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Analysis

Digitalization and energy consumption. Does ICT reduce energy demand?

Steffen Lange[a,b,*], Johanna Pohl[c], Tilman Santarius[a,d,e]

[a] Institute for Ecological Economy Research, Berlin, Germany
[b] Resource Economics Group, Humboldt-Universität zu Berlin, Berlin, Germany
[c] Technische Universität Berlin, Centre for Technology and Society, Berlin, Germany
[d] Technische Universität Berlin, Department of Social Transformation and Sustainable Digitalization, Berlin, Germany
[e] Einstein Centre Digital Futures, Berlin, Germany

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ABSTRACT

This article investigates the effect of digitalization on energy consumption. Using an analytical model, we investigate four effects: (1) direct effects from the production, usage and disposal of information and communication technologies (ICT), (2) energy efficiency increases from digitalization, (3) economic growth from increases in labor and energy productivities and (4) sectoral change/tertiarization from the rise of ICT services. The analysis combines empirical and theoretical findings from debates on decoupling energy consumption from economic growth and from debates on green IT and ICT for sustainability. Our main results: Effects 1 and 3 tend to increase energy consumption. Effects 2 and 4 tend to decrease it. Furthermore, our analysis suggests that the two increasing effects prevail so that, overall, digitalization increases energy consumption. These results can be explained by four insights from ecological economics: (a) physical capital and energy are complements in the ICT sector, (b) increases in energy efficiency lead to rebound effects, (c) ICT cannot solve the difficulty of decoupling economic growth from exergy, (d) ICT services are relatively energy intensive and come on top of former production. In future, digitalization can only boost sustainability when it fosters effects 2 and 4 without promoting effects 1 and 3.

1. Introduction

Greenhouse gas (GHG) emissions and consumption of fossil energy carriers need to decrease fast if environmental goals are to be reached. If the planetary boundaries are not to be transgressed, factors that negatively impact the environment need to decrease significantly (Steffen et al., 2015). For example, GHG emissions need to decrease 45% until 2030 compared to 2010 levels, reaching net zero around 2050 to stay within the 1.5 °C target (IPCC, 2018). Currently, the opposite is the case: Global fossil CO2 emissions increased annually from 2008 to 2017 by 1.5% (Quéré et al., 2018).

A key question in solving these issues is whether economic growth can be decoupled from energy consumption. The quest for decoupling economic growth from various environmental indicators has been discussed in numerous articles and studies (Conrad and Cassar, 2014; Ekins, 2000; Ekins and Hughes, 2017; Fischer-Kowalski et al., 2011; Parrique et al., 2019; UNEP, 2011; von Weizsäcker et al., 2014). If decoupling is possible, strategies along the lines of green growth and a 'Green New Deal' can lead to environmental sustainability (Antal and van den Bergh, 2016; Ekins and Speck, 2011; OECD, 2011). If decoupling is unrealistic or at least unlikely, strategies beyond growth are needed, with different concepts referring to post-growth (Alexander, 2014; Chancel et al., 2013; Jackson, 2019; Petschow et al., 2018), degrowth (Kallis, 2011; Kallis et al., 2018, 2012; Vandeventer et al., 2019; Weiss and Cattaneo, 2017), a-growth (van den Bergh, 2011; van den Bergh and Kallis, 2012), economies without growth (Jackson, 2016; Lange, 2018; Victor, 2019) and parts of the literature on a circular economy (Giampietro, 2019).

Digitalization – the increasing application of information- and communication technology (ICT) throughout the economy and society – has triggered great hopes of reducing energy demand and emissions (GeSI and Accenture, 2015; GeSI and Deloitte, 2019; Mickoleit, 2010). At the same time, criticism has been raised about the overall effects of digitalization on energy demand (Faucheux and Nicolaï, 2011; Hilty, 2012; Hilty and Bieser, 2017; Lange and Santarius, 2020; The Shift Project, 2019). The relationship between digitalization and energy

Abbreviations: ICT, Information and communication technology; EKC, Environmental Kuznets Curve; kgoe, kilogram oil equivalent per dollar; GHG, Greenhouse gas; GDP, Gross Domestic Product; TWh, terawatt hours.

* Corresponding author at: Potsdamer Str. 105, 10785 Berlin, Germany.
E-mail addresses: steffen.lange@ioew.de (S. Lange), pohl@ztg.tu-berlin.de (J. Pohl), santarius@tu-berlin.de (T. Santarius).

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consumption plays a decisive role in determining whether digitalization helps or hinders environmental sustainability, in particular regarding climate change.

Climate change mitigation scenarios reveal that energy consumption must be reduced – in addition to a shift from other energy carriers to electricity and establishing a renewable electricity system (Rogelj et al., 2018). In the last decades, as more and more digital devices have been produced and used, the detrimental direct effects of digitalization – i.e., the emissions due to increasing production, use and disposal of ICT – have increased (Andrae and Edler, 2015; Belkhir and Elmeligi, 2018; Malmodin and Lundén, 2018). If digitalization is to help decarbonisation, its beneficial effects – reducing energy consumption and facilitating the shift towards renewable energy – need to outweigh these direct and other detrimental effects. In this paper, we focus on digitalization's effect on energy consumption with reference to four central effects: direct effects, energy efficiency, economic growth and sectoral change.

We combine empirical literature on the relationship between digitalization and energy consumption with theoretical and empirical literature on decoupling. Insights from this literature explain the current relation between digitalization and energy consumption. The article starts with a definition of different types of decoupling and central debates on whether decoupling is feasible (2). Next, the literature on the relationship between the application of ICT and energy consumption on a macroeconomic level is reviewed (3). Afterwards, an analytical model is developed to analyse the relation between digitalization and energy consumption (4). This model is then connected to four effects of digitalization on energy consumption: direct effects (5), changes in energy efficiency and subsequent rebound effects (6), economic growth (7) and sectoral change/tertarization (8). The results are summarized and discussed (9) and the article concudes with the implications regarding digitalization's potential to alleviate environmental problems (10).

2. Decoupling

Whether digitalization can help to decrease energy consumption is related to an ongoing debate in environmental and ecological economics on whether economic growth can be decoupled from environmental aspects such as energy consumption. Further literature also considers the decoupling of environmental aspects from human needs (Brand-Correa and Steinberger, 2017; Steinberger and Roberts, 2010) – a topic not investigated in this paper. The literature on decoupling economic growth and environmental aspects usually distinguishes between relative and absolute decoupling (Bringezu et al., 2004; Giljum et al., 2005; Naqvi and Zwickl, 2017; Parrique et al., 2019). Various authors suggest that, given the current challenges, slight decoupling is not enough. Drastic absolute decoupling is necessary to remain within planetary boundaries (Lange, 2018; Svenfelt et al., 2019; Xue et al., 2016; Petschow et al., 2018; Antal and van den Bergh, 2016). Therefore, besides relative and absolute decoupling, we introduce 'sufficient absolute decoupling' as a third form of decoupling (definition see below).

We define the level of the energy consumption (E) as the product of the production level (Y) and the energy intensity of production (a): $E = Y * a$. Economic growth combined with reductions in energy consumption is **absolute decoupling**. It signifies that the energy consumption overall declines: As $\widehat{E} = \widehat{Y} + \widehat{a}$ (see Appendix III), the decline of energy intensity (a) needs to be larger than the growth of the level of production (Y): $\widehat{Y} < -\widehat{a}$. Absolute decoupling is usually contrasted with **relative decoupling**, which takes place when energy intensity decreases but economic growth is faster: $\widehat{a} < 0$ and $\widehat{Y} > -\widehat{a}$.We define a third form of decoupling that refers to the sufficient extent of decoupling in a given timeframe. **Sufficient absolute decoupling** means that economic growth and its environmental impact can be decoupled quickly enough so that certain environmental goals are achieved. For example, according to the IPCC (2018), to stay within the 1.5 °C target, emissions need to decline about 45% from 2010 levels by 2030, reaching net zero around 2050. Similarly, Antal and van den Bergh (2016) calculate that the "sufficiently rapid pace" (p. 2) of decoupling would be a decrease in energy intensity of 1.5% per year to stay within the 2 °C target. To reach climate targets, energy consumption must be reduced. In two conservative scenarios of the IPCC (2018), sufficient absolute decoupling requires final energy demand to decrease by 15% in 2050 relative to 2010. Additionally, the share of electric energy in energy end-use has to rise and renewables need to supply 70%-85% of electricity in 2050 in the 1.5 °C pathway, with no or limited overshoot (Rogelj et al., 2018).

We structure the theoretical work on decoupling economic growth and energy around four debates. The first is the relation between energy and physical capital. Daly (1990) prominently argued that, contrary to neoclassical assumptions, energy and physical capital are complements rather than substitutes. Therefore, economic growth cannot be decoupled from energy consumption by substituting energy with physical capital. The second debate concerns whether the strategy of increasing energy efficiency is successful in sufficiently decreasing energy consumption. A central argument is that increasing energy efficiencies would lead to various rebound effects, which would lead to an increase in energy consumption and thereby partly or fully counteract the potential energy savings (Brookes, 1978; Khazzoom, 1980; Santarius et al., 2016; Sorrell, 2009). Third, the debate on entropy laws laid the foundations for the relationship between economic activity and energy consumption (Georgescu-Roegen, 1971). The debate rests on three core arguments: energy plays a much more important role for economic activity than neoclassical economists assume (Ayres, 1999), economic growth and useful work/exergy are closely related (Serrenho et al., 2014) and technical limitations to increase the conversion efficiency from energy to exergy implies limitations to decoupling economic growth from energy (Brockway et al., 2014). Fourth, the hypothesis of the Environmental Kuznets Curve (EKC) states that environmental impacts first increase but later decrease when an economy grows (Dinda, 2004; Stern, 2004). However, this hypothesis is controversially debated on empirical grounds, in particular regarding global environmental aspects (Markandya et al., 2002; Stern, 2004), and on theoretical grounds, in particular regarding whether the services actually replace industrial and agriculture production or come on top (Kümmel, 2011). As is shown below, these four key debates are closely related to the four effects of digitalization on energy consumption. The insights from the four debates help in understanding the four effects.

3. State of literature: ICT and energy on the macroeconomic level

Before investigating specific effects, this section reviews the empirical literature on the macroeconomic relation between digitalization and energy consumption. Literature on the overall relationship between ICT and the energy consumption of entire economies indicates a positive relation – more digitalization results in more electricity consumption. A panel data analysis for OECD countries finds that, in the long run, a 1% increase in Internet users increases per capita electricity consumption by 0.026% (Salahuddin and Alam, 2016). Similarly, an investigation of emerging economies discovers that a 1% rise in Internet users increases per capita electricity consumption up to 0.108% (Sadorsky, 2012). Research using dynamic panel data models also finds a positive relationship for eleven emerging countries from 1990-2014 (Afzal and Gow, 2016). Using panel data analysis for BRICS countries (Brazil, China, Russian Federation, India, and South Africa), Haseeb et al. (2019) find a unidirectional causal link running from ICT towards electricity consumption. Salahuddin and Alam (2015) ascertain that Internet use spurs electricity consumption in Australia.

However, this positive relationship does not hold for all countries and all energy carriers. According to Ishida (2015), ICT investments have a negative impact on overall energy consumption in the long run in Japan. ICT investments are a substitute for both labor and energy in some industrial sectors in South Korea and Japan (Khayyat et al., 2016). Finally, Schulte et al. (2016) investigate sectors in OECD countries and obtain the result that "a 1% increase in ICT capital reduces energy demand by 0.235%" (p. 130). Interestingly, that reduction is due to reductions not in electricity consumption but in other, non-electric energy. A possible explanation is that the direct effects of ICT (see Effect I in Section 5) and ICT services (see Effect IV in Section 8) are mostly based on electricity while ICT application in other parts of the economy can save on other energy carriers (see Effect II in Section 6).

Overall, evidence for a positive relationship between digitalization and electricity consumption is strong, but not true for all countries. The relation between digitalization and other energy carriers is less clear and needs additional research. If the findings by Schulte et al. (2016) hold true, CO_2 emissions could also potentially be reduced by digitalization – when the necessary additional electricity is supplied by renewable energy and the use of other energy carriers decreases. To improve understanding of the relationship between digitalization and energy consumption, the next step is to develop an analytical model. It decomposes the relationship at the macroeconomic level into several effects.

4. Analytical model to investigate the potentials and risks of ICT for decoupling

Brock and Taylor (2005) have developed a useful model to discuss the relationship between the economy and the environment. It allows differentiation of three different mechanisms related to how the economy's impact on the environment (in our case, on energy consumption) can change: (1) due to economic growth (scale), (2) due to more efficient production methods (technology), and (3) due to change in the relative shares of different sectors of the economy (composition). Energy consumption (E) depends on the level of output (Y), the energy intensity per unit of output (a_i) of each sector (i) and the sectors' relative shares (s_i). There are n sectors. The energy consumption is therefore determined by $E = \sum_{i=1}^{n} a_i s_i Y$. Differentiating to time results in (see derivation in Appendix I):

$$\widehat{E} = \sum_{i=1}^{n} \pi_i (\widehat{a}_i + \widehat{s}_i) + \widehat{Y} \tag{1}$$

with $\widehat{E} = {}^{dE/dt}/_{E}$, $\widehat{a}_i = {}^{da_i/dt}/_{a_i}$, $\widehat{s}_i = {}^{ds_i/dt}/_{s_i}$ and $\widehat{Y} = {}^{dY/dt}/_{Y}$. The change of energy consumption ($\widehat{E}$) hence depends on the change in energy intensities ($\widehat{a}_i$), the changes of the relative sector shares ($\widehat{s}_i$) and economic growth ($\widehat{Y}$). π_i is the ratio between the energy consumption of sector (i) and the overall energy consumption: $\pi_i = {}^{E_i}/_{E}$.

To investigate digitalization's impact on the relationship between the economy and energy consumption, we adjust this equation by separating the ICT sector from the rest of the economy. This separation allows us to investigate the specific issues regarding digitalization. We further assume that the impact of digitalization on energy intensity is the same for all other sectors in the economy. The change in energy consumption is then determined as follows (see Appendix II):

$$\widehat{E} = \widehat{E}_{ICT}\pi_{ICT} + \pi_R \widehat{Y} + \widehat{a}\ \pi_R + \sum_{i=1}^{n-1} \widehat{s}_i \pi_i \tag{2}$$

The impact of digitalization on the change in energy consumption ($\widehat{E}$) depends on four aspects: (I) the change in the direct effects, that is, the change in the energy consumption of the ICT sector ($\widehat{E}_{ICT}$), (II) the impact of digitalization on economic growth, (III) its impact on energy efficiency and thereby on the development of the energy intensity in the rest of the economy ($\widehat{a}$) and (IV) the effect on the sectoral composition in the economy ($\widehat{s}_i$) – that is sectoral change. π_R is ratio between the energy consumption of the rest of the economy (the entire economy less the ICT sector) and the overall energy consumption: $\pi_R = {}^{E_R}/_{E}$. In the next four sections, we discuss these four effects in detail.

5. Effect I: Energy consumption of the ICT sector

As argued in Section 4, the overall relationship between digitalization and energy consumption depends on four effects: direct effects, changes in energy efficiencies, economic growth and sectoral change. The subsequent four sections of this text cover these effects in turn. Table 2 in the appendix gives an overview over the empirical literature referred to in these sections, including methods and data used. This section begins with the direct effects (Börjesson Rivera et al., 2014; Hilty and Aebischer, 2015; Mickoleit, 2010; Pohl et al., 2019).

The changes in the direct effects are represented in equation (2) by $\widehat{E}_{ICT}$. The development of the ICT sector's direct energy consumption depends on two aspects: the sector's growth and the change in the sector's energy intensity. The definition of the ICT sector differs between studies but usually encompasses the production, use and disposal of hardware as well as ICT services. For example, the OECD includes four subsectors into ICT: ICT manufacturing, software publishing, telecommunications and IT and other information services (OECD, 2015).

The ICT sector has grown worldwide. Comparing a diverse set of countries, Mas et al. (2018) find that all of them experienced growth in the ICT sector. In almost all of the countries, mean annual growth rates of value added for the ICT sector between 2006 and 2015 were higher than mean annual growth rates of the entire national economy. In China, the role of ICT for economic growth gains in significance. The sector represents a rising share of value added (from 2.2% of GDP in 2001 to 4.2% in 2008 (Simon, 2011)) and contributes greatly to economic growth (ICT growth accounted for 20% of GDP growth (Heshmati and Yang, 2006)). Also in India, ICT's contribution to GDP rose from 1.2% in 1998 to 5.2% in 2007 and 5.8% in 2008 (Simon, 2011). In the EU28, the ICT sector also grew significantly between 1995 and 2015; the value added increased by a factor of 3.5. This dynamic can also be seen in the employment rates, the productivity per person employed and productivity per hour worked in the ICT sector (Mas et al., 2018). In OECD countries, the ICT sector's share in GDP has remained relatively constant since 1995, implying a growth in total value added as GDP has also grown in that time (OECD, 2019, 2017, 2002).

The growing role of ICT is also reflected in the growing role of ICT capital. ICT capital stock expanded by more than 5% every year in the US, UK, Germany, Italy and Spain in 1992 to 2007 (Strauss and Samkharadze, 2011). The same authors concluded that ICT capital has grown significantly and even the share of ICT capital in the aggregate capital stock has increased in virtually all these economies. A more recent study also shows that ICT investments have been continuously increasing since 1995 in OECD countries in total terms and that the ratio between ICT investments and GDP even increases when looking at volumes (number of ICT devices) rather than monetary terms (Guérard and Spiezia, 2019). Additionally, the role of ICT investments gains further importance when their contribution to indirect investments – "ICT assets embodied in non-ICT investments" (Cette et al., 2018, p. 6) is considered.

While the ICT sector overall is growing in many parts of the world, the subsectors within the ICT sector are developing differently in countries and world regions. Manufacturing is the dominant subsector of China's ICT sector: it maintained an average growth rate of 32% between 1995 and 2005 (Chen et al., 2005) and had a higher average growth rate than GDP from 1978 – 2006 (25.8% compared to 15.84%) (Simon, 2011). In OECD countries, the value added from ICT goods (ICT manufacturing and telecommunications) has been falling, while the value added from services (software publishing, IT and other information services) has been rising (OECD, 2017). Similarly, Eurostat (2019) find that the value added in ICT manufacturing has stayed roughly constant while value added in ICT services increased by 18.3% for 16 EU countries from 2010 to 2016. The same tendency can be observed in other countries such as Canada, Switzerland, Norway or Russia (Mas et al., 2018). One possible reason for this difference is the relocation of manufacturing to non-OECD countries such as China or India (OECD, 2019). In sum, the ICT sector as a whole is growing worldwide, but growth of ICT manufacturing and services differs between regions. Ceteris paribus, the growth of the ICT sector contributes to growing direct energy consumption.

At the same time, energy efficiency has been increasing in the ICT sector for decades. Koomey shows that processors have become more efficient, and Koomey's law states that the energy consumption per processing unit used to halve about every 1.5 years (Koomey et al., 2011). Similarly, the energy consumption per data transmission has decreased and is predicted to decrease further (Coroama and Hilty, 2014). Data centers have also experienced fast increases in energy efficiency (Avgerinou et al., 2017; Hintemann and Clausen, 2014; Shehabi et al., 2016).The extent of efficiency improvements, expected increases in data volumes and their impact on electricity consumption however is currently controversial (Hintemann and Hinterholzer, 2019; Masanet et al., 2020).

Whether the ICT sector's total energy consumption increases or decreases depends on which of the two former effects prevails – the growth of the sector or the increases in energy efficiency. A number of studies calculate the operational energy demand of communication networks, end user devices and data centres (see Table 2 in the appendix). The findings indicate that the ICT sector's electricity consumption remains at least stable or is even increasing. Malmodin et al. (2010) estimate that, in 2007, electricity use from the ICT sector accounted for 3.9% of total global electricity demand. Van Heddeghem et al. (2014) find an overall growing operational energy demand from 658 terawatt hours TWh in 2007 to 909 TWh in 2012 (or an increase in the share of ICT in global electricity consumption from 3.9% to 4.6%). Other studies also found that direct energy consumption of ICT is increasing. Corcoran (2013) estimate the total electricity consumption at 1.817 TWh in 2012 or 7.4% of total global electricity. Their scenarios for ICT usage in 2017 show an increase in the sector's electricity consumption of between 9% and almost 90% compared to 2012, representing a share of ICT in global electricity consumption of between 6.9% and 12%. Andrae and Edler (2015) develop three scenarios for the global electricity consumption of ICT between 2010 and 2030. In all three scenarios, the ICT sector's electricity consumption increases – from 1500 TWh (8% share of global electricity consumption) in 2010 to as much as 30700 TWh (51%) in 2030. In a revision of the 2015 study, Andrae (2019) adjusts the sector's electricity demand forecast to 5700 TWh in 2030 (14% share of global electricity consumption). As a reason for these significantly lower growth rates he cites strongly increasing data center energy efficiency. In contrast, Malmodin and Lundén (2018) conclude that the operational electricity consumption of the ICT sector remained roughly constant at around 800 TWh between 2010 and 2015, representing a share of ICT in global electricity consumption of 4.3% for 2010 and 3.8% for 2015. The authors attribute these differences to overestimated sales forecasts for end user devices in other studies. Yet unpublished research by the same authors indicates that electricity consumption (including manufacturing) is slightly rising, between 2015 – 2018 from 1010 TWh to 1.080 TWh (Malmodin et al., 2020). The question remains as to why ICT electricity consumption is generally found to be increasing, at the most remaining stable although the sector is experiencing fast-paced increases in energy efficiency.

Two major insights from the decoupling debates explain why absolute decoupling of the ICT sector's growth from its energy consumption does not take place despite immense increases in energy efficiency. The first insight refers to measurement issues. Energy efficiency is measured in technical terms for single devices. For example, a newer processor uses less energy per calculation than an older one. Economic output and economic growth, on the other hand, are measured in real monetary terms (nominal monetary terms that have been adjusted for product quality changes and inflation). There has been a fast relative decoupling between the growth "in technical terms" (for example the growth of computing capacity) and energy consumption due to the increases in energy efficiency. However, this decoupling did not lead to absolute reductions in energy consumption because the growth in technical terms was so strong. Growth in technical terms has not been accompanied by an equivalent economic growth (for example, the current price of a smartphone is similar to that 10 years ago although its computing capacity is much greater). Thus, the relative decoupling between economic growth of the ICT sector and energy consumption has been much slower than that between growth in technical terms and energy consumption. Additionally, many of the services from digitalization (such as social media, email providers or search engines) are being paid for via a flat rate rather than per data unit. Therefore, the value of these services might be underestimated (Reinsdorf et al., 2018). This underestimation further contributes to high energy intensity of the sector, as the energy intensity is measuring the relation between energy consumption and the economic value of the sector.

The second argument is based around whether physical capital and energy are substitutes within the ICT sector. In most production functions, substitutability between production factors is assumed (Barro and Sala-i-Martin, 2004) – implying that the production level can remain constant despite a decrease in energy consumption when the supply of physical capital increases. However, as indicated in Section 2, ecological economists argue that energy and physical capital are complements – so that decreasing the amount of energy cannot be outbalanced by additional physical capital. As a result, decreasing energy supply would greatly affect output – compared to the situation where the two are substitutes. The empirical literature is controversial on this issue and cannot even agree on the overall direction – complements versus substitutes – in question (Apostolakis, 1990; Broadstock et al., 2007). This controversy cannot be definitely solved unless energy supply were to be tightly limited and the empirical implications could be observed in the real world. As shown above, in the ICT sector, all three variables – production, physical capital and energy consumption – have increased in the past. Hence, in the ICT sector, physical capital and energy consumption do not appear to be substitutes. Whether, they are substitutes in other sectors is the issue of the next section.

6. Effect II: Energy efficiency and rebound effects

Energy conservation, energy efficiency and energy sufficiency are the most important strategies to achieve absolute or even absolute sufficient decoupling (Bertoldi, 2020, 2017; von Weizsäcker et al., 2009). Applied to the digitalization issue, the question is in how far applying ICT improves energy efficiency in the rest of the economy. This is the second effect of the relationship between digitalization and energy consumption. It is represented by $\hat{a}$ in equation (2).

Influential quantitative studies on digitalization's potential to increase environmental efficiencies exhibit methodological weaknesses. Most prominently, a study by the Global e-Sustainability Initiative, a cooperation of about 40 IT and telecommunication firms, predicts up to 12 Gt CO_2e abatement potential of ICT technologies, which would equal a 20% reduction of global CO_2e emissions from 2015 to 2030 (GeSI and Accenture, 2015). However, the results of that study are controversially discussed because the methodologies applied are fairly simple and ICT-related consequential effects are not taken into account (Bieser and Hilty, 2018).

There are also theoretical arguments that digitalization can imply environmental benefits and energy savings. Berkhout and Hertin (2001) identify five areas in which ICT can help optimize the production process and thereby decrease energy consumption: (1) Simulation of production processes; (2) intelligent design and operation of products and services; (3) intelligent distribution and logistics, e.g., supply chain efficiency or alternative distribution structures; (4) changing seller-buyer relationships, e.g., mass customisation; (5) work organisation, e.g., teleworking. Sui and Rejeski (2002) call such positive environmental effects of ICT the "three D's for the new economy" (p. 156): dematerialization (e.g., shifting from "books to bytes"), decarbonization (including a less energy intensive economy) and demobilization (e.g., telework and e-commerce reduce the need for transportation). Beier et al. (2018) argue that the Industrial Internet of Things enables more resource-efficient manufacturing, improved recycling processes and predictive maintenance. Predictive studies suggest that applying digital devices and programmes can increase energy efficiencies in various sectors, including agriculture, mobility, housing and industry (Horner et al., 2016; Mickoleit, 2010). However, results are mixed. Smart energy feedback for example has the potential to massively reduce energy demand in the housing sector (Buchanan et al., 2015; Jensen et al., 2016; Malmodin and Coroama, 2016; Nilsson et al., 2018). Results from a living lab study however showed that energy consumption remains roughly the same (Buhl et al., 2017).

Several empirical studies exist on the impact of digitalization on energy efficiency with regard to specific goods or services (compare Table 2). The results are mixed. On the one hand, there are potentials for information services. Moberg et al. (2010a) find an annual energy saving potential of electronic invoicing of up to 1,400TJ in Sweden. In a second study, Moberg et al. (2010b) calculate a potential energy saving by switching from conventional to online newspapers of up to 60%. Similar results are shown by Weber et al. (2010) for downloading music instead of physical CD delivery and by Amasawa et al. (2018) for the adoption of e-readers. Mayers et al. (2015) find contradictory results by assessing higher GHG emissions for the distribution of games by Internet download than by physical Blue-ray discs. Also, studies on energy savings in e-commerce show mixed results (e.g., Horner et al., 2016; Mangiaracina et al., 2015; van Loon et al., 2015). For example, a study of the Japanese book sector found that e-commerce is about as energy intensive as conventional retailing in rural areas, but more energy intensive in urban areas (Williams and Tagami, 2002). According to Horner et al. (2016), decisive factors are population density (based on delivery in the last mile), freight mode, product return rate, trip allocation (share of multi-purpose trips) and type of packaging. This is also shown by Borggren et al. (Borggren et al., 2011). The authors compared paper books sold by traditional vs. online book shops and concluded that the internet bookshop was slightly beneficial. From a buyer perspective, means of transport and the combination with other purposes has a great influence on the result.

In sum, whether digitalization can significantly increase general energy efficiency is still uncertain. But even if it could, the overall effect on energy consumption is unclear due to multiple rebound effects (Jevons, 1906; Khazzoom, 1980; Santarius, 2014; Sorrell, 2007). The general literature on rebound effects discusses why increases in energy efficiency do not lead to proportionate reductions in energy consumption. The reason is that increases in energy efficiency foster energy consumption via various mechanisms, such as a re-spending of savings and a substitution of other production factors by energy. Estimates on the overall quantitative dimension of rebound effects are heterogeneous. Ayres and Warr (2009) argue that “most of the economic growth of our Western civilization in the past 200 years stems from the rebound effect” (p. 233). Several researchers claim that rebound effects lead to backfire, implying that increases in energy efficiency *increase* rather than decrease energy consumption (Brookes, 1978; Jenkins et al., 2011; Saunders, 2000, 1992). Some researchers do not deny the rebound effect in principle but estimate that its practical significance is relatively low (e.g., Gillingham et al., 2009; Goldstein et al., 2011; Nadel, 2012; Schipper and Grubb, 2000). However, most rebound researchers conclude that rebound effects are great enough to prevent a sufficient absolute reduction in energy demand (Azevedo et al., 2012; Greening et al., 2000; Maxwell et al., 2011; Ruzzenenti and Bertoldi, 2017; Santarius, 2015; Sorrell, 2010).

Several authors argue that the ICT sector is particularly prone to high rebound effects or even backfire (Coroama and Mattern, 2019; Galvin, 2015; Gossart, 2015; Hilty and Aebischer, 2015; Santarius, 2015; Walnum and Andrae, 2016). For instance, despite the improved availability of video conferencing systems, the number of international scientific conferences is increasing (Coroama et al., 2012). Overall, the number of printed books is not declining, while e-books and reading of online-websites is increasing. Video streaming can save energy compared to DVD purchases or rentals from stores (Shehabi et al., 2014), but the steep rise of hours streamed and of data traffic associated with video streaming will likely outplay such savings potentials (Cisco, 2019). Regarding processors in general, according to Koomey et al. (2011), energy intensities of processing units (CPUs) halve about every 1.5 years. Yet, Moore’s Law suggests a doubling of processing capacities every 1.5 years, too. As a result, the potential to save energy due to increases in energy efficiency are outbalanced by rise in processing services (Lange and Santarius, 2020). It is unclear how much of such growth in scientific conferences, books, data traffic and processing capacities can be causally explained by the increase in energy efficiency (and would therefore count as a rebound effect) or is due to other causes. It seems clear however, that increases in output commonly balance out increases in energy efficiency, which is why we turn to the issue of economic growth in the next section.

7. Effect III: Digital growth cycle or digital stagnation?

In the debate on decoupling, the speed of economic growth is of major importance. The faster the economy grows, the stronger energy efficiency increases and/or sectoral changes must be to achieve absolute decoupling. Therefore, a central question is how digitalization influences the rate of economic growth. The previous section has already discussed that rebound effects (partly) outbalance the potential energy savings of digitalization. Such rebound effects also imply economic growth, as they increase consumption and production (Lange et al., 2019). However, digitalization increases economic growth in other manners covered in this section. The effect of digitalization on economic growth is the third effect, denoted with $\widehat{Y}$ in equation (2).

Robert Solow said in 1987: "You can see the computer age everywhere but in the productivity statistics" (Solow, 1987). Thirty years later, the vast majority of empirical literature on digitalization and economic growth finds a positive relationship between the two – but digitalization is still not the main driver. Empirical literature exists both on large sets of countries and on case study analyses for high- and low-income countries (see Table for an overview). While the positive relationship exists for almost all investigations (and there are none that find a negative relationship), the causal direction is often only weakly investigated.

Salahuddin and Alam (2016) identify a positive relationship between ICT and economic growth in OECD countries. Katz and Koutroumpis (2013) find that a 10-point increase in a self-constructed digitalization index (ranging from 0 to 100) had an annualized effect of 0.5% on GDP from 2004 – 2010. Farhadi et al. (2012) determine that, for a panel of 159 countries from 2000 to 2009, an increase of 1% in an ICT Index raises economic growth by 0.17%. Additionally, they find that this relation is stronger in high-income countries. Jorgenson et al. (2016) claim that ICT has played an important role in US growth since the Second World War. Labor productivity has increased particularly fast in the ICT sector, and they argue for spillovers to other sectors. Jalava and Pohjola (2008) discuss how the increasing role of ICT has contributed significantly to economic growth in Finland. Lee and Brahmasrene (2014) argue that “[t]hough researchers generally agreed that ICT development has a positive relationship with economic growth, the causal relationship between ICT development and economic growth in developing countries has been somewhat mixed” (p. 96). However, they find that a 1% increase in the ICT development increases economic growth by 0.672% in seven South Asian countries. Hofman et al. (2016) find a low but positive ICT contribution to economic growth in Latin American countries from 1990-2013. Several single-country case studies for countries with lower income also find positive relationships, such as India (Erumban and Das, 2016), Malaysia (Kuppusamy et al., 2009) and the Small Pacific Island States (Kumar et al., 2015) and Taiwan (Wang, 1999). Only one study on Japan finds no statistically significant relation between ICT and economic growth – however, it does neither find the opposite (Ishida, 2015).

However, so far, digitalization has been accompanied by low growth rates, at least in high income countries (Gordon, 2015; Lange et al., 2018). So, how can the positive but rather low effect of digitalization on economic growth be explained? The vast majority of growth theories look at the supply side and argue that the growth determinant is the supply and effectiveness of production factors such as labor, capital and natural resources (Acemoglu, 2008; Barro and Sala-i-Martin, 2004). Accordingly, it is argued that the increasing application of ICT throughout the economy increases labor productivity (Frey and Osborne, 2017; Wolter et al., 2016). Not only can such technologies be used to rationalize work in industrial production, they can also replace cognitive human labor and have, therefore, the potential to increase labor productivity in service sectors as well (Brynjolfsson and McAfee, 2012). However, Gordon (2015) points out that digitalization lacks the ability to increase labor productivity to the extent earlier technological changes did.

Another explanation of low growth despite digitalization refers to the demand side and income inequality. Brynjolfsson and McAfee (2014) describe two central effects of how digitalization leads to increasing income inequality. First, wages polarize. While digitalization can rationalize labor throughout all wage brackets, jobs with low income are expected to be affected more heavily (Frey and Osborne, 2017), and new jobs tend to necessitate high education levels (Wolter et al., 2016). As a result, demand for highly skilled labor increases, while demand for low-skilled labor decreases – leading to wage polarization. The second effect is a decreasing wage share. The wage share has fallen in the last decades for almost all OECD countries, with multiple causes (ILO, 2013; Trapp, 2015). Digitalization is expected to aggravate this development as work is increasingly being conducted by robots and algorithms (Brynjolfsson and McAfee, 2014). Rising income inequalities have been a major explanation of recent low growth in high income countries (Krugman, 2014), and estimates presume digitalization will perpetuate this relation in the future (Lange and Santarius, 2020; Staab, 2017).

Now let us link the discussion on digitalization's impact on economic growth to this paper's key question on decoupling energy demand from growth. The literature contains a central debate on decoupling that helps to explain the overall positive relation between digitalization and energy consumption that has generally been found so far (see Section 3). The central debate regards the output elasticities of energy. According to some, the energy has a low output elasticity, as indicated by its low factor cost share (e.g., Solow, 1974, 1956). Others argue that energy has a much higher output elasticity (Ayres et al., 2013; Kümmel, 2011; Lindenberger and Kümmel, 2011; Stern, 1993; Stern and Cleveland, 2004), so that the low price of energy does not imply a low importance in the production process (Ayres, 2003; Kümmel, 2011). These two views have different predictions concerning the effects of increases in energy efficiency. If energy plays an important role in economic growth, increasing its efficiency fosters growth significantly. This fostering, in turn, leads to additional demand for energy. Hence, if digitalization was to increase energy efficiency in the future, it would bring with it greater economic growth so that energy consumption overall stays high.

This effect explains why digitalization does not lower energy consumption – but why does bring increasing levels of energy consumption? One explanation might stem from insights of a new area of research that distinguishes between the role of energy and the role of exergy (sometimes also called useful work) in economic growth (Warr et al., 2010; Warr and Ayres, 2012). Energy is a physical concept and relates to a certain amount of energy in a specific energy carrier – for example one barrel of oil. Exergy on the other hand is a measure of the capacity of a certain type and amount of energy to conduct work in the economic process. For example, when a certain amount of oil and a certain amount of electricity contain the same amount of energy, the amount of electricity contains more exergy in the sense that it is capable of conducting more work such as moving an object (Grubler et al., 2012). The implication for the relation between energy and economic growth is that decoupling is limited (Parrique et al., 2019). The reason is that there is increasing evidence that economic growth and exergy have developed in a relatively constant relation over the last decades and even centuries – implying not even a relative decoupling between the two (Serrenho et al., 2014). Additionally, there are physical limits to increasing the efficiency of converting energy into exergy. As a result, there are limits to decoupling economic growth from energy (Brockway et al., 2014). Therefore, if digitalization is to lead to economic growth, e.g., via increasing labor productivity, it is likely to bring with it increasing energy consumption.

8. Effect IV: Sectoral change

The fourth and final effect of explaining the relation between digitalization and energy consumption in this paper is the sectoral change that comes with digitalization. The question here is whether digitalization is accompanied by tertiarization, as some argue (OECD, 2015). If this was true, energy consumption could decrease, as the energy intensity of services is lower than that of industrial production (EnerData, 2016). This effect is $\sum_{i=1}^{n-1}\hat{s}_i\pi_i$ in equation (2), with the change in sector i's relative share in total production $\hat{s}_i$ and the sector's share in total emissions π_i. A prominent concept relating sectoral change to environmental aspects is the concept of the Environmental Kuznets Curve (EKC). It suggests that environmental impacts rise and then decrease in growing economies (Stern, 2004). The central explanation is that emissions are low in agrarian economies, rise in the process of industrialization and decline again during the transformation to a service-based economy (Arrow et al., 1996; Dinda, 2004). According to Smulders et al. (2014) "[t]he empirical literature on the EKC […] is huge and far from unambiguous" (p. 440). However, a major difference lies in the type of environmental aspect under investigation. On the one hand, several studies find an inverse U-shaped relation between economic growth and environmental impacts that are regionally limited (e.g., Grossman and Krueger, 1995; Selden and Song, 1994; Yandle et al., 2002). Caviglia-Harris et al. (2009), on the other hand, show that the curve does not hold for overall measures of environmental pollution, in particular for the environmental footprint. According to Markandya et al. (2002), "while it [the EKC] has been observed for pollutants whose effect is felt locally and currently, it tends not to be observed for transboundary pollutants, or those whose effect will be felt in the future" (p. 122). Savona and Ciarli (2019) give a possible explanation, coming to the empirical conclusion that even tertiarization is not always accompanied by lower energy consumption.

Whether digitalization contributes to tertiarization, and thereby to a decrease in energy consumption, depends on two aspects: The first aspect is whether digitalization actually leads to tertiarization. The contribution of the ICT sector to this development differs between countries. Manufacturing grows fast in China's ICT sector: it maintained an average growth rate of 32% between 1995 and 2005 (Chen et al., 2005) and had a higher average growth rate than GDP from 1978 – 2006 (25.8% compared to 15.84%) (Simon, 2011). In OECD countries, the value added from ICT goods (ICT manufacturing and telecommunications) has been falling, while the value added from services (software publishing, IT and other information services) has been rising (OECD, 2017). Similarly, Eurostat (2019) find that the value added in ICT manufacturing has stayed roughly constant while value added in ICT services increased by 18.3% for 16 EU countries from 2010 to 2016. The same tendency can be observed in other countries such as Canada, Switzerland, Norway or Russia (Mas et al., 2018). One possible reason for this difference is the relocation of manufacturing to non-OECD countries such as China or India (OECD, 2019). Additionally, the process of 'economic globalization' has shifted certain industrial

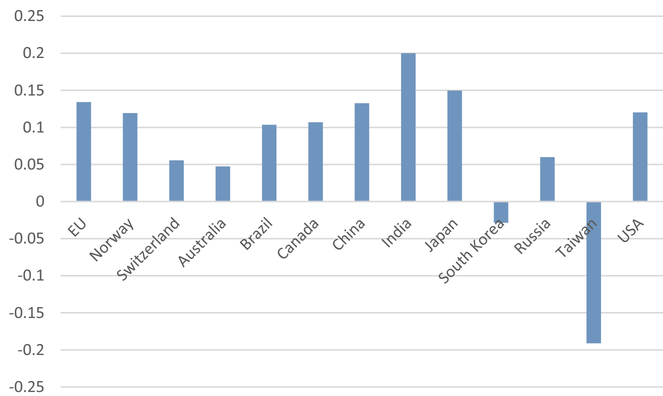

Fig. 1. Change in the share of ICT services in the total ICT sector
It displays the change in the share of ICT services in total ICT sector, comparing the years 2016 and 1995. The Share of ICT services in the total ICT sector from 1995 is subtracted from the share in 2016. Own calculations, based on (Lopez Cobo et al., 2019).

production capacities (e.g., textiles, steel, cars, consumer goods) into countries of the Global South and spurred tertiarization in high income countries (Cornia, 2003; Sachs and Santarius, 2007; Savona and Ciarli, 2019; Schiller, 2000). Digitalization might overlap with such processes. Hence, the tertiarization experienced in European and OECD countries can bring further industrialization in other regions of the world.

If we look at the share of ICT services in the overall ICT sector, the picture is clear however. ICT services made up the lions share in the ICT sector in 2014, with 73.1% compared to 26.9% of ICT manufacturing (Mas et al., 2017). More importantly: Its share rose in basically all countries with data available (and the EU treated as one country) form 1995 to 2016. The only country with a significant increase in the share of manufacturing was Taiwan and South Korea experienced a minor increase (see Fig. 1).

The development within the ICT sector therefore fosters a tertiarization. However, this does not conclusively answer the question, whether digitalization also fosters tertiarization in the rest of the economy. Many countries experience a tertiarization, that is, an overall increase in the share of services in overall GDP. At the same time, industrial and agricultural production are growing as well – only slower than services. Tertiarization in the strict sense (entailing that industrial production and agriculture decline, while services grow) does not take place. These developments hold for example for the EU (Eurostat, 2020) as well as for China (The World Bank, 2020). Unfortunately, there are no empirical investigations on the effect of digitalization on the overall sectoral composition of the economy (this is why there is no empirical literature on sectoral change included in Table 2 in the appendix).

The second aspect for whether digitalization leads to less energy consumption via tertiarization regards the energy intensity of the new services. The worldwide energy intensity in industrial production is 0.12 kgoe/$ (kilogram oil equivalent per dollar), in agriculture 0.036 kgoe/$ and in services 0.016 kgoe/$ (EnerData, 2016). Clearly, a shift from the industrial towards the service sector would decrease the economy's energy intensity. However, services derived from applying ICT are relatively energy intensive, compared to other services. The increasing role of ICT in services is therefore a major factor increasing the energy intensity of services (Mulder et al., 2014). Both observations - that the share of services increases, while all sectors are still growing and that services are energy intensive – are in line with the criticisms of the idea of an EKC from section 2. Kümmel (2005) argues that the shifts in the shares of agricultural, industrial and services sectors are a statistical construct. In agriculture and industry, energy is increasingly replacing human labor. This change leads to decreasing product prices and a decreasing share of value creation in these two sectors – and an increasing share in the service sector. However, it does not need to imply a decreasing number of items produced or energy and material used in the former two sectors. This theoretical argument has been supported by empirical evidence using constant rather than current prices to calculate sector shares (Henriques and Kander, 2010).

In sum, the expanding ICT service sector contributes to economic growth and is therefore tightly connected to digitalization's effect on economic growth (see section 7). Additional research is needed to answer whether digitalization leads to a tertiarization in the sense that the share of services increases. However, the rise in the share of services within the ICT sector itself suggests some momentum towards tertiarization due to digitalization.

9. Results and discussion

In the following, we present the major results regarding the four effects. These findings are put into relation with the analytical model developed in Section 4. Additionally, we summarize four important interdependencies between the effects and point out implications for future developments of energy consumption.

In Section 4, we developed a model with four effects to analyze the relationship between digitalization and energy consumption. Sections 5-8 conducted analyzes of these effects, combining empirical findings with theoretical considerations. Table 1 summarizes the findings.

Broadly speaking, there are two energy-increasing and two energy-reducing effects. The energy-increasing effects are direct effects and economic growth. Direct effects (Effect I) have increased in the past and are currently either stable or even increasing. In addition, digitalization goes along with stronger economic growth (Effect III). The energy-reducing effects are energy efficiency and sectoral change. Applying ICT allows increases in energy efficiency in the rest of the economy (Effect II). While the effect of digitalization brings with it tertiarization is the least clear, existing evidence suggests a small but energy-reducing effect (Effect IV).

Overall, digitalization has so far been associated with higher energy consumption; the two increasing effects – direct effects and economic growth – have been stronger than the reducing effects – energy efficiency and sectoral change. Using the analytical model from Section 4 provides

$$\widehat{E}_{ICT}\pi_{ICT} + \pi_R\widehat{Y} > -\hat{a}\,\pi_R - \sum_{i=1}^{n-1}\hat{s}_i\pi_i \tag{3}$$

The analysis also brought to light that these four effects are mutually interdependent. These dampen the prospects of digitalization to reduce energy consumption in the future. The energy-reducing effects also trigger the energy-increasing effects, so that 'one cannot have the one without the other', at least under the existing economic circumstances. Four interdependencies are of major importance:

- Increases in energy efficiency due to ICT (Effect II) lead to rebound effects that trigger additional energy consumption and economic growth (Effect III).
- The sectoral change towards ICT services (Effect IV) comes on top of existing agricultural production, industry and services, and therefore fosters economic growth (Effect III).
- Both, energy efficiency improvements throughout the economy (Effect II) and ICT services (Effect IV) are dependent on the usage of ICT devices (Effect I).
- The growth of the ICT sector itself (Effect I) is a significant reason for economic growth (Effect III).

Therefore, the more successful digitalization is in increasing energy efficiency and pushing towards tertiarization, the stronger the direct effects and the positive effect on economic growth will tend to be. Digitalization thereby wrecks its own potentials. As a result, it is

Table 1
Summary of Results: Four effects of digitalization on energy consumption

	Empirical main findings	Explanation
Effect I: Direct effects	• The ICT sector's electricity consumption has been increasing or is, at least, stable.	• The ICT sector has experienced strong increases of (technical) energy efficiency but has also grown. • Measurement issues: "technical growth" (e.g., increases in computing capacity) is not proportionally translated into economic growth. • Physical capital and energy consumption are complements in the ICT sector.
Effect II: Efficiency and rebound effects	• Plausible theoretical arguments that ICT increases energy efficiency in the rest of the economy, but mixed empirical results regarding ICT's effect on energy efficiency in the rest of the economy. • Indications that rebound effects are significantly high for ICT.	• ICT allows for more efficient production and products but sometimes also leads to new behaviors that are more energy intensive. • Increases in energy efficiency of ICT and ICT services lead to increasing consumption levels. • ICT services are often complements to rather than substitutes for traditional goods and services (e.g., online and physical conferences).
Effect III: Economic growth	• Positive effect of digitalization on economic growth.	• Labor productivity increases due to ICT, but more slowly than for past technological changes. • Digitalization brings with it rising income inequality, which dampens consumption demand. • It is difficult to decouple digitalization and energy consumption as digitalization is associated with economic growth and there are limits to decoupling economic growth from exergy.
Effect IV: Sectoral change	• The share of services within the ICT sector rises. • The effect of digitalization on the sectoral composition in the rest of the economy is unclear. • Digital services are more energy intensive than other services.	• The growth of ICT services in some countries does not replace but comes on top of existing production. Therefore the known effect on tertiarization is limited to the effect of increasing ICT services.

difficult to invert the relative sizes of the energy-increasing and energy-reducing effects, so that the latter would prevail over the former.

10. Conclusion

The hopes set on digitalization reducing energy consumption have not yet been justified. Instead of saving energy, digitalization has brought additional energy consumption; the energy-increasing effects (direct effects and economic growth) of digitalization have been greater than the energy-reducing effects (energy efficiency increases and sectoral change). This increasing energy consumption is likely to persist as the energy-reducing effects tend to trigger mechanisms leading to the energy-increasing effects.

This article has investigated the relationship between digitalization and energy consumption as it is – or rather, as it has been in the past. Much of the hope that digitalization could save the environment, however, is based on potential future developments, many of which foster exactly those two energy-reducing effects we have indicated in this analysis – energy efficiency and tertiarization. If these potentials are to reduce energy consumption, the energy-increasing effects of digitalization need to be prevented – most importantly the increasing direct effects and the various mechanisms leading to economic growth. A central question for future research is therefore to investigate, how digitalization can be steered into such a more sustainable direction.

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Appendix A. Appendixes

A.1. Appendix I: Derivation of the change in energy consumption in general

$$E = \sum_{i=1}^{n} a_i s_i Y \tag{4}$$

$$\widehat{E} = \frac{\frac{d}{dt}\sum_{i=1}^{n} a_i s_i Y}{E} \tag{5}$$

$$\widehat{E} = \frac{1}{E}\sum_{i=1}^{n}\left[\frac{da_i}{dt}s_i Y + a_i\left(\frac{d}{dt}s_i Y + s_i\frac{dY}{dt}\right)\right] \tag{6}$$

$$\widehat{E} = \frac{1}{E}\sum_{i=1}^{n}\left[\frac{da_i}{dt}s_i Y + a_i\frac{d}{dt}s_i Y + a_i s_i\frac{d}{dt}Y\right] \tag{7}$$

$$\widehat{E} = \frac{1}{E}\sum_{i=1}^{n}\left[a_i\widehat{a}_i s_i Y + a_i s_i\widehat{s}_i Y + a_i s_i Y\widehat{Y}\right] \tag{8}$$

$$\widehat{E} = \frac{1}{E}\sum_{i=1}^{n}\left[\widehat{a}_i E_i + \widehat{s}_i E_i + \widehat{Y}E_i\right] \tag{9}$$

$$\widehat{E} = \frac{1}{E}\sum_{i=1}^{n}(\widehat{a}_i + \widehat{s}_i + \widehat{Y})E_i \tag{10}$$

$$\widehat{E} = \frac{1}{E}\left[\sum_{i=1}^{n} (\widehat{a}_i + \widehat{s}_i)E_i + \sum_{i=1}^{n} \widehat{Y}E_i\right] \tag{11}$$

$$\widehat{E} = \frac{1}{E}\left[\sum_{i=1}^{n} (\widehat{a}_i + \widehat{s}_i)E_i + \widehat{Y}\underbrace{\sum_{i=1}^{n} E_i}_{=E}\right] \tag{12}$$

$$\widehat{E} = \frac{1}{E}\sum_{i=1}^{n} (\widehat{a}_i + \widehat{s}_i)E_i + \frac{1}{E}\widehat{Y}E \tag{13}$$

$$\widehat{E} = \frac{1}{E}\sum_{i=1}^{n} (\widehat{a}_i + \widehat{s}_i)E_i + \widehat{Y} \tag{14}$$

$$\widehat{E} = \sum_{i=1}^{n} (\widehat{a}_i + \widehat{s}_i)\underbrace{\frac{E_i}{E}}_{=\pi_i} + \widehat{Y} \tag{15}$$

$$\widehat{E} = \sum_{i=1}^{n} (\widehat{a}_i + \widehat{s}_i)\pi_i + \widehat{Y} \tag{16}$$

A.2. Appendix II: Derivation of the change in energy consumption with a separate ICT sector

$$\widehat{E} = \sum_{i=1}^{n-1} (\widehat{a}_i + \widehat{s}_i)\pi_i + (\widehat{a}_{ICT} + \widehat{s}_{ICT})\pi_{ICT} + \widehat{Y} \tag{17}$$

$$\widehat{E} = \sum_{i=1}^{n-1} (\widehat{a}_i + \widehat{s}_i)\pi_i + (\widehat{a}_{ICT} + \widehat{s}_{ICT})\pi_{ICT} + \pi_{ICT}\widehat{Y} + (1 - \pi_{ICT})\widehat{Y} \tag{18}$$

$$\widehat{E} = \sum_{i=1}^{n-1} (\widehat{a}_i + \widehat{s}_i)\pi_i + (\widehat{a}_{ICT} + \widehat{s}_{ICT} + \widehat{Y})\pi_{ICT} + (1 - \pi_{ICT})\widehat{Y} \tag{19}$$

Using equation (31) provides:

$$\widehat{E} = \sum_{i=1}^{n-1} (\widehat{a}_i + \widehat{s}_i)\pi_i + \widehat{E}_{ICT}\pi_{ICT} + (1 - \pi_{ICT})\widehat{Y} \tag{20}$$

We define $1 - \pi_{ICT} = \pi_R$

$$\widehat{E} = \sum_{i=1}^{n-1} (\widehat{a}_i + \widehat{s}_i)\pi_i + \widehat{E}_{ICT}\pi_{ICT} + \pi_R\widehat{Y} \tag{21}$$

Assumption: $\widehat{a}_1 = \widehat{a}_2 ... = \widehat{a}_{n-1} = \widehat{a}$

$$\widehat{E} = \sum_{i=1}^{n-1} \widehat{a}_i\pi_i + \sum_{i=1}^{n-1} \widehat{s}_i\pi_i + \widehat{E}_{ICT}\pi_{ICT} + \pi_R\widehat{Y} \tag{22}$$

$$\widehat{E} = \widehat{a}\underbrace{\sum_{i=1}^{n-1} \pi_i}_{=\pi_R} + \sum_{i=1}^{n-1} \widehat{s}_i\pi_i + \widehat{E}_{ICT}\pi_{ICT} + \pi_R\widehat{Y} \tag{23}$$

$$\widehat{E} = \widehat{a}\ \pi_R + \sum_{i=1}^{n-1} \widehat{s}_i\pi_i + \widehat{E}_{ICT}\pi_{ICT} + \pi_R\widehat{Y} \tag{24}$$

A.3. Appendix III: Derivation of the change in the ICT sector's direct effects

In general, this holds:
Be:

$$b = c * d \tag{25}$$

Then:

$$\widehat{b} = \frac{\frac{db}{dt}}{b} = \widehat{c} + \widehat{d} \tag{26}$$

Therefore, this also holds:
Be:

$$E_{ICT} = a_{ICT} * Y_{ICT} \tag{27}$$

Then:

$$\widehat{E}_{ICT} = \widehat{a}_{ICT} + \widehat{Y}_{ICT} \tag{28}$$

And this holds as well:
Be:

$$Y_{ICT} = s_{ICT} * Y \quad (29)$$

Then:

$$\widehat{Y}_{ICT} = \widehat{s}_{ICT} + \widehat{Y} \quad (30)$$

Combining equations (28) with equation (30) provides:

$$\widehat{E}_{ICT} = \widehat{a}_{ICT} + \widehat{s}_{ICT} + \widehat{Y} \quad (31)$$

A.4. Appendix IV

Overview over the empirical literature on the effects of ICT on energy consumption

Table 2
Empirical literature on the effects of ICT on energy consumption

Article	Year	Method	Data
Direct effects			
Andrae, A. S. G., Edler, T.	2015	Energy Footprint	Various sources
Andrae, A. S. G.	2019	Energy Footprint	Various sources
Corcoran, P. M., Andrae, A. S. G.	2013	Energy Footprint	Various sources
Malmodin, J., & Lundén, D.	2018	Energy and Carbon Footprint	Various sources
Malmodin, J., Moberg, Å., Lundén, D., Finnveden, G., Lövehagen, N.	2010	Energy and Carbon Footprint	Various sources
Van Heddeghem, W., Lambert, S., Lannoo, B., Colle, D., Pickavet, M., Demeester, P.	2014	Energy Footprint	Various sources
Energy efficiency			
Amasawa, E., Ihara, T., Hanaki, K.,	2018	LCA	Various sources
Borggren, C., Moberg, Å., Finnveden, G.	2011	LCA	Various sources
Horner, N. C., Shehabi, A., Azevedo, I. L.	2016	Literature Review	-
Mangiaracina, R., Marchet, G., Perotti, S., Tumino, A.	2015	Literature Review	-
Mayers, K., Koomey, J., Hall, R., Bauer, M., France, C., Webb, A.	2015	LCA	Various sources
Moberg, Å., Borggren, C., Finnveden, G., Tyskeng, S.	2010	LCA	Various sources
Moberg, Å., Johansson, M., Finnveden, G., Jonsson, A.	2010	LCA	Various sources
van Loon, P., Deketele, L., Dewaele, J., McKinnon, A., Rutherford, C.	2015	LCA	Various sources
Weber, C.L., Koomey, J.G., Matthews, H.S.	2010	LCA	Various sources
Williams, E., Tagami, T.	2002	LCA	Various sources
Growth			
Erumban, A. A., Das, D. K.	2016	Growth accounting and productivity measurement at the industry-level	Time series data and industry-level data India, 1986 - 2011
Farhadi, M., Ismail, R., Fooladi, M.	2012	Regression analysis	ICT index 159 countries, 2000 - 2009
Hofman, A., Aravena, C., Aliaga, V.	2016	Growth accounting	Panel data 18 Latin American countries, 1990 - 2013
Ishida, H.	2015	Regression analysis	Time series data Japan, 1980 - 2010
Jalava, J., Pohjola, M.	2008	Growth accounting method	Time series data Finland, 1980 - 2004
Jorgenson, D. W., Ho, M. S., Samuels, J. D.	2016	Productivity measurement at the industry-level	86 industries USA, 1947 - 2010
Katz, R. L., Koutroumpis, P.	2013	Growth accounting	Digitization index 150 countries, 2004-2010
Kumar, R. R., Kumar, R. D., Patel, A.	2015	Growth accounting	Panel data eleven Small Pacific Island States, 1979 - 2012
Kuppusamy, M., Raman, M., Lee, G.	2019	Regression analysis	Time series data Malaysia, 1992 – 2006
Lee, J. W., Brahmasrene, T.	2014	Regression analysis	Panel data nine Southeast Asian countries, 1991 - 2009
Salahuddin, M., Alam, K.	2016	Regression analysis	Panel data OECD countries, 1985–2012
Wang, E. H.	1999	Regression analysis	Time series data Taiwan, 1980 – 1995

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