Practical tools for identifying, evaluating and preventing rebound effects: Application to residential heating and mobility in Austria

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ABSTRACT

Many countries state ambitious targets for reducing carbon emissions. Their policy strategies emphasize energy efficiency by means of technological innovations. However, these strategies are at risk of severe rebound effects, as savings from more efficient products and facilities may be (over-)compensated by rearrangements in consumer behavior. While rebound effects are widely acknowledged, it is less clear how they arise from the complex interactions between market actors, consumer preferences and policy initiatives.

We propose a simplified representation of these complex dynamics, in order to point out levers for counteracting rebound effects. A system model integrates (semi-)quantitative data from fuzzy cognitive mapping of expert knowledge, a household survey on adoption and usage and macroeconomic modelling of energy efficiency policies. Core drivers identified across all methods are joined to a cause-and-effect diagram. The respective strengths of influence are standardized to effect coefficients. By tracing policy impulses through the web of interlinked drivers, the system model illustrates direct, mediated and unintended impacts on market diffusion, rebound and carbon emission reductions of energy efficient technologies.

Applying this methodology to building renovation and electric cars in Austria, the need to balance technology adoption and use becomes apparent. Convergent drivers stimulate the market uptake of the energy efficient technology, and simultaneously constrain rebound effects. For instance, educating customers on product features and activating their pro-environmental values, encourage technology adoption as well as ecological use. Contrastingly, divergent drivers have opposing effects on adoption and use. For example, fuel taxes counteract rebound, but also hinder adoption by increasing lifetime costs. Higher income enables adopters to carry upfront investment costs, but also increases spending in other, carbon-intensive consumption domains.

Policy interventions should be carefully designed to leverage convergent and to circumnavigate divergent drivers. However, empirically parameterizing a system model requires that the technology has already entered the market. Therefore, in extension to the system model, we propose a checklist for preventive rebound management of upcoming transport technologies. An indicator system outlines technology attributes, consumer groups and technology effects that make rebound more likely. Innovations scoring high on those indicators merit dedicated policy efforts to cushion potential rebound effects.

Introduction

In order to achieve the ambitious climate targets set by COP21 in Paris in 2015, many countries are relying on innovative, energy-efficient technologies. The broad market launch of electric cars or the refurbishment of existing buildings through thermal insulation are intended to reduce energy demand and greenhouse gas emissions. This strategy of advancing energy-efficient technologies is successful if, on the one hand, these technologies quickly penetrate the mass market (i.e. adoption) and, on the other hand, the gain in technical efficiency is not compensated for by a change in use (i.e. rebound). The present article argues that these two processes, adoption and rebound, are affected by the same factors. Climate policy instruments aimed at increasing adoption rates often lay the groundwork for a later rebound effect. For example, the parking benefits given to e-cars in many cities, may make the purchase of an e-car more attractive (Holtsmart and Skonhoft 2014). However, the good parking space availability may entice users to use the e-car on trips where they previously took the bicycle or public transport. Building renovation is promoted with the prospect of lower heating costs. The more this motivation stands in the foreground, the more strongly the residents are encouraged to treat themselves to a more comfortable room temperature with the cheaper heating system (de la Rue Can et al. 2015, Font Vivanco et al. 2016).

Adoption and use are linked by several facets. At the time of the purchase decision for an energy-efficient technology, one already anticipates how the technology is expected to be used - how well it will meet one's everyday needs, when the investment costs will be amortized, how high the operational costs will be, etc. (Wolf and Seebauer 2014). Since the efficient technology provides the energy service with less energy consumption and therefore lower costs, the frequency and intensity of use increases (direct rebound effect; Sorrell 2007, Santarius 2014). In addition, cost savings increase the disposable income that can be spent on other energy-consuming goods and services (indirect rebound effect; Azevedo 2014, Thomas and Azevedo 2013). These supply and demand adjustment processes add up across all economic sectors (economy-wide rebound effect; Allen et al. 2007, Turner 2013, Gillingham et al. 2016). Rebound effects at the level of private consumers are not only caused by monetary incentives, but also by moral licensing: with the adoption of an efficient technology, one has the feeling of having already made an ecological contribution. Now one can indulge oneself in other consumption domains without a guilty conscience (Friedrichsmeier and Matthies 2015).

The observation that realized emission savings from energy-efficient technologies often fall short of initial expectations is increasingly being taken up in the political discussion (Font Vivanco et al. 2016). Direct rebound effects in housing and transport are estimated at 10-30% of the expected savings (Sorrell 2007). Estimates of indirect and economy-wide rebound effects range from 20% to 300% (Allan et al. 2007, Guerra and Sancho 2010, Turner 2009). Given this level of rebound effects, there is an urgent need to develop policy options for rebound prevention.

Both adoption and (changed) use take place within the same socio-technical regime, in interaction with the same market actors and influenced by the same consumer attributes (Geels 2004). Acquisition and operating costs, existing infrastructure and competing products on the market are relevant both for the purchase decision and for ongoing use (Boulanger et al. 2013). Subsidies and regulations as well as communication in the mass media also play a double role (Steg et al. 2015). Both the buying decision and everyday use depend on income, environmental values and the level of consumer knowledge (Peters et al. 2012). A policy instrument that targets infrastructure, for example, or provides incentives for individual market players such as retailers and tradespeople, will therefore influence both adoption and rebound.

So far, factors influencing adoption and rebound have mainly been investigated from disciplinary approaches. Integrating these approaches is often difficult because they only highlight parts of the overall problem and use different methods and units of measurement (Freeman et al. 2014). Here we introduce a system model that compactly illustrates how adoption, rebound and a range of factors influence each other. This system model is necessarily a simplification compared to focused, disciplinary approaches, but illustrates well the overarching dynamics. By tracing pathways of cause and effect within this model, it becomes apparent how a political intervention may trigger unintentional or counterproductive effects.

Method

The system model (Walker and van Daalen 2013) integrates three complementary research methods, each highlighting specific elements from the conflict between adoption and use. These methods are: (i) fuzzy cognitive mapping, which uses expert interviews to identify the basic factors and actors and describes their causal connections (Fruhmann et al. 2017); (ii) a survey of e-car owners and persons who have carried out a building renovation to determine individual influencing factors on direct and indirect rebound effects (Seebauer 2017); and (iii) a general equilibrium analysis of energy efficiency measures in private households to determine macroeconomic effects and sectoral impact channels (Kulmer and Seebauer 2017). For space reasons, this article focuses on the overall dynamics between adoption and rebound and the common influencing factors. Details of the individual research methods can be found in the respective publications. The analyses refer to the case studies of e-cars and building renovation in Austria.

The system model was developed and applied in five steps; although presented as a linear sequence here, in practice the model was developed iteratively, especially recurring between the consolidation and integration steps (Freeman et al. 2014):

1. Identification,
2. Consolidation,
3. Scaling,
4. Integration and
5. Policy analysis.

Identification determines the critical elements from each of the three research methods which have a significant influence on the adoption and use of efficiency technologies. Each method approach describes the relationships between these elements regarding their causal direction and strength of influence.

Consolidation integrates these elements and their relationships into a common framework. Elements that are covered by more than one method approach are combined by clarifying a joint definition. Here, the unique advantage of the system model comes into play that almost everything can be described as a system element – actors, personal attributes, technical or infrastructural aspects. The consolidated elements (see Table 1) form the basis of the system model.

In *scaling*, the different quantitative effects are reconciled. The expert-based weighting of fuzzy cognitive mapping and the regression coefficients of the survey are estimated using linear relationships between elements; the macroeconomic analysis also considers exponential relationships. Thereby, all method-specific effect coefficients are transformed to a common scale from 0 "no relation" to 1 "non-linear strong relation" (see Table 2).

Integration creates the actual system model. The sequence of adoption, use (in terms of a direct and indirect rebound effect) and the cumulative effect resulting from use (economy-wide rebound effect) constitutes the core framework. The elements are lined up in this framework in terms of their impacts and connected with directional arrows indicating direction and strength. The system model shows which elements act where and to what extent in the conflict between adoption and use, thus triggering or avoiding rebound effects. Single impacts are summed up to impact pathways, which either reinforce each other or cancel each other out. The system models presented here focus on common factors influencing adoption and use; for simplification, the obvious direct influence of purchase/investment on macroeconomic elements is excluded.

Policy analysis employs the system model to identify levers for avoiding rebound. Selected policies change the level of individual system elements. This impulse propagates through the system via the relationships between the elements, depending on the sign and magnitude of the effect coefficients assigned to the directional arrows. The system model thus enables an analysis of which policies are best suited to counteract rebound effects holistically and to resolve the conflict between adoption and use.

Table 1. List of elements per system model

Element	**Definition**
Elements included in both case studies	
Purchase / investment	E-car: number of e-car purchases; share of e-cars in national car stock Renovations: number of renovations; number of applications for subsidies
Direct rebound	After adoption of the energy-efficient technology, demand for the respective energy services increases
Indirect rebound	Due to freed-up income or moral licensing, demand for other energy-intensive services and goods increases
Economy-wide rebound	Production and demand shift to more energy- and carbon-intensive sectors
Acquisition costs / expenditure	E-car: Acquisition costs Renovations: Expenditure, depending on the intensity and quality of renovation
GDP	Gross value added of the economy including taxes and/or subsidies on goods
Savings in carbon emissions	Reductions in national greenhouse gas emissions across all sectors of the economy
Mass media	Communication of product information, including carbon footprint, sustainability, and consumer benefits of various energy-efficient technologies
Social norms	Expectations of the social network as to whether one should acquire an energy-efficient technology
Environmental values	Personal conviction that one should engage in protecting the environment
Variable costs	E-car: costs per km, both monetary and convenience/time costs Renovations: Costs per comfortably heated m^2 of living space after completing the renovation
Disposable income	Household budget available; possibilities for consumption are exhausted up to the personal savings rate
Product knowledge	E-car: knowledge about range, information from manufacturer’s certificate, carbon emissions per km, etc. Renovations: Knowledge of renovation options, insulation materials, technologies, etc.
Welfare	Benefits to all households in the economy, measured as the amount of possibilities for consumption limited by disposable income
Additional elements in the e-car case study	
Quality of alternative transport modes	Timetables and coverage of public transport, bicycle path network
Car dealers	Communication of product information, costs, fuel consumption, etc.; car dealers are a trusted and credible source of information
Charging infrastructure	Public access to charging stations, the possibility to charge the e-car at home, at work or during leisure activities, availability of fast charging stations, etc.
E-car product range	A wide range of different e-car models / e-car classes
Showcase projects	E-mobility model regions or e-car sharing pilots as a communication channel for the dissemination of product information, and as platforms for testing e-cars

Table 1 (cont.). List of elements per system model

Element	Definition
Additional elements in the building renovation case study	
Defect-free implementation	Implementation without technical/structural defects, integration and correct dimensioning of insulation elements within the building, pre-settings of heating systems, etc.
Energy poverty	Before renovation, one could not afford to keep the apartment adequately warm
Energy consulting	Communication of product information on building insulation, insulation materials and technologies as well as the appropriate use of technology
Window of opportunity from stock turnover	Remaining technology lifetime and urgency of renewal of building elements such as heating, windows, etc.
Habits	Automatic maintenance of everyday routines
Plumbers and construction companies	Responsible for planning, implementation of renovations; communicate product information
Difficulty of applying for subsidies	Necessary steps to obtain subsidies, number of involved bodies and actors up to the grant approval (e. g. banks, municipal/state and federal authorities)
Knowledge about the use of technology	Knowledge about proper heating and ventilation

Table 2. Scale definition of effect coefficients in the system models

Numerical value	Definition
0	No connection, changing one element does not change the other element.
0.25	Weak correlation, a change of one element causes a small change in the other element.
0.5	Strong correlation, a change of one element causes a large change in the other element.
0.75	Perfect correlation, a change of one element causes an equivalent change in the other element.
1	Non-linear relationship, changing one element causes a non-linear change in the other element.
Positive coefficient	Positive causal direction, an increase of one element leads to increase of the other element.
Negative coefficient	Negative causal direction, an increase of one element leads to a decrease of the other element.

Results

Dynamics and interdependencies of the system elements

The e-car system model features several factors that promote the purchase of an e-car, as shown in the left section of Figure 1. Elements with a positive coefficient support e-car adoption, for example: high social norms, high disposable income, a well-developed charging infrastructure, a wide product range of different e-cars, etc. In addition to these psychological, socio-economic and technical factors, car dealers and showcase projects as market players also promote e-car purchases. In contrast to these favorable elements, acquisition costs and variable costs act as limiting factors.

The middle section of the system model underscores divergent impacts on adoption versus use. On the one hand, the prospect of higher costs per kilometer, eventually caused by rising electricity prices, makes the purchase of an e-car less likely (negative coefficient); on the other hand, higher variable costs reduce the frequency of use and thus help to prevent direct rebound. A comparison of the two coefficients shows that from an environmental policy point of view, the drawback of higher costs per kilometer slowing adoption (-0.1) may be acceptable in order to benefit from a strong reduction of the direct rebound (0.8). Disposable income and social norms favor the purchase of an e-car, but exert the same influence on consumption in other areas, thus instigating indirect rebound.

The system model also contains elements with convergent effects. Product knowledge and environmental values promote acquisition and avoid direct and indirect rebound. Taken together, the divergent and convergent effects enacted by specific elements underline the counterproductive effects of policies that focus heavily on financial incentives or gains in social prestige. Informative or awareness-raising measures, on the other hand, steer both adoption and use in an environmentally desirable direction.

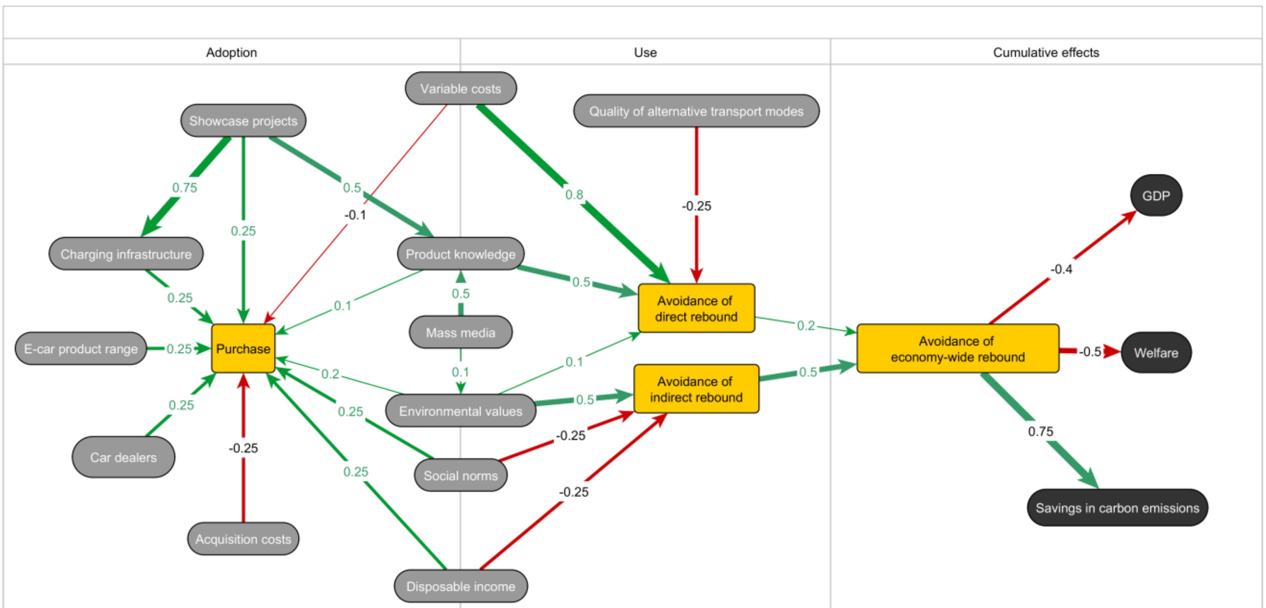

Figure 1. E-car system model. Coefficients are compiled from three disciplinary approaches. Negative coefficients highlighted in red.

The building renovation system model contains more elements with more complex interrelations (Figure 2) than the e-car case. Nevertheless, central impact patterns are similar: environmental values reconcile adoption and use, while disposable income, social norms and variable heating costs increase the conflict between adoption and use. Important factors influencing the uptake of renovations are windows of opportunity from stock turnover and the difficulty of applying for public subsidies. The latter is by far the biggest obstacle to carrying out a renovation. Compared to the e-car system model, two additional factors counteract direct rebound: energy poverty and technical implementation.

The building renovation system model illustrates the role of upstream actors. Mass media, plumbers and construction companies, and energy consultants have little direct influence on adoption or use, but act indirectly through other system elements such as product knowledge or knowledge about the use of technology. The latter has high potential to avoid direct rebound and is advanced by all these upstream actors. These upstream relationships indicate that effective policies should address a mix of elements rather than pinpoint only those elements directly connected to adoption or use.

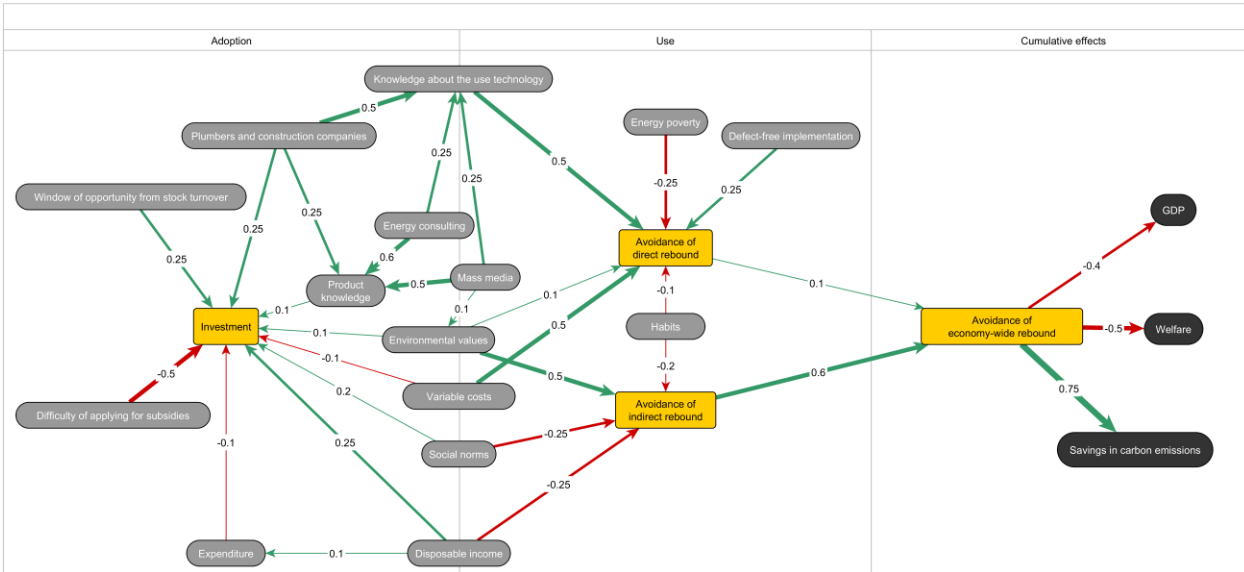

Figure 2. Building renovation system model. Coefficients are compiled from three disciplinary approaches. Negative coefficients highlighted in red.

Both system models point to key actors who can resolve contradictory incentives for adoption and use. The more plumbers and construction companies are trusted and the more competence is attributed to them, the sooner a household decides to renovate a building. At the same time, plumbers and construction companies increase household knowledge about proper heating and ventilation, thus counteracting direct rebound. In the e-car system model, this balancing role is played by showcase projects: they create favorable conditions for the purchase of an e-car and at the same time contribute to environmentally friendly use through knowledge transfer. Policymakers are well advised to include such key actors in policy deployment.

In both system models, the economy-wide rebound is primarily driven by indirect rebound. Reallocating savings from efficiency gains to other consumption domains has a much stronger rebound effect than the increase in direct use. A high economy-wide rebound reflects contradictory economic, social and environmental objectives. Increased consumption leads to economic development, as the GDP grows and subsequently, due to higher wages and more possibilities for consumption, welfare rises. However, increased consumption also means that energy and carbon savings turn out lower than originally expected. Because of economic interdependencies, this compensatory effect can go so far that the total energy and carbon savings are offset by increased consumption.

Both system models show the same levers to avoid indirect (and by extension economy-wide) rebound: (i) high environmental values, which shift consumption mainly to non-energy-intensive sustainable products; (ii) weak social norms, since the gain in prestige from adopting an energy-efficient technology then serves less as a justification for increased consumption; and (iii) low disposable income, which reduces consumption or shifts expenditures to cheaper and less energy-intensive products. However, leveraging income for rebound prevention by introducing a flat-rate tax on efficiency gains is likely to come up against the limits of political feasibility and public acceptance.

Simulating policy impacts using a system model

In a simulation exercise, we outline which policy measures are best suited to counteract rebound effects and to resolve the conflict between adoption and use. Yet, as an important caveat, the effect coefficients assigned during system model scaling are associated with uncertainties from combining different disciplinary approaches, and only reflect the current Austrian context. In other countries, under other socio-political conditions, other effect coefficients would yield different numerical results. However, the focus here is to simulate the relative proportions of the different policy instruments in order to identify central levers. Thereby, we extend current rebound prevention pathways (Font Vivanco et al. 2016) with a comparative impact assessment of various policy measures.

Current policy strategies for the promotion of energy-efficient technologies primarily rely on fiscal instruments designed to reduce variable costs. In Austria, for example, electricity for the operation of the vehicle is not subject to fuel tax; and in many large cities, e-cars not need pay parking fees. In the e-car system model, a reduction of the variable costs per kilometer by one unit means that purchase increases by 0.1 units, but at the same time the direct rebound increases by 0.8 units (see Figure 1, arrows originating from Variable Costs). The direct rebound continues in the system and leads to a reduction in carbon emission savings of 0.12 units (0.8*0.2*0.75). A similar, but less pronounced picture can be seen in the building renovation system model: lower energy taxes for certain heating energy sources (e. g. biomass, district heating) reduce the costs per comfortably heated m² of living space. This results in an investment activity marginally higher by 0.1 units, but reduces carbon savings by 0.04 units (0.5*0.1*0.75, rounded).

Educational campaigns to increase environmental values and environmental literacy, on the other hand, promise significantly higher effects. Here too, the direct effect on adoption is small (0.2 for e-cars, 0.1 for renovation). However, since environmental values address both direct and indirect rebound, the effects on carbon savings stack up. In the renovation case, an increase in environmental values by 1 unit reduces carbon emissions by 0.23 units; mostly via the indirect rebound pathway (0.5*0.6*0.75=0.225) and slightly via the direct rebound pathway (0.1*0.1*0.75=0.0075). With the e-car, environmental values have a 0.20 impact on carbon emissions (0.1*0.2*0.75 (direct) + 0.5*0.5*0.75 (indirect)). Thus, promoting environmental values seems to be an effective intervention strategy. However, a far-reaching shift in values might only be achieved through protracted social change. Contrastingly, financial incentives are much easier and faster to implement.

Key actors may swiftly and effectively accelerate the market uptake of energy-efficient technologies. In the case of e-cars, expanding showcase projects by 1 unit will support the purchase of an e-car by a total of 0.49 units (direct influence: 0.25; via charging infrastructure: 0.75*0.25; via product knowledge: 0.5*0.1). The impact of showcase projects on product knowledge propagates through the system and contributes slightly to the reduction of carbon emissions (0.04 = 0.5*0.5*0.2*0.75). Plumbers and construction companies, the renovation system model's counterpart to showcase projects, have similar effects. These actors increase adoption by a total of 0.28 (direct influence: 0.25; via product knowledge: 0.25*0.1) and lead to carbon emission savings of 0.02 (0.5*0.5*0.1*0.75). Thus, it seems advisable to involve those key actors in policy deployment since they offer double benefits: they increase adoption, and additionally initiate carbon savings by imparting product knowledge.

As mentioned above, it is important to keep in mind that these multiplicative effects only apply to the exemplary Austrian context as observed in the year 2017. Integrating additional research methods in the selection and parameterization of system elements may yield more valid estimates. The system models are most sensitive to changes in the upstream effects of direct/indirect rebound on economy-wide rebound, or of economy-wide rebound on carbon emissions (i.e. right-hand sections of Figure 1 and 2). The higher those upstream effect coefficients, the more severely downstream conflicts between adoption and use may undermine overall climate policy efforts.

Rapid assessment of rebound risk

E-cars and building renovation represent mature technologies already established on the market. Here, substantial scientific and practical knowledge have accumulated which allow selecting system elements and parameterizing effect coefficients. However, policymakers often encounter emergent technological innovations which currently cater to market niches, but may soon turn into full-fledged products or services. If a technology cannot (yet) be observed in a real-world market environment, developing a system model may be difficult due to lacking or incomplete empirical data.

Nevertheless, decision makers need to anticipate possible rebound effects in order to enact precautionary actions, such as introducing regulations or building consumer awareness. Figure 3 presents a rapid assessment tool for screening the rebound risk of specific innovations. These indicators capture technology attributes which are associated with higher direct and indirect rebound effects. The rapid assessment may help to consider rebound during the deployment of low carbon policy programs, when the detailed lens of a system model is not (yet) available.

Ideally, both tools, the rapid assessment and the system model, are used in conjunction: During market entry, different variations of the technology may be assessed in regards to their rebound risk; in later market stages, as soon as dominant use cases of the technology have crystallized, critical rebound indicators point to core system elements.

Figure 3. Indicators of rebound risk in passenger transport (left) and freight transport (right). *Sources:* Boulanger et al. (2013), Jenkins et al. (2011), Peters et al. (2012), Seebauer (2017), Fürst and Seebauer (2018). Full indicator sheets available at http://rebound.joanneum.at (English and German versions available).

Conclusions and outlook

The broad market introduction of energy-efficient technologies is widely considered a cornerstone in the low-carbon transformation of modern societies. However, this policy strategy faces an inherent conflict between adoption and use. The system models for the e-car and building renovation case studies presented here, integrate results from three complementary research methods and determine levers for resolving this conflict. The system models illustrate the dynamics between adoption, rebound effects and common influencing factors.

Financial incentives such as tax exemptions for e-cars (as in Austria and Germany) or excluding e-cars from urban toll systems (as in London and Stockholm) are at the heart of the conflict between adoption and use. These incentives weakly promote the acquisition of the energy-efficient technology, but also have the side-effect of advancing direct rebound. The overall effect of financial incentives on carbon savings is weak, since they apply only to specific technologies and neglect indirect rebound. Regardless of these shortcomings, market-oriented instruments are very popular among policymakers.

Instead, our analysis suggests considering the role of environmental values and key actors in policy design. Both factors accelerate market penetration and cushion indirect rebound. Media campaigns and social networks could convey environmental mindsets and make existing pro-environmental values salient. Plumbers and construction companies could be trained in product knowledge transfer. State programs could support the implementation of showcase projects and pilot regions.

Combined policies instead of stand-alone measures may also compensate for different measures becoming effective over different periods of time. Taxes and subsidies have a direct and short-term effect; training, campaigns or media activities deploy in the medium term; a change in values or consumption practices develops over the course of up to one generation. The transformation to a low-carbon society will take several decades. Therefore, it seems sensible to systematically stagger short-, medium- and long-term measures. To account for a temporal dimension, the system models presented here would have to be extended, though; e. g. to include feedback effects and non-linear relations between system elements, or to allow that over time causal directions may reverse, coefficients may shift in magnitude, or new elements may enter the system.

Both system models underline that indirect rebound, i.e. shifting savings from efficiency gains to other consumption domains, by far outnumbers the increase in direct use. Indirect reallocation of consumption often leads to increased demand for energy-intensive goods and services such as electronic equipment, tourism and transport. Product standards or an emission cap could counteract those indirect effects. Product standards already exist in several consumer domains (e. g. fuel standards for vehicles, energy efficiency labels for electronic devices, and various ISO standards). The more areas of consumption are subject to emission standards, the lower the proportion of fossil fuels used in the production of products and services; as a result, the effect of shifting to other consumption domains would be less carbon intensive. Individual emission caps, such as an annual personal carbon budget, would steer consumers towards low-carbon products and services. Whereas product standards are a well-established policy instrument, it is difficult however to imagine how personal carbon budgets could be administered and controlled in practice.

For mapping the dynamics of product standards and personal carbon budgets, the system boundaries of both models presented would have to be extended. At present, the system models are tailored to the two case studies and only cover direct indirect effects on adoption and use. Other consumption domains, production-side economics or factors beyond the scope of household decision-making, are not (yet) included. However, the introduction of additional system elements would make the models more complex and harder to interpret.

Still, the simplified approach of this study suffices to demonstrate the inherent conflict of market-oriented instruments, which promote the adoption of energy-efficient technologies but also the rebound effect in their subsequent use. Integrated strategies for low-carbon transformation should therefore not underestimate the role of socio-psychological characteristics and key actors.

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