Chapter 2
After 35 Years of Rebound Research in Economics: Where Do We Stand?

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Abstract The phenomenon of rebound effects has sparked considerable academic, policy and press debate over the effectiveness of energy efficiency policy. In recent years, a plethora of theoretical and empirical rebound studies have been published, fueling the discussion but also raising further issues and unanswered questions. At the same time, it seems that there is a lack of understanding of how to treat and measure central aspects such as potential energy savings expected and the energy services impacted by an efficiency increase. Moreover, there is a lack of clarity and understanding in how we move from micro- to macrolevels of analysis and reporting. In terms of policy understanding, the crux of the problem is that there is no such thing as a simple formula for all aspects of rebound. The aim of this chapter is to clarify the correct perspective on how to look at economic dimensions of rebound, with particular attention to what policy-makers can do with rebound analysis and findings. Further, we attempt to synthesize existing rebound taxonomies and to provide, in a concise manner, the economic rebound mechanisms at work. We then approach the rebound theme from both micro- and macroperspectives, before bringing the two angles together. Overall, we argue that both policy-makers and researchers need to be aware that rebound is an issue that ought to be tackled at multiple levels and that there are policy trade-offs, especially between economic growth and ecological sustainability. This may be resolved at least to a certain extent by welfare considerations.

Keywords Energy economics · Economic rebound mechanisms · Rebound taxonomy · Economy-wide rebound

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Increasing energy efficiency by implementation of new technology is still seen by many as a kind of 'silver bullet' for energy and climate policy in terms of its cost-effectiveness and many other benefits stemming from technological innovation. An intensive debate was triggered by Brookes and Khazzoom in the early 1980s on the remaining energy efficiency potentials in the presence of rebound. Rebound is triggered by the reduced cost of delivering or receiving an energy service when increased efficiency reduces physical energy input required. However, beyond this basic 'trigger', there has been debate in terms of how different types (and mechanisms) of the 'rebound effect' should be named, measured and reported. This debate has been partly between engineers and economists but also among economists and other social scientists. Over the last 35 years or so, critical minds have continually warned that rebound effects undermine the potential benefits to be reaped in terms of resource savings and make efficiency policies less attractive cost-wise (i.e. in terms of the physical energy savings delivered per monetary unit invested).

However, at the same time, it is important to note that rebound is driven by processes that also deliver economic benefits such as increased incomes, improved competitiveness, better quality of services etc. Thus, others have then joined the discussion by arguing that the energy-saving perspective is just one out of many that will be taken into account by policy-makers working in a context of multiple objectives. In this context, hence, there is a need for analyses to consider a careful balancing of the manifold and often delicate policy trade-offs involved. These tradeoffs, as well as the heterogeneity of energy efficiency and rebound impacts throughout the economy, require a better and sound understanding of the complex mechanisms at work. Besides, in more recent research in economics (e.g. Gillingham et al. 2016; Borenstein 2015; Turner 2013) rebound is considered less in terms of being exclusively a negative factor to be minimized (as ecologists would argue). Rather, many economists would argue that rebound minimization may or may not be the welfare-optimal outcome (due to opportunity costs of forfeiting the utility of energy services and related indirect benefits).

***What is the right perspective to look at rebound*?**

Some of the existing rebound research has been very narrowly focused, for example by estimating direct rebounds—the intensified use of a durable good that has become more energy efficient, thus lowering the marginal cost of using the energy service in question. Other rebound studies have been extremely broad in focus, trying to attribute many or all increases in the energy use of society to rebound effects. That is, not just those stemming from technical efficiency improvements (thereby lowering the cost of providing an energy service), but extending, for example in Druckman et al. (2011), to those that stem from lifestyle changes (and simply involve a change in the level of use of an energy service with no change in cost). Van den Bergh (2011) also extends the concept of rebound to conservation activity, where the price of the resource (rather than the service delivered) will trigger an economic response. This raises questions in terms of what different authors mean when they refer to rebound, questions regarding the 'trigger' for rebound (and any economic benefits sharing that trigger), as well as what we regard as the potential or anticipated energy 'engineering' savings that any economic rebound response is measured against. This raises issues as to whether malfunctioning of new and energy-efficient hardware or a poor match between the technological capabilities of the hardware and the ability of the user to learn how to exploit these, is actually part of the rebound effect measured. Moreover, consideration of the trade-off between energy-use minimization and economic benefits raises questions such as whether energy *sufficiency* (i.e. voluntarily consuming less energy than one can afford) can be considered a viable option to combat rebound.

What can policy-makers do?

There has been a tendency in the rebound literature to regard rebound as 'bad' that policy-makers should attempt to minimize it in order to maximize reductions in energy use if energy efficiency policies are to be regarded as effective. Rebound has also been presented as something of an additive process, with the effect multiplying as consideration of the impacts on energy use extends beyond that of the user whose efficiency is the target of policy. A central objective of this chapter is to highlight contributions to date, and encourage greater focus in the future on the range of reasons why the rebound 'problem' is not so simple in its nature or implications as many believe, make believe, or hope for. At the most fundamental level, we raise issues regarding how policy expectations regarding 'potential energy savings' may be framed and determined in practice relative to how they are considered in different academic studies. That is, do policy-makers start from the perspective of a pure engineering saving so that zero rebound implies no response to energy efficiency improvements beyond the pure energy savings expected from engineering calculations? Transparency is required in rebound research regarding the perspective taken, on just what type of responses are analyzed, the nature of trade-offs involved, as well as the extent to which rebound mechanisms can be considered purely in economic terms.

We attempt to focus attention on developments in rebound research that can be of immediate practical use to policy-makers. For example, we highlight consideration of embodied energy 'multipliers' to assess the impacts of switching expenditures between more and less energy-intensive goods and services, and how impacts may vary at local, regional, national and (where there is concern over issues of pollution leakage/displacement or 'carbon footprints') global levels.

2.1 The Rebound Architecture

2.1.1 Another Taxonomy of Rebound Effects?

A common categorization of energy efficiency rebound is the one in direct, indirect and economy-wide rebound effects (cf. Turner 2013, Sect. 2). The complex nature of rebound, however, raises the need for introducing more layers, for instance in terms of source of efficiency improvement and whether this is on household (consumption) or the industry (production) side of the economy (of course the emerging notion of the "energy prosumer" blurs the division line between producer and consumer). However, we also have to consider the type of energy use concerned, as well as what share of the difference between potential/expected and actual energy savings is due to rebound and what is due to technical performance or human learning problems, or changes in lifestyles/preferences, that prevent the full efficiency improvement being realized. This lack of consensus and clarity in the rebound taxonomy—after 35 years of intensive rebound research and a burgeoning literature—is an issue on the micro-, meso-, and macrolevels, but relates especially to the indirect and economy-wide effects.

An important field of controversy concerns the issue of what is, or should be, called "rebound" and what is due to other effects. In this respect, studies that measure rebound need to be able to separate all other effects on energy use from those that are caused by energy service cost reductions due to an increase in technical energy efficiency. Another discussion is on what should be counted as an "energy service" in order to assign energy rebound effects.

Figure 2.1 summarizes the taxonomy of rebound. It shows that two very central distinctions are those between direct and indirect rebound effects on the one hand side, and between private household and firm rebound on the other hand. From the microlevel, which can be thought of either as the individual or firm/household level (cf. Fig. 2.2), the level of analysis can be widened by moving to the sectoral (meso)

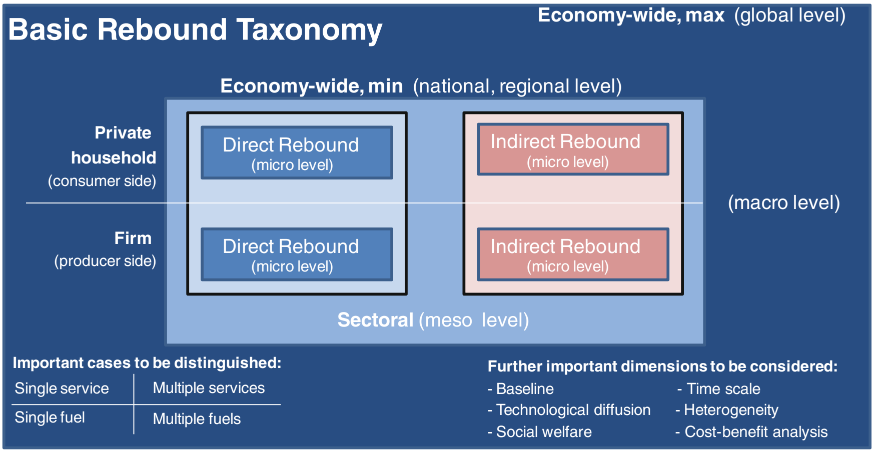

Fig. 2.1 Basic rebound taxonomy. The rebound literature is full of taxonomies, and taxonomy discussions, so that the reader is sometimes overwhelmed (at best) and often confused (at worst) by the many different versions. The present one is intended to be useful by being relatively simple and yet comprehensive

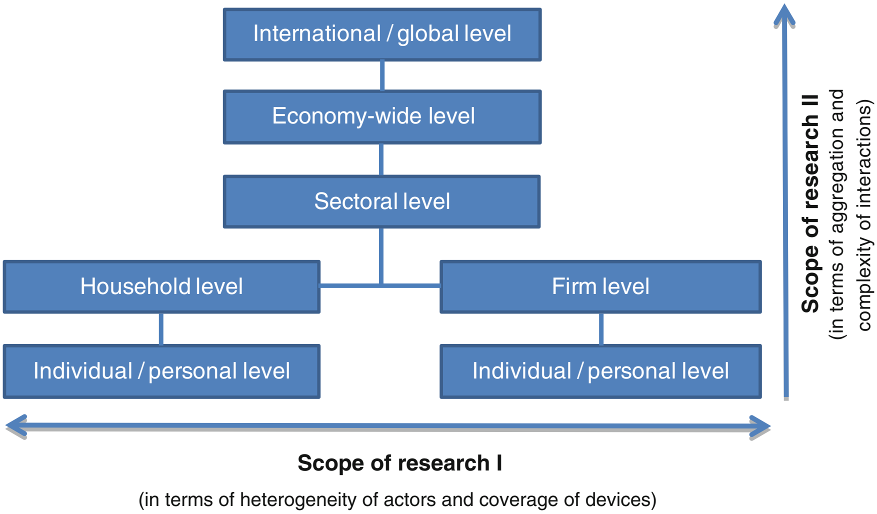

Fig. 2.2 Levels of rebound effects. Rebound can be analysed at different levels and by means of different methodologies/approaches. Dynamics and interdependencies remain hard to tackle, as do new kinds of energy services on which data may not yet be available

level of analysis, and on to a more macroeconomic, i.e. regional (province/state, urban/rural), national or global perspective. Further, the analyst needs to be clear about whether to study a single or multiple fuel energy rebound and whether a single service or multiple services are involved. The latter has to do with fuels such as electricity, which can be used for providing a multitude of energy services. Finally, the choice of an appropriate baseline, the time frame and dynamics of rebound, heterogeneity of consumers and firms, and social welfare considerations are important additional dimensions to deal with.

2.1.2 Rebound Mechanisms

Besides definitions of rebound and terminology, the mechanisms at work also need to be clearly identified. So far the probably most comprehensive collection of rebound mechanisms ("types of rebound pathways") is provided by van den Bergh (2011). The 14 mechanisms identified comprise the following: (1) direct rebound (price effect); (2) adoption of larger units or such with more functions/services; (3) respending (income effect); (4) extra demand for energy-intensive goods (composition effects); (5) changes in the processes of one phase of the product chain or life-cycle on a later phase/later phases; (6) change in factor input mix; (7) increase in total factor productivity and production output; (8) energy efficiency induced relative price changes rippling through the economy (general equilibrium or macroeconomic effect); (9) international trade and relocation effects; (10) capital investment and accumulation effects; (11) technological innovation and diffusion effects; (12) changes in preferences; (13) indirect energy use effects due to investment in new technology (embodied energy effect) and (14) time savings (time rebound effect). It becomes clear that some mechanisms overlap with the definitions of certain types of rebound (e.g. direct, indirect, economy-wide and macroeconomic rebound). Additional mechanisms that can lead to rebound effects are identified in later chapters of this volume (most notably, in part II).

Note that a useful analysis is likely to involve more than simply attempting to aggregate over the different rebound effects that can be investigated along these rebound pathways or mechanisms to arrive at a single overall rebound effect. Rather, they all take a different perspective of how induced technical energy efficiency improvements ripple through the economy and, thus, need to be understood individually. Further below we will discuss that some rebound categories impact each other (i.e. if the direct rebound is large, indirect rebound from re-spending can, under specific circumstances, be expected to be small) and that some rebound effects have a negative sign, thus compensating positive rebound effects elsewhere in the system.

Figure 2.2 makes the two dimensions more explicit that complicate matters in rebound research. One dimension is the scope of research in terms of the aggregate investigated (from the household and firm that are both composed of individual actors or decision-makers all the way from sectoral-, economy-wide- to the international and global level of analysis). This impacts the complexity of interactions that need to be tackled. The other dimension has to do with the heterogeneity of actors considered, the heterogeneity of devices and energy services involved, and the multi-tasking increasingly enabled by software agents and automation.

In terms of type of research and analysis, we move up from very micro, partial equilibrium analysis (at the household and firm level) through micro-/meso-level but still partial (sectoral level) analysis to the analysis of inter-sectoral effects. Such inter-sectoral impacts (supply chain interdependencies; see below) can most easily be addressed by studying multiplier effects—even where prices are assumed to be fixed. When prices are flexible, changes in demand and impacts on revenues matter, rather than just the required capacity, while macroimpacts may be limited. On this basis, one may decide to potentially link meso-level and economy-wide rebound analysis. Note that at the level of inter-sectoral analysis, we have a combination of still partial effects (prices may still be fixed) but working with meso-level or economy-wide input-output (I-O) analysis, e.g. for the computation of multiplier effects or, alternatively, general equilibrium impacts (to capture inter-sectoral effects while also allowing for the price changes involved). Finally, for international/global analysis of rebound, I-O multiplier analysis is still relevant in terms of partial analytics, although economy-wide analysis (e.g. by means of computable general equilibrium, CGE, modelling) could extend up to the inter-country global level where changes in relative prices and terms of trade are likely to be important.

2.2 The Micro Perspective

2.2.1 Enhanced Microeconomic Foundations

There have recently been some key contributions in the area of micro-level rebound analysis. First, Borenstein (2015) shows that non-marginal cost pricing, as it is often used in a utility industry context, may have a large impact on rebound effects due to income effects. Moreover, he discusses some implications of substitution and income effects when sub-optimal behaviour on the one hand leads to an "energy efficiency gap" (i.e. seemingly rational but nonetheless ignored opportunities for monetary savings by improving energy efficiency), and on the other hand reduces substitution-effect rebound.

Chan and Gillingham (2015) focus on the direct rebound effect and aim at guiding both modellers—on the usability of the canonical relationships between different elasticities relevant to the rebound effect (e.g. efficiency elasticities and price elasticities of energy demand)—and policy-makers—on how to take welfare considerations into account when dealing with rebound effects. In contrast to many studies in which the analysis is simply based on demand functions (and a grossly simplified world with only one fuel and a single energy service), and not on the underlying consumer preferences, they deal with the implications of studying situations with multiple fuels and multiple energy services. In doing so, they show that empirical estimates may be severely upward or downward biased depending on whether the energy services considered are gross substitutes or gross complements. They conclude that commonly used elasticity identities are especially problematic for investigations of household electricity consumption, but likely less of a problem for investigating petrol use for car driving. In terms of welfare analysis, the authors find that efficiency improvements are more likely to enhance welfare when the surplus gained from energy services is high, when service-based external costs are low, and when the rebound effects are modest. Interestingly, and less intuitively, the authors further demonstrate that when pollution-induced external costs are high for other goods and services, then the welfare effects depend again on whether the energy services in question are gross complements or gross substitutes to each other.

2.2.2 New Empirical Evidence on Direct and Indirect Rebound

In recent years, a number of empirical studies have been published on both the direct and the indirect energy rebound. Only a few studies, typically only investigating direct rebound effects, have so far focused on rebound heterogeneity (e.g., Madlener and Hauertmann 2011—residential space heating; Frondel et al. 2012; Wadud et al. 2010—automobile travel; Saunders 2013—manufacturing industry).

By and large, these studies come to the conclusion that rebound varies considerably among the different energy-using groups investigated. For private households, these may be income-rich versus -poor groups of society, owners versus tenants etc. In manufacturing, it is a well-known fact that industries differ a lot from each other, and in automobile travel demand these studies even find large differences, for instance, in the direct rebound estimates between the US and Europe (Germany), the former interestingly being much smaller than the latter.

2.2.3 Further Research Needs

Aside from the benefit to "pause and reflect" (Turner 2013) before undertaking more rebound research, especially empirical work using the same limited approaches over and over again (e.g. the use of simple estimates of the elasticity of energy demand with respect to energy price as proxies for direct rebound effects), there are research needs in terms of scope, theoretical advancement and methodology.

In light of a rapidly changing world, with many new kinds of energy services being provided in an increasingly digitalized and automated economy and society, there seems to be an urgent need to undertake more research on such new services, provided the data are available.

Moreover, there is definitely a need for more sound empirical evidence on under-researched energy services but also on particular types of countries and regions. For China, for instance, an impressive number of new, by and large empirical studies have emerged over the last years (e.g. Lin and Tian 2016; Lin and Liu 2015; Lin and Du 2015; Wang et al. 2012, 2014). However, there is a dearth of work particularly on energy efficiency and rebound in developing/low-income countries, where rebound in itself could be positive in terms of investment in, and uptake of, even quite basic energy service systems.

The theoretical contributions of Borenstein (2015) and Chan and Gillingham (2015)—mentioned above—identify new challenges for applied research of energy efficiency rebound (beyond the relatively straightforward estimation of energy price elasticities). The former sheds new light on the size of rebound effects when (1) goods are not priced at marginal cost; (2) when consumers are optimizing their utility in an imperfect manner and (3) the role of technological progress. On the other hand, the latter study makes an attempt to cast rebound analysis in a more generalized modelling framework that formally enables to incorporate welfare optimization considerations. Furthermore, both studies emphasize that elasticity identities—e.g. that efficiency elasticities can be treated as equal to price elasticities of energy demand—must not be used lightheartedly given that the complement and substitute relationships govern their validity.

From a methodological point of view, econometric rebound estimates are limited in many ways, not just because they are typically based on standard assumptions, so that they comply with microeconomic theory or are simply easier to handle, but also because the functional form impacts the results. For example, if global concavity is forced on a translog model, a fairly flexible functional form that has been frequently used in energy demand studies, then this automatically leads to backfire, i.e. rebound greater than 100 % (cf. Saunders 2008, 2013).

Hunt and Ryan (2011) use a utility-theory-based model with multiple energy services and multiple input fuels, thus also starting off from the underlying preferences rather than just demand functions. They find that due to the unavailability of expenditure data on each energy service, empirically estimating rebound effects in such a framework is very difficult.

2.3 The Macroperspective

2.3.1 Differences in Economy-Wide and Macroeconomic Methods and Focus

Generally, economic rebound occurs where a portion of the potential (engineering) energy savings from uptake of efficiency-enhancing technologies are offset by a variety of economic responses triggered by the initial change in the price of energy services faced by a more efficient user. This user's response to the initial energy service price impact gives us direct rebound. However, as argued in the growing literature on rebound effects, this is only a part of the story—and potentially just a small part. A variety of indirect and economy-wide rebound effects also come into play as prices and incomes adjust throughout the economy and as expenditure and production decisions change. The net effect of these various mechanisms gives us economy-wide rebound. For example, cost-effective energy efficiency improvements by producers (e.g. steel manufacturing) lower the marginal cost of energy services, thus encouraging increased use of those services, as well as lowering output prices. This boosts economic productivity and competiveness (both in the sector where efficiency improves and downstream, e.g. in white goods manufacture), thereby triggering economic expansion and, consequently, energy use throughout the economy. This is the type of productivity-led expansion considered by Jevons (1865) in what has come to be widely considered as the first thesis on the rebound effect. It is also what Greening et al. (2000) implicitly identify as the source of 'secondary' rebound when firms increase the efficiency with which they use energy. In his consideration of more efficient use of coal in the context of productivity-led expansion during the industrial revolution, Jevons (1865) also highlights what has come to be known as the backfire argument that is developed by Brookes (1990, 2000), Saunders (1992, 2000) and others.[1]

Consideration of economy-wide rebound is also relevant in the context of efficiency improvements in household energy use. If households improve the efficiency

[1]More recent survey contributions focusing on the issue of backfire are provided by Alcott (2005), Dimitropoulos (2007), Sorrell (2009), Madlener and Alcott (2009) and Azevedo (2014).

with which they use energy—for example, by installing a condensing boiler that uses less gas to produce a given amount of hot water—this frees up income to spend on other goods and services (e.g. going on holiday or buying a new TV). This changed and additional consumption of services may involve direct energy use by the household, but also indirect use of the energy that is 'embodied' in all goods and services from different stages of their supply chain, both within their home economy and abroad. However, this is demand—rather than productivity-led expansion and shifts in domestic consumption patterns may also change the demand for locally produced and imported goods relative to exports. Thus, depending particularly on labour and capital market responses, there may be negative impacts on economic activity, prices and energy consumption in a range of different industries, markets and regions (Lecca et al. 2014).

While such arguments are intuitive and have (to varying extents) been explored in a number of studies over the last ten years, the evidence on the size of economy-wide rebound effects remains limited, contradictory and controversial. One crucial issue is that rebound from increased efficiency in household energy use has been the subject of most microeconomic studies of direct rebound. However, investigations of economy-wide rebound (particularly those using CGE models) have tended to focus more on impacts of industrial energy efficiency. This has led to some confusion (and conflation) in relating analyses and results from direct rebound studies to investigations of economy-wide rebound that are essentially analyzing different things.

However, there are issues of comparability even among economy-wide rebound studies that share a focus on industrial energy efficiency. In the major review of rebound evidence reported in the UK Energy Research Centre (UKERC) study edited by Sorrell (2007), economy-wide rebound findings from studies using CGE modelling studies ranged from 37 to >100 %. The UKERC review established common ground across the studies in terms of cases of backfire generally being limited to cases where energy efficiency improves in highly energy-intensive and traded electricity production. However, a key conclusion was that economy-wide rebound is dependent on the nature and location of the energy efficiency improvement and the economic conditions prevailing in the economy under study.

The findings of more recent CGE studies reiterate this conclusion. For example, Broberg et al. (2015) report that rebound and other micro- and economy-wide impacts of increased industrial energy efficiency in Sweden are dependent on a range of factors, particularly costs of introducing efficiency improvements, energy intensity of the sector where efficiency improves, and how the labour market functions. The key implication is that it is generally not possible to directly relate the findings of individual CGE studies, or to compare between CGE studies simulating 'what if' scenarios and macroeconometric studies analyzing historical trends or forecasting future ones.

This latter point is key in distinguishing between economy-wide studies, which consider rebound in the context of a full range of impacts across the economy, including those on key macroeconomic variables such as GDP. Macroeconomic rebound is often considered through macroeconometric studies that take an *ex post* perspective on aggregated effects on energy demand as the energy intensity of the economy is observed to have changed over time. Economy-wide rebound studies, in contrast, tend to focus on *ex ante* 'what if' scenario analyses involving simulation of how the impacts of an energy efficiency in one or more sectors of the economy ripple out through various markets and mechanisms.

That the problem of comparability across different macroeconomic and economy-wide rebound studies continues is further evidenced in IEA (2014). The studies reviewed there involve a range of different methods and models applied to different types of energy efficiency improvements in a range of countries and geographical regions, with some using CGE simulation models to consider a range of 'what if' type scenarios, while others (e.g. Barker et al. 2007, 2009) use econometric methods to project future rebound effects of different policy packages. Moreover, while some studies focus on impacts of pure efficiency improvements, others focus instead (or as well) on the expansionary impacts of investment decisions preceding the implementation of actual efficiency improvements.

2.3.2 Economy-Wide Sectoral Level Impacts Versus Macroeconomic Effects and the Questioning of a Single Rebound Measure

It is important to distinguish between the provision of CGE and other macroeconometric modelling techniques for another reason. A key issue demonstrated in multi-sector CGE modelling studies of energy efficiency improvements is that, even where high-level general equilibrium impacts on macroeconomic variables such as GDP are limited, there can be important inter-sectoral effects.

For example, Anson and Turner (2009) find that a 5 % improvement in efficiency in energy use in the Scottish passenger and freight transportation industry has what may be considered limited impacts on key macroeconomic variables, generating long-run changes in Scottish GDP and employment of around 0.02 %. However, this is accompanied by important impacts in the domestic fuel supply industry, including a short-run decrease in revenues and return on capital that triggers what Turner (2009) terms as a 'disinvestment' effect. To halt a process of shedding capital stock/mothballing of production capacity, the local price of refined fuel—which initially falls due to decreased demand from passenger and freight transporters—has to rise again to restore the return on capital and achieve a new equilibrium in the sector (at a reduced level of activity) and the economy as a whole. This, in turn, impacts on fuel and other energy demands and rebound effects at sectoral and economy-wide levels over time.

More generally, building on the sectoral detail of input-output and social accounting matrix databases, CGE modelling studies consider economy-wide rebound through the lense of up- and downstream supply chain interactions and impacts channelled through changing quantities, prices and returns in markets for different goods and services as well as for capital and labour. This offers the advantage of being able to identify and consider both increases and decreases in different types of energy use in different areas of the economy when energy efficiency increases in any one (or more) sector/s. In this respect, multi-sector CGE models do respond, to some extent, to the need to incorporate an extent of meso-level detail beyond a purely 'top down' macroeconomic approach. However, studies must be transparent in terms of their assumptions and specifications in key areas of CGE model specification that influence price, capacity and output decisions particularly in energy supply and demand. For example, Turner (2009, 2013) explains that where the return on capital in energy supply sectors is assumed to be fixed or exogenously determined, any downward pressure on long-run rebound through the aforementioned disinvestment effect will not be captured.

However, there is a more fundamental problem in the form of a lack of agreement and clarity in the literature regarding how 'rebound' should be measured. Moreover, this is amplified when we move to the economy-wide or macro-context where a wide range of potential and complex mechanisms come into play. One issue is that rebound research generally has tended to neglect the issue of energy supply responses to changing demand, prices and profitability. Moreover, as noted above in the context of Borenstein's (2015) work at a microeconomic level, economy-wide studies have neglected the issue of non-marginal cost pricing in energy supply industries. Turner (2013) notes that energy market effects may impact what have become accepted theoretical underpinnings for a single rebound measure at the macroeconomic level. In particular, lower prices in energy markets may confound the zero rebound condition identified by Saunders (2000) while higher prices cast uncertainty on his 100 % rebound condition. This raises the question of whether these reference conditions for macro-level/economy-wide rebound should be reconsidered in light of energy market effects or does the notion of a single measure become less useful as a multitude of determining factors are identified?

Indeed, one specific example of where a single rebound measure beyond the direct level may cause confusion arises in the context of Guerra and Sancho's (2010) argument regarding definition of rebound in a general equilibrium context. The crux of the Guerra/Sancho argument is the treatment of any downward quantity (but not price-driven) adjustment in (direct or indirect) energy use in the supply chains serving any energy commodity directly impacted by an efficiency improvement (e.g. different fuel uses in both gas extraction and supply serving a gas-fired electricity station servicing households that have increased the efficiency with which they use electricity). They argue that this should be considered as part of the potential energy saving (PES) in the denominator of the conventional rebound (R) calculation (where $R = [1 - \text{AES/PES}] \times 100$, with AES being actual energy savings). Turner (2013) disputes this, arguing that, since indirect savings in energy supply chain activity will not be known *ex ante* (unless policy analysts have access to appropriate fixed price input-output models), practical considerations and the understanding of policy-makers should overrule the strict general equilibrium conditions that Guerra and Sancho (2010) propose. The Turner argument is that the PES in the denominator of the economic rebound calculation should be restricted to projected engineering savings (that is, proportionate to the extent of the efficiency improvement), with all other changes in energy use (positive and negative) that occur as a result of economic responses included only in the actual energy savings in the numerator. In this respect, Turner's economy-wide argument coincides with the microeconomic one of Borenstein (2015) in arguing that substitution between more and less energy-intensive goods and services will put downward pressure on rebound, and may even lead to net negative rebound effects.

Whatever the stance one takes on this particular argument, the central lesson would seem to be that there is a need not only for the identification of solid theoretical foundations for the range of mechanisms governing indirect and economy-wide rebound effects. On the one hand, there is a need for the development of a common and transparent methodology for how impacts on different energy uses are brought together in a single rebound measure. On the other hand, it may also be argued that the definition and measurement of a single 'rebound' measure is in danger of becoming a distraction from actually understanding and explaining how energy efficiency improvements work and impact on a full range of activities and agents in the wider economy in different case study and policy contexts. From this perspective, it may be more important to clearly report and explain a full range of both upward and downward impacts on energy use in different sectors of the economy when energy efficiency improves in any one sector. Moreover, this must be set in the context of both economic benefits (e.g. increased income in low-income households) and costs (e.g. contractions in activity and employment in fuel-refining activity) that accompany these changes.

This latter argument corresponds with that of the IEA (2014), where energy efficiency and rebound are considered in the context of a 'multiple benefits' framework. This involves consideration of impacts on a range of indicators including energy prices, supply security and poverty, along with GHG emissions (the 'energy trilemma'), alongside a range of macroeconomic indicators such as GDP, employment and public budgets, as well as 'health and well-being'. A key role of multi-sector economy-wide modelling in this wider policy context would then be scenario analysis to consider how benefits in different sectors may be maximized while 'costs' of physical resource use (which must be clarified beyond simple arguments of energy saving) are minimized. This viewpoint is shared by Gillingham et al. (2016), who argue that rebound has come to be perceived as an 'evil' with an implicit focus on energy minimization rather than welfare maximization. Gillingham et al.'s argument reiterates that in the introduction to this chapter regarding the need to balance multiple and often delicate policy trade-offs. In this context, the key question is not one of focusing on mitigating rebound, rather it is one of whether rebound can be reduced (thereby maximizing energy savings or emissions reductions) without sacrificing the macroeconomic, welfare-enhancing benefits that share the same trigger. This may be possible if increased energy efficiency in a particular sector (e.g. public transport) leads to a change in the relative price with a more energy-intensive competitor (e.g. private transport). In the public versus private transport example, the central issue is the extent to which households are prepared, or can be persuaded, to respond to the increased competitiveness of public transport by substituting away from private options in their (increased) consumption bundle. As this increases, it may be possible to reduce economy-wide rebound (which includes petrol/diesel use by households) through a change in the composition rather than the level of economic activity. In this context and more generally, analysis should ideally extend to identifying and understanding the distributional implications across different industries and households. Where there is a binding constraint underlying the need to reduce energy use (e.g. climate change commitments), taking a welfare-maximizing perspective implies that this should be treated in a similar way to any other macrolevel constraints (on government budget, balance of payments etc.).

2.3.3 Research Needs

There is a clear need to clarify the role of economy-wide and macroeconomic analyses and modelling in energy efficiency policy analysis. Put simply, what are the questions that policy-makers need answered? Macroeconomic rebound analysis is appropriate if questions related to how the energy intensity of a growing economy has changed in the wake of technological progress (though causality may be difficult to infer from correlation). On the other hand, if policy-makers are more interested in what may happen to energy use in different areas of the economy in response to different energy efficiency initiatives, economy-wide scenario analysis is more appropriate. Given that the motivation for this chapter is to consider the state of understanding of rebound effects at different levels, we have focused more on the analysis of mechanisms driving economy-wide rebound. However, particularly as we move to the level where economy-wide rebound is considered in the context of a range of macroeconomic indicators (IEA 2014), it is not clear that the questions that have engaged the research community align with the concerns and analytical needs of policy-makers.

Therefore, a starting point in setting out research needs at the macrolevel is less about debating over the 'right' way to define macroeconomic or economy-wide rebound, or whether CGE models do a 'better' job than, for example, macroeconometric models. Rather, our focus should be on considering how economic rebound mechanisms impact different outcomes that policy-makers are concerned about and how best to develop and report analytical frameworks for policy-relevant analyses.

In informing this process, a key research need is to establish the type of microfoundations we need in CGE or other 'whole system' models, as well as in meso-modelling frameworks. In modelling, just how efficiency improvements actually occur in different sectors of the economy—including any technology uptake or investment decisions involved—we must consider whether this can be configured in the micro-specification of an economy-wide model or whether soft/hard linking between micro, meso, economy-wide or macromodels is required.

The next challenge, then, is to establish the key specifications required to consider how economy-wide impacts may spread through interactions between different agents through different markets in the context of macroeconomic closures and constraints. That is, to improve key specifications in terms of, for example: how labour and capital markets function and respond to the changes in economic behaviour triggered by energy efficiency improvements at the microeconomic level; how government may look to spend additional revenues or balance budgets; how we model dynamic adjustment processes etc.

Lessons learned from existing economy-wide rebound research suggests that there is a serious need for serious research on how we model different elements of energy supply. This is both in terms of pricing and capacity decisions (set in a context where imperfectly competitive market structures tend to prevail in practice) but also understanding key issues such as energy use (and related emissions) embedded in energy and non-energy supply chains.

In this context, there is also a need to consider how different elements of models and sub-models may provide useful tools for policy analysts. For example, in the previous subsection we have considered the debate over how negative and positive impacts on energy use embedded in energy and non-energy supply chains should be treated in rebound calculations. This argument is concerned with what are commonly termed 'negative multiplier' effects in reallocation of spending between different types of goods and services when income is freed up from spending on energy when efficiency improves. Many policy analysts are familiar with the concept of input-output-based multipliers that, computed from published input-output accounts, report the level of output, employment, emissions, energy use etc. required throughout the economy for one monetary unit of final demand spending on the output of (or commodity produced by) any given sector or industry. From this perspective, calculating and reporting 'output-embodied energy' (and related GHG) multipliers from input-output databases that underlie CGE models provides a useful tool for policy analysts. This facilitates basic assessment of whether economy-wide energy use impacts of any switch in spending between two or more commodity outputs are likely to be positive and negative. Where there is an interest in pollution leakage or global 'footprint' impacts of spending decisions, recent availability of inter-country input-output databases such as WIOD[2] allow multiplier analyses to extend their focus beyond domestic supply chain impacts. At the other end of the spatial scale, the availability of regional input-output accounts permit multiplier methodologies to be deployed as a tool for policy analysis were energy efficiency initiatives are implemented at a sub-national level.

More generally, there is a need to develop the type of modelling frameworks that give policy-makers the answers they require to make informed decisions. CGE models sit between more top-down purely macroeconomic approaches and more bottom-up, data-rich meso approaches. Rather than continue debates over macroeconometric versus CGE (particularly in the current absence of research activity at the meso-level), there is a real need to focus on the type of questions policy-makers need answered and select models/suites of models on this basis.

[2]http://www.wiod.org/new_site/home.htm.

2.4 Putting the Two Perspectives Together

2.4.1 The Micro Level as the Starting Point Triggering Rebound and Other Economic Processes

The study of human behaviour, also in economics, naturally starts at the level of the individual (person or household). The overall economy is understood as a system composed of individuals, and individual decisions, that in the aggregate lead to an entity called "the economy". How the individual and groups of agents then interact in the wider economy gives us the next level for investigation.

2.4.2 Limitations to Microlevel Analytics, Need for Multi-level Analysis, and Link to Other Research Disciplines

Due to the many impacts rippling through an economy following an energy efficiency improvement in any one sector, the micro-level analysis needs to be complemented by meso- and macrolevel analysis. Likewise, standard economic analysis needs to be complemented by analysis rooted in other research disciplines, such as psychology, sociology and engineering.

2.4.3 Need for Partial Equilibrium Analytics and Relevance of a Meso-level (Sectoral) Analysis

The meso level has been neglected in rebound research to date. While micro-level research continues to provide insights on how individuals respond to energy efficiency changes, and multi-sector economy-wide CGE analyses capture key interactions between sectors, there is a 'missing level' to rebound analytics. Economy-wide models such as CGE build on microfoundations but generally this involves aggregation to representative household and industry level groupings that then interact through markets within a context of a set of macroeconomic 'closures'. However, there may be missing insights in terms of the dynamic and complex interactions between individual technologies and different groups of actors (with heterogeneous characteristics) at the level of different system elements. This may occur at the sectoral level and give rise to key regime/group behaviours that are important in terms of the response of different societies to energy policies. Moreover, as argued by Santarius (2015; see also Chap. 5 in this volume), meso-level analysis may uncover a layer of rebound effects arising from sectoral level interactions that would not be uncovered by micro- or macro-focused analyses. This again raises the issue of economy-wide versus macroeconomic rebound analyses: in Sect. 2.1, we have highlighted the use of CGE to consider important inter-sectoral effects even where macroeconomic impacts (e.g. on GDP) are limited. To what extent would meso-level analyses add value in analyzing the type of effects identified there?

2.4.4 Limitations to General Equilibrium Analytics in 'Whole System' Analysis

In general equilibrium analytics, there is an important trade-off between conformity with general equilibrium theory and the impact assumptions of the functional forms have on the outcome. For example, a common assumption in the aggregation across sectors is that consumer utilities follow a Cobb-Douglas functional form. This, however, albeit being very convenient, assumes that demand for sectoral outputs are independent from each other and can be aggregated easily (cf. Saunders 2013, p. 1325). Likewise, assuming perfect elasticity of labour, materials and energy supply is consistent with the extreme of perfect market clearing in neo-classical general equilibrium theory, but may lead to systematic distortions of unknown sign and magnitude). Hence, the question arises how to best deal with such "hidden effects" arising from assumptions considered necessary based on theoretical grounds.

Of course, it should be emphasized that CGE modellers are increasingly challenging the restrictions of historical comparative static neo-classical general equilibrium theory to incorporate considerations of imperfect competition (particularly in labour markets where unemployment and wage setting are important realities) and to consider dynamic adjustment processes. However, particularly in recognition of energy supply issues raised in more recent rebound contributions, the question remains as to how general equilibrium models can be improved in such a way that they better fit the theory. Or should the theories be modified (enhanced) in order to provide a more realistic picture of what is actually happening in an economy? In this respect, and again emphasizing the importance of how energy supply is treated, there is a real need to consider how issues such as engineering insights on issues such as physical constraints and technological innovations may inform and be informed by the insights of economic models at all levels. More generally, is there a need to consider suites of soft- or hard-linked economic, engineering, sociological etc. models that may offer more integrated insights on a wide range of energy-economic system issues?

2.5 Conclusions, Policy Recommendations, and Outlook

In this chapter we have discussed some of the achievements and some of the remaining issues and problems in rebound research. We argued that despite the considerable attention rebound phenomena have seen in recent years, there are quite a few open questions. Probably, the most challenging item on the list is how to move from micro to macrolevels of analysis, and how to provide simple messages regarding what policy-makers can do with the evidence that is provided by rebound researchers. We conclude that rebound should be taken as a complex phenomenon that in principle needs to be tackled at multiple scales, and be analyzed from different perspectives. A holistic picture and comprehensive analysis of rebound effects calls for interdisciplinary and integrated research, but bears the danger of becoming fuzzy. Moreover, all methodologies available have their limitations and, even worse, may lead to different results. Hence, decision-makers should be cautious with regard to false interpretations of insights, or unjustified comparisons across studies, sectors and regions.

At the microlevel, we conclude that while there is a need for further and sound (unbiased) empirical estimates also of new energy services, relying on direct rebound for policy guidance is clearly insufficient and one-dimensional. Further, despite the insights on important interactions and interdependencies between sectors of multi-sector CGE models, there is a real need for meso-level analyses to provide insights on complex behaviours between different types of actors. We also argue that extending consideration of multiplier effects beyond the industry level focus of input-output and CGE models to micro- and meso-level analyses can provide very practical, useful and complementary insights to policy-makers. Finally, we have identified more generally a need for much better policy guidance and 'usability' in view of the multi-facetted implications of rebound and the trade-offs involved. This is especially so between economic expansion and resource efficiency, but also regarding a systematic (and ideally comprehensive) inclusion of welfare analysis in rebound research. Policy-makers need to learn (and be educated) on how to "work with rebound", and to better understand the various rebound mechanisms at work at different levels, in order to be able to mitigate the 'bads' associated with rebound while maximizing the merits.

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