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Digitalization and the Decoupling Debate: Can ICT Help to Reduce Environmental Impacts While the Economy Keeps Growing?

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Abstract: Digitalization can increase resource and energy productivities. However, the production and usage of information and communication technologies (ICTs) require materials and energy, and the application of ICTs fosters economic growth. This paper examines whether digitalization helps or hinders an absolute decoupling of environmental throughput from economic growth. The paper combines the literature on “green IT” and “ICT for green” with studies on decoupling, i.e., the relationship between economic growth, technological change, and environmental throughput. The paper identifies several strains of the decoupling debate and connects them to the environmental implications of digitalization. We focus on the relation between digitalization and (1) the question of finite non-renewable energies, (2) the environmental Kuznets curve, (3) the role of energy consumption for economic growth, (4) efficiency improvements vis-à-vis rebound effects, and (5) the role of general purpose technologies for resource and energy demand. We find that the empirical basis regarding digitalization’s relation to these four aspects is still weak and hence, further research is needed. Comparing the mitigating and the aggravating impacts of digitalization, we conclude that a more active political and societal shaping of the process of digitalization is needed to make ICT work for global environmental sustainability.

Keywords: decoupling; economic growth; green growth; degrowth; ICT for sustainability; green IT; Kuznets curve; general purpose technologies; limits to growth; energy economics

1. Introduction

In many countries of the world, particularly industrialized countries, environmental throughput has increased during the past years and decades [1]. For example, greenhouse gas (GHG) emissions increased from 2000 to 2010 by 2.3% per year compared to 1.3% per year from 1970 to 2000 [2]. If certain environmental boundaries are not to be transgressed [3], the rise in resource use and environmental impacts cannot continue at the current rate, but rather has to decrease. According to an IPCC report, annual GHG emissions need to decline to 50% of 2010 levels by 2050 in order to limit the global temperature rise to between 1.5 and 2 degrees Celsius [2].

The size of the economy has also increased in the past, both on a global scale as well as for individual countries. While there is a consensus that the increase of environmental throughput needs to come to an end, it is controversially discussed whether economic growth should continue

or not e.g., [4]. This debate needs to be differentiated between high-income and middle/low-income countries. In high-income countries, arguments in favor of economic growth are that it is necessary to achieve a high level of employment [5], to finance social security systems and state expenditures [6], and to facilitate investments in green production [7–10]. On the other hand, it is put forward that strong environmental regulations [11] or reductions in average working hours could prevent unemployment in non-growing economies [12]. It is argued that further economic growth does not increase well-being empirically (based on subjective well-being research, see for example [13]), in particular, because additional consumption does not lead to additional utility as it is primarily conspicuous consumption [14]. In countries with lower incomes, these counterarguments do not apply or to a lesser degree. Therefore, the case for economic growth is stronger and economic growth is often regarded as necessary to achieve high welfare and a green(er) economy [9,15].

So far, different conclusions have been drawn from these considerations. (1) If one agrees that environmental throughput needs to decline and economic growth is necessary to invest into transforming unsustainable modes of production and consumption towards green alternatives, strategies for decoupling economic growth from resource use are the best way to achieve environmental sustainability. The feasibility of such decoupling has been investigated by various authors e.g., [1,7,9,15–20]. Particularly, it has been noted that neither a “relative decoupling” nor an only slight “absolute decoupling” of economic growth from environmental impact is enough, at least in industrialized countries, but that a sufficient absolute decoupling (), [16] (p. 2), [21] (p. 33), [22] (p. 59)) is needed—i.e., a decoupling that is fast enough and deep enough to reach important sustainability goals. (2) If one does not believe that such a sufficient absolute decoupling is possible, one has to analyze the drivers of economic growth and identify ways to eventually limit those, while at the same time finding ways to secure investments into green transformations and high well-being without further economic growth. These endeavors have been discussed in debates about post-growth or degrowth, e.g., [4,5,14,22–26].

In this paper, we address both of those considerations and link them to the debate about digitalization. By the process of digitalization, we broadly understand the increased use of digital devices and algorithm-based applications in many areas of economic and social life. Digitalization is often attributed to increase energy and resource efficiency and dematerialize production and consumption patterns [27]. The general point of departure of this article is that the process of digitalization may challenge both: the debates about decoupling, as well as the debates about green growth versus degrowth.

As for decoupling, several studies outline both opportunities but also limits of digitalization to increase energy and resource efficiencies and dematerialize patterns of production and consumption e.g., [27–30]. We review these lines of reasoning and link them to the core arguments of the (conventional) decoupling debate in order to investigate whether digitalization alters the prospects for decoupling. Note that we focus on the need to reduce resource use, energy, and associated impacts in absolute terms. Therefore, we do not address the prospects for relative decoupling but focus on absolute decoupling, particularly in high-income countries [20,31,32].

Our structure is as follows. In Section 2, we briefly present an empirical overview of the long-term developments of information and communication technology (ICT) sector growth, economic growth, and environmental impacts according to certain indicators and selected country groups. In Section 3, we identify core arguments and state of literature of several decades of decoupling debate(s). On this basis, Section 4 analyzes whether and to what extent digitalization mitigates or aggravates the prospects for the absolute reduction of energy and resource use. In Section 5, we discuss our findings. Given that the lessons learned in Sections 4 and 5 suggest that digitalization will not contribute to a sufficient absolute decoupling in the necessary timeframe, Section 6 outlines key research avenues to make digitalization work for environmental sustainability.

2. Empirical Developments of Digitalization, Environmental Impact, and Economic Growth

As a starting point, we have analyzed long-term country-specific data (1995–2017) in order to identify the developments of economic growth, ICT sector growth, energy demand, and CO₂ emissions in the recent past. Figure 1 presents those correlations for the group of 28 EU countries, the United States, China, and India.

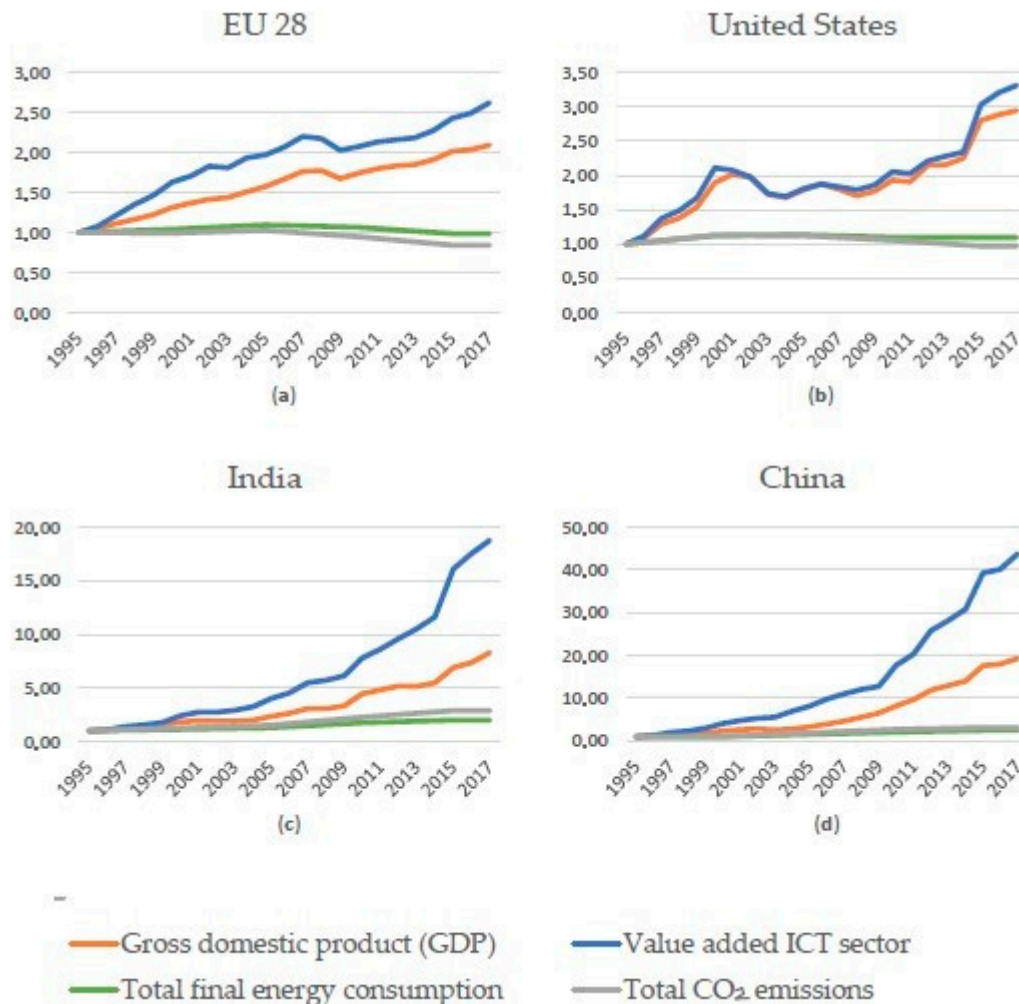


Figure 1. Empirical developments of digitalization, economic growth, and environmental impact for selected countries. This graph shows economic growth, energy consumption, growth of the ICT sector and CO₂ emissions from 1995 to 2017 for (a) EU 28, (b) US, (c) India and (d) China (Index 1995 = 1). GDP and Value added of the total ICT sector are in Millions of current EUR PPS (Monetary values are expressed in euros and Purchasing Power Standards (PPS) at current prices). Energy Total Final Consumption is measured in Mtoe. Co₂ emissions from fuel combustion are measured in Mt of CO₂.

For all presented countries, ICT sector growth (i.e., growth in ICT value added) outnumbers overall GDP growth. This trend is mirrored by results from other studies, which also show that economies are increasingly digitalized [33,34]. Yet, while the ICT sector growth is disproportionately fast in the EU and in particular in China and India, ICT growth is only slightly faster than GDP growth in the US.

Regarding energy and CO₂ emissions, the results also differ between countries and regions. In the EU28 and the USA (early industrialized countries), both stay roughly constant or decrease slightly. Comparing 1995 with 2017, the EU has experienced a 1% drop in final energy consumption, while it has grown in the US by 10%. CO₂ emissions have slightly decreased for both—in the EU by 16% and in the

US by 3%. The developments have been rather different in China and India. Energy consumption has increased significantly in both countries: in China by 149% and in India by 100%. CO₂ emissions have also grown, in China by 211% and in India by 188%. Of course, these increases in the two countries have been accompanied by much higher economic growth rates than in the EU and the US.

Overall, the developments show that economic growth and a digitalization of the economy have been accompanied by relative—and in some cases even a slight absolute—decoupling of energy consumption and CO₂ emissions. Of course, these are merely developments and no causal inference can be made. Therefore, and in order to deeper understand the interrelationships between digitalization, environmental impacts, and economic growth, we will now dive into a qualitative analysis that intertwines findings from the “decoupling debate” with findings from the more recent “ICT for sustainability” literature and identify factors that either mitigate or aggravate the chances for a sufficient absolute decoupling.

3. State of Literature: Key Arguments of the Decoupling Debate

In the following section, we summarize key arguments from various strains of the decoupling debate. Without claiming to be exhaustive, we focus on five strains of that debate: the “limits to growth” debate, which started with a seminal study with the same title in 1972 (Section 3.1); the debate about the environmental Kuznets curve (EKC), which has been the key reason in the debate on structural economic change and environmental impacts (Section 3.2); the debate on the role of energy as a production factor for economic growth, including both views from energy economics and ecological economics (Section 3.3); the debate on energy efficiency improvements and rebound effects as one particular focus of the role of energy for growth (Section 3.4); and finally, the debate on the role of general purpose technologies for both environmental impacts and economic growth (Section 3.5). Afterward, in Section 4, we will revisit the key arguments of these five strains and link them to the question of digitalization.

3.1. *Limits to Growth and Scarce Resources*

The debate on the relationship between economic growth and material throughput experienced its first peak in the 1970s. In 1972, the report *Limits to Growth* [35] argued that natural resources will become scarce if the trajectories of economic growth and growth in material use continue. Focusing on the limited supply of non-renewable resources, early contributions within economics investigated the conditions for economic production in the long term. Three concepts to align ongoing economic growth with reduced environmental impacts were put forward: “substitution, resource-augmenting technical progress, and increasing returns to scale” [36] (p. 134). Note that all three of these concepts refer to technological solutions. Substitution means that natural resources are to be substituted by another production factor, in particular physical capital [37]. Resource-augmenting technical progress signifies that new technologies facilitate the same amount of production with less natural resources [38]. Increasing returns to scale imply the more efficient use of natural resources for larger levels of production. In the end, these discussions showed that the only way to facilitate constant or even rising production in the long run, while assuming a finite non-renewable resource base, is by continuously increasing resource productivity. How fast it has to increase depends on the combination of the size of production, the stock of natural resources, and the time horizon [36].

3.2. *Environmental Kuznets Curve*

The concept of the environmental Kuznets curve (EKC) gained momentum with the evolving sustainability debates in the late 1980s and 1990s [39,40]. The original Kuznets curve postulates that income inequality first rises and then decreases in the process of economic development. Similarly, the EKC suggests that environmental impacts rise and then decrease in growing economies [41]. Hence, it can be considered a strain of the decoupling debate, because arguments based on the EKC assume that environmental impacts would decrease with rising economic growth, at least in industrialized

countries. Two key explanations for this decoupling have been brought forward in the EKC debate. The first directly refers to Kuznets's [42] argument on the direction of sectoral change: environmental impacts are low in economies with a high share of agriculture. When the share of industrial production increases, so do environmental impacts. Yet the key assumption of the EKC is that when a potential subsequent transition to a service economy takes place, environmental intensity would decrease again [43,44]. The second explanation of the EKC refers to the ability and willingness to pay for a cleaner environment, which are affected by rising incomes, increased information about environmental impacts, and changing values and norms. According to Dinda, "[W]hen a country achieves a sufficiently high standard of living, people attach increasing value to environmental amenities" [45]. Hence, people are willing to spend more of their income for greener products and a cleaner environment.

Overall, meta-analyses on the various empirical contributions to the EKC deliver mixed results. While some research found an EKC for specific environmental aspects, e.g., [46–48], Smulders et al. [49] point out that "[t]he empirical literature on the EKC [...] is huge and far from unambiguous" [49] (p. 440). Stern concludes: "It seems that emissions of most pollutants and flows of waste are monotonically rising with income, though the 'income elasticity' is less than one and is not a simple function of income alone" [41] (p. 1435). Caviglia-Harris et al. [50] and Markandya et al. [51] come to the conclusion that global environmental problems such as the environmental footprint or greenhouse gas emissions do not follow an EKC.

3.3. Role of Energy for Economic Growth

Another strain in the decoupling debate focusses on the relationship between economic growth and energy. Empirically, gross energy demand and GDP appear highly coupled in the vast majority of countries worldwide [52]. However, the question is whether this could be different in the future. This debate goes back to the early oil crisis in the 1970s, became a key topic of the subdiscipline of energy economics throughout the 1980s (e.g., [53,54]), and remains heavily debated until today [55]. The key question is: is energy of particular importance to economic growth, or can it be easily substituted so that economic growth can be decoupled from energy use? Two arguments are central in that debate.

First, the output elasticity of the production factor of energy is discussed, but remains unsolved between different schools of thought. In neoclassical growth theories, energy plays a limited role and, therefore, the output elasticity of it is small [56]. Other authors argue that energy plays an important role in the level of production despite its low cost share compared to capital and labor [57,58]. Not only the quantity of energy demand but also the shift from low-quality energy carriers (i.e., wood, coal) to high-quality energy carriers (i.e., electricity) are key drivers of growth [56,59]. Second, a long-standing debate investigates whether the production factors capital and energy relate like "substitutes", so that capital actually replaces energy, or whether they rather relate as "complements", so that increased investments in, or spending of capital bring about an increased demand for energy [60]. Regrettably, the empirical literature is far from uniform on this question and cannot even agree on a range of the elasticity in question [61,62]. Hence, the debate about whether energy and economic growth can be decoupled remains unsolved.

3.4. Energy Efficiency and the Rebound Effect

One particular focus of the energy–growth debate centers on the role of energy efficiency improvements for economic growth, which relates to the phenomenon of the rebound effect [63–65]. It is well documented that the history of industrialization brought about continuous efficiency improvements in the conversion of energy resources to energy services (e.g., coal/oil/gas to heat/power/light), but also in the provision of energy services to utility and value [66,67]. If these efficiency improvements lead to rebound effects, i.e., an increase in the demand for energy services, such energy efficiency improvements play out as a driver of economic growth. At the same time, parts or all of the technical savings potential can be "eaten up" by the increased demand for energy. If rebound effects are high, the contribution of energy efficiency improvements to decouple economic growth from energy consumption is limited.

The estimation of the overall size of rebound effects varies highly across studies. At one end of the spectrum, it is stated that “most of the economic growth of our Western civilization in the past 200 years stems from the rebound effect” [66] (p. 233). In a similar vein, other rebound researchers believe that improvements in energy conversion technologies would contribute to increasing economy-wide energy demand over and above the initial level—a phenomenon that is termed backfire [53,68–70]. At the other end of the spectrum, some researchers argue that the contribution of rebound effects to energy consumption is relatively insignificant, e.g., [71–74]. Most rebound researchers appear to position themselves somewhere in the middle, finding that rebound effects do not generally lead to backfire, but that they are high enough to countervail a sufficient absolute decoupling of energy demand from economic growth [21,75–78].

3.5. General Purpose Technologies

Another strain of research focusses on the specific role of “general purpose technologies” (GPTs). In a comprehensive analysis, Lipsey et al. [79] classify 24 different technologies, including the steam engine, railway, electricity, automobile, airplane, and computer, but also “organizational technologies” such as mass production or lean management, and others [79] (p. 132). According to Lipsey et al. [79], GPT can be assigned characteristics such as genericness, scope for improvement, multiple applicability, and complementarity to existing technologies. Other definitions of GPT focus more on criteria such as pervasiveness and innovation spawning [80].

For the decoupling debate, three key findings from research on GPT can be distinguished. (1) Particularly during the expansive phase of a given GPT, its environmental impact strongly depends on the energy intensity of that GPT. (2) The impacts of GPT are pivotal explanatory factors of long-term economic growth: “One of the most important aspects of GPT is that they rejuvenate the growth process by creating spillovers that go far beyond the concept of measurable externalities” [80] (p. 100). (3) These positive effects on economic growth are only temporary for a single GPT [79]. Regarding the relationship between energy use and economic growth, Lipsey et al. [79] postulate that these function as complements, not as substitutes. Overall, research on GPT suggests that the contribution to decoupling is limited. It should be noted, however, that there is still little research on this issue.

4. Digitalization, Resource Use, and Environmental Impacts

In this section, we revisit the five strains of the decoupling debate summarized in Section 3 and link them to the role of digitalization (ICT) for economic growth and environmental impacts. Each subsection is condensed in a preliminary conclusion for each strain of the decoupling debate, which we merge in the overall discussion in Section 5.

A few studies have attempted to balance ICT’s positive and negative environmental impacts throughout all sectors [28,81,82]. However, these studies do not seem reliable, and methodological developments for a comprehensive and consistent synopsis are still at the beginning stages [81]. In order to come closer to an answer, in the following, we revisit the aforementioned arguments of the decoupling debate(s) with a focus on digitalization’s effects on resource use, energy demand, and economic growth.

4.1. ICT and Scarce Resources

The potential end of (non-renewable) resources as an absolute limit to economic growth has been one key argument since the early debates on decoupling (see Section 3.1). Digitalization is supposed to help prevent this absolute limit by increasing resource efficiency. At the same time, it is clear that the production (and application) of ICT itself requires resource consumption. There is little research to date that attempts to quantify ICT’s resource demand, both regarding past and future demand.

Marscheider-Weidemann et al. [83] investigate changes in raw materials demand between 2013 and 2035 due to technological change. Among the technologies investigated are eight emerging ICT technologies. They identify sixteen raw materials of particular relevance, such as lithium,

dysprosium/terbium, rhenium, tantalum, cobalt, germanium, scandium, and neodymium. Driven by the growing demand for ICT and of various other emerging technologies, the demand for several of those resources is projected to exceed the total 2013 production levels by 2035 [83]. Malmmodin et al. [84] present high-level estimates of the worldwide ICT sector's material footprint for 2015, including electronic and media devices. The results show that the sector has a rather low impact on the global usage of sector-relevant materials (representing about 0.5% of the global annual usage of the selected materials). However, for single materials such as gallium, germanium, and indium, the ICT sector represents the dominant use with as much as 80–90% of global usage [84]. A study by Henckens et al. [85] focuses on the scarcity of metals and clusters over 40 metals according to their geological scarcity. Among the five metals identified as “very scarce” or “scare”, several materials relevant to the ICT sector can be found [85]. A study on the material effects of emerging data storage technologies shows low demand for critical elements compared to their global production rates. However, a significant increase in hard disk drive production could affect the supply chains of neodymium and platinum-group metals [86]. Vaalma et al. [87] estimate that with growing demand for lithium-ion batteries, lithium and cobalt could become scarce by 2050. The increasing demand is partly due to ICT devices, but also stems from e-mobility and other applications [87].

Research on the substitution of certain elements in the ICT sector is at an early stage. Instead of lithium-ion batteries, for instance, sodium-ion batteries could be a possible substitute for certain applications. However, portable ICT devices are still expected to require lithium-ion or other cobalt-rich batteries [87]. Investigations on substitution opportunities of rare earth metals in low-carbon technologies such as lighting, wind turbines, or electric vehicles show mixed results [88–90]. While in both the wind industry and lighting sector, technology development has the potential to lower the demand of rare earth metals [88,90], the opposite has been found for the electric vehicles sector. Growing demand for electric vehicles is expected to also increase the demand for rare earth metals [89].

Preliminary conclusion: The ICT sector's demand for resources and energy only accounts for a small share of global demand. However, several resources that are important for ICT devices are scarce or expected to become scarce within the next decades. As of current knowledge, a stark scaling up of production, i.e., for millions of digital devices in the upcoming Internet of Things, seems challenging at least. There is literally no evidence for an increasing share of renewable materials in the production of ICT devices. Research on substitution potentials of certain critical materials is still very weak—recalling the state of research during the limits to growth debate in the 1970s. These facts support the argument that digitalization rather aggravates the challenges for decoupling regarding natural resources.

4.2. *ICT and the Kuznets Curve*

The first argument for the environmental Kuznets curve is that environmental impacts decrease when economies develop from primarily producing industrial goods to focus on the services (see Section 3.2). Several studies suggest that ICT leads to particularly high growth rates in various service sectors [91–93]. According to Sapprasert [94], ICT on average leads to higher growth rates of productivity and profitability in service sectors compared to manufacturing sectors. In an increasingly ICT-driven industry, ICT services and maintenance gain in importance in many areas of manufacturing [95]. ICT has also been argued to play a role in the division of labor, leading to stronger tertiarization in countries of the Global North and stronger industrialization in other countries [96–98]. However, some authors argue that certain digital technologies, such as 3D printing, may lead to a relocation of manufacturing back into the Global North in future years [99–101]. From a global environmental point of view, the central question is whether ICT may spur a global environmental Kuznets curve, rather than relocating dirty production into other parts of the world. Research on such global developments is still missing.

The second argument for an EKC is that the level of information and the prevalence of environmental values and norms increase with the level of economic wealth and, therefore, the ability and willingness to pay for environmental protection and more sustainable forms of production and

consumption rises. There is little doubt that digitalization carries the potential to increase the amount, and also the granularity, of information about more sustainable forms of production and consumption. Consumers can search the internet or use certain blogs or apps (e.g., apps based on bar code scanning) to access information about product derivation and characteristics, such as a product's ecological footprint [102–104]. More information and more timely information (i.e., in real-time; while shopping), as well as better visualization of information through apps, increase the chances for informed consumer decisions [105–107]. This increases the ability of consumers to choose more sustainable ways of needs satisfaction. Digitalization also improves the ability of firms to serve consumers' interest in sustainable consumption. By way of digital supply chains, companies may take better control of production standards of supply components [108,109]. ICT can also improve coordination and communication between producers and consumers and, hence, more readily include consumer preferences in the design, production, and marketing of products [110–112].

However, as the role of information in consumer choices has been well researched in various fields, it cannot be stated that improved information generally leads to more sustainable consumption behavior [113,114]. At the same time, countervailing forces are at work: information provided by online marketing and personalized advertisement serves as an effective tool to drive consumer choices towards more consumption and fewer sustainability concerns [115–118].

Preliminary conclusion: Existing evidence suggests that digitalization spurs a further tertiarization of the economy in countries of the Global North. The global effect, however, is unclear. Digitalization improves the amount and quality of information about production standards and more sustainable consumption opportunities. At the same time, it remains open whether digitalization actually changes social values and norms towards sustainability and, hence, improves the willingness to pay for more sustainable products and services.

4.3. ICT and Energy Demand

As we have outlined in Section 3.3, both the price of energy as well as changes in the kinds of energy carriers used may impact economic growth and, hence, resource demand. Studies on the energy consumption of the ICT sector show a steadily and quickly increasing energy demand over recent years [119–121]. According to some scenarios, ICT's future electricity consumption is expected to rise from 1500 TWh (8% of global electricity consumption) in 2010 to 5700 TWh (14% of global electricity consumption) in 2030 [119,122]. In contrast, other authors find that the operational electricity demand of the ICT sector remained roughly constant at around 800 TWh between 2010 and 2015 (4.3% of global electricity consumption for 2010 and 3.8% for 2015) and was slightly rising between 2015 and 2018 [123].

Next to the electricity consumption of ICT itself, the question is how the electricity consumption for an entire economy is related to digitalization. For OECD countries, a panel data analysis for the years 1985–2012 by Salahuddin und Alam [124] suggests that growing ICT use results in increasing both electricity consumption and economic growth. This corresponds to the result of a previous panel data analysis by Saidi et al. [125]. Sadorsky [126] finds a positive relation between the share of internet users and electricity demand. Digitalization, hence, tends to go along with higher electricity consumption.

However, several authors find that ICT can be associated with decreasing overall energy consumption [127,128] and can substitute energy as a production factor [129]. It may therefore be, that digitalization supports a switch from other energy carriers towards electricity [130]. According to the arguments raised by Stern and Kandler [56,59], this may spur further economic growth and increases in resource demand. This goes hand in hand with the empirical result that digitalization is associated with higher levels of economic growth (see Sections 2 and 3).

Preliminary conclusion: Studies suggest both a complementary relationship of ICT electricity demand and economic growth and a shift towards electricity as the main energy carrier due to digitalization. While the basis of literature is still weak, these facts support the argument that digitalization rather aggravates the challenges for decoupling regarding energy demand.

4.4. ICT, Efficiency Improvements, and Rebound Effects

Regarding the potential of ICT to save energy and resources, several studies suggest that the application of digital devices and programs can increase efficiencies in several areas, including the important sectors agriculture, transport, and industrial production, e.g., [28,131]. Sui and Rejeski [132] call these positive environmental effects of ICT the “three D’s for the new economy”: dematerialization, decarbonization, and demobilization. Berkhout and Hertin [133] describe the use of ICT as an enabling technology for reducing environmental throughput. Many other sources of “grey literature” promise that the virtualization by way of ICT would also lead to dematerialization and provide for a win–win of the economy and the environment [134–136].

In fact, the application of ICT tends to increase energy and resource efficiencies when looking at specific goods or services, as shown by several empirical studies. The following references highlight some examples. Coroama et al. [137] evaluate the GHG abatement potential of virtual conference meetings, where the exchange between two slots was provided by a video conferencing system. The results indicate a GHG abatement potential of 37 to 50% compared to an on-site conference. Moberg and colleagues evaluate the energy-saving potential of electronic invoicing [138] and the environmental advantages when switching from conventional newspapers to checking news online [139]. Other studies highlight the potentials savings from streaming videos versus DVD rental when driving to the rental outlet by car [140,141]. Beier et al. [142] investigate whether the Industrial Internet of Things enables more sustainability in industry. The authors cite additive manufacturing technologies such as 3D printing, which enable resource-efficient manufacturing of prototypes and products with small lots and high variances.

However, several studies also show mixed results. In a study of the Japanese book sector, Williams and Tagami [143] compared e-commerce and conventional retailing. Results show that in urban areas, retailing uses significantly less energy per book. In rural areas, both systems use a similar amount of energy. Other studies on energy savings in e-commerce also show ambiguities, e.g., [144–146]. Opportunities for resource reduction in the production sector also arise from increasing supply chain transparency, improved recycling processes, and predictive maintenance.

In addition to those and many other studies showing the positive effects of efficiency improvements or mixed results, there are strong arguments that increases in efficiency are often countervailed by negative environmental effects, such as incomplete substitution, rebound effects, and induction effects [105,147–149]. For instance, potential savings from video streaming vis-à-vis DVD rental are likely countervailed by the increased hours watched [27]. In more general terms, the ICT sector may be particularly prone to high rebound effects [30,65,150].

Preliminary conclusion: Literature abounds on energy saving potentials from ICT-based efficiency improvements in various production and consumption processes. Yet, those studies focus on micro-level effects only and neglect any global effects at the macro-level. Additionally, they mostly describe potentials rather than actual developments. Theoretical arguments for incomplete substitution and potential rebound and induction (growth) effects are strong and are backed by anecdotal evidence, while empirical evidence on the causal link between digitalization and rebound effects has not yet been sufficiently researched on empirical grounds. These ambiguous facts suggest that ICT’s overall effect on energy consumption via energy efficiency and rebound effects still remains unclear.

4.5. ICT as One or Several General Purpose Technologies

Research on GPT stresses that the characteristics of a given GPT strongly influence both the speed of economic growth and the change in energy intensity throughout the economy, particularly in its early “take-off” phases (see Section 3.5; [79]). The relation of ICT to these aspects, therefore, has a strong impact on the prospects to decouple economic growth from energy consumption in the near future.

There is an almost unanimous agreement for a positive relation between digitalization and economic growth. Several studies find a positive relation between digitalization and the level of GDP [151] and the speed of economic growth [124,152–155] for a diverse set of countries ranging from

the US over OECD countries to South Asian and Latin American economies. In addition to these studies at the macro-level, various micro-level studies suggest increased investments and profits for businesses due to digitalization [28,91,93,95,156,157].

On the other hand, different studies suggest that digitalization contributes to increased unemployment, as well as a polarization of income [158–161]. High income inequality usually dampens aggregate demand and economic growth [162]. So, despite the significant number of studies suggesting a positive effect from digitalization on economic growth, in the future, this effect might be lower if distributional effects of digitalization on economic equality will countervail its growth potentials.

The literature regarding GPTs in general (Section 3.5) suggests that a GPT's impact on economic growth is mainly temporary. However, the question arises: can "ICT" be classified as one single GPT, or does it rather cover multiple GPTs? Several authors suggest that the computer (i.e., microprocessor), the Internet, mobile ICT equipment, and cloud computing might be considered as separate GPTs which are already in place, while machine learning ("artificial intelligence"), the (Industrial) Internet of Things, or virtual/augmented reality might be considered GPTs still in their beginning [163–166]. Accordingly, the expansive phase of ICT as multiple GPTs and their (temporary) impact on overall economic growth would span several phases, during which energy use and economic output would both significantly increase. Reports on the expected potential of cloud computing, big data analytics, artificial intelligence, automation, and robotics on future economic growth support the assumption that ICT may have a longer-term impact on economic growth [28,91–93,95,98,124,156].

As for energy intensities, measured as energy input per unit of GDP (e.g., US dollars), producing and running ICT devices and applications is less energy intensive compared to former GPTs such as trains, cars, or airplanes see [67]; yet they are probably more energy intensive than GPTs such as the laser or "lean management" techniques. The energy intensity of ICTs as multiple GPTs can probably not be grasped by looking at single devices or applications, but by their sum. Since ICTs have an outstanding diffusion potential—the number of devices and their pervasiveness in working life and everyday life is much higher compared to any former GPT except for electricity—their share in global electricity demand is already high today, and may increase significantly in the future (see Section 4.3). At the same time, as has been mentioned in Section 4.4, ICT has a far higher potential than former GPTs to reduce energy and resource demands in many sectors by way of efficiency improvements, optimization, and substitution. Comparing the GPTs "ICT" and "electrification", Jovanovic and Rousseau [167] suggest that the introduction of electrification was more pervasive, while ICT may be more efficiency increasing and innovative.

Preliminary conclusion: The process of digitalization yields not only one, but several GPTs. Their energy intensity is lower compared to former GPTs. However, due to high pervasiveness and diffusion, their aggregated effect on economic growth is likely to be strong and long term. Hence, also, the effects on global resource and energy demand are likely to be significant, in particular during each of the single GPT's expansive phases. These arguments suggest that at least during the coming one or two decades, digitalization rather aggravates the challenges for decoupling.

5. Discussion: Lessons Learned on Digital Decoupling

As we have seen, research about decoupling and digitalization is still at the beginning stages, and empirical quantifications covering various sectors and use cases are limited. It is not (yet) possible to draw a line under all beneficial and detrimental environmental effects and to fully answer whether, overall, digitalization facilitates decoupling or makes it more difficult.

In Section 2, we presented the empirical developments of ICT sector growth, economic growth, and environmental impacts which, amongst others, showed that a digitalization of the economy takes place, while a sufficient absolute decoupling is not taking place. Against this background, we have summarized five strains of the decoupling debate in Section 3 to provide qualitative analyses in order to understand these developments. The five strains have developed historically and often quite

separately. Therefore, it is not obvious how they are connected and how each of them links to the role of digitalization (ICT). In order to shed light on the role of digitalization regarding decoupling, the most insightful connection between the different debates is the role of technology. The existing and anticipated technologies determine how fast resource use can be augmented and production factors can be substituted (see Section 3.1). The EKC implies a switch of the shares of technologies used from agricultural to industrial to service-related technologies (Section 3.2). Technological possibilities determine how far it is possible to use physical capital instead of energy (Section 3.3), and to what extent efficiency improvements deliver a more economical use of energy (Section 3.4). General purpose technologies have a strong impact on economic growth and its relation to energy intensity (Section 3.5). The impact of ICT on the relation between economic growth and energy consumption (in other words, on decoupling) is, therefore, how the digital technologies change these respective aspects.

Table 1 condenses the preliminary conclusions from Sections 4.1–4.5 as well as Section 5 and, hence, summarizes how digital technologies aggravate or mitigate the challenges of decoupling—structured along the five debates on decoupling. Additionally, the table encompasses open questions in this new domain of research on digitalization and decoupling.

Table 1. Digitalization and the decoupling debate—summary of key arguments.

	Digitalization Aggravates the Challenges for Decoupling	Digitalization Mitigates the Challenges for Decoupling	Open Research Questions
Limits to growth debate	Upcoming scarcities of certain materials Currently low/no substitutability of certain materials	–	In how far does ICT increase resource efficiencies in other sectors?
Environmental Kuznets curve debate	Improved personalized marketing incentivizes consumption	Tertiarization of the economy in high-income countries Improved process and product information facilitates sustainable consumption	Does ICT go along with tertiarization on a global scale?
Efficiency debate	Potential for rebound and induction effects increase demand	Potential for efficiency improvements decreases demand	How strongly does ICT increase energy efficiencies in other sectors?
Energy and economic growth debate	Shift towards electricity as main energy carrier spurs economic growth	Shift from other energy carriers towards electricity (which has a relatively high share of renewables)	Can ICT sector growth be absolutely decoupled from ICT energy demand?
General purpose technology debate	Complementary relationship of ICT energy demand and economic growth	–	What is the long-term impact of digitalization on economic growth?
	Prolonged impact on economic growth due to several ICT-born general purpose technologies	–	

Table 1 shows that we have at least as many questions as answers regarding the impact of digitalization on decoupling in the past. Regarding future developments, the overall result is even

less clear. To summarize the state of knowledge, there is significant empirical evidence for the energy and resource use directly related to ICT—both have been rising in the past. In addition, there is clear evidence that ICT supports economic growth. Both aspects rather aggravate the problem of decoupling. We know less regarding the potential environmental benefits of ICT. It is unclear in how far the application of ICT actually improves energy and resource efficiencies throughout the economy and whether it spurs tertiarization worldwide (and not merely represents a division of labor between high-income and other countries). The ability to understand the impact of digitalization on decoupling rests to a large degree on the answers to these questions.

Taking both the empirical correlations (Section 2) and the conceptual arguments (Section 4) as they are, there are considerably more indications that digitalization aggravates the challenges for decoupling than mitigates them. Four aspects are central. (1) The resource and energy use of ICT is growing. While the overall resource use of the ICT sector is relatively small, its dependence on crucial materials may limit its spread in the medium run. (2) Whether digitalization initiated a strong tertiarization on the global scale (and not only within certain countries) is questionable. The expectation that ICT helps the environment significantly due to this mechanism does not seem probable. (3) More promising is that the application of ICT throughout the different sectors of the economy allows for large increases in energy and resource efficiency. This is the central potential of ICT to facilitate decoupling. (4) However, this is likely to be counteracted by rebound effects and economic growth. While the size of rebound effects is difficult to measure, the positive impact of ICT on economic growth is evident—making fast absolute reductions in energy and resource consumption difficult.

Hence, and notwithstanding the limited empirical evidence available, it seems unlikely that digitalization as it unfolds today improves the prospects of decoupling. In other words, digitalization might play a role in explaining relative decoupling but not absolute decoupling, which has taken place at least in the EU in the past 20 years (Section 2). Rather, our analysis suggests that digitalization increases absolute energy and resource consumption. If this is true, the experience of (slight) absolute decoupling has to be due to other factors than digitalization. To enhance the prospects of digitalization to support absolute decoupling, it is necessary to speed up increases in energy and resource efficiencies and at the same time limit rebound effects and economic growth. Another conclusion seems relatively safe to make: digitalization by itself does not lead to a sufficient absolute decoupling, i.e., a cut back of resource and energy demands and environmental impacts fast enough and deep enough to reach important sustainability goals, such as keeping global warming at or below 1.5 degrees Celsius. Hence, a more active shaping of digitalization appears needed, which involves policies and measures that intend to maximize digitalization's savings potential and to minimize respective countervailing forces.

6. Conclusions and Further Research Needs

Given our preliminary conclusions in Section 5 above, we would like to highlight four overall conclusions. First of all, our discussion shows that there is a strong need for further research to improve the empirical implications of digitalization on the prospects for decoupling. In particular, research is needed that examines the open research questions indicated in Table 1. Additionally, methods are needed that interrelate effects of digitalization on the micro-scale—e.g., improved efficiency, improved information on certain process and production standards, etc.—with effects on the macro-scale—e.g., economy-wide rebound effects, or the energy–growth nexus. For instance, digitalization may indeed contribute to improved energy efficiency on the micro-scale. However, meso- and macroeconomic effects may induce additional energy consumption elsewhere, so that economic growth and energy demand remain coupled at the macro-scale. Moreover, hands-on empirical research is needed with regard to several aspects, e.g., the substitutability of certain critical and scarce materials, or meta-analysis evaluating the efficiency potential of various digitalized products and services to bring together knowledge that is often selective and dispersed.

Second, we draw from the discussion and the lessons learned in our paper that calling for further empirical research will not solve the overall question discussed in this article. Additional theoretical

research is needed, too. The complexity of the discussion and, in particular, the interdependencies of various and diverse implications of digitalization suggest that it will not be possible to ultimately empirically verify or falsify whether digitalization mitigates or aggravates the prospects for decoupling. For instance, the implications and dynamics set in motion by digital GPT cannot be fully determined empirically. The implications of digitalization are too complex and widespread in society for empirical research to deliver comprehensive (and unequivocal) results. Hence, more profound theoretical understanding of the interrelationship between digitalization and drivers of production, consumption, and overall economic growth are strongly needed.

Third, given both the complexity as well as the rather limited prospects of digitalization for sufficient absolute decoupling, we suggest that research should also follow a “precautionary principle approach” and investigate alternative questions that may also—or maybe better—contribute to achieving sustainable development goals. Most notably, research may focus on the opportunities and limitations of digitalization to foster growth-independent development, i.e., “post-growth” or “degrowth” economic development, e.g., [20,22,168,169]. Such research on “digitalization and degrowth” would aim at realizing steep reductions in resource use and emissions, while making social wellbeing as well as the functionality of the economy more independent from continuous economic growth. For instance, research could focus on how digitalization enables cooperative or non-profit-oriented business cases or how digitalization can empower consumers to make better use of practices such as sharing, repairing, reusing, prosuming, and the like. However, even in a post-growth and sharing economy, a certain level of products and services still need to be produced and maintained. Hence, we suggest to also follow alternative concepts, i.e., how digitalization can advance the prospects for a “circular economy” or even “circular society” [170–173].

Fourth, and with regard to conclusions relevant for policy-makers and other practitioners, our paper suggests that believing in the assumption that digitalization by itself will lead to sufficient absolute decoupling may be short-sighted. However, if political measures and instruments, business initiatives, and user behavior focus on realizing the saving potentials of ICT while countervailing energy- and resource-intensive hardware production as well as energy- and data-intensive applications, this can strongly improve ICT’s contributions to achieving sustainable development goals.

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