Energy-related behaviour and rebound when rationality, self-interest and willpower are limited

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Abstract

The extent to which adopting energy-efficient technologies results in energy savings depends on how such technologies are used and how monetary savings from energy efficiency are spent. Energy rebound occurs when potential energy savings are diminished due to post-adoption behaviour. Here we review empirical studies on how six behavioural regularities affect three energy-relevant decisions and ultimately rebound: adoption of energy-saving products or practices, their intensity of use, and spending of associated monetary savings. The findings suggest that behaviours which reflect limited rationality and willpower may increase rebound, while effects of behaviours driven by bounded self-interest are less clear. We then describe how interventions associated with each of the behavioural regularities can influence rebound and thus serve to achieve higher energy savings. Future research ought to study energy-relevant decisions in a more integrated manner, with a particular focus on re-spending as this presents the greatest challenge for research and policy.

(Main text)

Energy rebound denotes that potential energy savings of adopting an energy-efficient technology or practice, possibly triggered by some policy, are offset by subsequent behavioural and systemic responses that increase energy use, resulting in diminished net energy savings[1,2]. There are three main types of rebound: *direct rebound* or intensity-of-use effect – a technology becomes more energy-efficient and thus less costly in its use, causing consumers or producers to use it more intensively; *indirect* rebound or re-spending effect – spending less due to using a more energy-efficient technology releases money that is subsequently spent on other products or services that use energy over their life cycle; and *economy-wide rebound* – more energy efficiency leads to many other changes in the economy, such as investments in expansion of production, impacts on capital and labour markets, and indirectly increases in consumption, all with consequences for energy use. Figure 1 illustrates these rebound types, and their joint impact on energy savings, for the case of switching to a more fuel-efficient car.

While there is little doubt that rebound is an important issue that warrants serious attention in policy design, the exact magnitude of rebound effects is surrounded by uncertainty. This is partly the result of the difficulty of assessing rebound empirically, because of a lack of appropriate data and a clear counterfactual, and as rebound lacks unambiguous system and temporal boundaries[3–5]. Estimates for direct rebound range from 0 to 87%, differing between application areas, such as space heating (2-60%), cooling (0-50%) and transportation (5-87%)[5]. Evidence from 33 macrolevel studies shows that economy-wide rebound effects tend to exceed 50%, and may include backfire (>100%)[6].

Among economists, a conventional way to think about rebound is that it results from optimal adjustment to observable and perfectly known changes in marginal costs due to improvements in the energy-efficiency of a product or technology. In accordance with this, rebound can be estimated as the combination of price and income effects. However, rebound is the result of more than just changes in relative prices[7–12]. It also depends on behavioural reactions to policies, markets, technologies and social peers. A realistic representation of individual decision-making is therefore necessary to allow inferences to be drawn about when rebound is likely to occur, the magnitude of the effect, and how it can be curbed.

Many studies of decision-making implicitly or explicitly assume rational and selfish agents, who consistently optimize a utility or profit function and are unaffected by behaviours or opinions of others. However, modern behavioural sciences demonstrate that people are bounded in their rationality, willpower and self-interest[13]. Bounded rationality means they do not always optimize decisions because they cannot perfectly calculate future costs and price effects; bounded willpower, also known as limited self-control, prevents agents from acting upon their preferences; and bounded self-interest indicates that factors such as concerns about others, self-image or social norms affect peoples' behaviour. While bounded self-interest suggests that individuals have additional motivations beyond strictly selfish goals, bounded rationality and willpower have implications for the way individuals try to achieve these goals. Limits to rationality and

willpower often result in individuals not achieving their goals – irrespective of whether these are selfish or non-selfish. For example, potential financial benefits could motivate individuals to save energy by lowering the thermostat level of their heating system, but limited awareness about such benefits, or habits of wearing light clothing indoors, may prevent them to from doing so. In other words, bounded rationality and willpower moderate how motives affect behaviour.

In Table 1, we present six behavioural regularities relevant for the case of rebound. These are well-documented behavioural patterns that emanate from the underlying behavioural assumptions of bounded rationality, willpower and selfishness, as explained in Box 1. In this Review we present evidence of how each of them influences the three energy-relevant decisions, with the aim of assessing whether they have a propensity to increase or decrease the rebound effect (see Figure 2).

In particular, potential energy savings and thus rebound can be thought of as the result of individual energy-relevant decisions following energy-efficient technology adoption, namely intensity of use and re-spending. Intensity of use indicates how intensively adopters use the energy-efficient product as compared to pre-adoption use levels. This in turn determines direct rebound. Re-spending denotes that adopters spend monetary savings associated with initial energy savings on additional goods or services that in turn cause energy use. This gives rise to indirect rebound.

Here we review studies from any field that relates rebound to behaviour, including the broader behavioural and social sciences. While a few studies have already employed insights from behavioural sciences to explain rebound[7–12], here we provide a comprehensive review of the available evidence on energy-related decisions irrespective of whether the corresponding study explicitly described implications for rebound. We derive many of the insights regarding intensity of use and re-spending from studies on curtailment and low-carbon consumption, respectively. We draw on the general literature addressing energy-efficient behaviour to draw inferences about when direct and indirect rebound are expected to occur. We will discuss how this can inform improved policy design for, and future research on, effectively controlling or curbing rebound.

Behavioural regularities, energy decisions and rebound

Inattention and misconceptions

People lack the cognitive capacity and time to properly analyse all the available information before reaching a decision. In some cases, they disregard relevant information and in others they misinterpret it, leading to biased beliefs or misconceptions. As a result, the effects of prices and income on the one hand, and moral and social motivations on the other, are moderated by inattention and misconceptions. Evidence for vehicle purchases suggests that agents pay limited attention to financial data[14], or imperfectly assess these[15].

Similarly, consumers' environmental concerns affect car purchase choices but this is moderated by inaccurate perceptions of emissions[16].

Inattention has been identified as a main factor hindering adoption of energy-efficient technologies. Consumers and firms tend to pay more attention to purchasing than to operating costs, causing them to underinvest in energy-efficient options[17].

Regarding intensity of use, evidence shows that this increases due to inattention. In general, consumers tend to underestimate energy costs, and as a result they increase energy use. For example, evidence from the UK refrigerator market shows that consumers underestimated future energy costs by 35%, which led to a 9,2% increase of average use compared to what perfectly rational consumers would consume[18]. This effect is more pronounced for energy-efficient products. One study found adopters of heat pumps to be unaware they were using them more intensively than the conventional heating, resulting in higher indoor temperature[19]. According to another study consumers incorrectly infer that high energy efficiency translates to low overall energy use, which may consequently lead them to use energy-efficient products more intensively[20]. Finally, in a quasi-experimental setting, consumers used significantly less electricity during a month following the receipt of a bill that crossed a salient threshold[21].

Indirect evidence suggests that inattention increases re-spending. According to the studies mentioned in the previous paragraph, consumers underestimate energy use after adoption and therefore overestimate energy and associated monetary savings, in turn translating into increased spending. In addition, people systematically misjudge information about energy use: they underestimate energy consumption and savings associated with high-energy activities and overestimate them for low-energy activities[22,23]. Taken together the evidence suggest that re-spending increases and is directed towards more energy-intensive or larger appliances. However, direct evidence is lacking. In summary, compared to what the rational-agent theory would predict, inattention leads to lower adoption rates and, in case of adoption, to higher intensity of use, which may translate to higher direct rebound. Effects of re-spending are uncertain.

Mental accounting

In the face of cognitive limitations and overwhelming information, individuals adopt heuristics to simplify their decisions. Mental accounting describes common ways people use to organize their budget which include coding, categorizing and evaluating economic outcomes[24]. It has various elements. Instead of considering their entire budget as fungible, individuals keep various smaller mental budgets which they consider in isolation. Examples of more specific accounts are clothing and entertainment expenses[25]. The marginal propensity to consume – i.e. how easily money is spent – varies across mental accounts. A common feature of all accounts is that they have a reference point, where the account is considered balanced in the minds of consumers. Exceeding this point is classified as a gain and being below it as a loss. The distinction is important as losses create stronger reactions than gains, known as loss aversion[26]. To illustrate,

when in 2001 the US government attempted to boost the economy by transferring $38 billion to taxpayers, instead of spending the received money, most people saved it. This arguably happened because the government called the transfer a "rebate", a term that implied that money was initially owned by individuals and subsequently returned to them, restoring an imbalance[27]. In terms of mental accounts, people placed the transferred "losses" to a mental "savings" account, with a low propensity for consumption. Further research suggested that had the transfer been framed as a bonus, it might have stimulated spending[39]. Mental accounting has indeed been suggested to significantly shape energy-related behaviours[28].

Loss aversion hinders adoption of energy-efficient products. It leads people to focus disproportionally on immediate and certain investment costs versus potential long-term savings on energy expenditures. Survey data from across Europe places loss-aversion among the strongest predictors of not adopting energy-efficient technologies, such as hybrid vehicles, energy-efficient light bulbs, energy-efficient household appliances and house insulation[29,30]. In addition, more than half of households that decide to not switch to an alternative energy provider state that they do not do so out of fear that something might go wrong[31].

The effect of mental accounting on intensity of use depends on the specific mental accounts that consumers hold. Evidence suggests that people have 'topical' mental accounts, meaning that they classify money according to the topic of the decision. For instance, money saved in transportation will most likely to remain in this account[32], leading to increased intensity of use. Direct evidence comes from the 'UK winter payment', a direct cash transfer to households, whose name led households to spent it disproportionately on heating[33]. At the same time people tend to keep separate mental accounts for one-shot investments and monthly energy bills. This means that after adoption, there will be more budget available on the second account, further increasing intensity of use. For example, when asked to calculate monthly car costs, only 29% of respondents included depreciation of the initial investment[34]. This is further confirmed by empirical evidence for travel[35] and heating expenses[11,19]. In addition, the effect is likely to be exaggerated by the sunk cost effect, which is considered an expression of mental accounting[36]: having invested money on adopting an energy-efficient product, people feel compelled to use it more.

Regarding re-spending, if energy savings are classified by consumers as gains, the propensity of spending the savings will be high[25]. There is evidence that in such cases consumers tend to buy goods that they do not normally consume[37], which tend to be more energy-intensive[38]. However, this may depend on the particular area of energy conservation: while re-spending from vehicle and food measures has been directed to goods with higher emissions, savings from heating and lighting improvements have been directed to goods and services with lower emissions[39]. Overall, loss aversion seems to reduce adoption, while mental budgeting may lead to higher direct rebound by increasing intensity of use, and higher indirect rebound by directing re-spending to higher energy-intensive products. The latter effect may depend on the type of consumption.

Defaults and Habits

Decisions by default and habitual behaviour are quasi-automatic processes that function at a low level of consciousness. A default denotes the option that individuals select if they do not make an active choice. Default bias refers to the observation that the probability of the default being chosen is disproportionally high[40]. This is due to inertia (avoid costs of searching for alternatives), loss aversion (avoid potentially inferior alternatives) or it being interpreted as the suggested option[41]. Habits are repetitions of past behaviours and determine individuals' default decisions in the presence of certain stimuli[42]. They are considered a principal barrier for behavioural change[43]. Defaults and habits characterize many decisions that pertain to energy use – think of mobility, electricity use and eating.

Defaults and habits hinder adoption of energy-efficient products since they both contribute to the status quo, weakening the connection between intentions and behaviour. For example, although the majority of people express that they favour a green-energy provider and are willing to pay a premium for it, only 2% end up selecting it, due to the default effect[44]. It is part of the reason why information-provision interventions signalling the availability of energy-efficient options having limited effect[45]. On the positive side, once people switch, the new product or practice becomes the novel status quo, causing default bias and habitual behaviour to stabilize it. For example, when the default in housing renovations changed from incandescent to CFL bulbs, the percentage of consumers choosing CFL went up from 56% to 80%[46].

Regarding use-intensity, adoption of an energy-efficient product is a source of habit disruption. For instance, switching to a hybrid car will often lead to distinct refuelling intervals. In theory, the final effect on use intensity will depend on the consumption type and on other details. The available evidence seems to suggest that the more habitual individuals are, the more intense their post-adoption use is. Individuals exhibiting habitual behaviour were found to overheat their apartments after insulating it[11] or after purchasing a heat pump[19], and to drive slightly more after buying an electric car.[11] Regarding insulation, habitual behaviour is expected to have an influence only in the absence of thermostats. Evidence suggest that only 27% of household vary thermostat levels over time[43]. Overall, habitual behaviour tends to have a negative effect on intensity of use, but the evidence is not conclusive.

Direct evidence is lacking regarding the specific effects of defaults and habits on re-spending behaviour. A model-based analysis showed that habitual behaviour deters consumers from moving to low-carbon alternatives[47]. One can argue that if people are habitual in their spending of unexpected monetary savings, such as on weekend trips or other short holidays involving long-distance travel, then this could create considerable rebound. However, if people are more habitual in the specific travel rather than the spending, rebound might be contained. To sum up, habits and status quo lead to decreased adoption rates; habitual behaviour may increase intensity of use, while effects on re-spending are situation-dependent and thus uncertain.

Present bias

Present bias refers to the tendency of people to overvalue immediate costs and benefits compared to future ones that leads them to make time-inconsistent choices. In more technical terms, people discount costs and benefits at a non-constant rate, i.e. depending on when they discount them[48]. This leads individuals to procrastinate, or make decisions that they may regret in the future[27]. Present bias therefore prevents individuals from acting upon their preferences, values, social expectations and long-term interests, causing stronger reliance on habitual behaviour. A wide range of phenomena that involve trade-offs between short-run costs and long-run benefits are evidently sensitive to present bias, such as obesity, failure to quit smoking and insufficient saving for retirement[49]. The same holds for energy-relevant behaviour since adoption of energy-efficient products or practices involves trade-offs between present and future cost and benefits.

Several studies find that present bias impedes adoption of fuel-efficient cars, home insulation, energy-efficient appliances, and curtailment behaviour[18,50–52], while fewer cannot establish such a relation[30,53]. For example, car buyers consistently underestimate future fuel costs, leading to a lower likelihood of adopting high fuel efficiency cars[54].

Present bias is associated with higher intensity of use. Among participants in a goal-setting energy program in the US, those with hyperbolic time preferences had higher post-adoption intensity of use[55]. Importantly, awareness of present bias mitigated this effect. In addition, procrastination is associated with less interest in reducing indoor temperature[56]. While no studies have examined the potential role of present bias on re-spending decisions, it likely will contribute to inefficient choices characterized by relatively low up-front costs. Overall, present bias decreases adoption, tends to increase intensity of use and thus direct rebound, while the effect on re-spending decisions and indirect rebound is not clear.

Pro-environmental values and moral licensing

Pro-environmental values may emanate from concerns about the wellbeing of other people, other species or the environment[57]. Such preferences motivate individuals to behave so as to decrease their environmental impact[58]. However, although people intend to act upon such values, they do not always manage to do so because financial and contextual factors, such as available budget and infrastructure, may be constraining. This holds especially true for energy efficiency investments[59–61].

Additionally, people might choose alternative options that are more alluring. In an attempt to self-justify deviations from what their morals prescribe, and to avoid cognitive dissonance and associated feelings of guilt or loss of self-esteem, people may use pro-environmental behaviours at earlier times or in other domains as a moral excuse. This is known as moral licensing[62] and has been employed to explain rebound[9]. For example, the purchase of an electric vehicle may be used as a moral excuse for subsequent intense use of it. It is as if individuals have a moral mental account which they try to keep balanced[8].

Phenomena such as compensatory behaviours[63], behavioural spillovers[64] and moral hazard[65] describe similar processes whereby engaging in one behaviour can trigger other behaviours that contribute to energy rebound. Additional reasons for the mismatch between preferences and behaviour include inattention, lack of knowledge regarding the effectiveness of potential solutions to environmental problems and self-control problems associated with individuals' bounded willpower.

Pro-environmental values increase the probability of adopting more energy-efficient products and practices. There is considerable of evidence in this respect regarding insulating houses[66], buying a fuel efficient car, using energy-efficient light bulbs[67] or participating in carbon offsetting[68] and green-electricity programs[69].

Regarding intensity-of-use effects of moral licensing, the evidence is mixed. A study among Swedish drivers switching to more efficient cars estimates the direct rebound effect was on average 24%. However, among the subsample that switched to a green-labelled car, the direct rebound was found to be zero[70]. A potential interpretation is that whenever adoption was motivated by pro-environmental reasons, the intensity of use did not increase, even if driving had become cheaper. Similar evidence is found among German[71] and Austrian[11] e-car drivers. At the same time however, there is evidence for moral licensing among electric car adopters. In a study of rebound in Norway, the degree to which a driver accepts responsibility for, and is willing to mitigate, the negative outcomes of driving a car was found to significantly drop after adopting an electric efficient car[72]. In another study, individuals scoring higher in a moral licensing scale (that is, justifying compensatory behaviours) were found to have higher intensity of use after adopting an e-car and after insulating their house[11].

Regarding re-spending, there is a well-established link between environmentally significant consumption and pro-environmental values[73]. Controlling for income and other socio-demographics, people with strong pro-environmental values have a spending pattern characterised by relatively low carbon emissions[74]. In fact, consumers with pro-environmental values are willing to pay a premium for green products[75]. To the extent that re-spending and general consumption patterns are behaviourally similar, the positive effect extends to re-spending and thus to indirect rebound. Indeed, there is evidence that pro-environmental values are the strongest predictor of a reduced re-spending pattern after adoption[11]. Overall, pro-environmental values tend to increase adoption and divert re-spending to low-carbon options. Their effect on intensity of use and thus direct rebound is less clear, however, due to potential moral licensing effects.

Peer influence

Individuals' behaviour is strongly affected by what other people think and do. Peer influence can take various forms: people comply with the norms to avoid social sanctions; they imitate others to fit in a group, or as a social heuristic when there is uncertainty about what is the right behaviour; and they signal socially

desirable personal traits through conspicuous consumption, in order to gain social status that comes with preferential treatment in social interactions[76]. In the domain of energy conservation, the effects of peer influence tend to be larger the more costly or effortful is a given behaviour, notably in the public (vs private) domain, where behaviours are more observable[77,78]. As such, the strength of peer effects is expected to be higher for energy-efficiency than curtailment behaviours. And within efficiency behaviours, installing solar panels is more relevant for social status than indoor house insulation, since the latter is not easily observable by third parties[78].

There is considerable evidence that peer influence encourages the adoption of more energy-efficient products and practices[79]. For example, purchase for the Toyota Prius is enhanced by social pressure and status[80], while people are more likely to install solar panels and subscribe to energy-efficiency programs when their neighbours do so[81].

Regarding intensity of use, the evidence is limited. An indication of a positive effect comes from a series of experiments done with household electricity demand when households' electricity consumption was compared to that of their neighbours. Results indicate that the effects of social norms on energy use are significant: on average they motivated consumers to reduce their energy use by 2%[82]. There is some evidence that such effects are long-lasting[83]. However, the latter interventions targeted total household energy use, not post-adoption intensity of use. In addition, status concerns might even lead to an increase in intensity of use. To illustrate, in an attempt to signal pro-environmental behaviour, owners of electric or hybrid vehicles might use them more frequently in order to increase visibility.

Regarding re-spending behaviour, various controlled experiments have shown that individuals who perceive a strong descriptive or injunctive pro-environmental social norm, tend to switch to low-carbon consumption patterns[84–86]. However, in the context of industrialized societies, where high consumption is the norm, peer effects might trigger more consumption, inducing higher re-spending. Somewhat counterintuitively, the stronger the pro-environmental social norm, the higher the re-spending[11]. In sum, while peer influence tends to lead to higher adoption rates, its effects on intensity of use and re-spending are less clear and can go either way[87]. Figure 3 summarizes the effects of the six regularities applied to energy-relevant decisions.

Behavioural interventions

Policy-makers can directly address the behavioural regularities in order to minimize their distortions on the effectiveness of policy instruments by employing instruments that recognize peoples′ limits on rationality, willpower and self-interest. The use of such behavioural interventions is becoming widespread in the field of energy conservation due to their cost effectiveness and political feasibility. There is now considerable evidence on what works and under which conditions[45,88–93]. Similar interventions can be used in the case of rebound. However, given that the end goal of the policy is not to curb rebound per se, but rather to reduce

total energy consumption, the real challenge is to promote adoption and decrease rebound or at least not increase it. Thus the effective policy will have a dual intention: encourage adoption and provide incentives to discourage rebound. Below we briefly describe behavioural interventions that can address the various behavioural regularities and describe how they affect the three energy-relevant decisions and hence rebound: adoption which will help closing the energy gap, intensity of use to address direct rebound, and re-spending to curb indirect rebound. Table 2 provides a summary.

Inattention & misconceptions

Regarding adoption, energy labels have been used to succinctly communicate energy efficiency and lifecycle energy consumption of durables in a visually friendly way employing colours and scales. However, their effectiveness has been found to be rather limited[88]. Consumers' responsiveness is found to be higher when efficiency is expressed in monetary terms[94].

The effects of inattention on intensity of use can be addressed by providing feedback regarding consumption levels. In the case of household consumption, feedback is given traditionally in the form of disaggregated energy consumption information at the end of the month (i.e. billing). However, feedback given this way does not permit consumers to calculate intensity of use of a particular source and even less to compare pre- and post-adoption levels. Smart meters can better address the temporal and spatial disassociation by providing frequent, near real-time and detailed resolution feedback, thus allowing consumers to observe and calculate energy improvements[95,96]. For example, the following personalized message "If you reduced the thermostat temperature in your house one degree you would save 11 kWh; this is equivalent to £1.43" reduced indoor temperature from 22.4 to 21.7 on average[97]. Modern disaggregation technologies can indeed provide energy feedback at the appliance level. Creative examples include light bulbs that change colour after prolonged use[27], or a polar bear standing on a melting ice floe during a shower[98]. In summary, to promote adoption and minimize rebound, energy labels and lifecycle energy information can be combined with real-time post-adoption feedback.

Mental accounting

A recent meta-analysis of studies using gain vs loss frames suggests that the latter are more effective in promoting pro-environmental behavior[99]. In the case of promoting adoption of more efficient options this means that the best way to promote adoption is to focus on the negative aspects – forgone long term monetary incentives or negative environmental consequences – of the less efficient options. To do so, the policy maker needs to assure that individuals combine adoption and intensity of use in the same mental account.

In addition, an integrated mental budget can provide a key mechanism for curbing intensity of use. Consumers wanting to keep their mental budgets balanced will assume a frugal post-adoption behaviour in

order to progressively balance it. This will essentially distort the core economic mechanism of direct rebound. In terms of policy intervention, the aim is to make consumers think of the initial investment as part of the topical mental budget, such as "heating", instead of a separate one, such as "one-time investments". The ideal behavioural intervention will do so without discouraging adoption in the first place.

In the case of heating, one might use, for example, a smart meter (illustrated in Figure 4) to assist consumers become aware of the time left for the initial investment until full payback. This nudges households to consider adoption and intensity of use in tandem. In addition, consumers can be given the option to adjust their daily energy consumption level according to a desired payback time, which can serve as a clear reference point. This will address inattention, and activate goal-setting mechanisms. What is more, this intervention of mental-account management will have direct implications for re-spending, since adopters will perceive no monetary savings until the end of the payoff period. Negative savings will then keep re-spending to a minimum.

Defaults & habits

Policy-makers may employ status quo bias to promote adoption. There is plenty of evidence that setting an energy-saving option as an opt-out, rather than as opt-in, significantly increases adoption of energy-efficient products, practices and energy-saving programs[41]. On the other hand, breaking less efficient habits is much more difficult to do in practice[100], especially given that adoption oftentimes includes large one-off purchases. That said, there are a few successful examples of disruption, such as temporality closing a highway[101], giving one-month free bus tickets[102] to promote use of public transportation, or exchanging car keys for a one-month free electrical bike[103]. In addition, there is evidence that interventions to promote sustainable behaviours are more effective shortly after important changes in peoples' lives, such as moving house[104].

Leveraging on status quo bias has been less exploited in the case of intensity of use but presents considerable potential. Lower temperature defaults of thermostats[105] and washing machines[106] have been shown to be effective in reducing energy use. Therefore, if after adoption intensity of use is set automatically to the pre-adoption levels (think of a thermostat), it is expected to have a significant effect. Simultaneous application of pre- and post-adoption defaults can therefore both promote adoption and curb rebound.

Present bias

To overcome present bias and promote adoption, policy-makers can draw the consumer's attention to the long-term implications of the energy-efficient choice[107]. In addition, long term benefits can be broken down and communicated in shorter periods intervals. However, as noted, such interventions have not always led to significantly higher adoption rates[53,108]

Commitment and goal-setting programs provide additional opportunities for addressing present bias, procrastination and lack of commitment. The basic idea is that consumers after adoption commit to an energy-reduction target regarding a particular electrical device or overall electricity use[109]. These programmes are designed to direct consumers' attention to the activities at hand, to engage them and, crucially for addressing present bias, to motivate them to prolong their commitment[110].

In addition, such programmes offer the opportunity to define the way potential benefits can be spent by tailoring them with particular activities, or eco-friendly shops and products, potentially linking to white certificates and complementary currencies[111]. This resembles commercial loyalty projects that involve earning points, which can be redeemed in eco-friendly products and services (e.g., free public transportation), such as the "NU-Spaarpas" and "Zet Milieu op de Kaart" projects in the Netherlands and Belgium, respectively.

Pro-environmental values and moral licensing

Policies and behavioural interventions using moral suasion and social marketing techniques have been used extensively to promote adoption of energy-efficient products and practices, frugal energy use, and low-carbon consumption[85]. They leverage on peoples' pro-environmental values and they have been proven to be even more effective than financial incentives in certain occasions. For example, a randomized control trial for electricity reduction revealed that communicating public health risks outperformed communicating financial gains[112].

The challenge of such interventions, however, is to minimize potential negative spillovers due of moral licensing. For example, eco-labels aimed at inducing 'greener' consumption can stimulate overconsumption[113]. The issue is even more pronounced in the case of adoption since it is easier for individuals to consider adoption in tandem with the subsequent post-adoption use, which provides the ideal environment for moral licensing to take place[9]. That said, moral licensing is less probable when adoption is costly in monetary or in other terms[114]; when it is motivated by underlying pro-environmental values and identity[115]; and when individuals conceive adoption as part of a process and not the end of it, therefore creating a feeling of progress and self-efficacy[64,101,116–118]. The policy-making implications of such findings are that in order to avoid moral licensing when promoting adoption, monetary incentives, if in place, should not the main focus of the campaign or intervention. Additionally, it should be clearly communicated that adoption is only the first of a two-step procedure and will be insufficient unless combined with subsequent prudent intensity of use. Adding adoption and post-adoption use in the same mental account might be sufficient.

Peer effects

Policies involving peer comparisons, status concerns, and communication of social norms can promote adoption by making the object of adoption visible[119]. Examples include the United Kingdom requiring registration plates of low fuel-consumption vehicles to be green, the Project Sunroof that allows homeowners to find out who of their neighbours have installed solar panels through aerial photos illustrating clustering[120], and other visible symbols that serve as a welcome gift after adoption, such as sticker, doorplate, email signature or magnet[121,122]. These interventions may, however, backfire if not combined with post-adoption policies or nudges. To illustrate, in an attempt to signal pro-environmental behaviour, owners of electric or hybrid vehicles might use them more frequently in order to increase visibility.

Regarding intensity of use, the effects of social norms is expected to be more limited since most of the times, the behaviour is ultimately private. The energy company O-power in the US, nevertheless, employed social norms in order to motivate households to moderate their energy use. In a series of experiments, households received messages regarding the mean energy use of their neighbours. On average, consumption is reduced, but below-average users increase their consumption after they learned about the norm. This negative effect can be overcome if the descriptive norm is accompanied by normative messages conveying approval, such as messages mentioning "Great" or smiley emojis[123]. An alternative way to employ peer influence is via community programs, such as the as the EcoTeam program or the Global Action Plan, where community members discuss ways of promoting energy conservation in general. Their effectiveness is not guaranteed, however[124].

Conclusions

The extent to which adopting energy-efficient technologies and practices results in energy savings depends on how such technologies are used and how any associated savings are spent. The review reveals that bounded rationality and willpower tend to increase overall energy use as they magnify the rebound effect through higher intensity of use and re-spending on energy-intensive products. This involves moderation of the negative effects of economic factors and the positive effects of non-economic (bounded self-interest) factors. While the latter tend to increase adoption rates, their effect on direct rebound is uncertain due to moral licensing and social norms that encourage consumption.

While bounded rationality is often employed to explain the puzzling energy gap – namely as a failure to engage in rational behaviour – rebound does not represent a puzzle, since it is consistent with both rational and limited-rational behaviour. The latter merely reduces or increases the magnitude of 'rational rebound'. In this respect, the Review finds that effects on re-spending are the most uncertain, as they are difficult to identify and quantify given that they require observing behaviour across the whole set of consumption decisions by individuals. This poses a huge challenge for research on rebound.

In terms of policy, we find that many behavioural interventions may be effective in promoting adoption and controlling intensity of use – thus curbing direct rebound – but not so much regarding re-

spending behaviour. We provide examples of interventions that can be combined to address both adoption and post-adoption behaviours. We have identified smart meters as a key tool to limit negative effects of inattention, habits and inertia on intensity of use. Using insights from the literature on mental accounting, we suggested that an additional feature of a smart meter can help to curb direct and indirect rebound. However, such interventions should not serve as a substitute for, but rather as a complement to, instruments that are known to effectively address rebound, such as carbon and energy pricing[125,126]. The extent to which a combination of interventions has positive or negative synergetic effects deserves further investigation. In particular, future research is needed on investigate how behavioural regularities affect the performance of pricing instruments like carbon taxes or energy subsidies, and the extent to which they interact with behavioural interventions in terms of rebound effects[127].

The review showed that evidence for certain behavioural regularities is quite mixed and sometimes scarce or missing. Most studies zoom in on the effect of a particular behavioural regularity on only one of the three rebound-relevant decisions. Studying them simultaneously will lead to a better picture of their joint effect on rebound while also providing insight into suitable combination of interventions to address adoption and post-adoption behaviours in tandem. Further research is needed to improve our understanding of rebound due to re-spending. A key question here is to what extent consumers are aware of energy-related savings, and if they are, whether this affects the way they spend these.

Competing interests

The authors declare no competing interests.

DISPLAY ITEMS

Table 1. Behavioural regularities emanating from bounded rationality, willpower and self-interest

	Standard economic assumptions	**Insights from behavioural sciences**	**Behavioural regularities relevant to rebound**
(Bounded) Rationality	Unlimited cognitive abilities	Limited abilities & time	Inattention & misconceptions
	Optimizing behaviour	Satisfying & heuristics	Mental accounting
	Well-defined preferences	Important "irrelevant" factors	Defaults & habits
(Bounded) Willpower	Perfect self-control	Limited self-control	Present bias
(Bounded) Self-interest	Self-regarding preferences	Other-regarding preferences & moral values	Pro-environmental values & moral licensing
	Socially isolated agents	Social interactions	Peer influence

Table 2. Behavioural interventions and their impacts on energy-relevant decisions. *The suggested interventions in each row should be used in tandem to promote adoption and control intensity of use and re-spending.*

Behavioural regularity	**Adoption (energy gap)**	**Intensity of use (direct rebound)**	**Re-spending (indirect rebound)**
Inattention & misconceptions	Energy-efficient labels and lifecycle information	Real-time feedback employing smart meters	
Mental accounting	Loss frames for less energy-inefficient options	Encourage a mental budget that combines adoption & intensity of use	
Defaults & habits	Energy defaults to energy-efficient options & energy-habit disruption	Setting defaults to pre-adoption levels	
Present bias	Move incentives of energy-efficient options closer to the present	(Gamified) goal setting programmes	Tailor savings to eco-products
Pro-environmental values & moral licensing	Moral & social framing Avoid moral licensing by making identity motivations salient and communicating that adoption is not enough		
Peer influence	Public, status-enhancing 'green signals'	Peer comparison of energy consumption	

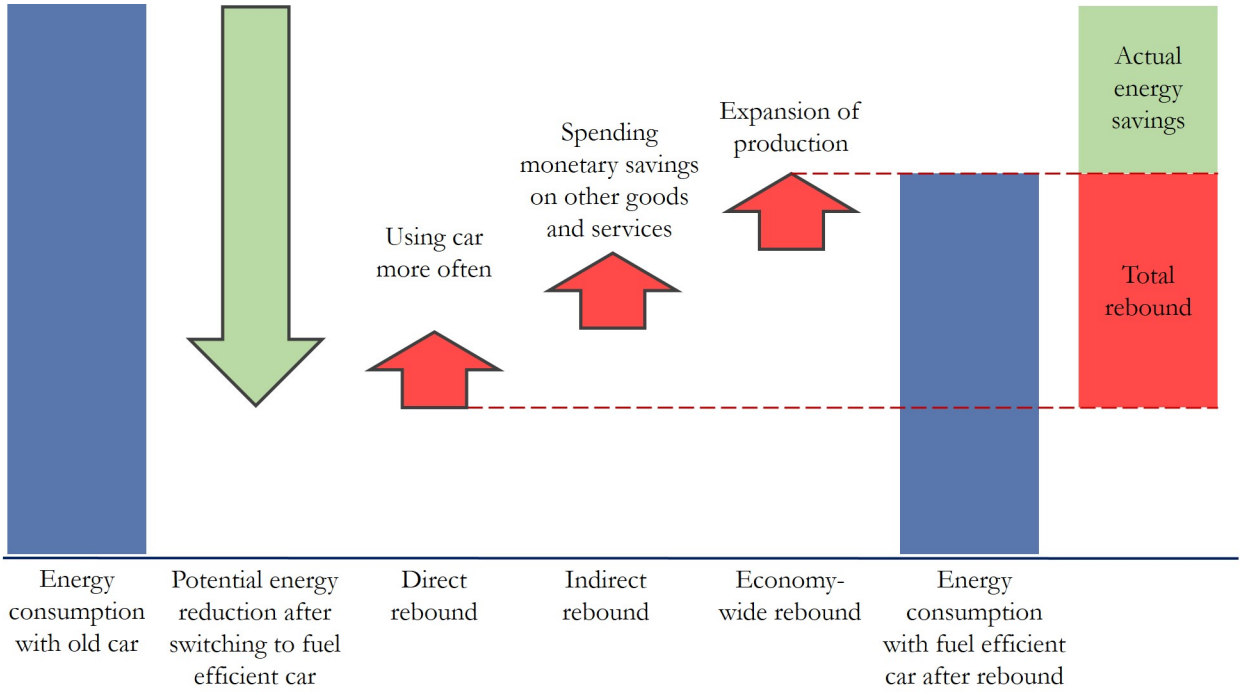

Figure 1. Graphical illustration of the three types of rebound*. Potential energy reduction after switching to a more fuel-efficient car is not fully realized due to three post-consumption behavioural reactions that lead to increased energy demand. These correspond to the three kinds of rebound, depicted in the figure by the red arrows: direct rebound results from using the car more often due to the reduced costs of driving (intensity of use); indirect rebound results from spending the monetary savings on other products and services whose production and consumption require energy (re-spending); and economy-wide rebound results from increased economic activity, due to various macroeconomic processes, such as higher economic growth or new economic activities. The figure is adapted from reference*[128] *which illustrates rebounds for the case of switching to more energy-efficient light bulbs.*

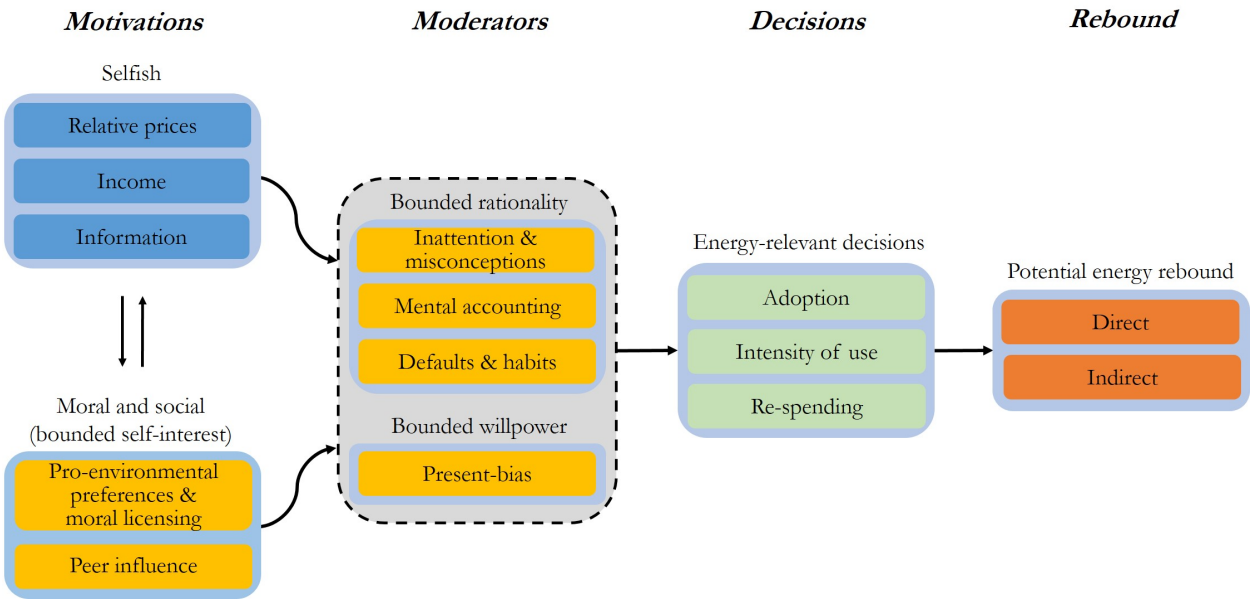

Figure 2. A schematic representation of the review. *Selfish, moral and social motivations, moderated by bounded rationality and willpower, affect energy-relevant decisions, which in turn influence direct and indirect rebound. The elements of bounded rationality, willpower and self-interest explain the behavioural regularities listed in Table 1. For each regularity, we review empirical evidence for its impact on the three energy-relevant decisions.*

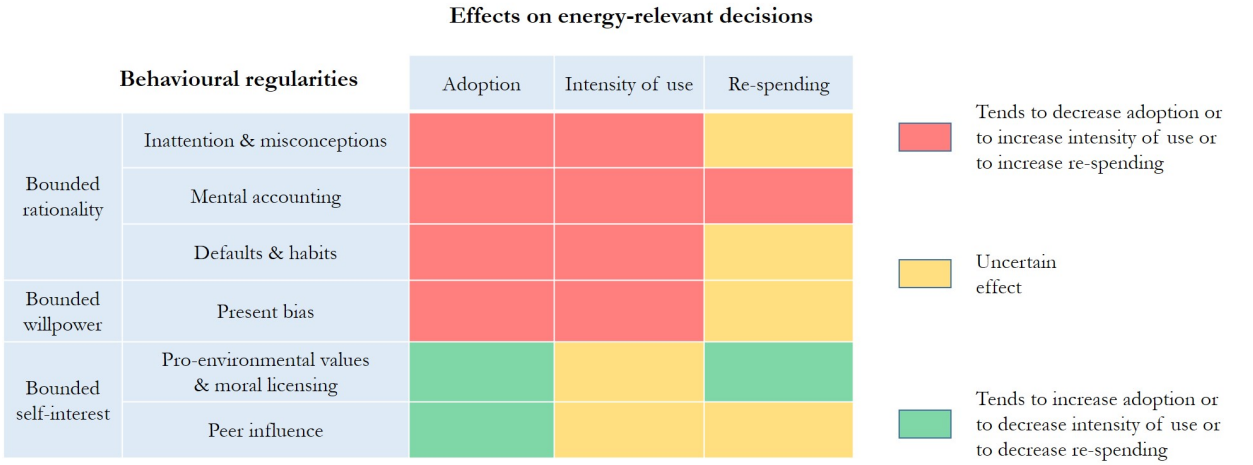

Figure 3. Dominant effects of behavioural regularities on energy-relevant decisions and rebound. *Behavioural regularities that reflect limited rationality and willpower tend to decrease adoption and increase rebound, while those driven by bounded self-interest tend to increase adoption while their effects on rebound are less clear.*

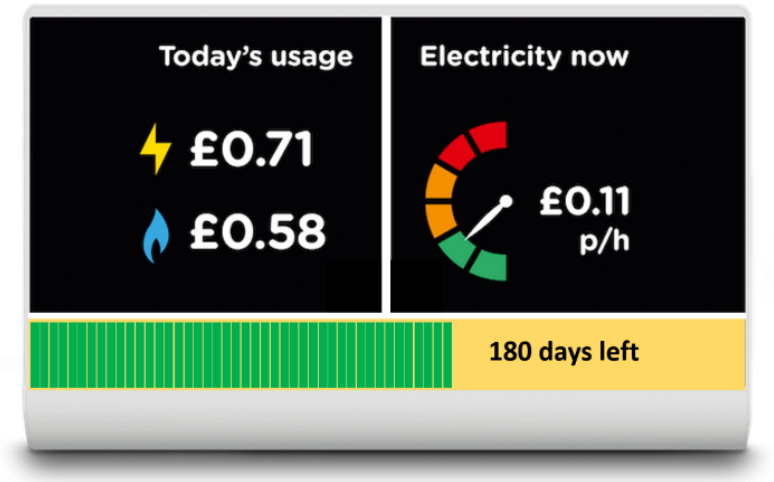

Figure 4. Smart meter adapted to indicate the days left for the initial investment on house insulation to be paid back. *The additional feature nudges consumers to include the initial investment and post-adoption use in the same mental account, in turn encouraging them to reduce intensity of use.*

Box 1. Behavioural dimensions of bounded rationality, willpower and self-interest that give rise to behavioural regularities

Bounded rationality

Rationality can be decomposed into three behavioural assumptions[129]: people possess good cognitive skills, have well-defined preferences, and exhibit optimizing behaviour. Bounded rationality describes that oftentimes individuals lack the cognitive capacity or simply the time to collect and analyse all relevant information before reaching a decision[130]. In the face of these limitations, they are not looking for strictly optimal solutions, but are *satisficing* instead, meaning that they settle for 'good enough' solutions. To this end, they employ heuristics or simple rules of thumb that allow them to make decisions in a fairly efficient way[131]. This, however, leads to cognitive biases, i.e. systematic errors in judgment and decision making. In addition, under heuristics the choice environment strongly affects peoples' choices: apart from prices and preferences, other factors – supposedly irrelevant according to rational choice theory – determine people's decisions. As an implication, policy-makers can nudge people to behave in a particular way by applying subtle modifications to the choice environment[27].

Bounded willpower

Rational agent theory assumes that an action taken by an individual is the most preferred option in her choice-set. This ignores that people often lack the willpower to follow their preferences, instead being driven by temptations. Willpower is positioned in the zone between preferences and behaviours[132]. Bounded willpower involves a trade-off between long- and short-term goals, or between moral and selfish considerations. Due to self-control issues and attractiveness of short-term and selfish gains, people often opt for the latter.

Bounded self-interest

In a narrow sense, self-interest means focusing on personal outcomes, and is thus independent of the social context. Bounded self-interest recognizes that people care about the well-being of others and about moral values that act as internal constraints on behaviour[133]. Economists refer to these as "other-regarding preferences" or "identity concerns" while sociologists and psychologists call them "moral values". These values in turn are shaped through social interactions, by what other people do or think, as captured by notions such as social norms, imitation or status-seeking[134]. These factors do not rule out that the underlying motives can be ultimately selfish. For instance, people often act pro-socially because they want to maintain a positive self-image or they follow a social norm just to avoid social punishment. In addition, bounded self-interest does not exclude the influence of narrowly selfish motives. Indeed, most of the time behaviour is the outcome of an interaction between selfish, moral and social motives.

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