirect rebound effects as cross-price elasticities for n goods (or n services). Following this estimation, total rebound effects are computed as represented in eq. (4). Most studies have focused on studying indirect rebound effects on the consumption side. These models assume that constant returns of 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 can be modeled as constant or variable, and re-spending is usually assumed to be proportional in each good and service. Widely used data inputs include Consumer Expenditure Surveys, Eora data, EXIOBASE, the Global Trade and Analysis Project (GTAP), and the World Input-Output Database (WIOD).

Modeling RE with an EEIO model, Thomas and Azevedo [2013b] found that IREs are inversely proportional to DREs and are bounded by consumers, budget constraints. Freire-González [2017b] developed risk and vulnerability indicators for rebound effects.

Table 11 shows a review on selected consumption-side studies.

Table 11: Review of selected studies

Author (year)	**Spatial focus**	**Sectoral focus**	**Typology**	**RE channel**	**RE magnitude**	**Welfare**	**GHG red./ rebound**	**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 e	NA	NA	
Freire-González [**2017b**]	EU 27C	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.

EE representation: AEEI: autonomous energy efficiency improvement.

3.3.2 Macroeconomic simulation models

Computable general equilibrium models (CGE)

[Böhringer and Löschel, 2006], [Allan et al., 2007] and [Turner and Figus, 2016] provide comprenhensive reviews on these ex-ante "what-if" neo-classical models and their applicability to model energy-economy-environment inter-dependencies 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]. Energy efficiency improvements in this review are modeled as exogenous autonomous energy efficiency improvement and energy-augmenting, or endogenous technical change as latent variable approach of policy-induced type (taxes or subsidies on production or consumption). However, induced technical change as in Witajewski-Baltvilks et al. [2017], Lemoine [2017] and diffusion effects remain to be further studied. RE is calculated using eqs. (7) and (8). Advances in the analysis of RE tractability have also been applied, namely the decomposition of energy and GHG rebound effects from partial to general equilibrium, as described in section 2.5. To parse the rebound effect in direct and indirect partial equilibrium components, as described in tables 2 to 5 (i.e. substitution and income effects), modelers set all prices fixed except for the energy sector or service in analysis. To calculate the general equilibrium component, common used channels are: price, growth: sectoral allocation, labor supply [Böhringer and Rivers, 2018] [Chang et al., 2018], and growth: fiscal stimulus [Figus et al., 2017a]. Finally the total rebound effect is obtained summing 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 estimations mainly on the upper bound of the spectrum. Moreover, studies have investigated the influence of RE on macroeconomic parameters such as GDP, employment, etc. [Madlener and Turner, 2016] and on welfare [Gillingham et al., 2016].

Following Turner and Figus [2016], we checked the adaptation and tailoring of models for relevant interactions that might potentially impact on calculations of energy and GHG rebounds: (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 energy efficiency improvement representation. (2) Most models do not integrate adjustment of capital/labor growth (or decline) with regard to energy efficiency improvement. (3) Revised models assumed perfect competition, except Figus et al. [2017b], Figus et al. [2018]. For (4) and (5), mobile representation of capital between national sectors, investments, and labor increase gradually. (6) Recent models are not only dynamic, such that they capture consumer's responsiveness [Figus et al., 2017b],[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 also regional-specific (or spatial CGE models) [Helgesen et al., 2018]. (7) To represent energy and non-energy goods, CES/Cobb douglas functions are commonly used and inputs in the energy sector are usually modeled as Leontief composites, with no possibility of substitution, in RE studies assessed in this overview. (8) While energy efficiency improvement in total factor productivity has not commonly been modeled, it is 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 et al., 2018].

Tables 12-16 show recent studies for production and consumption.

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./ rebound**	**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 Eq. (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 Ref. petrol. Electricity/steam Gas supply	(4), (8.1) ZCB	AEEI Exogenous energy augmenting,-specific prod. shock, RE Eq. (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, $RE < 0$	$0.02 - 0.9\%$	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 Ref. 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.

EE representation: AEEI: autonomous energy efficiency improvement.

[1] Reported only inter-fuel substitution scenario.

Table 13: Review of selected CGE models focused on production

Author (year)	Spatial focus	Sectoral focus	Typology	EE / RE channel	RE magnitude	Welfare	GHG red./ rebound	Insights
[**Lemoine, 2017**]	Theory	Production	(4), (5), (8.1) ZCB	AEEI Exogenous productivity shock $\Delta\varepsilon = 1\%$ Theoretical	Does not reject H_0	NA	NA	Gen. eq. 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 [Böhringer et al., 2016]	SR US, China, EU 67% $\sigma_x = 0.5$, , Leontief fossil fuels Does not reject H_0	NA	NA	Partial eq. RE > Gen. Eq. 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	$0.13 - 0.51\%$	LR 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 14: Review of selected CGE models focused on consumption

Author (year)	**Spatial focus**	**Sectoral focus**	**Typology**	**EE / RE channel**	**RE magnitude**	**Welfare**	**GHG red./ rebound**	**Insights**
Figus et al. [**2017a**]	Scotland	Household	8.1 ZCB	AEEI prod. shock. RE Energy in economic units aggregate Eq. (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 acitivity/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 Transport private	Theory Simulation ZCB	Endogenous vehicle-augmenting, physical units (fuel/miles). $\Delta\varepsilon = 10\%$. Part. Eq. 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.

EE representation: 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./ rebound**	**Insights**
[**Landis et al., 2018**]	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.

EE representation: AEEI: autonomous energy efficiency improvement.

Table 16: Review of selected CGE models focused on consumption

Author (year)	**Spatial focus**	**Sectoral focus**	**Typology**	**EE / RE channel**	**RE magnitude**	**Welfare**	**GHG red./ rebound**	**Insights**
[**Duarte et al., 2018**]	Spain	Household Electricity Transport	8.1 ZCB	EEI Diffusion: Logistic schedule captures gradual EEI from real evolution. RE Eq. (8). Part. Eq. 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	Households	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.

EE representation: AEEI: autonomous energy efficiency improvement.

3.4 Integrated assessment models

There are two main types of ex-ante Integrated Assessment Models (IAMs), detailed process (DP) IAMs and benefit-cost (BC) IAMs. 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. On the other hand, BC IAMs represent sectoral (or regional) aggregation functions and climate change mitigation costs into a single economic metric, whose main goal is to analyse 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 energy efficiency), 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 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 of trade-offs between mitigation and adaptation strategies on global scales, which useful for international negotiators, and national and/or regional decision makers. BC IAMs are helpful to highlight critical issues in the understanding of the cost-effectiveness of climate change policies (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.

Pindyck [2017] contrasted the current state of IAM models, which add much noise, are at an early stage, and would require sensitivity analysis on key parameters. With the time pressure exerted by climate change, he concluded that simple models to calculate upper bounds would also be useful. In particular, Martin and Pindyck [2017] assessed the likelihood of catastrophes in a model of catastrophe avoidance, making a distinction between the ones that cause destruction (or reduction in the consumption stream), and more severe ones that cause death. Their model identify death as a welfare-equivalent reduction in consumption, in order to find a formulation for the willingness to pay to avert it, using as proxy, the “value of a statistical life”. They found that simple benefit-cost analysis break down, decisions to avert major catastrophes are interdependent, and provided guide on how to determine which catastrophes to avert. 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.

Models included in this overview, have included zero-cost breakthrough or policy-induced energy efficiency improvements, as exogenous or endogenous shocks. However, energy or GHE rebound effect magnitudes are not yet commonly explicitly calculated or presented, as shown in tables 17 and 18.

Table 17: Review of selected CGE models focused on production

Author (year)	**Spatial focus**	**Sectoral focus**	**Typology**	**EE / RE channel**	**RE magnitude**	**Welfare**	**GHG red./ rebound**	**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 industral 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 43% av.	NA	NA	End-user LED scenario under electricity and hydrogen sourced energy could lead to +1.5° 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° 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 18: Review of selected CGE models focused on production

Author (year)	**Spatial focus**	**Sectoral focus**	**Typology**	**EE / RE channel**	**RE magnitude**	**Welfare**	**GHG red./ rebound**	**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°C objective it not possible to attain if emissions peaks are delayed until 2030, and EEI policies in Industry 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°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°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.

EE representation: LBD: Learning by doing.

4 Synthesis and motivation for future research

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 rebound effect from the production and consumption side. We highlight the equal importance and complementarity of ex-ante and ex-post studies given the observed symmetry between models and computation of rebound effects, which requires the calculation of expected and realized energy savings. Moreover, given the tension between theory and reality, to reach a 'reasonable' level of identification, we consider it good practice to have a clear picture about the motivation behind modeling, similar to what Blanchard [2018] presented, considering 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.

Ex-post studies

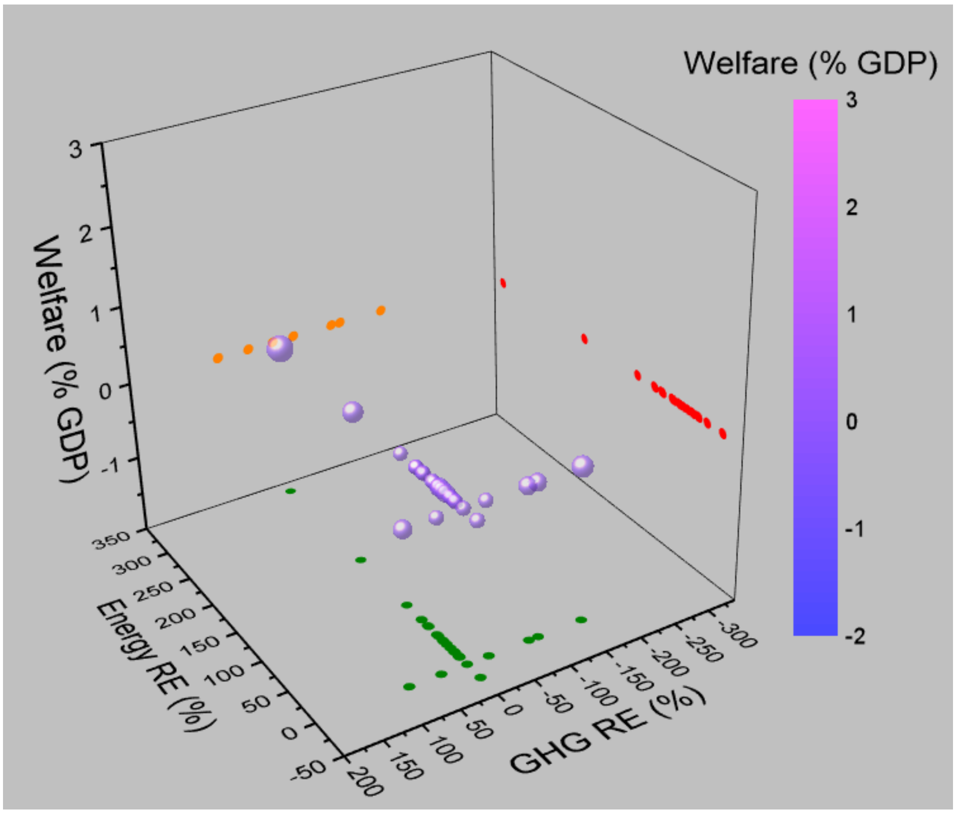
Both on energy systems and economy-wide levels, we find that structural functions are the most often used methodology on the production side. Although there are clearly several limitations imposed by structural forms and assumptions [Gillingham et al., 2016], and these types of models have been criticized 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 rebound effects. Moreover, on the consumption side, Schmitz and Madlener [2017] similarly found that the magnitude of the rebound effect is sensitive to model specification, and they recommend modeling energy services as an alternative to energy commodity models. The distinction between consumption and production direct rebound effects 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 causality 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 energy efficiency policies and on the rebound effect. Wang et al. [2016] recommends studying final energy consumption habits across a plethora of household appliances.

Thus, we find that ex-post studies that put emphasis on reality depiction (policy and/or zero-cost breakthrough) are of high importance in providing empirical evidence that could serve as an input for ex-ante studies, in order to feed accurate parameters to ex-ante studies.

Figure 2 shows that ex-post studies in our review estimate either energy RE or GHG RE effect separately, while welfare effects are not computed. From 26 RE calculations performed in studies shown in previous tables, the magnitudes of the energy RE have an average of 66% and a standard deviation of 79%, with a maximum of 334% and minimum of -22%. GHG rebound effects have an average of -38% and a standard deviation of about 83%, with a maximum of 78% and minimum of -161%.

Figure 2: Results on ex-post studies



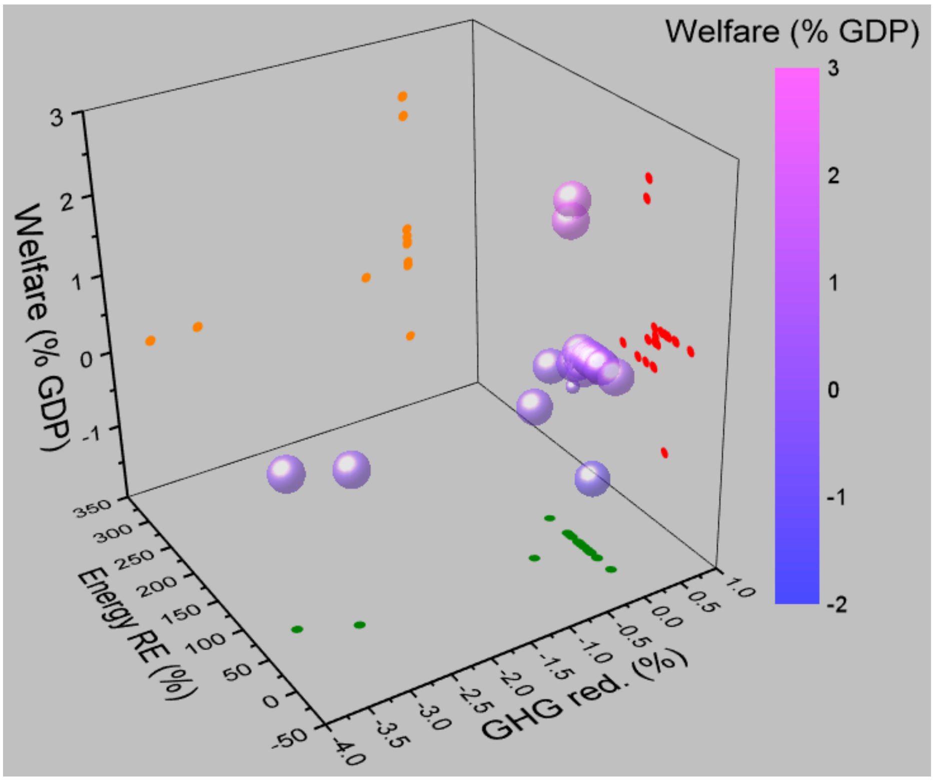
Ex-ante studies

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 revise the adequacy of CES functions to represent the nested production function, and to better match the energy-augmenting technical progress paradigm . With regard to the elasticity parameter, studies show that a low elasticity of substitution between energy and non-energy inputs, would result in a larger general equilibrium RE component [Wei, 2010]. In contrast, other studies have found that low elasticity of inter-fuel substitution would reduce the magnitude of the energy rebound effect [Lu et al., 2017], and Lemoine [2017] concludes that this parameter is not a reliable guide to the likelihood of backfire. Nonetheless, there is need for ex-post empirical evidence on fossil fuel supply elasticities [Böhringer and Rivers, 2018]. Moreover, Böhringer and Rivers [2018] also find that a more elastic elasticity of substitution between capital and labor would reduce the energy rebound effect magnitude. With regard to the intensity of the energy of sector, rebound effects may be larger if energy efficiency improvements are found or implemented in these sectors [Broberg et al., 2015], [Lemoine, 2017], [Zhou et al., 2018]. In addition, the larger size of the other sectors not affected by energy efficiency improvements could also increase the rebound effect magnitude [Böhringer and Rivers, 2018], and the substitution effect would govern [Zhou et al., 2018]. Another topic to examine more closely is the impact of energy efficiency improvements on primary energy, which could benefit 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 energy efficiency improvement. Finally, investigating rebound effect behavior in 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, Lu et al. [2017] finds that the long-run energy rebound effect diminishes.

On the consumption side, studies find that a more elastic 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 energy rebound effect 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 3 shows RE magnitudes obtained in ex-ante studies examined in this review. Joint estimations of energy RE and welfare effects have been carried out, while GHG RE has not been computed. From 19 RE calculations performed in studies shown in previous tables, the magnitudes of the energy RE have an average of 49% and a standard deviation of 22%, with a maximum of 98% and minimum of -0.1%. Welfare effects have an average of 0.4% of GDP and a standard deviation of about 0.7%, with a maximum of 2.25% and minimum of -1%. Jointly, there can be high energy RE associated with high welfare effects (2.25%) but also low (0.05%). In our overview, RE from ex-ante studies show lower average magnitudes than ex-post studies.

Figure 3: Results on ex-ante studies



Combined insights

Taking both sides into account, studies validating elasticities with historical data and the use of more sophisticated methods (i.e. causality identification) and sensitivity analyses would improve the reliability of studies [Saunders, 2013], [Wei and Liu, 2017], [Saunders, 2017]. Explicit and endogenous representations of energy efficiency improvements 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 energy efficiency improvements on both sides. For example, some studies found that a inelastic supply combined with an elastic demand may induce a higher energy rebound effect [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 energy efficiency improvement 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 energy efficiency improvements in place could result in higher GHG rebounds. Furthermore, the dynamics of the incorporating of energy efficiency improvements in primary and/or secondary energy would provide further insights [Zhou et al., 2018]. Another branch of the RE study includes externalities (e.g. pollution effects). Chang et al. [2018] found that ignoring these impacts could result in underestimation of the energy rebound effect magnitude.

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/light 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 energy efficiency improvement adoption and rebound effect in time, both using ex-post and ex-ante studies. Overall, the potential effect of energy efficiency improvements and rebound effects on the economy would be higher on industry than households; however, we find mixed results. Finally, ex-ante studies can also be used to monitor rebound effects in the economy, not just for forecasting (e.g. using now-casting or back-casting methods in CGE models).

After carrying out an extensive review of 118 recent studies on the rebound effect along the aggregation level, out of which 25 computed and reported energy or GHG rebound effect magnitudes in from table 6 to 18, figure 4 shows that the overall average rebound effect under different methodologies and rationale is of the order of 58% with a median of 49%, considering only energy rebound effects. When we also take into account GHG rebound calculations we find an average magnitude of around 43%, with a median of 47%. Our results are similar to the total expected rebound effect of 60%, as in Gillingham et al. [2016]. However, these estimates remain a very rough approximation, considering that we find a very high standard deviation of approximately 58% and 55%, respectively, with a maximum per source, sectoral, or national rebound of 334% (there are also higher magnitudes for specific provinces within developing countries, e.g. China), and a minimum of -161%. Combining previous, recent, and future studies on rebound effect magnitudes could provide more data to increase the analytic power of rebound effect estimates, through a future meta-analysis study of the rebound effect or crowdsourcing data analysis strategies as in Silberzahn et al. [2018].

Figure 4: Results on all revised studies

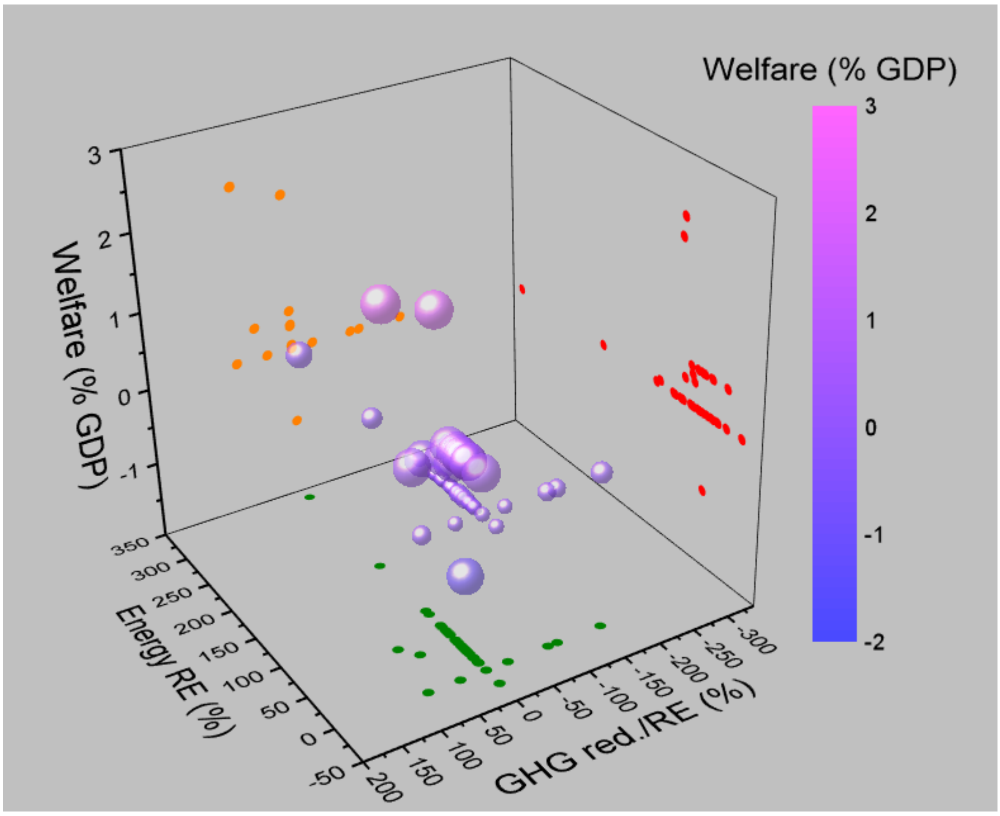


Figure 5 shows RE magnitudes obtained on developed country studies examined in this review. Joint estimations of energy RE and welfare effects have been carried out, or GHG RE has been computed. From 22 RE calculations performed along the level of aggregation, shown in previous tables, the magnitudes of the energy RE have an average of 50% and a standard deviation of 23%, with a maximum of 78% and minimum of -22%. Welfare effects have an average of 0.27% of GDP and a standard deviation of about 0.8%, with a maximum of 2.25% and minimum of -1%. Jointly, there can be high energy RE associated with high welfare effects (2.25%) but also moderate (0.32%).

Figure 5: Results on developed countries

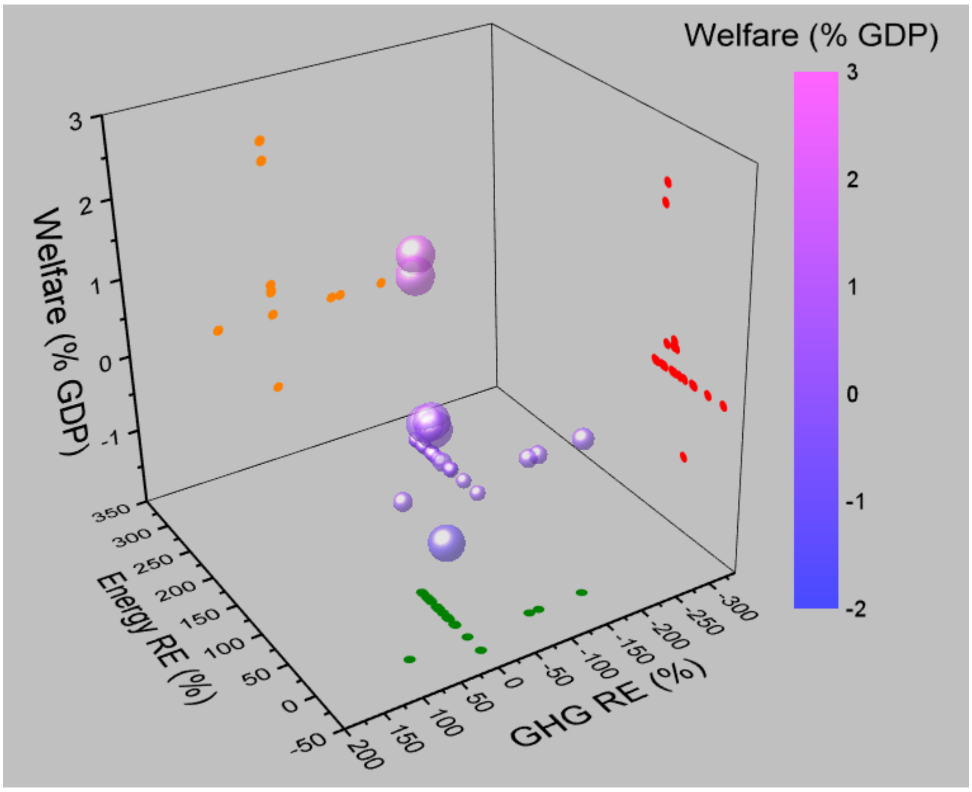
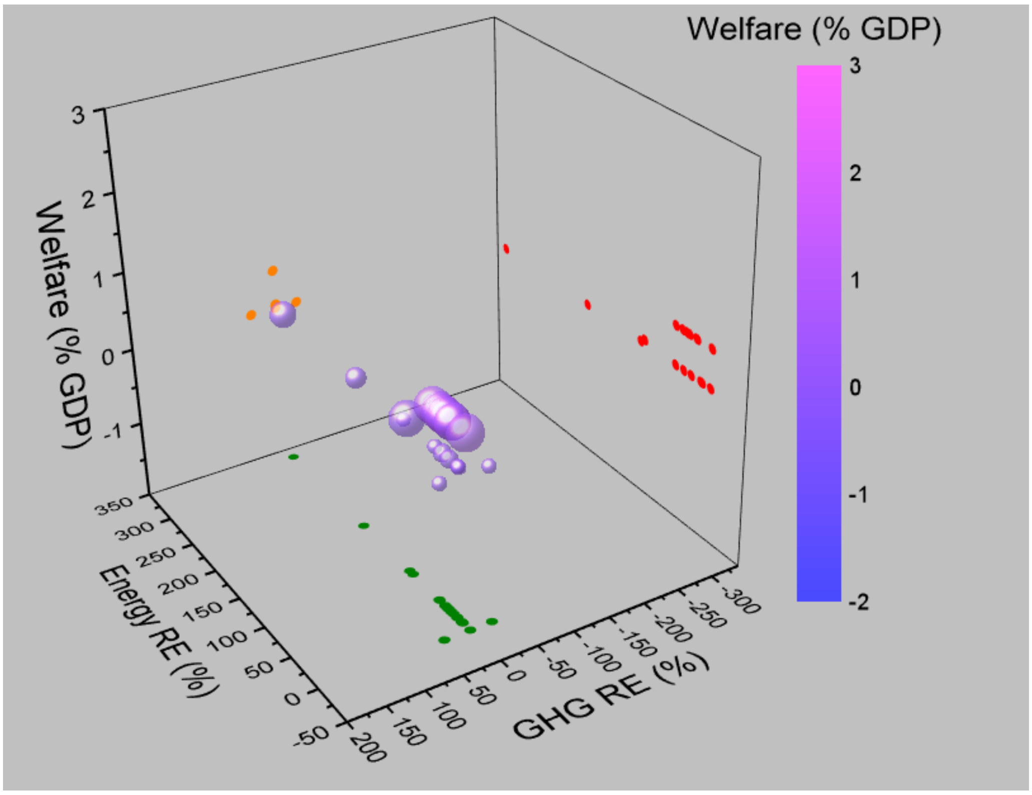


Figure 6 shows RE magnitudes obtained on developing country studies examined in this review. Joint estimations of energy RE and welfare effects have been carried out, while GHG RE has not been computed. From 16 RE calculations performed along the level of aggregation, shown in previous tables, the magnitudes of the energy RE have an average of 67% and a standard deviation of 85%, with a maximum of 334% and minimum of -0.1%. Welfare effects have an average of 0.4% of GDP and a standard deviation of about 0.2%, with a maximum of 0.5% and minimum of 0.05%. Jointly, there can be high energy RE associated with moderate welfare effects (0.5%) but also low (0.05%). In our overview, RE from developed studies show lower average magnitudes and standard deviation than developing studies. Welfare effects from developed studies show lower average magnitudes and higher standard deviation than developing studies.

Finally, all figures imply that welfare is a function that depends on GHG reductions and energy savings. Furthermore, given that the calculation of rebound effects has two components one expected (or-ex-ante), and another real (or ex-post), we suggest that GHG reductions and energy savings would be better indicators for policy assessment, due to the possible high variability of the expected component.

Figure 6: Results on developing countries



4.2 Motivations and scope for future research

Energy efficiency improvements 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 energy efficiency improvements simultaneously on both sides, and in particular that involve rebound effect as described in section 2.5, complementary RE (6), composition rebound effects (7.3), effect of economies scales (7.4), and transformational rebound effects have not yet been found.

Heterogeneity. On the production side, and considering the GHG emissions reduction goal, Lemoine [2017] indicates that energy efficiency improvement policies should target energy-efficient sectors with low elasticity of substitution between energy and non-energy inputs; 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 on 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 on the production side, Ryan et al. [2017] suggests that the policy focus should expand to consider not only improvements in energy efficiency in energy-intensive sectors, but also how these improvements interact with less energy-intensive sectors, and in China, Wang et al. [2016] found that in residential electricity consumption, investment should be promoted in energy-saving technologies. Moreover, while it is common to consider heterogeneity in energy services, attributes, etc. In energy system approaches, Bye et al. [2018] found that modeling energy efficiency improvement on a specific sector (i.e. the electricity sector), instead of considering energy efficiency improvements on all energy uses in an economy, could result in economic distortions that may lead to welfare loss, though the electricity sector in Norway is mainly produced from renewable sources. Thus, the question here would be to what degree and for what cases is heterogeneity relevant for policy analysis.

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 energy efficiency improvements, but EEI policies should be accompanied by taxes to control and level-up price reductions. On the other hand, Lu et al. [2017] found that policies should target the efficiency of energy efficiency improvement policies in the long run, where REs diminish. In that vein, Frieling and Madlener [2017b] concluded from a comparison of production factor-augmenting structural partial equilibrium models for Germany, USA and UK, that energy consumption is relatively immutable in the short run. It remains to be further analyzed how the rebound effect affects the emissions, peak time-frame.

Uncertainty due to expectations and the counterfactual. Engineering estimates on energy savings found in actual energy efficiency 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] conclude that including causality could produce higher upper-bound RE estimates than assuming 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 rebound effect estimates.

Energy efficiency up-front costs. More poliy-induced studies such as [Burlig et al., 2017], [Fowlie et al., 2018], and [Bye et al., 2018], which include energy efficiency investment costs, give a more complete picture regarding the cost-effectiveness of energy efficiency policies.

Imperfect markets, externalities and imperfect regulations. 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 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 et al. [2018] found that the economic costs of energy efficiency 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 the economic costs of EEI policies for dwellings (i.e. a cap on residential use and energy intensity) are highly costly even 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 3 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 GHG rebound effect. Furthermore, energy conservation policies are usually modeled in integrated assessment models, as the common strategy in mitigation scenarios, but transition pathways that can meet such targets are less commonly studied. From 6 IAMs and 5 shared socio-economic pathways (SSPs), 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 temperature rise below +1.5°C by 2100; while scenarios with scattered short term climate policy, strong inequalities in SSPs, and high baseline fossil fuel use, did not. Gidden et al. [2018] analysed 13 scenarios with open-access and reproducible higher gridding spatial resolution (aneris), comparing SSPs to representative concentration pathways (RCPs), and recommended that the assessment of the role of uncertainty is carried not only between scenarios, but also between model results for a certain scenario, such as F-gas trajectories. Additionally, as carbon dioxide and methane gasses are well-mixed climate forcers nature that have higher impact from a political rather than physical perspective, adding spatial detail would provide more meaningful insights for policy analysis.

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 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.

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 to consumer's preferences, could contribute to reduce energy consumption in the short or medium run.

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 energy efficiency improvements 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 energy efficiency and rebound may act as engines of economic growth [Ayres, 2010], there might be a potential trade-off between climate-based policies and economic growth (e.g. carbon taxes to reduce rebound, restricting economic growth). Thus, interactions between energy consumption, energy conservation, GHG emissions and economic growth would require further analyses on macroeconomic levels in order to find adequate policy strategies.

To move beyond, and given the historical time we live in, future large shifts in policy will require answers and solutions to many open questions regarding complex interactions, to understand how energy efficiency and conservation 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 be targeted differently between actors, sectoral, regional, and national levels, they should find common ground at global level. Studies on spillover effects and strategic alliances between regions could also shed light on feasible futures. A proper understanding and consideration of the RE from both theoretical and empirical grounds, in contrast to national or sectoral policy objectives, is required to better guide policy decisions in the future.

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