Digital Rebound – Why Digitalization Will Not Redeem Us Our Environmental Sins

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***Abstract*— Digitalization as a technological phenomenon of the 21st century has the power to redeem most environmental sins of our 20th century technology. This seems to be a popular belief shining through many of the optimistic media reports on digitalization. We believe, however, that this mindset is far too simplistic and counterproductive. The many indirect economic and social effects of digitalization, which turn efficiency gains into increased resource consumption, are often ignored. We discuss these countereffects in general, as well as their digitalization-specific flavor (i.e., the *digital rebound*). We give examples of digital rebound, and also analyze several conditions that seem to lead to its eschewal. Altogether, we try to make the case for a faithful consideration of the rebound effects of digitalization.**

***Index Terms*—Rebound, efficiency, resources, energy, digital rebound.**

I. INTRODUCTION

The potential economic and societal benefits of digitalization[1] are far-reaching and are often addressed in today's public discourse. Moreover, digitalization is often envisioned as a silver bullet to tackle – or at least mitigate – the world's increasingly urgent environmental issues; in particular, it is seen as a possible key factor in reducing carbon emissions and resource consumption across various economic sectors (e.g., [1-3]). Such assertions rely on the ability of digital systems to either optimize the performance of energy- and resource-intensive systems and processes in industry and commerce, or to virtualize and substitute them altogether. Digitalization can further enable more environmentally desirable solutions, which would be too complex to achieve or manage otherwise, such as the smart electrical grid. Finally, through more detailed, real-time information at their fingertips, consumers can decide in favor of more environmentally friendly alternatives, such as buying goods with a small carbon footprint or avoiding products with palm oil.

The continuingly rapid digitalization of societies and economies also has its downsides and does not go undisputed. Some of the more obvious reasons for concern are possible security breaches due to the increasing complexity, heterogeneity, and interconnectivity of systems, as well as some increasingly intricate privacy issues. Such negative side effects seem to be generally accepted by society as the many benefits of digitalization are perceived to largely outweigh these disadvantages (which are believed to be manageable to some degree).

Increasing evidence, however, also sheds a critical light on the attributes of digitalization usually perceived as wholly positive. It turns out that the increased efficiency or the improved access to information afforded by digitalization can often induce indirect effects, which can reduce or even reverse its positive impact. In economics, these unwanted countereffects are known under the umbrella term of *rebound effects*.

In a nutshell, rebound effects occur when positive initial effects (e.g., increased efficiency) make a good or service more attractive (through lower prices or added benefits), which in turn is likely to spur demand either for the same good or service (which is more attractive), and maybe for other products, due to the increased disposable income or time. This, in turn, stimulates more energy and resource consumption (and consequently more pollution), diminishing the initial positive effect or, in the worst case, even outweighing it.

While relatively well-known in economics, rebound effects have not yet been thoroughly investigated for digital goods and services, and even less so for the broad digitalization of whole industrial and economic sectors. This is partly understandable because, as will be shown below, rebound effects are diverse and involve subtle yet far-reaching mechanisms. Although their principal workings are relatively well understood, quantifying rebound effects remains a challenging task. As digitalization pervades ever growing areas of societies and economies, and given the broad dissipation of the effects, assessing the rebound effects of digitalization is a particularly serious challenge.

We use the umbrella term *digital rebound* to denote any such rebound effects induced by digitalization technologies,

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[1] Traditionally, the term "digitalization" basically meant the technical process of converting analog signals into digital form. In recent years, however, *digitalization* took on a much wider meaning – in business contexts, it now stands for the broad use of digital information and communication technology (ICT) and the induced change in business operations or whole business models ("digital transformation"), often restructuring or disrupting economic processes and social practices.

whether they stem from individual IT goods and services, the digitalization of entire economic sectors, or indeed the whole economy. Ignoring digital rebound can lead to a misunderstanding of the environmental effects of digital technologies, and possibly result in inappropriate policy or misallocated monetary incentives. Despite its difficult quantification, this paper thus aims to increase digital rebound awareness.

Section II starts with a familiar example for emerging digitally enhanced products, self-driving cars, discussing some of their possible rebound effects. Section III presents a more in-depth theoretical analysis of several types of rebound effects. Section IV then shows the relevance of rebound effects in the context of digitalization, discussing both apparent environmental benefits and also the counteracting digital rebound for several types of digital services. By contrast, Section V examines some digital services with little or no rebound. Finally, Section VI contrasts the two categories, distilling insights into the design of digital services that seem to be truly environmentally beneficial even after taking possible digital rebound into account.

II. SELF-DRIVING CARS: ENVIRONMENTAL CURE OR MENACE?

With recent advances in computer vision technologies based on pattern recognition and machine learning, paired with progress in other digital technologies such as wireless communication and high-precision localization, *self-driving cars* – or *autonomous vehicles* – are now expected to become a reality in the not too distant future. Major car manufacturers as well as IT companies are developing technologies for autonomous vehicles. Since it receives much media coverage, the topic is one of the better-known examples for how digitalization can permeate various sectors of the economy and society, and thus serves well as an introductory example case for our statements and claims.

Self-driving cars can bring about undeniable societal benefits, such as better inclusion of the elderly or people with disabilities [4, 5]. Additionally, numerous researchers have also highlighted their potential benefits on traffic and the environment. Some [6] alleged that autonomous taxis could considerably reduce vehicle emissions, while others [7] argued that platooning (coordinated travel in close proximities on highways) can substantially reduce the average fuel consumption by coordinating driving speed and behavior, and by minimizing the distance between vehicles to reduce wind resistance. It has even been argued that autonomous vehicles are inherently safer than traditional vehicles driven by humans, and thus require lower safety standards, which in turn leads to lower vehicle weight and thus lower fuel consumption [8]. Finally, some argue that the emergence of autonomous vehicles would boost the market for sharing such vehicles to the detriment of private car ownership, reducing the overall car fleet and thus the grey energy required for vehicle manufacturing [9, 10].

These positive direct effects, however, only tell half of the story. There are also a number of subtler mechanisms and indirect consequences that induce effects to the contrary: Better inclusion of the elderly or disabled means they will also be able to ride autonomous vehicles instead of public transport, worsening the environmental impact of their mobility [4]. Even children could ‘drive’ autonomous vehicles to school! Self-driving cars are also likely to induce a substantial number of empty runs [11], an impossibility today. Until now, one of the reasons not to take the car in urban environments has been the difficulty of finding a parking spot at the destination. If one can, however, drive to a meeting in the city center and send the empty car back home, it is quite likely that such empty runs will occur, inducing additional mileage [12]. As Chase [13] pointedly puts it, these induced trips could be far beyond what we might imagine today: “I schedule the FAV [fully autonomous vehicle] to return at 9:30 a.m., but I don't rush out because the car will just circle the neighborhood until I tell it *I'm here!* As I get a friend a gift at a hand-made jewelry shop, my FAV circles the block for 15 minutes. Rather than trip-chaining to get the dry cleaning, we send the FAV out anytime to pick it up (an employee places the cleaned and pressed clothes in my car for me). Ditto for our take-out dinner”.

Finally, the time spent in an autonomous vehicle is likely to be more enjoyable or productive than when driving one’s self. The time while riding an autonomous vehicle free of stress or attention can be used for socializing or work. This is likely to increase the appeal of car rides, which might lead to more frequent and longer trips [7]. Car rides would also become more attractive as compared to other modes of transport, leading to a partial substitution of the former for the latter. This substitution was theorized for example in [14], while a questionnaire of paired comparisons devised in [11] hints that shared autonomous vehicles might indeed displace almost exclusively public transport, not private car ownership.

III. TYPES OF REBOUND EFFECT: AN OVERVIEW

All of the above are examples of *rebound effects* for autonomous driving. These noteworthy effects do, however, also appear in other contexts. Before analyzing their relevance for the broad domain of digitalization, it is worthwhile to gain a deeper theoretical understanding of rebound effects in general.

Several definitions of rebound effects exist, some narrower, others wider. In its classical economic interpretation, the notion of rebound evolved from describing one rather narrow phenomenon in the energy market to an entire class of effects. A definition of today’s broader understanding is given by Sorrell [15]: “The ‘rebound effect’ is an umbrella term for a variety of mechanisms that reduce the potential energy savings from improved energy efficiency.” While broad, this definition still considers only the energy domain. As Binswanger [16] comments, however, the concept of rebound effect can easily be applied not only to energy, but to resource use in general.

A. The Direct Rebound Effect

Khazzoom [17] undertook an early systematic analysis of the rebound effect. His approach relies on a single-service model; meaning there are no repercussions from this service to the rest of the economy. The service is an energy-intensive one, such as mobility (measured in passenger-km) or room temperature. According to neoclassical economic theory, when the price of a good decreases, the demand for it increases, all other things being equal. If, due to advances in energy efficiency (e.g., more fuel-efficient vehicles or better house insulation), the passenger-km or an hour of a certain room temperature will cost less, and as long as their needs are not saturated, users will tend to use them more: more kilometers driven, the room temperature set higher or not turned off overnight. This effect may partially or entirely offset the savings from the original energy efficiency measure.

In this narrow sense, the rebound is often referred to as *direct rebound effect* – direct because the rebound occurs for the same service that had originally gained in efficiency, and because the rebound is a direct consequence of the price reduction that follows the lower input to produce the service. Although originally defined for energy markets, the effect appears for any resource efficiency measure: if less of a resource (any physical resource, though, in the general sense, also more labor or capital) is needed to produce a good or service, its price will decrease and, as a result, more of it will be demanded.

B. Jevon's Paradox or Backfire

More than a century before Khazzoom's work, British economist and logician William S. Jevons first referred to the phenomenon – without using the term 'rebound' – in his 1865 book "The Coal Question" [18]. The effect described by Jevons is different from Khazzoom's rebound in that it is more general (caused by more mechanisms) than the mere direct rebound put forward by Khazzoom. This will be discussed below.

Despite attributing it to different causes, Jevons and Khazzoom agree on the rebound's size. They both assume that it is larger than 100%, i.e. it is postulated to outweigh the original savings. As broadly discussed by Alcott [19], Jevons argues in his original work that the rebound effect not only reduces the potential savings of the energy efficiency measure, but that it actually outweighs the reductions, leading to an overall net energy increase: "[if] the quantity of coal used in a blast furnace, for instance, be diminished in comparison with the yield, the profits of the trade will increase, new capital will be attracted, the price of pig iron will fall, but the demand for it increases and eventually the greater number of furnaces will more than make up for the diminished consumption of each" ([18], page 156).

This particular case, when the magnitude of the rebound effect is more than 100%, is known in the literature as *Jevons' paradox*, or under additional names such as *boomerang* or, more commonly, *backfire*. A well-known formulation of Jevons' paradox is given by Saunders: "with fixed real energy prices, energy-efficiency gains will increase energy consumption above what it would be without these gains" [20]. Saunders calls it "the Khazzoom-Brookes postulate", after the more recent work by Brookes [21]. As both Alcott [19] and Sorrell [15] observe, 'postulate' is the correct term in this context as there is not enough evidence to support that the rebound always exceeds 100%. Discussing Jevons' work, Alcott observes "Jevons thus makes rebound theoretically plausible, but he has not yet proven that the amount of coal consumed must 'more than' make up for engineering savings" [19]. Likewise, Sorrell concludes that "such evidence does not yet exist" [15].

C. Indirect Rebound: Induction Effect, Income and Substitution Effects, Producer Rebound

The first citation from Jevons' work above already hints towards more mechanisms than the mere direct rebound. Another revealing passage can be found on page 144: "Whatever, however, conduces to increase the efficiency of coal, and to diminish the cost of its use, directly tends to augment the value of the steam-engine, and to enlarge the field of its operations" [18, 19]. The mechanism described here alludes to the *induction effect* [22], which other researchers consider merely a specific form of the rebound effect [23].

Such mechanisms that lead to different types of rebound were more formally presented soon after Khazzoom's work. Both Binswanger [16] and Berkhout et al. [24] discuss the *income effect* and the *substitution effect* as further causes for rebound. The effects are well-described in [16]. They are observed by leaving the single-service model behind and considering a model consisting of two services, *A* and *B*, which can be partially substituted for each other. A lower price for service *A*, as a consequence of efficiency gains for one of its inputs, has two consequences: i) consuming the same amount of *A* and *B* becomes cheaper, the consumer has a larger budget at his disposal, leading – ceteris paribus – to more consumption of both *A* and *B* (income effect); and ii) as service *A* becomes relatively cheaper, it will partially substitute service *B* (substitution effect). The total effect is equal to the sum of the two effects, as reflected by the Slutsky equation [25]. Both effects lead to more consumption of service *A*, and thus also of the resource that had originally gained efficiency, which triggered these effects in the first place.

Berkhout et al. [24] also define what they call the *producer rebound*, which is essentially a substitution effect on the producer side: Increased energy efficiency changes the optimal balance between energy and other production factors such as labor or capital. Due to the more efficient usage of energy, the producer will, to some extent, substitute energy for capital or labor.

D. Time Rebound

Binswanger [16] introduces what he calls *time rebound*, which stems from time-saving technological progress. He argues that a decline in the time needed to acquire a service (such as traveling a certain distance) reduces the costs associated with time. This is based on the economic model that someone's time can be monetarily represented by the foregone earnings one could have achieved during that time. Economists say in this context that "wages are the opportunity costs (i.e., the not taken alternative, hence 'opportunity costs') of time."

A time efficiency measure, thus, leads to time saving which can be monetarily expressed as its opportunity costs, i.e., the earnings that could theoretically be achieved in the time that was saved. To the extent that the costs of the time-saving measure continue to be cheaper than the costs of saved time, the former will be substituted for the latter. Time-saving technologies, however, are often quite energy intensive, such as the technologies enabling fast means of travel or transportation. The energy thus spent to save time, is what Binswanger calls "time rebound."

E. General Equilibrium Effects and Other Macro-Level Rebound

Finally, the price changes for the firms' output, as well as the income and substitution effects that follow efficiency gains, will lead to changes in demand and further readjustments along the entire economy. These *general equilibrium effects* are relatively hard to grasp and almost impossible to quantify. In the literature, they are also called *macroeconomic rebound* [26] or *world-wide rebound* [23].

One reason the global and long-term consequences of products becoming cheaper (due to energy efficiency improvements or technical progress in general) are difficult to assess (and even more so to predict), lies in the fact that consumers (and thus markets) may react in a non-linear and almost discontinuous way to price changes and product improvements. Indeed, once a certain price or usability barrier is surpassed, a product may suddenly become attractive to buyers. Emotional or networking effects, and even trends in fashion, are certainly also relevant for such *avalanche effects* and add to the complexity of their analysis and assessment.

For example, no one could have predicted the sudden boom of mobile phones. Car phones existed since the 1960s and have steadily been improved, evolving into portable phones during the 1990s ("car phones without a car", as an advertisement at that time nicely put it). But only when they became small enough to fit into trouser pockets and could run without heavy batteries, mobile phones quickly became a real market success (clandestinely paving the way for the next evolutionary step, their metamorphosis into smartphones).

The basic technological driver of the digitalization phenomenon is the steady progress (and, in fact, the steady efficiency improvements) in microelectronics neatly revealed in Moore's Law. Sustained steady progress on that level, however, can eventually lead to sudden disruptions on the macro scale: We now spend much more time with our mobile phones than we did previously with our landline phones. But when doing so, do we directly or indirectly use more energy? Whether an avalanche effect turns into a digital rebound effect on the global scale is a priori unclear and certainly depends on the circumstances of the particular case. In general, cause and effect relations become blurred at the macroeconomic scale because of undefined and unclear system boundaries and sector-wide spillover and feedback mechanisms.

Reviewing a large body of rebound literature, particularly by economists Len Brookes and Sam Schurr, Sorrell [15] points to another source of macro-level rebound: the catalyst effect of energy for productivity in general. He argues that energy efficiency technologies boost total factor productivity (in particular, capital and labor productivity) and thereby save much more than energy costs alone. Moreover, he argues that labor costs are much higher than energy costs (typically, 25 times larger in commercial buildings in industrialized countries). But if the total cost savings are much larger than energy savings alone, the rebound due to the income effect may also be much larger. This observation seems to apply only to energy efficiency measures and not to resource efficiency in general.

IV. DIGITALIZATION AND ITS REBOUND

The last paragraph of Section II mentioned several examples of rebound effects for self-driving vehicles: Riding autonomous vehicles, which can be much more affordable than taxi rides and might thus displace trips via public transport are examples of the substitution effect [24]. New categories of users such as the elderly, disabled, or even children 'driving' vehicles is a form of the induction effect revealed by Hilty [22]: the ease of accessing or using a service creates new demand. Induction effects are also the empty runs, which do not exist in a world without autonomous vehicles, such as the car circling the neighborhood waiting for the owner to finish a business meeting. Car rides becoming more attractive as they can be used for either work or socializing illustrates Binswanger's time rebound [16]. As these phenomena result from digitally-enabled autonomous vehicles, they can thus all be considered examples of digital rebound.

Numerous further ICT-based products and services that are popular for their efficiency gains or other resource-saving mechanisms are in fact prone to digital rebound. We present two examples below.

A. Teleworking

Teleworking, also called *telecommuting*, denotes working from a remote location without physically commuting to the office. Communication with colleagues and access to company data are ensured via digital means such as email, Skype and similar services, virtual private networks, screen sharing, etc. The physical location of work is often the employee's home although telework can also be performed from a holiday spot, the partner's house, etc.

Teleworking has the potential to significantly reduce commuting and therefore energy use for personal transport. This can be a significant reduction since the transport sector represents around 25% of the final energy demand in developed economies, 1/3 of which can be attributed to work commute [27]. Early studies have indeed indicated important reductions of both passenger vehicle use and traffic congestion due to telecommuting. In 1991, [28] concluded that teleworking in the Netherlands decreased the total number of trips taken by teleworkers by 17% and peak-hour traffic congestion by 26%. A California pilot project [29] in the same year resulted in 75% less distance travelled by teleworkers on their telecommuting days. A couple of years later, a different study yielded a similar 77% reduction in distance travelled for the same Californian pilot project [30].

Later studies addressing the possible rebound effects of teleworking, however, paint a mixed picture. For example, [31] emphasizes that telecommuters can no longer stop for shopping on the way home from work, but might take an extra trip by car for their shopping. (Empirical work, however, has shown that such non-commute travel on telecommuting days decreases as often as it increases [32], and [27] speculates this might be because some non-commute trips could be eliminated as, without the work commute, their destinations would be too far away to be attractive.)

Beyond the uncertain development of non-commute trips on teleworking days, there might be several other causes for telecommuting-induced digital rebound. A study [33] estimates that the 4 million US workers who telecommute one or more days per week reduce the country's primary energy consumption by 0.13-0.18% and its greenhouse gas emissions by 0.16-0.23%, and it lists two likely causes for rebound: For one, telecommuting could increase the number of weekend trips to compensate for the activities not performed during the week, such as shopping. Moreover, as they spend less days commuting to work, teleworkers could live further away from their workplace, increasing their commute effort to work on non-telecommuting days and, potentially, that of numerous other trips. One could add easily imagined scenarios wherein the family car is happily used by other family members for their yet unmet demands, rather than resting in the garage when the main income earner does not commute to work.

Widening the boundaries of its analysis, [27] accounts for the decreased energy consumption in commercial buildings due to teleworking and, at the same time, for the increased energy consumption in residential buildings, many of which would have otherwise been unoccupied during the day. For the teleworking practices of 2005, and accounting for uncertainties, it estimates national energy savings of only 0.01-0.4% in the US, and 0.03-0.36% in Japan. Even for an extreme future scenario with ubiquitous teleworking, in which 50% of information workers telecommute 4 days per week, the national energy savings are estimated at only about 1% in both cases because of the many countereffects.

Finally, [31] argues that "online work can produce new contacts that might generate the need for meeting people personally". The first author of this paper can confirm the occurrence of such induction effects from personal experience: Between February 2015 and August 2016, he was remotely employed by the KTH Stockholm while living in Bucharest, Romania for family reasons. Without modern digital communication technologies, this collaboration would not have been possible, nor would the induced travel (11 return flights jointly responsible for around 10 t CO_2e) have taken place.

B. E-commerce

E-commerce describes a variety of commercial practices, in which the Internet is central to ordering goods. When the goods to be delivered are digital, or can be digitalized (such as music, movies, or books), their delivery can also take place digitally (via Internet streaming), without a physical substrate such as a DVD, CD, or paper.

It has long been maintained that E-commerce is more energy efficient than traditional retail. Sivaraman et al. [34], for instance, compared two DVD rental networks: a traditional one in which the customer drives to the rental shop, on the one hand, and online ordering followed by mail delivery, on the other. Even though the respective online model did not take advantage of online streaming but was still delivering physical CDs, the study found that it nevertheless consumed 33% less energy and emitted 40% less CO_2 than the traditional option. Similarly, [35] concluded that online grocery order with subsequent home delivery can save between 18-87% of the CO_2 emissions of individual grocery shopping in Finland.

However, [34] already found that e-commerce consumes more energy in urban areas where, in the traditional model, customers usually do not drive to the shops but walk or take public transportation, while home deliveries are done by vans. Going one step further, and analyzing book delivery in Japan, [36] showed that home delivery of books does not perform better environmentally than the traditional model in suburban or rural areas, either. In contrast to the other two studies, [36] took the multipurpose use of car trips into consideration. Therefore, not driving to the city's bookstore saved almost no energy in the end, as the car trip still took place for other purposes, while the induced consumption of delivery trucks turned the e-commerce balance into the negative. This effect is probably more prominent for clothes ordering, where customers often order more models and several sizes of each, and then take advantage of return deliveries.

V. DIGITALIZATION WITHOUT REBOUND

We will now discuss some digital services that, in contrast to the examples presented above, seem to produce only a small rebound, if any.

A. Rebound with a Smaller Footprint: A Trip is not a Trip

In 2009, the first World Resources Forum (WRF) was organized simultaneously in Davos, Switzerland and Nagoya, Japan. This conference format was chosen so that the conference would stay truthful to its topic of resource efficiency; the expectation of the organizers being that offering conference venues on two different continents would reduce intercontinental travel. For the four hours of daily common sessions (due to the 7 hours time difference), the two venues were connected with telepresence services (i.e., highest quality videoconferencing), adapted from its usage among small teams in meeting rooms to audiences of hundreds of attendees [37].

As travel to the conference became, on average, shorter, simpler, and cheaper, a rebound effect in the number of participants was to be expected as compared to a regular single-site conference: 531 participants attended in either Davos (372) or Nagoya (159). Had the conference been organized in Nagoya only, approximately 238 people would have attended; the 159 who came anyway plus 79 of the 372 from Davos. Had it been a Davos-only conference, the 372 local attendees would have been joined by 76 from Nagoya for a total of 448 [37].

This means that the two-venue event generated indeed a rebound in the number of participants when compared to either of the traditional organization modes, 531 as compared to 238 and 448, respectively. Despite this increased participation, the distributed conference had a lower travel-related impact as compared to the traditional alternatives (119 t CO_2 as compared to 189 t and 235 t, respectively) [37]. This is due to the fact that the efficiency gains induced by the distributed organization method implied a substantial reduction in intercontinental travel. The rebound travel instances, on the other hand, were almost exclusively much shorter intra-continental trips. As trips have very different energy and carbon footprints, which are generally directly proportional to their lengths, the aggregated energy and carbon effects of the rebound travel instances were lower than the amount of energy and carbon saved by the original efficiency gains. It should be noted, however, that the study did not consider subtler effects such as possible income effects or time rebounds for those conference attendees who would have travelled intercontinentally as well, but given the opportunity to travel within the same continent saved both money and time.

B. A Different Limiting Factor: When Efficiency Gains Have no Market Effect

Vending machines are very popular in Japan. So popular, in fact, that in the early 1990s their energy consumption became a political issue: At that time, the 5.4 million vending machines were together responsible for 3.7% of the electricity consumed in Japan [38]. Following energy efficiency measures, the efficiency of Japanese vending machines improved by 52% from 1991 to 2007 [39].

Given such high efficiency improvements, one would expect a strong rebound effect. Yet, the number of machines increased over this time frame only slightly from 5.4 to 5.5 million throughout Japan [40]. Why was there only such a mild rebound effect despite the large energy efficiency improvements? The limiting factor for the installation of vending machines turns out to be space, not energy consumption. As [38] observes: “In a densely populated country like Japan, it may be just impossible or unaffordable to sacrifice more space to install additional machines. It is today possible to operate two or three machines with the power that has been needed for only one machine in 1990s, but it is not possible to operate them without claiming additional space.” A different (economic or physical) limiting factor than the energy or resources undergoing efficiency gains may thus be likely to lead to only modest rebound effects.

C. Market Saturation Reached: Gas Leakage Discovery

Natural gas is a popular source for heating energy, consisting primarily of methane (CH_4) together with smaller quantities of other hydrocarbons. Both the US and Europe have extended natural gas transmission and distribution networks. The US transmission network, for example, consists of over 300,000 miles of interstate and intrastate transmission pipelines, while the distribution network contains more than one million miles of low-pressure pipes [41]. As with any other pipes, natural gas transmission and distribution networks are prone to leaks, through which gas can be released into the atmosphere.

Methane, though, is a potent greenhouse gas. Overall, it represents the second most important source of anthropogenic warming after carbon dioxide (CO_2); its relative impact, however, is much higher: Over a time period of 20 years, a certain amount of CH_4 has a warming effect 72 times greater than the same mass of CO_2 (and, although the atmospheric lifetime of CH_4 is shorter, the effect is still 28 times greater over a period of 100 years). Anthropogenic sources are estimated to be responsible for around 60% of the total CH_4 emissions, nearly 350 megatons (Mt) CH_4 yearly [42].

One of the most important shares of anthropogenic methane sources are the leaks from transmission and distribution networks. Global estimates for the quantities released from these leaks are difficult to make, but estimates for individual regions reveal substantial numbers: [42], for example, estimates leaks of almost 0.5 Mt CH_4 yearly for California’s South Coast Air Basin alone.

In a collaboration between Google, the Environmental Defense Fund (EDF, an environmental NGO), and researchers from Colorado State University, a couple of Google street view cars were prototypically outfitted with methane sensors for the rapid identification of methane leaks from urban distribution networks [43]. The algorithm was tweaked using controlled releases of different flows of methane on an airfield and passes with various speeds at various distances from these controlled releases so that, in the end, it considers for each discovered plume (i.e., an area of elevated CH_4) its maximum CH_4 concentration, the plume extension and an index for the plume’s kurtosis. At the same time, plumes longer than 160 m are ignored, as they most likely belong to a different methane source nearby, such as dairy farms or landfills [43]. This prototypical system for leak discovery in the urban gas distribution network was deployed in a field experiment in New Jersey, in collaboration with the local utility company PSE&G. It has been estimated that through the faster discovery and fixing of high-flow leaks, as compared to traditional methods, this deployment might reduce yearly CH_4 flows into the atmosphere by 2.4 kt [44].

As natural gas is relatively cheap, the financial effect of these savings is rather marginal and hence no rebound effects are expected [44]. Even if there was a perceivable financial effect, however, the rebound effect might have been quite low had there been no additional need for heating gas. Although rising wages and relatively cheaper energy have clearly induced a rebound effect in the quantity of heating energy consumed over the centuries (the average winter home temperature increased in Europe from 13 degrees centigrade in the 1300s to around 21 degrees today), there is most likely an upper threshold to the comfort temperature in homes. Generally, when a market is saturated and there is no additional demand for a product, naturally there will be no direct rebound effects (although indirect rebound, e.g. income effects, may still occur).

D. Rebound of the Right Sort: Pushing Cleantech Products and Circular Economy Processes

One theory of how digitalization affects economic processes is that energy, time, and information are the main inputs to any economic task and can, to some extent, be substituted for each other [45]. According to this theory, the digitalization of a process allows either time or energy to be saved. The implicit assumption of this theory is that saving energy is generally environmentally beneficial, while saving time (i.e., doing things faster and thus being able to produce more) is environmentally harmful. Moreover, as the commercial imperative is output maximization, [45] establishes that "both, IT's potential to do things with less energy input, thus generally more sustainably, and IT's potential to do things faster, i.e., less sustainably, are enormous. Unfortunately, so far, the latter potential has been extensively tapped while the former remains but potential."

This dichotomy, however, has recently been challenged. In [46], it is suggested that not only energy-saving digitalization, i.e. *save impacts*, can be environmentally beneficial, but also some types of economy-accelerating digitalization, which are called *push impacts*. At the beginning of this section, it was argued that not all trips are equal, and that the type of rebound trips is essential for the environmental outcome of a dual-venue conference. More generally, [46] argues that not all products and economic processes are equal. In its view, push impacts operate by accelerating the output of products and processes which are beneficial for environmental sustainability. In particular, these are cleantech products (that substitute less resource-efficient technologies) and circular economy processes (i.e., the ones optimizing resource sharing, circulation, and longevity). If digitalization accelerates such products or processes, they will become more attractive and will tend to substitute other, more harmful activities. Acceleration is thus not harmful, per se, just the acceleration of the wrong kind of processes and products.

VI. DISCUSSION: DIGITALIZATION AS AN ENVIRONMENTAL SILVER BULLET?

Ongoing rapid digitalization is often envisioned as a silver bullet to tackle – or at least mitigate – the world's increasingly urgent environmental issues. In particular, it is seen as a possible key factor in reducing carbon emissions and resource consumption across various economic sectors. Statements to this effect have been put forward by the information and communication technologies industry itself [1, 47, 48], as well as academia [3, 49] and international bodies such as the European Commission [50], the OECD [51], the International Energy Agency [52], and even environmental NGOs such as the WWF [2, 53].

Many of these and further assessments, in particular those with an industry background, deployed questionable methods and yielded overly optimistic results. They deliver an almost religious promise, which is being heralded by some prominent proponents with much fervor: that digitalization can be our common savior, the messiah-like technology that redeems us our environmental sins and which promises that we can maintain our current lifestyles while digitalization will handle the consequences.

One of the main flaws of existing assessments is by and large their disregard of rebound effects. Digitalization, however, pervades nowadays virtually all economic sectors and has become an indispensable part of technological infrastructure, not unlike roads or the electrical grid. Thus, it also fosters efficiency gains throughout the economy. Given its immateriality, its potential for virtualization, and the low entry barriers for its adoption, it is also a technology phenomenon that develops its effects very rapidly (and often without geographic limits). For all these reasons, digitalization seems to be particularly prone to the various incarnations of rebound effects.

The efficiency gains induced by digitalization are not only traditional resource or energy efficiency; above all, it can save us all time and allow us to connect across continents and cultures. The induced secondary effects of the latter, and the time rebound of the former, are typical (although not necessarily exclusive) to digitalization, and arguably amongst the strongest mechanisms leading to rebound effects. Concerning time rebound, [16] writes that it "will be especially strong when wages are high and, at the same time, energy prices are low, as is currently the case in most industrialized countries. High wages, which represent the opportunity costs of time, in combination with low energy prices encourage the increasing use of time-saving but energy-intensive devices leading to an overall increase in energy use as people constantly try to 'save' time".

Of course, the life cycle of digitalization technologies (their production, use, and end-of-life disposal) also encompasses an energy and a material footprint. These effects are much better understood, however, and we refrain from discussing them in detail here since they are already thoroughly studied in the literature (e.g., [54-56]).

VII. CONCLUSION

Digitalization is unlikely to be the environmental silver bullet it is sometimes claimed to be. On the contrary, the way digitalization changes society, making it ever faster, more connected, and allowing us unprecedented levels of efficiency might in fact lead to a backfire. As Santarius [57] puts it: "Humanity's ecological footprint keeps growing although we have already digitalized significant parts of our economy and society over the past years. It seems that digitalization is not relaxing but rather reshaping societal metabolism in a way that tends to rebound on global energy and resource demand: Gains in efficiency are more than outweighed by the increase in consumption due to new digital services or falling prices caused by more efficient production processes.”

We cannot, however, agree to the conclusion of [57] that greater efficiency should never be the goal of digitalization, but its enabling power be used for human *sufficiency* and economic degrowth. Above, we presented several conditions that seem to lead to either no rebound or only a moderate rebound effect, and they are all related to *efficiency*, not to *sufficiency*: i) when the rebound activities inherently have a smaller footprint or resource consumption than the originally optimized activities (such as intra-continental flights compared to intercontinental flights), ii) when there is a different limiting factor (financial or physical) than the one becoming more efficient, or iii) when the market is saturated. Additionally, we mentioned an entire category of desirable rebound effects: the push effects discussed in [46], where the rebound of the right (i.e., environmentally beneficial) sort – cleantech or circular economy processes – displaces the wrong kind.

For most manifestations of digitalization, however, a strong digital rebound seems to be the rule rather than the exception. The sometimes spectacular per-usage efficiency gains of digitalization, bearing the toxic gift of strong digital rebound at their very core, hardly alleviate the global issue. As discussed in Section III, the mechanisms behind rebound effects in general, and thus of digital rebound as well, are essentially non-technical in nature. Their roots reside in economics and in human behavior. It is thus highly unlikely that digital rebound can be addressed solely through technological means. While digitalization does often wait on the sideline, ready to provide efficient substitutes for existing technologies and processes, the avoidance of digital rebound effects needs to be enforced differently, possibly by policy measures.

More research will hopefully further refine which parts of digitalization lead to significant rebound, and which digital goods and services induce either only moderate rebound or foster environmentally friendly technologies and processes. More research is also needed to understand which are the policy measures that can foster the latter and impede the former.

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