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A conceptual framework for understanding rebound effects with renewable electricity: A new challenge for decarbonizing the electricity sector

Ray Galvin [a, *], Elisabeth Dütschke [b], Julika Weiß [c]

[a] *Institute for Future Energy Consumer Needs and Behaviour, Mathieustr 10, 52074 Aachen, Germany*
[b] *Fraunhofer-Institut für System- und Innovationsforschung ISI, Breslauer Straße 48, 76139 Karlsruhe, Germany*
[c] *Institute for Ecological Economy Research, Potsdamer Str. 105, 10785 Berlin, Germany*

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ABSTRACT

We develop a conceptual framework for investigating rebound effects that occur consequent to increases in renewable electricity generation and use. This is vitally important due to countries' emerging commitments to decarbonize economies through sector-coupling and strategies such as the large-scale use of "green" hydrogen produced by electrolysis from renewable electricity. Rebound effects have been extensively studied in relation to energy efficiency, where they represent shortfalls in the achievement of expected energy savings after efficiency upgrades. We identify four clear elements that are essential to rebound studies to date: (a) an energy efficiency increase; (b) an associated shortfall in energy savings; (c) a clear chain of cause-and-effect from (a) to (b); and (d) a transparent, policy-useful means of quantifying the rebound effect. Our contribution to the literature is that we transfer this schema to the domain of renewable electricity, focusing on "an increase in renewable energy" for (a) and appropriate modifications to (b), (c) and (d). We offer this schema as a useful framework for research moving forward into rigorous and detailed investigation of rebound effects in the domain of renewable electricity.

1. Introduction

In this paper we explore key issues in extending rebound effect research from its origins in energy efficiency literature to the domain of renewable energy studies, particularly in relation to electricity production. This is potentially a vast topic, as the number and scope of studies of rebound effects in energy efficiency continue to increase (see recent reviews in Refs. [1,2]), while studies of rebound effects in renewable energy are only just beginning and have the potential to become a major topic in energy transition literature [3].

Our aim is nevertheless modest, namely, to suggest a conceptual framework for understanding and mitigating rebound effects that arise when renewable energy is produced and consumed. As Harré [4,5] and other philosophers of science have argued, researchers often need to offer a streamlined, relatively simplified conceptual framework to help stakeholders order their thinking and acting in domains that may initially only hint of order and rationality. A conceptual framework will therefore not cover all possible rebound phenomena in the renewable energy domain, but can give stakeholders such as engineers, policymakers, economists and consumers a practical tool to understand, manage and mitigate rebounds in connection with renewable electricity, at least to a substantial extent.

Conceptual frameworks of this type have often been offered for understanding rebound effects in the energy efficiency domain. For example, Lange et al. [1] suggest we can best understand these rebounds by conceptualising them as occurring at four different levels of the economy — the micro, meso, macro and global levels — where those on the lower levels combine and interact to produce rebounds on higher levels. Those authors compare their framework, which they call a "typology", with 11 others from earlier leading rebound researchers such as Greening et al. [6], Sorrell [7], Madlener and Alcott [8], and Gillingham et al. [9]. Lange and colleagues admit their model has limitations, for example it ignores all non-economic drivers of rebound effects. Nevertheless, it provides insights into how energy efficiency improvements affect consumer

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* Corresponding author.
E-mail addresses: rgalvin@eonerc.rwth-aachen.de (R. Galvin), elisabeth.duetschke@isi.fraunhofer.de (E. Dütschke), julika.weiss@ioew.de (J. Weiß).

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Abbreviations and symbols

Wp	Watt-peak, a measurement of the potential power output of an energy generator
R	rebound effect (magnitude)
S	energy services (magintude)
η	energy efficiency
E	energy (magnitude)
kWh	kilowatt-hour, a measure of energy produced or consumed
GDP	Gross domestic product, a measure of the total value of goods and services produced and consumed in a country in a given year
TWh	Terawatt-hours, a measure of energy equal to 10^12 -Watt-hours
y	year
TW	Terawatt, a measure of power, equal to 10^12 Watt
P	amount of renewable energy produced in a year
C	amount of electricity consumed in a year
∂	A symbol indicating partial differentiation, i.e. a mathematical comparison between two variables, where there may be other variables that also influence the magnitude of the numerator
GWp	Gigawatt-peak, a measurement of the potential power output of an energy generator, equal to 10^9 Watt-peak
km	kilometers

incomes and prices, and how this plays out at different levels of an economy. In our rationale we use a similar type of approach, by focusing on a selection of key aspects in our framework. Instead of aiming to capture the full complexity of rebounds in renewable energy, the aim is to provide a useful tool for a variety of stakeholder groups, including policymakers. This can provide a means of understanding how increases in renewable energy use can have unintended consequences, so that interventions can be devised to mitigate these.

Further, this study will not consider the entire scope of renewable energy types and carriers – which is vast, ranging from cow manure fuel to hydroelectric dams – but only renewable electricity. This keeps the topic manageable and focuses it on the main area of current renewable energy growth. All existing studies that we know of on rebound effects in renewable energy are concerned only with renewable electricity and almost all with household photovoltaics (see references in Sections 2 and 3). This study draws on these works but goes further, relating the topic to some of the authors' own current work on renewable electricity, which includes household photovoltaics but also the growing trend of electricity providers offering customers renewable electricity tariffs.

A study such as this has become necessary for two main reasons. First, as noted above, there is now a scattering of published studies investigating the magnitude of rebound effects among households with photovoltaic panels. This study will begin to bring order and clarity to this new topic – even though the framework it offers may be substantially modified as more empirical data comes to light.

Second, renewable electricity has recently become a key pillar of countries' plans to decarbonize their economies. The UK is forging ahead in decarbonizing its electricity grid [10], and US President Biden's Administration is planning a radical decarbonization of the grid in line with his stated policies [11–13]. In the EU and elsewhere, large, bold, rapid increases in renewable electricity capacity are being promoted as essential to decarbonize economies in time to avoid catastrophic climate change [14–18]. Some of these strategies focus on a "hydrogen economy" [17] where "green" hydrogen, produced by electrolysis from renewable electricity, will store energy for re-generation, enabling electricity grids to decarbonize while also greening transport, heating and industry [19] and providing heavier fuels like methane and methanol via catalysation.

Plans such as this require renewable electricity to be generated efficiently and with minimum waste, and household photovoltaics make up a substantial share of many countries' renewable electricity generation [12,20]. A framework for understanding rebounds in this domain is therefore urgently needed.

The term "rebound effect" first appeared in modern energy literature in the 1970s–80s [21] to describe the phenomenon that when energy efficiency is increased, the consequent reductions in energy consumption are lower than engineering calculations predict, due to increases in demand [22–24]. Originally this concern was driven by the oil crisis [25] but increasing concern over climate change brought persistent impetus to rebound effect studies. One of the central arguments of these studies was that policymakers' future scenarios envisaging reductions in energy consumption due to energy efficiency increases are compromised if the expected gains from efficiency increases are not substantially realized.

In recent years the concept of rebound effects has been extended to a number of other domains where energy efficiency is not the focus of attention. These include: water use rebounds from improving irrigation and agricultural techniques that are designed to save water [26–29]; rebounds in land use [30]; and energy rebounds in household saving and re-spending due to more sustainable lifestyle choices [31]. As noted above, a number of scholars have recently observed that a phenomenon akin to the rebound effect is occurring in relation to renewable energy, at least in the domain of renewable electricity. Most studies in this field have focused on rebound effects among households who produce electricity with photovoltaics, frequently called "prosumers[1]" (e.g. Refs. [33–39]). At least one has considered rebounds through household participation in a green electricity programme [40], and another explores similar issues [41]. Hence rebound effects have been considered on both the supply and demand sides of renewable electricity increases.

The main sources of renewable electricity are hydroelectric, biomass, solar and wind power, but the current big increases are in the latter two. Globally, total photovoltaic capacity installed each year increased from 8 GWp in 2008 to almost 120 GWp in 2019 [42]. Meanwhile total global cumulative wind power installed capacity increased from 120.9 GWp in 2008 to 650.8 GWp in 2019 [43].

Hence dependence on renewable electricity is set to increase enormously with little known about possible losses through rebound effects. We therefore offer a framework for beginning to explore this topic. We do this, firstly by teasing out the essential elements of classical rebound theory, in Section 2. In Section 3 we adapt these for renewable electricity. Here we focus mostly on household photovoltaics, since this is the area where empirical studies are identifying clear cases of rebound, but we also consider the case of demand side rebounds as these are likely to become more important at national level. In Section 4 we conclude and offer suggestions for policymakers.

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[1] The term "prosumers" was coined by Alvin Toffler [32] as a comment on how post-industrial society is reorganising such that more and more people both produce and consume the same type of goods or services. It was initially applied to mental health professionals who also seek mental health support.

2. The literature on rebound effects in energy efficiency

Since the 1980s hundreds of research papers have investigated rebound effects following energy efficiency increases. These have covered virtually every sector and subsector of the economy, often differentiated into micro, macro and global levels (and even "meso" levels, as in Lange et al. [1]), and as both short-run and long-run phenomena. Frameworks used include composite macro-level effects [8,44,45]; corporate or industry-level power-plays [46]; the evolution of thermodynamic effects [47]; social structural changes [48]; different levels of the economy [1]; plus a vast literature on rebounds and individual consumer behaviour (overview in Ref. [49]), framed in such terms as economics, morals, social practices, and sociotechnical mismatches. Distinctions are often made between "direct" rebound effects, where shortfalls in energy saving occur in the operation of the appliances or domains that have undergone energy efficiency increases, and "indirect" rebound effects, where shortfalls are carried over into other domains [50].

A number of studies have offered overviews and assessments of this large literature (e.g. Ref. [51]) and some have constructed systematic taxonomies and conceptual framings of the diverse field of rebound approaches (e.g. Refs. [6,7,52]).

We suggest that *four basic elements are common to more or less all schemas on rebound effects in the energy efficiency domain:* (a) an energy efficiency increase; (b) a shortfall in energy savings compared to what engineering calculations or tests would predict (which may be short-term, long-term or both; and direct, indirect or both); (c) a description of the events leading from (a) to (b), either as a clearly identifiable chain of cause and effect, or at least a "constant conjunction of events" [53] that links the two convincingly; and (d) a method of quantifying the rebound effect.

Beginning with element (a), rebound effect studies generally begin by identifying a specific energy efficiency increase in a specific appliance or technology. The technologies that have been most thoroughly covered in rebound research are: home heating and insulation (e.g. Ref. [54]); private road vehicles [55,56]; road freight vehicles [57,58]; household electrical appliances [59,60]; and industrial processes [61]. Some studies take a composite approach by aggregating consumer responses to energy efficiency increases over the full range of technologies, but even these depend on empirical evidence of rebounds from specific domains and technologies (e.g. Ref. [62]). It is important to be specific about the technology or sector where the energy efficiency increase occurs because, as has long been known, different psychological, economic, sociotechnical and social-structural influences are at play in human interactions with different technologies [63]. For example, Saunders [62] found average long-run rebound effects of 120% in home appliances but only 29% in car transport. Consumer interactions with technologies are likely to be different again for household production of electricity, and again different for consumption of electricity produced by the home – which is a further reason that a conceptual framework for rebounds in renewable energy needs to be developed.

Regarding element (b), this can be expressed either as a shortfall in energy savings compared to what engineering calculations and tests predict, or an increase in "energy services" consumption. Energy services are the utilities that individuals, households and societies get from energy consumption, such as acceleration, comfortable warmth in a room, or objects manufactured. When an energy efficiency increase leads to a higher level of energy *services* consumption, *energy* consumption overall does not usually increase (which would termed "backfire" [50]), but there is a *shortfall* in the level of energy savings that would have otherwise been achieved [8]. In some cases it is easier to identify the increase in energy services consumption (e.g. more km travelled); in others it is easier to identify the shortfall in energy savings (e.g. fewer kWh saved). Either approach can be used for element (b). It should also be noted that in some cases element (b) is negative: an energy efficiency increase can lead to a *reduction* in energy services consumption and hence *greater* energy savings than anticipated. This was first observed by Saunders [64], who called it a "conservation effect". Other researchers call it a negative rebound, or a spillover effect if it is indirect [3,65].

To clarify element (c), most rebound effect studies in the energy efficiency domain seek to identify a cause-and-effect chain from the energy efficiency increase to the increase in energy services consumption. Micro-economists often identify *price* effects, where an efficiency increase leads to cheaper energy services so that more energy services can be purchased without increasing expenditure (e.g. Ref. [66]). They also identify *income* effects, where higher energy efficiency leads to lower bills and therefore more disposable income, some of which might be spent on more energy services (e.g. Ref. [67]). A third cause-and-effect mechanism is *substitution* effects, where greater quantities of more energy-efficient goods are substituted for lower quantities of less efficient goods [58]. An advantage of the first two of these is that data from studies of price and income elasticities of energy consumption can be juxtaposed into studies of energy efficiency to predict the likely magnitude of rebound effects [54,59,68]. As we will show below, income effects can be a particularly useful route to estimate the likely size of rebound effects from households' production of renewable electricity, especially when they receive subsidised tariffs for this. Meanwhile, price effects can help estimate the likely size of rebounds from households' consumption of the electricity they produce, since this is often much cheaper than using electricity from the grid.

But economic drivers are not the only cause-and-effect mechanisms driving rebound effects. Psychologists often frame an energy efficiency increase as a life intervention which has the potential to change behaviours. For example, they identify normative behavioural effects and/or re-appraisals of behaviour such as "moral licensing", where consumers feel they have protected the environment by increasing their appliance's energy efficiency so this licenses them to consume energy services more liberally [3,15].

Alternatively, some engineers look to thermodynamic cause-and-effect chains, such as excess energy consumption due to power-consumption ratios in the Carnot cycle [47]. Others note how profit-seeking behaviour in industry uses energy efficiency increases to add enhancements to products that erode some of the energy saving gains [46]. Others trace rebounds due to sociotechnical mismatches in the interface between consumers and their energy efficient equipment [69]. These approaches can potentially identify specific chains of cause and effect between energy efficiency increases and shortfalls in the expected energy savings.

Other studies use statistical analyses to show correlations between energy efficiency increases and increased energy services consumption, often controlling for the effects of related variables, thereby implying cause-and-effect, though without proving it [46,70,71]. Either way, rebound researchers such as Lange et al. [1] argue that for rebound effects to be definitively identified, a cause-and-effect chain (or a constant conjunction of events) linking the energy efficiency increase and the increase in energy services consumption (or shortfall in energy savings) needs to be clear. In some cases, only a portion of the shortfall in energy savings may be a direct consequence of the energy efficiency increase, so it is essential to distinguish what is causing (or conjoined with) what.

This is a further reason why a conceptual framework for rebound effects in renewable electricity production and consumption is needed. Some of the cause-and-effect mechanisms that link household renewable electricity production with household electricity consumption are likely to be unique and not represented among energy efficiency rebounds. This is partly because the technical dynamics are very different between the two domains. For example, a prosumer household *produces* renewable energy, but a household can only benefit from energy efficiency by *consuming* energy. Further, a prosumer household may consume some of the electricity it produces, thereby avoiding the dynamics of always having to get its electricity from the grid, which households cannot avoid if they are merely benefitting from increased efficiency. These and other dynamics unique to renewable energy production are explored in Section 3.

To clarify element (d), there are different methods of quantifying rebound effects. Many studies quantify the rebound effect as the “energy efficiency elasticity of energy services consumption”, i.e. the marginal proportionate change in energy services consumption that occurs consequent to an energy efficiency increase, divided by the marginal proportionate change in energy efficiency:

$$R = \frac{\partial S}{S} \bigg/ \frac{\partial \eta}{\eta} \tag{1}$$

where S is energy services, and η is energy efficiency.

Since, as we noted above, it is sometimes easier to identify shortfalls in energy savings than increases in energy services consumption, Sorrell und Dimitropoulos [72] showed that equation (1) can be rewritten in terms of energy consumption (see derivation and comments in the Supplemental material):

$$R = 1 + \frac{\partial E}{E} \bigg/ \frac{\partial \eta}{\eta} \tag{2}$$

Some microeconomists take this a step further, substituting (the negative of) price elasticity for the term $\frac{\partial \eta}{\eta}$, arguing that the price of running an appliance is (negatively) proportional to the energy efficiency of that appliance (see discussion in Refs. [54,72]).

But large one-off changes also occur, which can also indicate rebound effects which need to be quantified. Some rebound scholars therefore use quantification models of the form:

$$R = \frac{Shortfall\ \ in\ \ energy\ \ savings}{Expected\ \ energy\ \ savings} \tag{3}$$

With regard to units of analysis, most rebound effect studies use energy units, such as kWh, as their dependent variable, but there is some diversity here, with some using CO_2 emissions. This is particularly useful at a global scale, since increases in the consumption of many different kinds of energy services may follow from a particular energy efficiency increase [73,74]. It is also useful at a more local scale when, for example, there is one energy service under consideration, such as private vehicle road transport, but there are different fuels involved [40,75].

Quantification methods need to be both appropriate to the dynamics of the situation and de-mystified, so that policymakers can make proper use of them. Researchers need to be able to report, for example, using equation (3): “When the 1930s-era council houses in in Dublin are thermally retrofitted to national standards, on average 30% of the expected energy savings are lost due to rebound effects.” Or they need to be able to say, using equation (2): “Over the past 5 years, each 1% of the ongoing incremental increase in thermal energy efficiency of the national housing stock has led to only a 0.8% reduction in heating energy consumption, hence a rebound effect of 0.2 or 20%.”

As we will also show below, these formulas cannot necessarily be directly adopted for renewable electricity rebounds, due to the different technical dynamics involved, but provide useful bases for extending to this domain. We therefore offer modifications to suit the dynamics.

3. Extending the discussion to renewable electricity

3.1. Evidence of rebound with renewable electricity

Evidence is emerging that the adoption of renewable electricity sources can lead to rebound effects. As mentioned in Section 1, almost all studies of this to date focus on prosumer households, i.e. households that produce electricity with photovoltaics.

Deng and Newton [35] found that energy consumption among households with photovoltaics in Sydney, Australia, was above the city's average if the price they received for feeding their electricity into the grid was heavily subsidised. This suggests an “income effect” (see above) where households' increased income from selling their electricity enables them to spend more on energy consumption.

In a US study, Toroghi and Oliver [36] found that each increase of 100 kWh in photovoltaic generation was associated with a net reduction of only 94.15 kWh of electricity drawn from the grid. Using an adaptation of equation (3) above, they calculated this as a rebound of 5.85% (since 100−94.15 = 5.85). This indicates that producing electricity led these households to consume slightly more electricity, though does not necessarily identify the cause-and-effect chain involved.

Qiu et al. [39] found rebound effects of 18% among photovoltaic households in Phoenix, Arizona, using price elasticity as a proxy for rebound effects, and Li et al. [34] found small negative rebound effects among US households who had been generously incentivised to feed their own-produced electricity into the grids – in this case an income effect in reverse.

It is not easy for such studies to clearly identify a constant conjunction of events between installing photovoltaics and overconsuming. However, a recent qualitative study [76] in Bavaria, Germany explored this in some detail. For example, one household interviewed, who were in the habit of overheating their house in winter, said they felt justified in doing so because they were reducing Germany's CO_2 emissions for most of the year with their photovoltaic panels – a form of “moral licensing” (see above) that shows a clear cause-and-effect chain.

Another very recent study brings together four sets of qualitative interviews with prosumer households in different parts of Germany [3]. This looks principally at psychological influences on households’ energy consumption as a consequence of their becoming prosumers. It also explores the limits of psychological explanations of rebound effect behaviour among these households, pointing toward other influences such as sociotechnical factors, regulatory constraints, and the fluctuating nature of photovoltaic power production which is out of phase with household energy-related practices.

Yet another recent empirical study in Germany brings together the results of qualitative interviews among prosumers and data gathered from government and electricity stakeholders, to specifically focus on the influence of the regulatory framework on rebound effects among prosumers [77].

These pioneering studies are bringing issues to light which add weight to the idea that the cause-and-effect mechanisms driving rebounds in the renewable energy domain can be similar to but also very different from those in the energy efficiency realm.

Given that there are indications of rebounds from renewable electricity, at least in relation to household photovoltaics, and that there are clear differences emerging between the two domains, we suggest a modified form of the four-part framework above as a frame of reference for its further analysis. Here it becomes: (a) identify the increase in renewable energy which is of interest; (b) identify the change in energy consumption (or shortfall in the reduction of non-renewables consumption); (c) identify the constant conjunction of events, such as a causal chain from (a) to (b); and if this can be identified, (d) quantify the rebound effect in a way that is transparent, coherent and useful to policymakers. We deal with each of these in turn.

3.2. Step (a): the change in renewable energy

This step highlights important differences between energy efficiency rebounds and renewable electricity rebounds. Firstly, with energy efficiency, step (a) is always on the *demand* side: an appliance that *consumes* energy undergoes an energy efficiency increase. With renewables, however, step (a) is on the *supply* side when considering a household or organisation *installing* renewable electricity, but on the *demand* side when considering a household or community *purchasing* renewable energy, such as with a green electricity tariff. This affects both the logic of the issues, and in some cases the type of formula that can be used in step (d) to quantify the rebound effect, as we show below.

A further difference is that with an energy efficiency increase there is always a pre-existing level of energy efficiency prior to the increase, whereas a household installing photovoltaics might not have been already producing renewable electricity. Energy efficiency never increases from zero, but renewable energy production often does. This will affect whether a researcher can use a modification of one of the above equations in step (d) or must develop some other equation, since an expression of the form $\frac{\partial\eta}{\eta}$ is nonsensical if $\eta = 0$.

There could also be differences in the psychological effects of installing photovoltaic panels for the first time, compared with installing a second or third set subsequently. Based on empirical studies of prosumer households, Dütschke et al. [3] ask “How does it influence the energy behaviour of households if they become prosumers?” *Becoming* a prosumer involves a decision-making process, planning and organising with installation firms, plus changes to the appearance and technical functioning of the house. This is highly likely to have a psychological impact. Installing a second set of panels will have a much lower technical impact even if the quantity of electricity produce is as great or greater, so its psychological effects on consumption behaviour might be different. Galvin [76] interviewed prosumers who had installed a second and in one case a third set of photovoltaic panels on their house and outbuildings, and found evidence of higher rebound effects for the latter installations. It seems the good intentions generated by becoming a prosumer sometimes gave way to moral licensing as households made greater contributions to the environment.

Further, consumers' engagement with renewable energy does not just apply to prosumer households, but also increasingly to households switching to a green electricity tariff. Most such households will previously have already been consuming some renewable electricity because most countries’ electricity grids include at least a portion of renewables. In cases such as this, rebound mathematics akin to those that deal with small increases in energy efficiency may prove directly useful: we can use elasticity functions similar in form to equations (1) and (2) but of course with changes in renewable energy, rather than energy efficiency, in the denominator. On a larger scale, such as a national electricity grid, policymakers might be interested in possible rebound consequences of increases in either the absolute level of renewables production, or the proportion of renewables in the electricity mix (both are issues of supply). A researcher would need to discern which of these to base her or his rebound calculations on, depending on the aims of the research, as each of the two cases will produce a different percentage value for the rebound effect (see Section 3.5).

Step (a) therefore depends on what the researchers are aiming for. Do they want to track the effects on consumption for a household becoming a prosumer, or a prosumer household increasing its number of photovoltaic panels, or a consumer increasing the renewables share of its electricity consumption? Do policymakers want a percentage figure for rebounds at grid level? Making these decisions is step (a).

3.3. Step (b): the outcomes and effects

Step (b) is to identify the consumption changes that appear to be associated with the renewable electricity increase. At household level, researchers such as Oberst et al. [37] surveyed prosumer and non-prosumer households and matched their characteristics to see whether prosumers consumed more *energy* overall than non-prosumers, controlling for all other factors, whereas Toroghi and Oliver [36] were interested in prosumer households’ consumption of *electricity* only. A more varied set of outcomes was considered in two qualitative studies. Galvin [76] provided an in-depth analysis of 18 prosumer households in Bavaria, where outcomes that followed from the adoption of rooftop photovoltaics included changes in a wide range of energy-related behaviour. This included such things as: holiday travel; environmental engagement; home heating practices; day by day recreational and commuting travel; electrical appliance load shifting; use of ICT; and investments in further technologies and their subsequent use. Palm et al. [78] also considered a range of different possible outcomes of producing electricity via photovoltaics, in a Swedish context.

Combining different types of outcome coherently for rebound studies would probably require these to be translated into a common measure such as changes in CO2 emissions or even size of ecological footprint. This has already been attempted in rebound research in the energy efficiency domain [79,80]. These studies make use of large amounts of already existing data, which are available in the field of rebound studies related to energy efficiency, but it could be some time before rebound studies in the renewable energy domain catch up with this.

Statistical approaches can also be useful on a national and supra-national scale, for example for tracking changes in total electricity demand against changes in renewable electricity production.

Step (b), then, requires a decision as to what outcomes and effects might arise consequent to specific increases in renewable energy production. This can include changes in electricity consumption in individual households, right up to changes in electricity consumption on a national level, or even energy consumption in general, or possibly even changes in ecological footprint.

3.4. Step (c): Identifying constant conjunctions of events

Research on identifying causal links between producing renewable electricity and making changes in consumption has only just started, and not all studies explicitly refer to rebound as a concept. Studies by Wittenberg et al. [81] and the above-mentioned studies by Galvin [76] and Palm et al. [78] imply there can be many different types of links in addition to classic economic and psychological motivations that are similar to those found in energy efficiency rebound studies.

For example, Galvin [76] found that what he called “geo-socio-technical” mismatches played a role that is not evident in the energy efficiency domain. By this he meant mismatches between photovoltaic technology, the sun's patterns and angles of shining, the angle of the roof where the photovoltaic panels lie, the regulatory framework, and the household's needs for energy at certain times of the day or year. In one example, a prosumer had mounted his photovoltaic panels on east and west facing roofs so that he could use his own electricity to charge his electric car battery before and after work in the summer. But this severely reduced his total production of electricity, since the strongest sunshine comes from the south. The “rebound effect” of lost renewable electricity production thereby had a cause-and-effect chain that is without parallel in energy efficiency rebound effects phenomena. Another household installed a garden fountain and ran it at midday in summer to make use of excess electricity which they were not allowed to feed into the grid on rare occasions due to overloading (see general discussion on this issue in Ref. [82]). Because the household cameto like the fountain, they got into the habit of running it every day, even though their feed-in to the grid was curtailed only occasionally – a clear rebound effect, again with a cause-and-effect chain that has no parallel in the energy efficiency domain. Other “geo-sociotechnical” rebound cause-and-effect chains included reduced electricity production due to shading from nearby tree growth and, in one case, persistent steam clouds from a nearby nuclear reactor's cooling tower – again issues with no parallel in energy efficiency rebounds.

However, some of the cause-and-effect chains in rebound effects with renewable electricity appear to be the same as or similar to those with energy efficiency. In particular, economic drivers can be similar. For example, Weiss et al. [77] report on possible price and income effects among Germany's prosumer households. They point out that in the 2000s prosumers received very high feed-in tariffs for feeding their electricity into the grid, so the installation costs of their photovoltaic systems paid back within 10 years and gave them a further 10 years of extra income. For installations more recently the price structure had changed so that it was much cheaper to use one's own electricity than grid electricity: an income effect has given way to a price effect. Both higher income and lower electricity prices can cause rebound effects, as a raft of meta-studies show (e.g. Refs. [83,84]).

Some of the psychologically driven cause-and-effect chains in renewable energy rebounds may be similar to those in energy efficiency rebounds. Moral licensing, referred to above, is one of these. Galvin [76] found that at least one prosumer households justified their use of excessive home heating on the basis of the good they had done for the environment by installing a very large array of photovoltaic panels. Dütschke et al. [3], whose work is based on four empirical studies of prosumer households, also find that moral licensing often occurs among prosumer households but that the cause-effect-chain is sometimes also reversed, i.e., that some households invest in a PV system to compensate for a high energy demand. Kratschmann and Dütschke [85] investigate the messages of firms promoting photovoltaics in Germany and find a combination of sales narratives that focus on economic motivations and that these could provide justification for moral licensing by neglecting other motivations. Another psychologically motivated cause-and-effect chain is the conservation effect, also referred to above. Here, households become more environmentally concerned as a result of installing photovoltaics and therefore reduce their energy services demand, just as others do after purchasing a more energy efficient appliance or having their house retrofitted to low-energy standards. Galvin [76] and Dütschke et al. [3] found this effect to be strong among several interviewed prosumer households. Some interviewees began to act to protect the environment as a result of installing photovoltaics, even though their original motivation for installing photovoltaics often had more to do with aesthetics or economics than environmental concern.

Nevertheless, identifying causal chains in rebound effect research is not always straightforward. It is by no means guaranteed that a researcher will bring to light all the energy consumption related effects of a change in renewables production, nor be able to identify what causes what. This is especially precarious when using *quantitative* questionnaire surveys to obtain data on household behaviour, since respondents only answer the questions put before them and cannot be cross-examined [86]. We can help close this gap by including a large number of likely parameters as control variables, as Li et al. [34] do very effectively. Control variables such as house size, type of dwelling (free-standing, semi-detached, multi-apartment house, etc), household income, householders' age, ethnicity and educational background can help to filter out influences on energy consumption that may not be related to rebound effects.

Even here, though, there may be gaps. An obvious case is where a household replaces most if its household electrical appliances at about the same time that it installs a photovoltaic system – which may happen, for example, if planning to install photovoltaics leads households to think about updating their household technology generally. Here there could be a combination of rebound effects from both energy efficiency and renewable energy, and a quantitative survey may not be detailed enough to trace the conjunctions of events. Similarly, if a household has photovoltaics installed during the construction of their house, it may be very difficult to separate the psychological impact of becoming a prosumer, from that of becoming a homeowner and/or coming to live in a completely new physical and sociotechnical environment. This could be an increasing issue for research in Germany, as the building regulations (the *Gebäudeenergiegesetz*[2]) now strongly favour the installation of photovoltaic panels on new houses.

For research purposes a useful mixed methods approach is to first use qualitative, semi-structured interviews intensively with a small sample or samples so as to identify “what” is happening among households (as in Refs. [3,76]), then use these findings to inform the content of a larger-scale quantitative questionnaire to find out “how much” it is happening and “how large” the rebounds are. The qualitative phase has the advantage that the interviewer “usually has some latitude to ask further questions in response to what are seen as significant replies.” ([86]: 716). This can bring to light hitherto unexpected causal chains between household electricity production and consumption, though it cannot quantify these effects on a large scale, such as nationally. The next step is to integrate these findings into the design of quantitative surveys, so that the questions in the surveys are likely to cover issues that are known to be relevant to various forms of rebound and their causes.

This approach can help identify causality in rebound effects that happen within prosumer households, but we also have to track causality when identifying renewables-driven rebound effects more widely, at a macro or country level. A start has already been made in this endeavour. Thombs [70] regressed CO_2 emissions per unit GDP against renewable energy production and control variables for 129 countries over 1990–2013. For 25 low-income countries he found reductions in CO_2 emissions correlated with renewable energy diffusion (which might suggest low or no rebound effects), but the opposite for 37 high-income countries (which might suggest high rebounds). Correlation does not prove

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[2] https://www.bmi.bund.de/DE/themen/bauen-wohnen/bauen/energieeffizientes-bauen-sanieren/energieausweise/gebaeudeenergiegesetz-node.html.

causality but can suggest it if other influences are controlled for.

In a further step, Dogan and Seker [71] regressed CO_2 emissions against renewable energy, trade and (other) control variables for EU countries in 1980–2012. By employing panel estimation techniques robust to cross-sectional dependence, these researchers were able to identify 2-way causality: increased renewable energy and trade led to reduced CO_2 emissions, and the other way round, suggesting that rebound effects from renewable energy, if any, were low in EU countries.

However, this type of approach is only a start, because there can be a mixture of effects leading from renewables production to CO_2 emission reduction, with some effects driving CO_2 emissions down, and others driving them up. For Germany, for example, Fig. 1 tracks renewable electricity production and electricity consumption through 2002–2019. We see an increase in renewable electricity generation, which is in line with policy goals, and no increase in consumption. This could be an indication of zero rebound effects from the increase in renewable electricity. But we would need to regress these, along with control variables such as increases in numbers of electric vehicles, increases in energy efficiency of appliances and industrial processes, shifts toward or away from electric heating, etc., to estimate how much of the variance in consumption is associated with the variance in renewable electricity production. Ideally, we would then need to identify what it is about renewable electricity production that leads to these effects on overall consumption: is it an increase of new technologies in relation to sector coupling (heat pumps, electric cars); a price elasticity effect due to the expense of the energy transition; a country-wide psychologically motivated "conservation" effect of being greener; or a sociotechnical effect of providers having to negotiate more and more wildly fluctuating bulk tariff prices, etc.? To confirm whether there are rebounds or reverse rebounds from the increasing share of renewables we need to identify constant conjunctions of events at finer levels where possible.

3.5. Step (d): quantifying rebound effects with renewables

Assuming the issues around steps (a), (b) and (c) can be pursued with some level of success, researchers then need suitable formulas that produce transparent, coherent and useful values for rebound effects.

An elasticity formula based on equation (1) or (2) is highly problematic for situations where a household installs photovoltaics for the first time. As noted above, elasticity-based formulas assume there is always already a non-zero value for energy efficiency. The problem with translating this into the renewable energy domain is that a household is not necessarily already generating renewable electricity when it installs a photovoltaic panel. The term $\partial\eta/\eta$ in equations (1) and (2) would become $\partial P/P$, where P is the quantity of renewable electricity produced. But since a non-prosumer household that installs photovoltaics is not increasing their proportion of renewable energy production but starting from zero, the denominator P of this term would be zero, making the term infinity, making the rebound effect 0% with equation (1) and (100)% with equation (2).

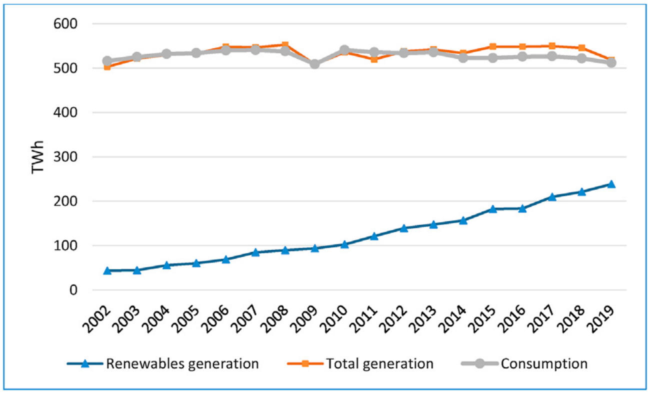

Fig. 1. Germany's electricity consumption, total generation and renewable generation, 2002–2019 (electricity exports make up the difference between total production and consumption). Data sources: [87,88].

Instead, we propose a modification of equation (3) as the default approach for most cases. For renewable electricity equation (3) can be modified to:

$$R = \frac{Increase\ \ in\ \ electricty\ \ consumption}{Magnitude\ \ of\ \ new\ \ renewable\ \ electricity\ \ production} \tag{4}$$

To clarify how this relates to equation (3), "Magnitude of new renewable electricity production" corresponds to an expected reduction in the consumption of non-renewable electricity, while "Increase in electricity consumption" corresponds to a shortfall in this reduction.

For example, a household installs photovoltaics that produce 1000 kWh/y of renewable electricity and subsequently increases its electricity consumption by 200 kWh/y, of which 80 kWh/y can clearly be traced to householder actions as a consequence of installing the photovoltaics. Using Equation (4), the rebound effect from the renewable energy increase is:

$$R = \frac{80kWh}{1000kWh} = 8\%$$

Note that this is only the rebound effect due to the renewable electricity increase. It does not take into account other rebounds due to energy efficiency increases that might have occurred at the same time.

It may appear at first that because this excess consumption is all renewable electricity, the rebound effect in this case is of no practical consequence. However, there is only a limited pool of renewable electricity in the grid, so any extra demands on it have to come from non-renewables. All of the extra 80 kWh/y is therefore effectively a demand on non-renewables and should be of concern to policymakers.

We can take this type of case one step further. Suppose we are in a situation where a country's electricity grid is fully decarbonized. Increases in a household's electricity consumption no longer cause extra production of non-renewable electricity, so in this sense there is no rebound effect. However, since renewable electricity will be used for decarbonizing other sectors besides the grid [89,90], renewable electricity is a scarce good and any extra demand for it takes it away from decarbonizing other sectors, such as transport or heating. In this situation the rebound effect is therefore relevant again.

For example, in Germany in 2019 total electricity consumption was 476 TWh and total renewable electricity production was 224 TWh [87]. Suppose the grid becomes completely decarbonized and electricity consumption increases to 570 TWh. Suppose most of the increase is due to the electrification of transport, etc., but that 30 TWh of it can be robustly traced to consumer attitudes to renewables: they consume more because they believe this is no longer damaging the planet. The increase from Germany's 2019 level of 224 TWh of renewable electricity to 570 TWh is 346 TWh. Since 30 TWh of this 346 TWh has been "taken back" for extra consumption, it either has to be additionally generated or can no longer be passed on to help decarbonize other sections of the economy via electrolysis and hydrogen, so the rebound effect is:

$$R = \frac{30TWh}{346TWh} = 8.7\%$$

Finally, it will be important to track this kind of rebound effect at countrywide level as decarbonization progresses. Suppose each 1% increase in renewable electricity production is associated with an increase in consumption of 0.1% that can be robustly traced to rebound-type cause-and-effect. This would enable an elasticity formula to be developed similar to equation (1), with the form.

$$R = \frac{\partial C}{C} \bigg/ \frac{\partial P}{P} \tag{5}$$

where P is renewable electricity production in a particular year, ∂P is the change in production in that year, C is electricity consumption in that year, and ∂C is the change in consumption in that year which can be robustly traced to the effects of increases in renewable electricity production. Because this type of formulation gives marginal effects, it could be useful to policymakers in forecasting ongoing shortfalls in gains from stepwise renewable energy growth.

4. Conclusions

As governments mandate and support increasing decarbonization of electricity supply, it will become increasingly important to quantify and understand rebound effects due to increases in renewable electricity production and use. In the field of energy efficiency, rebound effects indicate that less energy is being saved than is predicted by engineering calculations based on the size of the energy efficiency increase. In the field of renewable energy, rebound effects indicate that the reduction in consumption of non-renewable energy is less than the amount of additional renewable energy produced. Both these situations compromise government and societal aims for CO2 emissions reduction and climate change mitigation.

Research has recently begun on rebound effects in the renewable electricity domain. Studies to date focus on households with photovoltaics. Most such studies find indications that rebound effects are occurring and quantify the net magnitude of these. This is a good start, but we need finer grained studies because in addition to rebounds there are also reverse rebounds (conservation effects), and some of these appear to be happening simultaneously and partially cancelling each other out. One recent study has recognised this [3]. If policymakers are to devise interventions to curb rebound effects in the renewable energy domain, this will be much more effective if interventions are aimed at specific cause-and-effect mechanisms. In this way, mechanisms leading to rebounds can be mitigated while mechanisms leading to conservation effects can be supported and enhanced.

We have therefore offered a preliminary framework for better understanding rebound effects in the renewable energy domain. We based this on a 4-way framing of existing research on rebound effects in the energy efficiency domain, as a starting point for rebound effect research in the domain of renewable electricity. We proposed that research should aim to: (a) identify the change in renewable electricity, and whether it is a new installation of generating sources (supply side) or a shift to an increased share of renewables in consumption (demand side); (b) identify the increase in electricity or other energy consumption or CO_2 emissions, etc. that is of concern; (c) identify a clear cause-and-effect path from (a) to (b), so that other possible causes of (b) are clearly excluded; and (d) calculate the rebound effect using an appropriate formula to produce a transparent result that policymakers and others can make use of.

We have argued that there are both differences and similarities between rebound effects in the energy efficiency and renewable energy domains. Policymakers can make use of this to refine and adjust the interventions they already employ in their attempts to reduce rebound effects. The economic and some of the psychological drivers appear similar between the two domains. In economic terms, price and income effects appear to play similar roles in both domains, though the mechanisms of these need to be well understood. Paying prosumers over-large tariffs for feed-in to the grid can bring rebounds due to income effects, while setting the retail price of electricity too high can bring rebounds due to the much cheaper price of consuming one's own electricity – as in Germany, where the retail price is around 30 eurocents per kWh.

There are also similar psychological cause-and-effect mechanisms, particularly moral licensing, which leads to rebounds [91], and increased environmental awareness, which leads to conservation or spillover effects [92]. With renewable electricity, however, the installation of a photovoltaic system is often a much more dramatic and disruptive event for a household than an energy efficiency upgrade in appliances or in a boiler, so it is possible that the psychological impact is greater. Nevertheless, as photovoltaic systems become more widespread and normal this effect could diminish. This discussion also links up with the analysis started by studies as by Kratschmann and Dütschke [85] who looked into the societal framing of using photovoltaic systems. Policy interventions could make more use of the public's concern for the environment by highlighting the environmental benefits of photovoltaics and building up the image of prosumers as environmental champions who can lead by example.

Policymakers also need to pay heed to the broader differences between rebounds in energy efficiency and renewable electricity. One of these is that with energy efficiency, both the efficiency upgrade and the consumer response happen on the demand side, whereas with renewable electricity among prosumers, production happens on the supply side while consumption happens on the demand side. This can have profound psychological and sociotechnical effects which carry their own rebound mechanisms: generating one's own renewable electricity from a very visible photovoltaic array can make a household very aware that they are protecting the environment; wiring a house for photovoltaics can offer opportunities to change the configuration of some electrical devices in a household; and photovoltaics expose the household to a dynamic and fluctuating electricity generation environment closely tied to the moods of the sun, while the usefulness of electricity from photovoltaics is often compromised by the limitations of the electricity grid – another area that needs policymakers' urgent attention [82].

Another important difference is that every energy-consuming device already has a level of efficiency, so rebound effects after an increase in energy efficiency can be expressed in an elasticity formula. With renewable electricity production, however, since a household can jump from zero generation to a specific level, an elasticity formula does not work for the case of an individual household. This affects how we calculate the magnitude of rebound effects. However, it also brings some similarities with large, stepwise energy efficiency increases, such as when an old dwelling is comprehensively thermally retrofitted. Although the maths are different, the psychological and sociotechnical effects may be comparable: a very big physical change to a house, leading to a very different set of energy parameters and visible symbols of environmental protection, such as photovoltaic panels or external wall insulation.

The four-part framework we have offered in this paper is not intended as a straight-jacket or as the only possible way to understand the issues. Just as the frameworks and typologies for understanding rebound effects in energy efficiency have developed over the last few decades, so we expect frameworks for understanding rebounds in renewable electricity to develop as more empirical research is completed. With this beginning, however, we offer researchers and policymakers a useful tool for ordering and bringing clarity to a developing subject, and for beginning to devise and implement interventions for getting maximum CO2 emission reductions from the increasing numbers of photovoltaic systems on the roofs of households.

Finally, we set the work for this paper in the context of increasing demand for renewable electricity, which is likely to increase even more markedly and rapidly in the coming decades. This is due to aims to decarbonize electricity grids and substantially decarbonize transport, heating and industry via sector coupling, powered mostly by "green" hydrogen. As the demand for renewable electricity grows, issues of rebound effects in this sphere will become increasingly important.

Declaration of competing interest

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

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.renene.2021.05.074.

Authors' contributions

All three authors contributed detailed knowledge of rebound effect literature and did background empirical and literature research on renewable electricity. Elisabeth Dütschke wrote an initial overview. Ray Galvin conceived the conceptual framework and wrote the first draft of the current version. Julika Weiß and Elisabeth Dütschke extended and modified this and assisted Ray Galvin in writing the final version.

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