Skill rebound: On an unintended effect of digitalization

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ABSTRACT

Efficiency gains in economic processes often do not deliver the projected overall savings. Irrespective of whether the increase in efficiency saves energy, resources, time or transaction costs, there are various mechanisms that spur additional consumption as a consequence. These mechanisms are generically called rebound effects, and they are problematic from a sustainability perspective as they decrease or outweigh the environmental benefits of efficiency gains. Since one of the overarching purposes of digitalization is to increase efficiency, rebound effects are bound to occur frequently in its wake. Rebound effects of digitalization have been ignored until recently, but they have been increasingly studied lately. One particular mechanism of digital rebound, however, has been largely disregarded so far: the digitalization-induced lowered skill requirements needed to perform a specific activity. As with other types of rebound effects, this leads to an increase in the activity in question. In this paper, we propose the term *skill rebound* to denote this mechanism. We use the example of self-driving cars to show how digitalization can lower the skill bar for operating a vehicle, and how this opens 'driving' a car to entirely new socio-demographic categories such as elderly, children or even pets, leading to increased use of the (transportation) service in question and thus to rebound effects. We finally argue that these unintended environmental effects of skill rebound must be better understood and taken into account in the design of new digital technologies.

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CCS CONCEPTS

• **Applied computing** → **Environmental sciences**; • **Social and professional topics** → **Sustainability**; • **Hardware** → Impact on the environment.

KEYWORDS

rebound effect, efficiency, resources, energy, digital rebound, self-driving cars, autonomous vehicles.

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1 INTRODUCTION

Efficiency gains in production processes often fail to deliver, or at least to fully deliver, the expected overall energy or resource savings that were imagined beforehand. Increased efficiency typically enables lower prices, which in turn spur demand for the good or service being more efficiently produced. Increased demand then leads to more production, which offsets the efficiency gains of per-unit savings. This adverse effect, which may reduce partially, entirely or even outweigh the projected (or hoped-for) savings, is called the *rebound effect.* A rebound larger than 100% outweighs the initial efficiency gains and is thus also called backfire. It was described as early as 1865 by British economist William S. Jevons for coal markets [28], and brought back to modern scientific scrutiny by Khazzoom [29].

Questions regarding the *complexity* of modern society as well as of the computing systems we develop to "solve problems", the desired (or undesired) effects of *efficiency gains* and the issues of *unintended and undesirable effects* of technology are topics that have been treated in several *Computing within Limits* papers. Raghavan and Pargman [38] ask "what is the appropriate response to excessive sociotechnical complexity?", and suggest that the process of refactoring can be useful not only in computing but also for "simplifying large-scale sociotechnical systems while retaining all or most of their benefits". Raghavan [36] cites Sevareid's law, "The chief source of problems is solutions", discusses how "our problem-solving instinct may be leading us astray" and proposes "a set of principles for computing that is less likely to have unintended, harmful downsides" to ecosystems and human society. Swiss researcher Lorenz Hilty has grappled with the same issues over an extended period of time and discusses the relationship between Computing within Limits and the concepts of *efficiency*, *sufficiency* and *self-sufficiency* [21]. Raghavan and Hasan [37] ask "How do we design for self-sufficiency" given the seemingly intractable supply chains of modern economic processes, including the intricate dependencies of the (numerous) components and supply chains necessary to make the Internet work", while [38] proposes a a redesign approach that "focuses on redesigning existing systems that have potentially-undesirable layers" that add unnecessary, unwanted and costly complexity to a system. Their proposed solution, "disintermediation" identifies "layers within a system that can be removed while retaining the key functionality of the system, and without diminishing the system's usability or usefulness to the user". A notable paper [35] makes short shrift of the current "reformist, eco-efficiency paradigm". Efficiency improvement in the current paradigm, "the cornucopian paradigm", leads to a reinforcing feedback loop that stimulates growth in infrastructure capacity, leading to new services and increased demand which in turn leads to new investments in infrastructure capacity, and so on.

Since digitalization nowadays affects virtually all aspects of modern economies and societies, it is thus particularly prone to trigger many forms of rebound effects. We hereby use the term *digitalization* as defined in [7], which distinguishes between *digitization* "as the material process of converting analog streams of information into digital bits" and *digitalization* "as the way many domains of social life are restructured around digital communication and media infrastructures" [7]. *Digitization* is thus the localized process of taking something analogue and turning it digital (such as records), while *digitalization* is about the profound and permanent restructuring of activities, practices or services around ICT infrastructure and services. Reaching further and precisely describing our understanding of the distinction among the two concepts, Ringenson et al. [40] state that the definitions in [7] are "useful for highlighting the difference between the technological conditions necessary for digitally related societal change (digitisation) and the actual change (digitalization)."

How can digitalization trigger rebound effects? Smart resource allocation systems such as "smart logistics", for example, bring about efficiency gains, which in turn may lead to various unintended and undesirable rebound effects [42]. Travel booking systems are designed to dynamically adapt prices in a way that maximizes the number of seats filled, often lowering the price of the last seats and thus contributing to more travel. Digitalization helps individuals, companies and entire societies to make more efficient use of time, thereby contributing to a general trend of social acceleration [43] and increased consumption. A trend towards acceleration and increased speed helps bridge distances and thus contributes to globalization (including environmentally detrimental activities such as increased volumes of trade and travel etc.).

To introduce and discuss the concept of *skill rebound*, and embed it in the discussion about the possible rebound effects of digitalization, the paper is organized as follows: Section 2 shortly introduces several types of rebound effects and shows their relevance for digitalization. Section 3 provides an introduction to self-driving cars together with the promises they harbor in terms of efficiency gains, as well as several types of counteracting rebound effects that have been suggested in the literature. Section 4 defines skill rebound effects and discusses how self-driving cars are likely to induce them, while Section 5 places the skill rebound in a historic context, showing that while it is not specific to digitalization, it might nevertheless be raised to an unprecedented level by digital technologies. Section 6 finally discusses skill rebound, and rebound effects more generally, in the context of efficiency and sufficiency. We conclude by arguing that skill rebound must be better understood and taken into account in the design of new technologies.

2 DIGITALIZATION AND REBOUND EFFECTS

The phenomenon first described by Jevons[28] and where efficiency gains lead to more consumption of the same good or service (e.g. a higher consumption of coal in Jevons' case) is often referred to as a *direct rebound effect*. Although difficult to quantify, direct rebound effects are nowadays conceptually relatively well understood. By contrast, there is a wide array of more subtle and elusive mechanisms generically referred to as *indirect rebound effects*. They also lead to an increase of production or consumption, but either of a *different good or service* (instead of the specific good or service that becomes more efficiently produced), or by *other means* and not as a consequence of a price reduction.

There is, for example, the *income effect* – the monetary savings achieved from more efficient production of a goods or a service are spent on different energy- and resource-consuming activities [4]. There is also the*substitution effect*: a lower price for a good or service makes it relatively more affordable than another, similar product or service, which it will subsequently partly substitutes. If the price for petrol drops, for example, car rides become relatively cheaper than other forms of transportation and they are likely to substitute some of the former train rides. The substitution effect is not necessarily environmentally detrimental, however: if by contrast train rides become relatively cheaper than car rides and replace part of the latter, the substitution will most likely result in environmental benefits; this environmentally beneficial form of substitution effect has been called *push impact* [45]. Such beneficial outcome of a substitution might also be inversely triggered, i.e., when the *increased consumption* of a good due to factors other than the price (such as changed consumer values or preferences) *leads to a decrease* in the consumption of other products – this has been called *reverse rebound* [27]. Finally, there is the *rebound effect with respect to time* (also known as *time rebound*), i.e. when a technology does not save resources but instead saves time, which in turn is spent on resource-consuming (and often resource-intensive) activities [5]. More comprehensive overviews of rebound effects are provided by [10, 14].

Digitalization is the cause of numerous indirect rebound effects (which have been called *digital rebound* [14]). These have been increasingly studied over the last years [10, 12–14, 22, 24, 25, 47]. One possible rebound mechanism of digitalization, however, has been largely ignored so far: the fact that digitalization often, and partly dramatically, lowers the skill bar needed to perform various activities. As a result, some activities may suddenly become within reach of larger groups of potential users who had previously not possessed the necessary skill sets to perform them. This democratisation can have positive societal effects; it might, however, also bring about environmentally detrimental consequences. The main contribution of this paper is to outline and describe this phenomenon which we have chosen to call *skill rebound*. To illustrate it, we use the example of self-driving cars throughout the paper.

3 SELF-DRIVING CARS

Self-driving cars, also called autonomous vehicles (AVs) or self-driving vehicles, are a good example for an emerging technology driven by digitalization. While the application domain is the automotive industry, the technologies enabling autonomous driving are purely digital. Self-driving cars rely on advanced sensing technologies that feed their data into machine learning models, which are then able to infer the car's surroundings and steer it to its destination. The Society of Automotive Engineers defines 6 different levels of automation for cars [44], which are presented below. While they promise to yield substantial societal and environmental benefits, self-driving cars are also likely to induce increased driving comfort and (work) productivity, which in turn might spur the risk of rebound effects. Both promises and perils are addressed in this section.

Technology

Self-driving cars are capable of navigating without any human input. To achieve this goal, they deploy a multitude of sensors (such as GPS, lasers and a variety of cameras) to scan and perceive their environment. Machine learning algorithms then use this data as input to build models of the street layout, traffic, street signs as well as potential obstacles and dangers. The 6 levels of automation for cars (as defined in [44]) are:

- Level 0 (No automation): the car might have some warning systems, but the driver is in charge of all driving tasks.
- Level 1 (Driver assistance / "hands on"): some driver assistance systems are in place, such as adaptive cruise control or lane keeping assistance, but the driver is in full control and still has to manage most of the dynamic driving tasks.
- Level 2 (Partial automation / "hands off"): driving assistance systems can brake and accelerate automatically but can especially take over the steering. The driver nevertheless needs to be alert at all times to be ready to intervene – hence, 'hands off' is to be understood rather metaphorically.
- Level 3 (Conditional automation / "eyes off"): the car takes over additional tasks. It can independently steer itself over longer distances and even deploy rapid responses such as emergency braking. These capabilities, however, are limited to specific types of roads (e.g., motorways) or environmental conditions (e.g., only during the day and in the absence of fog), and the driver nevertheless needs to be able to react within a few seconds when these conditions are about to change.
- Level 4 (High automation / "mind off"): the car takes over all aspects of the dynamic driving tasks. It can complete longer journeys without any need for human intervention. It might, however, not be able to perform these tasks in unmapped areas or during severe weather.
- Level 5 (Full automation): The car is able to independently complete any journey, anywhere, at any time, and under any weather or further environmental conditions.

Their advanced cruise controls place most of today's higher-end cars slightly above automation level 1 and progressing towards level 2, while Tesla's autopilot is gradually improving from level 2 towards level 3 [3]. Numerous vehicle manufacturers invest substantial shares of their research resources into evolving the self-driving capabilities of their products; the emergence of a high level of automation and does not seem a question of 'whether' but of 'when'.

Social and environmental benefits

Self-driving cars can bring about important societal benefits. They can increase the mobility (and thus the independence and quality of life) of numerous people, for example the elderly and those with medical conditions that hinder them from using a car and who otherwise would be reliant on institutions, family or friends for their mobility [39].

Additionally, numerous studies have also highlighted the potential environmental benefits of self-driving cars. These benefits can be achieved, for example, by platooning vehicles on motorways [8]. Taking advantage of their sensing, communication and computation facilities, several vehicles can travel in close proximity, substantially reducing wind friction and thus fuel consumption. The efficiency gains depend on several factors such as the shape of the vehicles, their speed, how close they are to each other, the number of platooned vehicles, and of course also the time they spend in formation.

Self-driving cars can also be programmed to drive smoother. Less abrupt acceleration and braking would also result in increased fuel efficiency. It has even been argued that by being inherently safer than human-driven vehicles, self-driving cars require lower safety standards, which would in turn lead to lower vehicle weight and thus lower fuel consumption [39].

Above all, however, the largest potential seems to be in sharing self-driving cars, whether this vision is called "shared autonomous vehicles" (SAVs) [17, 30], "self-driving taxis" [46] or "autonomous taxis" [18]. Many have argued that shared self-driving cars would considerably reduce vehicle emissions while in operation [18] and that their increased convenience and flexibility should have them substitute private car ownership to a large extent, thus reducing the overall size of the car fleet, the grey energy required for vehicle manufacturing and the urban space required by vehicles [6, 9].

Rebound effects of self-driving cars

The time spent in self-driving cars promises to be both more enjoyable and more productive than the time spent in traditional cars. While 'driving' towards an upcoming meeting in a self-driving car one could, for example, prepare a presentation – alone or together with colleagues. Today, this would only be possible in public transportation, and in particular in long-distance public transportation such as trains. Likewise, on the way back from a business meeting, the time en route could be used for post-meeting analysis, individual relaxation, socializing or even sharing a bottle of wine.

If all these productivity gains and comforts typically reserved for public transportation can be enjoyed in a car, this will almost certainly lead to *time rebound*, as theorised above, time that will be used for various activities that can have environmentally detrimental effects. These activities could also include more frequent and/or longer car trips. Travelling in a private car can have perceived advantages compared to public transportation (less or no exposure to noise, smells or pathogens) and the relative appeal of car rides compared to public transportation will most certainly increase, leading to *substitution effects*. For self-driving cars specifically, this substitution was theoretically put forward by [30], while [34] has shown that according to the preferences of the German public, shared self-driving cars would almost exclusively be used as a substitute for public transportation and only to a very small extent substitute or replace private car ownership. Such a trend would likely increase rather than decrease traffic-related emissions.

According to [34], it is likely that today's traditional private cars would be replaced to some extent by self-driving cars. These, however, will most likely not be shared ones but rather privately owned self-driving cars. This finding stands in stark contrast to the positive expectations presented above, in particular that shared self-driving cars (or SAVs) would substitute private-car ownership and thus yield substantial environmental benefits. Such an opposed trend would not only not deliver the benefits proposed above, but it would instead lead to rebound effects due to the time savings and the increased comfort and productivity that self-driving cars bring about.

4 SKILL REBOUND OF SELF-DRIVING CARS

The above-mentioned rebound effects are brought about by the comfort and productivity boost of self-driving cars. Self-driving cars can, however, induce another, arguably even subtler effect: they *lower the skill bar* needed to drive a car. Once self-driving cars will reach level 4 of autonomy, anyone can 'drive' such a car (i.e. anyone can be driven without the need of a human driver). Elderly and those with medical conditions who could not drive traditional cars, will then be able to independently make use of self-driving cars [39]. This inclusion has obvious societal benefits; it will, however, also replace some former public transportation journeys with car rides [20] and induce entirely new journeys that would not have existed in a world without the convenience of self-driving cars.

Further socio-demographic categories could of course also benefit from the lowering of the skill bar for driving: youths and children could 'drive' to school [14], pets could 'drive' to the vet, violins could 'drive' to be repaired and your mobile phone charger can 'drive' home after you forgot it at your friends' house yesterday.

An experiment [19], which simulated the self-driving cars of the future by providing a week of free chauffeur service to the participating households, seems to substantiate these worries. Overall, participants travelled 83% more compared to the baseline. Retirees saw the highest increase of their mileage, millennials had the larges share of empty trips (48% of the additional mileage), while 69% of the increase for families was due to their kids be driven around.

This phenomenon is of course not limited to self-driving cars, but an effect that will appear in numerous domains as a consequence of the increased sensing, communication and decision capabilities brought about by digitalization. Some activities that had previously been out of reach for those who did not possess necessary skills, may suddenly become available to (possibly much) larger groups of potential users. This digitalization-induced democratisation of skills will surely have many positive consequences from a social sustainability perspective and possibly for vulnerable groups in particular. At the same time, these positive consequences will be intimately connected to the increased consumption of the now more accessible activities. If the activities being consumed more are energy- and/or resource-intensive (such as driving a car), they will almost certainly also have unintended and undesirable (environmentally detrimental) effects [26, 42].

With this paper, we propose that this phenomenon should be called **skill rebound**. Skill rebound refers to 1) a lowering of the skill requirements needed to perform a specific activity that 2) leads to an increase in that activity. This in turn results in an increase in the use of resources relative to projected (hoped-for) savings. This mechanism is very similar to the mechanisms behind all rebound effects. For direct rebound too, for example, a technological advancement leads to benefits in terms of energy or resource efficiency, which in turn advances the democratisation of the good or service in question (through its price decrease), subsequently fostering an increased consumption that has negative environmental consequences.

5 FURTHER EXAMPLES OF SKILL REBOUND

While it was so far discussed in the specific context of self-driving cars, skill rebound is obviously not a phenomenon that is limited to this particular case, nor only to digital technologies. Below are three examples of historical processes that have resulted in skill rebound – printing, computing and music. We do not go into depth, but each example opens up questions about skill rebound and suggests directions for future research. We find that examples that describe phenomena where a profession has been transformed into an object (e.g. “printers” and “computers”) are particularly intriguing.

Even before printers existed, scribes painstakingly copied manuscripts by hand. In the days of the scribe, manuscripts (“books”) were few and far between as well as exceedingly expensive (or only partially available in the marketplace). The printing press fundamentally changed the economics of printing and it represents a knowledge revolution that had far-reaching implications in numerous areas of society [15, 33]. Benedict Anderson [2] claims that the printing press, through the promotion of vernacular languages, heralded the rise of nationalism and the nation state. Of primary interest here, though, is the emergence of a specific profession, “printer”, that did not exist before. With the digital revolution, typesetters became a thing of the past, but an even more fundamental change was the arrival of desktop printing in the 1980s. With a personal computer and a printer, ‘anyone’ (with the requisite funds to buy a computer and a printer and who had the know-how to use them) could become a publisher. While the quality of the average piece of printed matter decreased, the quantity was vastly expanded.

The same changes that made first scribes and later printers redundant also affected the (usually female) computers who spent their days performing calculations “right up until the introduction of modern computers” [1]. Women had been employed to work as computers since at least the 18th century “in fields such as astronomy, aviation, and weapons research” [1], while the “tradition of women as computers has been traced back as far as Babbage’s time, where women assisted male astronomers in their calculations. By the 1890s it was common for university observatories to employ women computers to classify stellar spectra” [11]. Working as a computer was, during the second world war, considered a step up from being a secretary or typist [11] and women computers did not just perform calculations by hand, but partly also configured and operated the machines that would later take their jobs as well as the name of their profession [32]. Building on the continuously increasing spread of mechanical and electromechanical desk calculators from the beginning of the 20th century on, electronic calculators, invented in the 1960s, became widespread in the 1970s, and with advancing miniaturization and the ubiquity of digital calculators as well as computers, the ability to perform (also advanced) calculations was democratized. At the same time, the amount of calculations that were performed in society increased at a rapid pace, leading up to calculation-heavy areas such as “AI”, “Big Data”, and “Quantified Self”. Access to vast amounts of distributed and inexpensive computing power (“edge computing”) is also a trend that is important for self-driving cars that are distributed in space and need continuous access to computations in order to move and ‘make decisions’.

The last example we point to here is that of music. Until the end of the 19th century, to enjoy music, you either had to play it yourself, or listen to others who played in your immediate vicinity (e.g., in your family or at a party, a pub or a concert). With the arrival of mechanical reproduction of music (records and radio) and later the loudspeaker (1930s), the skill bar was lowered to such an extent that it was possible to listen to music all day long without any specific knowledge beyond turning on and tuning in your radio. Music-listening was thus democratized and it expanded vastly during the first half of the 20th century. Digital technologies including streaming music and services such as Spotify [16] not only enable convenient listening to almost any music anywhere and anytime, they also significantly reduce time, effort and money for discovering and exploring the music one loves.

6 DISCUSSION

In the context of self-driving cars, the potential for efficiency gains as described above is positive if 1) the efficiency of car travel is increased (as promised by the many technological innovations) while at the same time 2) the volume of car travel does not increase (as an effect of an increased service level, more comfort or a productivity boost), or that the volume of car travel at least does not increase as much as to overcompensate for the efficiency gains. If a ride in a self-driving car by someone with a medical condition replaces a car ride where someone else (family, friends or an institution) would have made that same trip, this results in a gain both of service level and of resources. The problem from an environmental perspective, however, appears if and when the opportunities for people to take car rides dramatically expands and results in a vast increase of the number of rides. This problem is not limited to the old and frail (who might at some previous point in time have had the skills necessary to drive a car) but to any person – old or young – who never has had the skills to autonomously drive a car (and who, due to the technology of self-driving cars, never need to acquire those skills). As noticed above, these newly acquired ‘driving skills’ can even be extended to animals and inanimate objects, who now in a sense would be able to ‘drive’ a car.

Processes of skill rebound do thus not necessarily need to have environmentally detrimental effects (or at least it is an open question whether they do or not). If a human activity – any human activity including printing, calculation or music-listening – increases by a factor of, say, several orders of magnitude, that activity is however bound to have some material or energetic, and thus environmentally detrimental, footprint. An increased environmental footprint does however also have to be weighed against the positive effects on human welfare of that innovation, while not forgetting that any innovation also can also have negative (possibly unintended and undesirable) effects on human welfare.

If, as has been stated before, rebound effects are bound to recurrently occur as an effect of digitalization, it becomes important to discuss how to control them. Hilty[23] suggested that absolute levels of consumption must be set before turning to efficiency measures and summarised this position with the slogan “no efficiency without sufficiency”. We believe there can be other factors (such as market saturation) that limit the consumption of resources and prevent rebound effects (see [14, 45]), but also suggest that another option would be to turn to regulation or to policy instruments. In the case of self-driving cars, it could be that there should be a policy that prevents empty runs or a hefty tax discouraging them (although there might of course be exceptions). While the hope is that the self-driving cars of the future will be shared rather than private, in the absence of policies or other limiting measures, it is easy to imagine that today’s cars will otherwise be replaced by privately-owned self-driving cars.

We are the first to admit that we do not have any ready-made solutions of how to “solve” the problem of skill rebound — just as there are no obvious solutions to handle other types of rebound effects. Rebound effects are *hard*. Worse, rebound effects imply that the systems we design can have detrimental outcomes even when designed with the best of intentions. The question of how problems that stem from skill rebound can be “solved” (or avoided in the first place) will have to remain unanswered for now. The fact that rebound effects are often both undesirable and unintended might imply that they are members of the class of problems that have been called “wicked” [41], e.g. problems that have no definitive formulation, where it is hard to know if or when they have been solved, where every problem is unique, where previous solutions are of little help, etc.

A specific observation is that if resources are limited or scarce, efficiency gains will always have environmentally positive effects since they can be expected to not result in increased consumption of neither the resource in question nor of other resources (there might nevertheless still result in societal side-effects, such as unemployed drivers, which are beyond our scope here). In a world of limited or shrinking resources, the shrinkage would always limit demand and a lowering of the skill bar would thus have only positive (albeit possibly not widespread) consequences. In a world of shrinking resources there would in fact be an “arms race” between (the effects of) lowering the skill bar and access to resources to make the service/product in question more widely available.

We end on a note about the term *skill rebound* that we used throughout the paper. It is possible to question the notion of *skill* in relation to the examples provided: to what extent is it possible to conflate the broad social and cultural competencies that go into performing a complex activity such as driving a car, and refer to it merely as a “skill”? Furthermore, would it not be relevant to discuss *deskilling* in the context of the examples we have used in this paper? We believe that such discussions have merit and hope to extend our analysis in such a direction in the future, but the broad social and cultural implications and ramifications of the phenomena we describe are beyond the scope of this paper. Here, we used *skill* and *skill rebound* in a more limited sense, referring strictly to their possible unintended environmental effects.

Above we wrote that “there is the *rebound effect with respect to time* (also known as *time rebound*), i.e. when a technology does not save resources but instead saves time, which in turn is spent on resource-consuming (and often resource-intensive) activities." The term *time* can (and has) naturally been problematized in various academic disciplines – time is for example obviously not a *thing* that can be *saved* (see further in e.g. [31]). We (as well as [5]), however, deem such discussions to be outside the scope of the phenomena we are interested in discussing in this paper, and similarly used the term *skill* here without further problematizing it. What we are primarily interested in in this paper is the existence of a (previously unidentified) rebound effect with respect to skill that we have chosen to call *skill rebound*, i.e. when a technology does not save resources but instead makes it easier (e.g. lowers the skill required) to perform an activity, which increases the frequency of the activity, which in turn leads to an increased use of natural resources.

7 CONCLUSION

Per-product freed-up resources can lead to an overall decrease in the use of the resource(s) in question (time, money, energy, materials etc.). The more usual case, however, is that at least some part of the savings are used to increase use of the very same resource(s) that were freed-up (direct rebound effects) or of other resources (indirect rebound effects). This means that projected and hoped-for efficiency gains are not fully realised (rebound effects), or in the worst case, that the use of resources increases *despite* efficiency gains (backfire effect). If efficiency gains result in increased use of resources elsewhere (indirect rebound effects), this could additionally be problematic if saved resources (for example money) result in an increased use of resources that have negative environmental effects (for example energy) compared to before. Thus, while efficiency gains are by their very nature positive, their potential for positive change only becomes realized when they result in decreased rather than increased use of environmentally problematic resources, *after accounting for rebound effects, including the skill rebound.*

In this context, the skill rebound represents a previously not explicitly highlighted, yet potentially crucial mechanism triggering increased consumption and thus energy and resource use. As the sections above have shown, skill rebound is not specific to, but very typical for digital technologies. Due to its potentially substantial impact, skill rebound should thus be taken into account when designing and/or deploying new digital services and technologies.

Digitalization has been criticised for its growing direct environmental footprint. By contrast, it has also been hailed for the indirect environmental benefits it might induce by making existing processes more efficient or substituting them altogether. The possible negative indirect consequences of digitalization, on the other hand, have received less consideration [14].

The crucial environmental influence of digital technologies, however, will most likely not come from their direct environmental footprint, although efforts towards their limitation are of course valuable. Quite literally for the better or the worse, the game-changing potential of digitalization lies in its indirect consequences. As a potential source of conflict among sustainability aims, with its potential for substantial societal benefits but also environmental damage, rebound effects in general, and the skill rebound in particular, need to be better understood.

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