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Economics of digital decoupling: a pluralistic analysis

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Digitalization supposedly fosters sustainability and brings about strong economic growth. These promises foster hopes that green growth – that is, to reconcile economic growth with environmental sustainability – is possible. However, digitalization has so far neither led to strong economic growth nor to substantial improvements for environmental sustainability. This article investigates why digitalization has not so far lived up to its promises based on a pluralistic method combining insights from neoclassical and ecological economics, and from post-Keynesian and neo-Marxian perspectives. It finds that the limited effect of digitalization on economic growth is due to its negative effect on aggregate demand, primarily via increasing inequality. The inability of digitalization to substantially improve environmental sustainability can be explained by a combination of distorted relative prices of inputs, missing government investment, and the high environmental footprint of the information and communication technologies sector. It is unclear whether policies to improve the environmental effect of digitalization foster or dampen economic growth. Therefore, gearing digitalization towards supporting environmental sustainability is compatible with an a-growth, rather than a green growth, strategy.

Keywords: *digitalization, ecological transformation, economic paradigms*

JEL codes: *B15, O40, Q55*

1 INTRODUCTION

On the 27th of November 2019, the first female president of the European commission held her inaugural speech before the European Parliament. Ursula von der Leyen stressed the concept of the twin transition. The twins are the environmental and the digital transformation. Digitalization is seen as a central tool to achieve environmental sustainability (GeSI/Deloitte 2019; Hedberg/Šipka 2020; McAfee 2019; WBGU 2019), for example within the European Green Deal: 'Digital technologies are a critical enabler for attaining the sustainability goals of the Green Deal in many different sectors' (European Commission 2019: 9). According to one estimate, information and communication technologies (ICT) 'can enable a 20% reduction of global CO2e emissions by

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2030' (GeSI/Accenture 2015: 8). At the same time, the digital transformation is regarded as an opportunity to boost economic growth (see, for example, European Commission n.d.). A prominent estimation argues that computerization has the potential to rationalize over 40 per cent of jobs (Frey/Osborne 2017), implying an immense growth in labour productivity and the potential for strong economic growth.

The two hopes – that digitalization fosters sustainability and that it brings about strong economic growth – make digitalization a central aspect in the debate on whether environmental sustainability can and should be pursued by following a green growth, de-growth or a-growth strategy. Proponents of *green growth* believe it is possible to decouple economic growth from environmental throughput (for example, Bowen/Hepburn 2014; Jacobs 2013) and even achieve sufficient absolute decoupling (Ekins 2000). Sufficient absolute decoupling means combining economic growth with a rate of reduction necessary to achieve certain environmental goals (Antal/van den Bergh 2016; Lange et al. 2020). Contrary to green-growth advocates, *de-growth* proponents are convinced that the economic and societal transformation necessary to achieve a sufficient reduction in environmental throughput cannot be accompanied by continued economic growth (for example, Jackson 2016; Kallis et al. 2018). *A-growth* can be seen as a midway concept between green growth and de-growth and suggests that it cannot be said with certainty whether stringent environmental policies will lead to positive economic growth or a shrinkage of the gross domestic product (van den Bergh 2011; 2017). A concept related to a-growth, also discussed in the de-growth literature, is growth independence. Within this concept it is argued that several social institutions are growth-dependent – in particular, social security systems and the labour market – and that this dependence may impede stringent environmental policy measures (Petschow et al. 2020; Seidl/Zahrnt 2010). If digitalization were able to simultaneously foster economic growth and environmental sustainability, green growth would become more feasible.

So far, digitalization has not lived up to its promises – on either front. Regarding economic growth, the vast majority of the empirical research on digitalization and economic growth indeed indicates that digitalization increases economic growth in high-income countries (Farhadi et al. 2012; Lange et al. 2020; Salahuddin et al. 2016). However, its magnitude is well below the high expectations placed on digitalization. The age of digitalization has been accompanied by rather modest growth rates, at least in high-income countries (Gordon 2015; Lange et al. 2018).

Neither has digitalization brought about major improvements concerning environmental throughput – that is, the raw materials and energy used and the emissions generated by economic processes. Regarding energy consumption, the literature identifies a statistically positive association with ICT: higher levels of digitalization lead to higher levels of energy use (Haseeb et al. 2019; Salahuddin/Alam 2015; 2016). A major reason is digitalization's direct effects: the energy used by the production and use of ICT devices and the infrastructure behind them. The ICT sector's electricity consumption constitutes a significant share of global electricity consumption and has risen in the past. Estimations of this sector's share of total electricity consumption vary between 3.8 per cent and 7.4 per cent (Corcoran/Andrae 2013; Malmodin et al. 2010; Malmodin/Lundén 2018; Van Heddeghem et al. 2014).

Regarding greenhouse gas emissions, studies yield ambiguous results. Studies that focus on the aggregate net effect find a positive relation between digitalization and greenhouse gas emissions (Kopp et al., work in progress; Salahuddin et al. 2016). Another approach focuses on specific transmission channels, finding that ICT reduces carbon dioxide (CO_2) emissions directly but increases energy consumption, which in turn increases CO_2 emissions (Haseeb et al. 2019; Lu 2018). However, no study finds a strong reduction in

greenhouse gas emissions due to digitalization. Again, a major reason is the emissions due to the production and use of the ICT sector itself (Andrae/Edler 2015; Belkhir/Elmeligi 2018; Malmodin/Lundén 2018; The Shift Project 2019). A recent study comparing different estimations reckon ICT's share of global greenhouse gas emissions to be between 2.1 per cent and 3.9 per cent (Freitag et al. 2021).

In sum, the effect of digitalization on economic growth is lower than expected and the empirical evidence does not support the hope that digitalization substantially reduces environmental throughput in the form of energy consumption or greenhouse gas emissions.

The main purpose of this article is to understand why digitalization has so far not lived up to its promises regarding economic growth and environmental sustainability. The analysis concentrates on countries of the Global North. The investigation follows a pluralistic approach (outlined in Section 2) that triangulates neoclassical economics (Section 3), ecological economics (Section 4), post-Keynesian theory (Section 5) and neo-Marxian perspectives (Section 6). The synthesis (Section 7) shows that the effect of digitalization to increase income inequality is the major explanation of the low positive effect of digitalization on economic growth. The inability of digitalization to substantially improve environmental sustainability can be explained by a combination of distorted relative prices of inputs, missing government investment, and a combination of factors responsible for the high environmental footprint of the ICT sector. In addition to explaining why digitalization has not lived up to its promises, Section 8 discusses the resulting policy implications and what this means for the growth debate. Policies to improve the environmental impact of digitalization have ambiguous impacts on economic growth – which is why they fit the a-growth rather than the green-growth or de-growth strategies. Section 9 concludes.

2 PLURALISTIC ANALYSIS

To understand why digitalization has not lived up to its promises, I apply a plural set of theories to the relation between digital technological change, economic growth and environmental throughput. The following analysis, in Sections 3–7, is based on the approach of 'interested pluralism' (Dobusch/Kapeller 2012). This pragmatic approach uses theories from different schools of thought to investigate a specific object of inquiry – in this case, the digital transformation of the economy. Dobusch/Kapeller's (2012: 1043) approach is 'striving for constructive interaction between different theoretical traditions in order to come up with an improved and expanded set of relevant explanatory statements'. The central underlying assumption is that different explanations from different theories are, by and large, complementary rather than contradictory. Theoretical statements from different schools of thought can be related to each other in six ways: they can be *identical*, *convergent*, *compatible*, *neutral*, *divergent* or *contradictory*. The relation then dictates which of four strategies can be applied: (i) Statements can be *integrated* when they apply to the same topic and if they are identical, convergent or compatible. (ii) When statements concern different topics but do not contradict each other – that is, are compatible or neutral – a *division of labour* between them makes sense. (iii) When statements are divergent – that is, are '(apparently) incompatible' (Dobusch/Kapeller 2012: 1052) at first sight – a strategy of *diversification* can be pursued. This strategy means taking a differentiated perspective on the topic at hand by the use of two or more theoretical views. (iv) Finally, when statements are contradictory, it may not be possible to reconcile them into a meaningful analysis. In this case, the researcher has to decide and make a *test of hypotheses* – due to the researcher's judgement, if possible, based on empirical grounds.

In the following, this pluralistic approach is applied to the topic of economic growth and environmental throughput in the face of digitalization. Four theoretical perspectives are employed to investigate the subject: a neoclassical, an ecological economics, a post-Keynesian and a neo-Marxian perspective.

3 PRODUCTIVITY AND RELATIVE PRICES: A NEOCLASSICAL PERSPECTIVE

In 1987, neoclassical economist Robert Solow (1987: 2) said: 'You can see the computer age everywhere but in the productivity statistics'. This so-called productivity paradox still occupies neoclassical researchers today. On the one hand, digital technologies bear great potential to rationalize production processes and thereby increase labour productivity (Brynjolfsson/McAfee 2014). On the other hand, high-income countries experience low growth rates at the same time as digital technologies are being applied throughout the economy (Gordon 2015).

Underlying this apparent paradox is the neoclassical perspective on the determinants of the level of production and economic growth. In the most prominent growth theory, the Solow–Swan model, the production level is determined by the growth in population and the savings rate, which influences the size of the capital stock (Solow 1956; Swan 1956). The most important factor explaining long-term growth is, however, technological change, or more specifically total factor productivity: the combined productivity of capital and labour. More recent approaches aim at endogenizing technological change in their models (for example, Arrow 1962; Lucas 1988; Romer 1986; 1990). Technological change remains to be the main determinant of economic growth in these endogenous growth models (Aghion/Howitt 2009).

It is therefore not surprising that debates among neoclassical economists about the relationship between digitalization and economic growth focus on the role of technological change. Several authors see great potential for digital technologies to increase labour productivity. In a highly influential study, Frey/Osborne (2017) calculate that more than 40 per cent of jobs in the USA are susceptible to being rationalized by the introduction of innovations related to computerization. Similarly, Brynjolfsson/McAfee (2014) argue that digital technologies bear the potential to rationalize many jobs because they can substitute not only physical but also cognitive labour. However, the predictions of these studies have not materialized so far (Arntz et al. 2017). The authors attributing a high growth potential to digital technologies retort that the positive impact on labour productivity will unfold only in the future (Brynjolfsson et al. 2017).

Other authors disagree with that position. Most prominently, Gordon (2012) points out that digital technologies do not increase labour productivity to the extent that former important innovations did. In the first industrial revolution (1750–1830), the combination of train tracks, steam engines and spinning wheels initiated immense growth. Growth in the second industrial revolution (1870–1900) was spurred by the dispersion of electricity, as well as by the introduction of the petrol engine. However, in the third industrial revolution, which Gordon dates from 1990 and is still ongoing, computers and the Internet have failed to initiate a comparable dynamic of innovation and economic growth in the early industrialized countries.

Since the 1970s, growth models have been developed that also incorporate environmental aspects. Early contributions focused on the relation between non-renewable resources and economic growth (Dasgupta/Heal 1974; Solow 1974; Stiglitz 1974). Later, energy as a production factor was included in models similar to the Solow model

(Ayres et al. 2019). Due to neoclassical assumptions, energy is regarded as relatively unproductive compared to labour and capital (Kümmel 2011). The cost–share theorem states that each production factor's marginal productivity is equal to its marginal costs. Hence, if energy is relatively cheap, it is also relatively unproductive (see Ayres et al. 2013). Another important assumption in these models is that a limited supply of one production factor – for example, energy – can be relatively easily substituted by other production factors (Ayres et al. 2019). Directed technical change models are particularly interesting with respect to the subject matter of this article. In these models, the direction of technological change towards cleaner or dirtier production is mainly driven by the prices of using environmental inputs (Aghion/Howitt 2009).

Regarding the relation between digitalization and the environment, McAfee (2019) argues that digital technologies have already brought about great improvements. The spread of digital technologies has supposedly helped to dematerialize the economy. McAfee proposes that, to further reap the potential of digital technologies for environmental issues, one should focus on combining technologies with capitalist competition – supported by a carbon tax. The combination of competition and higher prices for environmental throughput makes sense within the neoclassical paradigm overall. In models of directed technical change, higher prices for environmental throughput incentivize economic agents to introduce digital technologies that are more environmentally friendly (Acemoglu et al. 2012).

In sum, within the neoclassical school of thought, the characteristics of digital technological change are central for explaining both low economic growth and low reductions of environmental throughput. Digital technologies' limited abilities to increase total factor productivity explain low economic growth, and the low price of environmental inputs explains why digital possibilities are not used to develop technologies that focus on reducing environmental throughput. The next section covers ecological economics approaches, which also place high relevance on technological developments.

4 EXERGY AND REBOUNDS: AN ECOLOGICAL ECONOMICS PERSPECTIVE

Ecological economics is the major alternative school of economic thought when it comes to the relation between economic growth, technological change and environmental throughput. Several authors have criticized the neoclassical growth theories and developed a different theory of economic growth, focusing on the role of energy (Ayres/Warr 2009; Kümmel 2011). The starting point of the critique was that energy was either absent or that its role was understated and misconceptualized. In models such as the Solow–Swan model the largest part of economic growth cannot be accounted for empirically (Ayres 2003). This so-called Solow residual is attributed to technical progress or total factor productivity, but it is simply the residuum that cannot be explained by the production functions (Warr/Ayres 2012: 94). Neoclassical models that take into account energy as a production factor do not change this picture overall (Ayres et al. 2019).

Ecological economics approaches build on concepts related to energy from physics (Georgescu-Roegen 1971). Two central concepts in ecological economics are useful work and exergy. Useful work is work in the form of heat, mechanical work or light that is useful for the production process. Exergy, in turn, is the maximum amount of useful work that can theoretically be extracted from a given energy carrier (Ayres 2003). Approaches measuring exergy and useful work are able to explain the vast amount of economic growth – mainly due to an increase in the use of useful work

(Ayres et al. 2019; Serrenho et al. 2014). The amount of useful work used can either be increased by increasing the amount of energy used or by increasing the conversion rate. For example, the amount of useful work increases if a car is driven for a longer distance. This can either be facilitated by using more fuel or by introducing a new car engine that is more efficient in converting the exergy entailed in fuel into mechanical work – moving the car.

While the focus of this line of work is on empirically accounting for economic growth, it also delivers explanations. The central argument is that technological change makes energy services cheaper by increasing the conversion rate from primary energy to useful work. This increase allows production at lower costs, which lowers the prices of goods and services, fosters sales, and thereby induces economic growth (Warr/Ayres 2012). From that perspective, the central determinant of economic growth is, therefore, the speed at which technological change can increase the conversion rate from primary energy to useful work. The faster the technological change, the stronger is the effect on price reductions, additional demand and economic growth.

The role of this conversion rate for economic growth also provides the foundation for understanding low growth despite digitalization. From the perspective of ecological economics, the lack of rapid economic growth suggests that digital technologies do not have a strong positive effect on the conversion rate. The causal chain explained above is, then, only slightly triggered: prices do not fall substantially, demand stagnates, and economic growth is low.

Ecological economics suggests that the low impact of digital technologies on the conversion rate also explains why energy consumption is not reduced despite digital technologies. The hope that digital technologies could reduce energy consumption is mainly based on their ability to increase energy efficiency – similar to the concept of the conversion rate (Freitag et al. 2020). Hence a low impact of digital technologies on the conversion rate could explain their inability to reduce energy consumption so far. Indeed, concrete examples of digital technologies show that the net effect on energy intensity is mixed (Lange et al. 2020).

An additional explanation for the inability of digital technologies to reduce energy demand is the increasing energy consumption of the ICT sector itself (see Section 1). Ecological economics contributes two explanations to this development. First, the increase in the ICT sector can be seen as a result of the increase in the conversion rate in that sector due to rebound effects. In the ICT sector, energy efficiency and the conversion rate have increased immensely over recent decades. Koomey et al. (2011) show energy consumption per processing unit halves approximately every 1.5 years. Also, energy efficiency in data transmission (Coroama/Hilty 2014) and in data centres (Avgerinou et al. 2017; Shehabi et al. 2016) has increased fast in the past. The fast increase in the energy efficiency of processors has been a prerequisite for the invention and diffusion of digital technologies such as smartphones, sensors, etc. (Lange/Santarius 2020), and rebound effects are described as particularly large in the ICT sector (Hilty et al. 2006). Second, ecological economists have for a long time argued that the energy needed to produce the capital goods associated with new technologies needs to be taken into account when assessing the energy footprint of the ICT sector (Daly 1990). This so-called embodied energy (Sorrell 2007) is essential in calculating the net effect of introducing new technologies. If digital technologies are seen as tools to increase energy efficiency, the energy used for their production needs to be accounted for.

To sum up, while ecological economics attributes a low increase in consumption demand to an only slowly rising conversion rate, the next section covers post-Keynesian theories that bring forward additional reasons for stagnating demand.

5 INCOME INEQUALITY AND GOVERNMENT EXPENDITURE: A POST-KEYNESIAN PERSPECTIVE

Post-Keynesian theories characterize the economy and its growth as a dynamic interplay between aggregate supply and aggregate demand. They emphasize the importance of the development of aggregate demand for the rate of economic growth (because economies usually produce below full capacity). For post-Keynesian theories on economic growth, Kalecki's work is of the utmost importance (Hein 2014; Kalecki 1987). He developed a theory of the functioning of the entire economy by separating it into sectors for investment, capitalists' consumption and workers' consumption (Kalecki 1987). For economic dynamics, he regards the degree of monopolization as important. Economic growth is mainly due to the level of investment, which is influenced by a variety of factors (such as firms' expectations, monetary policy, animal spirits, etc.) and most importantly consumption demand, which in turn depends on income distribution. A higher degree of market concentration reduces consumption demand due to monopolistic power that leads to an increase in the capital share and a corresponding decrease in the labour share – that is, the share of total income paid to workers as opposed to capital owners. The (functional) income distribution is also decisive in Kaldor's work. Kaldor points out that investment leads to savings and develops the conditions under which the savings are of the same size as the preceding savings (Kaldor 1955). Kaldor also emphasizes the role of technological change for economic growth. He sees increases in labour productivity as being tightly linked to capital deepening – that is, increasing the capital per worker (Kaldor 1957; 1961).

From the perspective of post-Keynesian theories, the relation between digitalization and income inequality is a decisive aspect of how digitalization has influenced economic growth over recent decades. Researchers – who are mainly mainstream economists – argue that digitalization contributes to increases in income inequality threefold. First, using digital tools polarizes wage income. Even though digitalization is likely to rationalize some jobs at all wage levels, low-paying jobs are expected to be affected more heavily (Frey/Osborne 2017). On the other hand, new jobs created by digitalization tend to necessitate high education levels (Wolter et al. 2016). As a result, demand for high-skilled labour increases while demand for low-skilled labour decreases, leading to wage polarization. Acemoglu/Autor (2011) approach the polarization issue from a slightly different angle. They point out that digitalization is expected to replace routine tasks but not non-routine tasks. Non-routine jobs are located at the lower and upper ends of the earnings distribution. Digitalization will reduce the number of routine jobs in the middle-income bracket and replace them with either low- or high-paying manual and cognitive non-routine jobs. It will thus contribute to income inequality.

Second, digitalization promotes a reduction in the labour share. The labour share has fallen in recent decades for almost all OECD countries (ILO 2013; Trapp 2015). Because work in the digital economy is increasingly being done by robots and algorithms, digitalization is expected to worsen the bargaining position of employees and thereby aggravate the development of a falling labour share (Brynjolfsson/McAfee 2014).

Third, digitalization gives rise to 'winner-take-all' market structures due to the non-rival nature of the products in the digital economy such as knowledge, software and code. These non-rival products allow companies to achieve large economies of scale because the marginal costs of producing these products is extremely low or even zero. In these market structures, rents are particularly high because successful companies are likely to be in a dominant market position. This point is illustrated by the fact that firms in IT-intensive industries tend to have a comparatively high market share (Brynjolfsson et al. 2008). These winner-take-all

markets contribute to income inequality because the rents generated are distributed mainly to investors and top managers and less to average workers, thereby increasing the income share of the top income groups (Guellec/Paunov 2017).

As pointed out above, the income distribution plays a decisive role in post-Keynesian theories for determining the rate of economic growth. Higher inequality stifles consumption demand, and, as the economy is commonly below full capacity utilization, this means a lower level of production than what is possible. It also implies less investment since firms invest more when they expect to sell more products. By increasing income inequality, digitalization therefore dampens both consumption demand and economic growth.

Next to income inequality, a further connection between digitalization and slackening aggregate demand is government expenditure. In complex firm constructions, digital companies are particularly good for circumventing taxes and hence have a very low tax rate (Auerbach 2016; Duhigg/Kocieniewski 2012). This circumvention impedes upon the tax revenues of governments and hence also on their ability to spend – hence additionally reducing aggregate demand. The impact on income inequality and on governments' tax bases explains why digitalization leads to a lack in demand and is thus – according to post-Keynesian approaches – a reason for low economic growth (Lange/Santarius 2020; Staab 2017).

With regard to the relation between digitalization and environmental throughput, only few post-Keynesian economists have integrated environmental aspects into their work (Spash/Schandl 2009). Recently, several contributions have worked on integrating post-Keynesian and ecological economics – commonly under the term ecological macroeconomics (Fontana/Sawyer 2016; Jackson et al. 2014; Rezai/Stagl 2016; Rezai et al. 2013) – into contributions on methodological issues (Holt et al. 2009) as well as various concrete aspects such as the role of economic growth (Fontana/Sawyer 2016; Jackson 2016; Jackson/Victor 2014) or finances and the banking system (Campiglio 2016; Jackson/Victor 2015). An insightful contribution for the purpose of this article is the work of Harris (2001; 2008; 2013a; 2013b) to the issue of digitalization. He divides the economy into clean and dirty sectors and argues that, while the latter need to shrink, the former need to grow. Regarding policies, he refers to classic environmental policies such as environmental taxes and subsidies but also argues for fiscal policy to invest into the clean sectors. Applying Harris's analysis on the role of digitalization for the environment, stronger fiscal interventions would be needed to switch from dirty old sectors to clean new digital sectors. These interventions could, for example, be investment in an infrastructure giving better broadband and mobile Internet (so that digital services could be used to substitute physical goods) or into a renewable – and digitally facilitated – energy system.

In sum, the post-Keynesian approaches suggest that the dampening effect of digitalization on aggregate demand – via dampening consumption demand and limiting fiscal expenditure – is one of the factors explaining low growth in times of digitalization. Post-Keynesian theories contribute only slightly to the relation between digitalization and the environment. One aspect is that fiscal policies have so far not supported the switch towards the relatively clean digital sector. The next section will shed further light on why income inequalities are rising, and demand is ailing.

6 MONOPOLIZATION AND THE SALES EFFORT: A NEO-MARXIAN PERSPECTIVE

At the centre of neo-Marxian analyses lie dynamics of competition, new technologies and economic growth. In Marx's (1867 [1980]) analysis, firms compete on competitive

markets. Each firm tries to maximize profits and stay competitive by reducing costs – in particular, wages. The primary strategy is to develop and introduce new production technologies that facilitate production at lower costs. These new production technologies commonly go along with increasing the production capacity of firms due to economies of scale. The strategy to reduce costs per unit of production allows a firm to make extra profits (as long as other firms have not introduced such innovations) and stay competitive. The same dynamic also explains the tendency towards market power concentration: firms that win this technological race get an ever-bigger market share so that the number of firms in one market decreases over time.

Theoretical analyses under the term *monopoly capitalism* start from the point that many markets are controlled by a small number of large companies. These large companies also aim at maximizing profits, but due to the conditions of being oligopolies and often acting on saturated markets, their strategies look very different from companies in competitive, non-saturated markets. They do not compete primarily via price reductions, due to a common interest of the remaining large firms to refrain from them (Baran/Sweezy 1966). Instead, profits are maximized via, amongst other things, cost reductions, which mostly take place by reducing wages (Foster 2014). In addition, the large companies try to increase sales through the sales effort. This effort includes, in particular, two strategies. First, products are designed so that they need to be rebought at a high frequency: obsolescence. Second, commercials are used to induce additional consumption, in particular of new products. A further effort to increase consumption demand can be implemented by increasing government expenditure.

The issues of monopolization, cost reductions, and the sales effort are all highly present when it comes to digitalization. First, the digital world tends towards monopolization. Prominent examples are social media and search engines (Zuboff 2019). A central reason for this tendency is network effects and the fact that single firms not only gain market power but organize the markets themselves (Staab 2019). Second, large digital companies use their market power to reduce costs, in particular labour costs. Various examples show how labour regulation is circumvented in high-income countries or the devastating labour conditions with low wages in low-income countries (for example, China Labor Watch 2016; Sacom 2010). Third, the sales effort plays a particularly strong role in the digital sector. Various mechanisms related to obsolescence lead to a short lifetime of ICT devices such as laptops, smartphones, and electronic accessories (Kern et al. 2018; Proske/Jaeger-Erben 2019). The other central part of the sales effort – commercials – even makes up the primary business model of many large digital companies. Alphabet and Facebook make 87 per cent and 98 per cent of their revenues from advertisements respectively (Alba 2017).

The central explanation by neo-Marxists for the low effect of digitalization on economic growth is, therefore, that digital companies use their market power to reduce wages and thereby dampen consumption demand. The strong role of the sales effort in the digital economy explains the strong growth of the ICT sector but does not suffice to induce strong economy-wide growth.

Neo-Marxian theories regarding the environment also start from the dynamics of competition and the drive to increase profits. Both lead to an incentive for firms to externalize costs where possible – not only by reducing wages but also by exploiting or polluting the environment – whenever these measures increase profits (Magdoff/Foster 2011). This externalization is a strong obstacle to introducing environmental sustainability as firms either will try to circumvent regulation where possible (Altvater 2005) or will solve one environmental problem (for example, reducing greenhouse gases) by generating another (for example, lithium use for batteries) (Foster et al. 2010).

Further, economic growth since the industrial revolution is argued to have been strongly linked to the use of fossil fuels and – due to the characteristics of different energy carriers – shifting towards renewable energy is extremely difficult, in particular over all sectors in a relatively short period of time (Altvater 2005). In some sectors, this shift is particularly onerous because the companies' business models depend on fossil fuels. Those companies then try to use economic and political influence to prevent the respective environmental regulation in the first place (Foster 2005).

The major insight from neo-Marxian approaches on digitalization and the environment is that there is no reason why digitalization should change the fundamental forces and incentives in capitalism. Digital companies or traditional companies that make use of digital technologies still act within a system of market competition and try to maximize profits. Therefore, they still have the incentive to externalize costs where possible. Concrete examples are the disastrous disposal of electronic waste (von Finck/Manhart 2016) or the vast amount of packaging waste generated by online shopping (Chueamuangphan et al. 2020).

In sum, neo-Marxian theories contribute to understanding the role of increasing monopolization for income inequality and how competition and profit-maximization lead to firm strategies that further harm the environment. The next section combines the insights from the neoclassical, ecological economics, post-Keynesian and neo-Marxian approaches.

7 SYNTHESIS

The theories deliver different explanations for the low impact of digitalization on economic growth and the failure to contribute substantially to reducing environmental throughput. In the following, I first analyse – based on the pluralistic approach described in Section 2 – the relation between the statements of the different schools of economic thought for economic growth (Section 7.1) and for environmental throughput (Section 7.2). The goal of this synthesis is to develop an integrated and thereby more comprehensive understanding of the effect of digitalization on economic growth and environmental throughput. Afterwards, I point out major economic policies resulting from this analysis and what these policies mean for the debate on green growth, de-growth and a-growth (Section 7.3).

7.1 Economic growth

The statements from the different schools of economic thought are partly contradictory and partly compatible on the topic of economic growth (see Table 1). The neoclassical perspective emphasizes the limited impact of digitalization on labour productivity. However, the related criticisms stemming from ecological economics seem plausible. Simply assigning a large part of economic growth to a factor that cannot be measured (total factor productivity) puts the neoclassical growth theory in question – and therefore also its explanation of the effect of digitalization on growth. The explanation from ecological economics *contradicts* the neoclassical one. Hence, the strategy of test of hypothesis is applied here (compare Section 2). Introducing useful work as a factor of production explains the largest part of economic growth. Hence, the hypothesis that the limited impact of digital technologies on economic growth is related to the low increase in the conversion rate from primary energy to useful exergy is more plausible than the hypothesis attributing it to total factor productivity (compare Section 4).

However, the underlying causal explanations from ecological economics of how an increase in the conversion rate leads to economic growth are not satisfactory. The reasons are twofold. First, the explanation rests on the causal chain that increases in the conversion

Table 1 Relations of statements regarding digitalization and economic growth

Theory	Reasons for low economic growth	
Neoclassical	• Low impact on total factor productivity	Relation: Contradicting Strategy: Test of hypotheses
Ecological Economics	• Low impact on conversion rate	
Post-Keynesian	• Increase in income inequality • Reduces ability for government expenditure	Relation: Convergent Strategy: Integration
Neo-Marxian	• Tendency towards monopolies supports income inequality • Monopolies and oligopolies prevent strong reductions in prices despite reductions in production costs	

rate lead to reductions in prices and hence spur consumption demand. However, consumption demand clearly depends on additional factors. Second, the question remains whether increases in the conversion rate actually lead to (strong) reductions in prices.

The contributions from post-Keynesian and neo-Marxian theories help to shed light on these issues and are *convergent* with the ones from ecological economics. Therefore, a strategy of *integration* is pursued (see Table 1). Post-Keynesian theories emphasize the role of inequality. The application of digital technologies throughout the economy is accompanied by increasing inequality, which dampens consumption demand. In addition, digital possibilities are being used by multinational firms to circumvent taxes – making it difficult for nation states to gather revenues for investment. The effect of digitalization on consumption demand and government spending is a central reason behind relatively low growth rates.

The neo-Marxian approaches contribute explanations for both the increase in inequality and the lack of price reductions. As elaborated above, digitalization promotes market concentration, resulting in the concentration of market power among few firms. This power enables the firms to reduce wages, which further dampens consumption demand. In addition, neo-Marxian approaches argue that large firms do not compete via price competition. This argument helps to explain why increases in the conversion rate do not lead to a growth cycle – because they are not passed on in the form of lower product prices.

Overall, the central reason for digitalization going hand in hand with low economic growth is its negative effect on demand. This lack in demand is due to: (i) a low increase in the conversion rate; (ii) monopolistic tendencies leading to reductions in production costs being insufficiently transformed into lower product prices; (iii) digitalization leading to higher income inequality, which is due to several factors such as wage polarization and a decreasing wage share, both related to monopolization; and (iv) an adverse effect on the ability of governments to collect taxes and thereby to authorize expenditure.

7.2 Environmental throughput

As indicated in Section 1, the fact that digitalization does not substantially reduce environmental throughput entails two major aspects: that digital technologies are not being used to reduce the environmental intensity of production and that the environmental

footprint of the ICT sector itself is substantial. I investigate the relations of the theoretical statements from the different economic schools regarding these two aspects in turn.

For the first aspect, the statements of neoclassical theories and ecological economics seem to be *identical* at first sight (see Table 2). From both perspectives, digital possibilities have not been used more extensively to reduce the environmental intensity of production so far because the relative prices between energy and other production factors incentivize an intensive use of energy and greenhouse gas emissions. Upon closer inspection however, the underlying theories differ significantly and *contradict* each other. In particular, the neoclassical theories assume substitutability between production factors, whereas ecological economics approaches see substitution as limited. In addition, neoclassical economics regards energy as relatively unproductive – compared to the other production factors, in particular labour. Ecological economics, on the other hand, regards energy as the most productive production factor. These differences lead to contradicting predictions regarding what would happen if different relative prices of production factors would incentivize economic actors to focus the development and application of digital technologies on reducing environmental intensity. The neoclassical arguments consider that higher energy prices create incentives for the substitution of energy by other production factors and thereby allow for further growth. In ecological economics, a strong increase in the price of energy would lead to applications of digital technologies that reduce environmental intensities but at the same time cease to increase labour productivity and hence would also cease to facilitate economic growth. As these two schools of thought contradict each other, the strategy of the *test of hypothesis* is applied. As argued in Section 4, the reasoning of ecological economics is both theoretically and empirically more convincing, which is why their implications regarding economic growth are followed in Section 7.3.

The neo-Marxian school of thought contributes two aspects that tend to countervail the effectiveness of a change in relative prices and are *convergent* with the view from ecological economics (see Table 2). Hence, here, a strategy of *integration* is followed. First, firms are induced to externalize costs (to the environment) wherever this supports competitiveness and profit generation. Firms thus have an incentive to find loopholes in environmental regulations or shift environmental problems away from one environmental dimension towards another one. Second, the neo-Marxian theories point out that profit

Table 2 Relations of statements regarding digitalization and environmental throughput

Theory	**Reasons for inability to reduce environmental throughput**	
Neoclassical	• Relative prices	Relation: Identical in statement, contradicting in implications Strategy: Test of hypotheses
Ecological Economics	• Relative prices • Rebound effects • Embodied energy	
Post-Keynesian	• Missing government investments and spending in green sectors	Relation: Convergent or compatible, both regarding digitalization's effect on environmental intensity and environmental throughput of the ICT sector Strategy: Integration
Neo-Marxian	• Externalization • Obsolescence • Commercials • Political economy to prevent regulation	

generation is strongly linked to using fossil energy, in particular in energy-intensive sectors. Wherever environmental protection leads to lower profits – for example, when higher energy prices make certain products unprofitable – firms and shareholders will aim at preventing these policies.

Post-Keynesian approaches point out an additional aspect that is compatible with the ecological economics and neo-Marxian perspectives, and can therefore be integrated: the lack of public expenditure in digital infrastructures that enable sustainable transitions and in green digital goods and services. Compared to the contributions by the other schools of economic thought, this does not concern how the production of certain goods and services can become less environmentally intensive but concerns how to induce a sectoral change from dirty towards cleaner goods and services.

The second issue relates to the high environmental footprint of the ICT sector itself. Here, the ecological economics and the neo-Marxian approaches deliver central insights and are *convergent* (see Table 2). Ecological economics argues that the embodied energy in new digital technologies is substantial. In addition, one explanation of growth in the ICT sector is rebound effects due to strong efficiency improvements in digital technologies. The neo-Marxian perspective emphasises the role of sales strategies that include a short product lifetime (obsolescence), which helps to explain the large number of ICT devices sold. The other central sales strategy is commercials, which are at the centre of many digital business models and contribute to non-necessary consumption not only in the ICT sector but also of goods and services from other sectors.

Overall, the lacking ability of digital tools to reduce the environmental intensity of production is mainly due to distorted relative prices, missing government investment into green digital sectors, and firms' incentives to externalize environmental costs. The ICT sector's increasing environmental footprint can be explained by a combination of rebound effects, embodied energy, and obsolescence.

8 POLICY IMPLICATIONS AND THEIR RELATION TO THE GROWTH DEBATE

The empirical findings mentioned in Section 1 show that digitalization has so far been unable to substantially stimulate growth as well as improve environmental sustainability. The analyses from Sections 3–6 give insights on which policies could or should be introduced to improve the environmental effect of digitalization. In this section, it is discussed whether these policies are likely to increase or decrease economic growth.

Table 3 summarizes the main theoretical statements of each school of thought and visualizes the central policies that could improve digitalization's environmental effects and the influence these policies would likely have on economic growth.

Absolute limits or environmental taxes The central policy tools to facilitate the usage of digital technologies for environmental sustainability are similar to the main tools to reduce environmental throughput in general: either by absolute limits or environmental taxes. Both policies go along with an increase in the price of CO_2 emissions and resource use. Neoclassical and ecological economics differ in their predictions of the impact this limiting would have on economic growth.

Different forms of ownership in the digital economy In neo-Marxian theories, exploitation (particularly in markets with monopolies and oligopolies) is mainly due to the profit

Table 3 Environmental policy responses and their impact on economic growth

Theory	Reasons for inability to reduce environmental throughput	Policy responses	Impact on economic growth
Neoclassical	Relative prices	Absolute limits or environmental taxes	Uncertain
Ecological economics	Relative prices	Absolute limits or environmental taxes	Negative
	Rebound effects	Sufficiency in the ICT sector – e.g. longevity of devices or data-saving codes	Negative
	Embodied energy	Sufficiency in the ICT sector – e.g. longevity of devices or data-saving codes	Negative
Post-Keynesian	Lack of public expenditure in digital infrastructures for sustainable transitions and in green digital goods and services	Public expenditure on investment and in green digital goods and sectors	Uncertain
Neo-Marxian	Externalization	Different forms of ownership in the digital economy	Uncertain
	Obsolescence	Longevity regulation	Negative
	Commercials	Regulation of online commercials	Negative

motive of firms. Therefore, proposals regarding the digital economy concentrate on the ownership structure of firms. By organizing large platforms in cooperatives, by including various stakeholders or by giving public authorities a stronger role, the driving motivation of these platforms and firms can be changed and geared towards other – more sustainable – directions (Berg/Wilts 2019; Scholz 2016).

Public expenditure Government investment and spending in sectors that use digitalization and have a relatively low environmental throughput could push economic growth – for example, investment into the digital physical infrastructure, an energy system geared towards renewables, but also into better public digital services. But such public expenditure does not necessarily need to imply a positive effect on economic growth. As Harris (2013b) points out, a green transition entails not only more expenditure in environmentally friendly sectors but also less expenditure in environmentally destructive ones. If expenditure in such sectors – for example, road construction, air transportation, meat production, etc. – is reduced simultaneously to the increase of expenditure in environmentally friendly digital sectors, the effect on economic growth would be neutral or even negative.

Sufficiency in the ICT sector including longevity regulation and regulating commercials The policies suited to responding to the substantial environmental throughput by the ICT

sector itself are also clearly growth-reducing. Achieving greater longevity of devices would reduce the number of sales. Introducing software that requires less processing power and less server capacity would reduce the price of end devices and the cost of investment in the network infrastructure and server capacities. And regulating commercials would reduce the sales in other sectors as well.

Redistribution and political economy Redistribution is not directly aimed at improving the environmental effect of digitalization but should also be borne in mind. As argued in Section 5, digitalization is associated with increasing income inequality, which tends to reduce economic growth. Implementing policies to counteract this development and reduce income inequality would induce more private consumption and spur economic growth. The political economy of the digital economy has important implications on the feasibility of all policies proposed so far. However, discussing how this feasibility can be improved goes beyond the scope of this article.

The vast majority of policies suggested here reduce economic growth (compare the last column in Table 3). However, it is not possible to compare the sizes of effects of the different policies and these sizes also depend on the concrete policies and specific circumstances. Also, the public expenditure in digital infrastructures for sustainable transitions and in green digital goods and services have arguably a large potential for increasing economic growth.

Therefore, the policies suggested here match well with a-growth approaches. The major reason is that a-growth positions also argue that it is unclear whether environmental policies will lead to economic growth or economic shrinkage.

9 CONCLUSION

The analysis of this article started from many hopes being associated with digitalization to facilitate environmental sustainability and green growth. Based on empirical findings that this has not been the case so far, I discussed possible explanations from the perspective of different schools of economic thought, based on a pluralistic methodology.

It turned out that many of the contributions from these schools can be integrated into a more comprehensive understanding of why digitalization does not lead to strong economic growth or a speedy reduction in environmental throughput. Regarding economic growth, it is not primarily and certainly not only the limited capability of digital technologies to increase labour productivity, as argued by neoclassical economics. Rather, the application of digital technologies as it takes place at the moment goes along with low aggregate demand, primarily explained by digitalization's effect to increase income inequality. This low aggregate demand is the major connection between digitalization and its low effect on economic growth. The inability of digitalization to substantially improve environmental sustainability can be explained by a combination of distorted relative prices of inputs, missing government investment, and a combination of factors responsible for the high environmental footprint of the ICT sector.

Looking at the policies following from this pluralistic approach to improve the effect of digitalization on the environment suggests that it is unclear whether the combination of such policies would foster or dampen economic growth. Therefore, gearing digitalization towards supporting environmental sustainability is compatible with an a-growth, rather than a green-growth, strategy.

REFERENCES

Acemoglu, D., Autor, D. (2011): Skills, tasks and technologies: implications for employment and earnings, in: Ashenfelter, O., Card, D. (eds), *Handbook of Labor Economics*, Vol. 4, San Diego: Elsevier, 1043–1171, URL: https://doi.org/10.1016/S0169-7218(11)02410-5.

Acemoglu, D., Aghion, P., Bursztyn, L., Hemous, D. (2012): The environment and directed technical change, in: *American Economic Review*, 102(1), 131–166, URL: https://doi.org/10.1257/aer.102.1.131.

Aghion, P., Howitt, P. (2009): *The Economics of Growth*, Cambridge, MA: MIT Press, URL: http://discovery.ucl.ac.uk/17829/.

Alba, D. (2017): Google and Facebook still reign over digital advertising, in: *Wired*, URL: https://www.wired.com/story/google-facebook-online-ad-kings/.

Altvater, E. (2005): *Das Ende des Kapitalismus, wie wir ihn kennen*, Münster: Westfälisches Dampfboot.

Andrae, A.S.G., Edler, T. (2015): On global electricity usage of communication technology: trends to 2030, in: *Challenges*, 6(1), 117–157, URL: https://doi.org/10.3390/challe6010117.

Antal, M., van den Bergh, J. (2016): Green growth and climate change: conceptual and empirical considerations, in: *Climate Policy*, 16(2), 165–177, URL: https://doi.org/10.1080/14693062.2014.992003.

Arntz, M., Gregory, T., Zierahn, U. (2017): Revisiting the risk of automation, in: *Economics Letters*, 159, 157–160, URL: https://doi.org/10.1016/j.econlet.2017.07.001.

Arrow, K. (1962): The economic implications of learning by doing, in: *The Review of Economic Studies*, 29(3), 155–173.

Auerbach, M. (2016): *IKEA: Flat Pack Tax Avoidance*, URL: http://www.mbl.is/media/28/9628.pdf.

Avgerinou, M., Bertoldi, P., Castellazzi, L. (2017): Trends in data centre energy consumption under the European code of conduct for data centre energy efficiency, in: *Energies*, 10(12), No 1470, URL: https://doi.org/10.3390/en10101470.

Ayres, R.U. (2003): Exergy, power and work in the US economy, 1900–1998, in: *Energy*, 28(3), 219–273, URL: https://doi.org/10.1016/S0360-5442(02)00089-0.

Ayres, R.U., Warr, B. (2009): *The Economic Growth Engine: How Energy and Work Drive Material Prosperity*, Cheltenham, UK and Northampton, MA: Edward Elgar Publishing.

Ayres, R.U., van den Bergh, J.C.J.M., Lindenberger, D., Warr, B. (2013): The underestimated contribution of energy to economic growth, in: *Structural Change and Economic Dynamics*, 27, 79–88, URL: https://doi.org/10.1016/j.strueco.2013.07.004.

Ayres, R.U., Brockway, P., Aramendia, E. (2019): The key role of energy in economic growth, Environmental Science, Oxford Bibliographies, Oxford: Oxford University Press.

Baran, P.A., Sweezy, P.M. (1966): *Monopoly Capital: An Essay on the American Economic and Social Order*, New York: Monthly Review Press.

Belkhir, L., Elmeligi, A. (2018): Assessing ICT global emissions footprint: trends to 2040 and recommendations, in: *Journal of Cleaner Production*, 177, 448–463, URL: https://doi.org/10.1016/j.jclepro.2017.12.239.

Berg, H., Wilts, H. (2019): Digital platforms as market places for the circular economy: requirements and challenges, in: *NachhaltigkeitsManagementForum*, 27(2019), 1–9, doi: 10.1007/s00550-018-0468-9.

Bowen, A., Hepburn, C. (2014): Green growth: an assessment, in: *Oxford Review of Economic Policy*, 30(3), 407–422.

Brynjolfsson, E., McAfee, A. (2014): *The Second Machine Age: Work, Progress, and Prosperity in a Time of Brilliant Technologies*, New York: W.W. Norton.

Brynjolfsson, E., McAfee, A., Sorell, M., Zhu, F. (2008): Scale without mass: business process replication and industry dynamics, in: *SSRN Electronic Journal*, URL: https://doi.org/10.2139/ssrn.980568.

Brynjolfsson, E., Rock, D., Syverson, C. (2017): Artificial intelligence and the modern productivity paradox: a clash of expectations and statistics, Working Paper No w24001, National Bureau of Economic Research, URL: https://doi.org/10.3386/w24001.

Campiglio, E. (2016): Beyond carbon pricing: the role of banking and monetary policy in financing the transition to a low-carbon economy, in: *Ecological Economics*, 121, 220–230, URL: https://doi.org/10.1016/j.ecolecon.2015.03.020.

China Labor Watch (2016): Apple making big profits but Chinese workers' wage on the slide, China Labor Watch, URL: http://www.chinalaborwatch.org/report/120.

Chueamuangphan, K., Kashyap, P., Visvanathan, C. (2020): Packaging waste from e-commerce: consumers' awareness and concern, in: Ghosh, S.K. (ed.), *Sustainable Waste Management: Policies and Case Studies*, Singapore: Springer, 27–41, URL: https://doi.org/10.1007/978-981-13-7071-7_3.

Corcoran, P.M., Andrae, A.S.G. (2013): Emerging trends in electricity consumption for consumer ICT, Technical Report, National University of Ireland, Galway, Connacht, Ireland.

Coroama, V.C., Hilty, L.M. (2014): Assessing Internet energy intensity: a review of methods and results, in: *Environmental Impact Assessment Review*, 45, 63–68, URL: https://doi.org/10.1016/j.eiar.2013.12.004.

Daly, H.E. (1990): Toward some operational principles of sustainable development, in: *Ecological Economics*, 2(1), 1–6, URL: https://doi.org/10.1016/0921-8009(90)90010-R.

Dasgupta, P., Heal, G. (1974): The optimal depletion of exhaustible resources, in: *The Review of Economic Studies*, 41(Symposium on the Economics of Exhaustible Resources), 3–28.

Dobusch, L., Kapeller, J. (2012): Heterodox United vs. Mainstream City? Sketching a framework for interested pluralism in economics, in: *Journal of Economic Issues*, 46(4), 1035–1058, URL: https://doi.org/10.2753/JEI0021-3624460410.

Duhigg, C., Kocieniewski, D. (2012): Apple's tax strategy aims at low-tax states and nations, in: *The New York Times*, 28 April, URL: https://www.nytimes.com/2012/04/29/business/apples-tax-strategy-aims-at-low-tax-states-and-nations.html.

Ekins, P. (2000): *Economic Growth and Environmental Sustainability: The Prospects for Green Growth*, London: Routledge.

European Commission (n.d.): Shaping Europe's digital future, URL: https://digital-strategy.ec.europa.eu/en/policies/strategy-data (accessed 5 November 2021).

European Commission (2019): Communication from the Commission to the European Parliament, the European Council, the Council, the European Economic and Social Committee and the Committee of the Regions: the European Green Deal, 11 December, URL: https://eur-lex.europa.eu/resource.html?uri=cellar:b828d165-1c22-11ea-8c1f-01aa75ed71a1.0002.02/DOC_1&format=PDF.

Farhadi, M., Ismail, R., Fooladi, M. (2012): Information and communication technology use and economic growth, in: *PloS One*, 7(11), No e48903, URL: https://doi.org/doi:10.1371/ journal.pone.0048903.

Fontana, G., Sawyer, M. (2016): Towards post-Keynesian ecological macroeconomics, in: *Ecological Economics*, 121, 186–195, URL: https://doi.org/10.1016/j.ecolecon.2015.03.017.

Foster, J.B. (2005): The treadmill of accumulation: Schnaiberg's environment and Marxian political economy, in: *Organization/Environment*, 18(1), 7–18, URL: https://doi.org/10.1177/1086026604270442.

Foster, J.B. (2014): *The Theory of Monopoly Capitalism: An Elaboration of Marxian Political Economy*, 2nd edn, New York: Monthly Review Press, URL: http://books.google.com/books?hl=de&lr=&id=-Z-mAwAAQBAJ&oi=fnd&pg=PT6&dq=The+theory+of+monopoly+capitalism.&ots=yISBXPasmE&sig=VI64nWKRl9RJxFS1l3NmJ2sv7Ik.

Foster, J.B., Clark, B., York, R. (2010): *The Ecological Rift: Capitalism's War on the Earth*, New York: Monthly Review Press.

Freitag, C., Berners-Lee, M., Widdicks, K., Knowles, B., Blair, G., Friday, A. (2020): The climate impact of ICT: a review of estimates, trends and regulations, Report, Unpublished, University of Lancaster.

Freitag, C., Berners-Lee, M., Widdicks, K., Knowles, B., Blair, G.S., Friday, A. (2021): The real climate and transformative impact of ICT: a critique of estimates, trends, and regulations, in: *Patterns*, 2(9), No 100340, URL: https://doi.org/10.1016/j.patter.2021.100340.

Frey, C.B., Osborne, M.A. (2017): The future of employment: how susceptible are jobs to computerisation?, in: *Technological Forecasting and Social Change*, 114, 254–280, URL: https://doi.org/10.1016/j.techfore.2016.08.019.
Georgescu-Roegen, N. (1971): *The Entropy Law and the Economic Process*, Cambridge, MA: Harvard University Press, URL: http://scholar.google.com/scholar?q=The+Entropy+Law+and+the+economic+process#0.
GeSI/Accenture (2015): Smarter 2030: ICT solutions for 21st century challenges, Report, Global e-Sustainability Initiative.
GeSI/Deloitte (2019): Digital with purpose: delivering a SMARTer2030, Report, Global e-Sustainability Initiative.
Gordon, R.J. (2012): Is US economic growth over? Faltering innovation confronts the six headwinds, NBER Working Paper Series, No 18315, URL: http://www.nber.org/papers/w18315.
Gordon, R.J. (2015): Secular stagnation: a supply-side view, in: *American Economic Review*, 105(5), 54–59, URL: https://doi.org/10.1257/aer.p20151102.
Guellec, D., Paunov, C. (2017): Digital innovation and the distribution of income, Working Paper No w23987, National Bureau of Economic Research, URL: https://doi.org/10.3386/w23987.
Harris, J.M. (2001): Macroeconomic policy and sustainability, Global Development and Environment Institute, Working Paper, No 01-09, URL: http://ase.tufts.edu/gdae/publications/working_papers/macroandsust.pdf.
Harris, J.M. (2008): Ecological macroeconomics: consumption, investment, and climate change, Global Development and Environment Institute, Working Paper, No 08-02.
Harris, J.M. (2013a): Green Keynesianism: beyond standard growth paradigms, Working Paper, Tufts University.
Harris, J.M. (2013b): The macroeconomics of development without throughput growth, in: Cohen, M., Brown, H., Vergragt, P. (eds), *Innovations in Sustainable Consumption: New Economics, Socio-Technical Transitions and Social Practices*, Cheltenham, UK and Northampton, MA: Edward Elgar Publishing, 31–47.
Haseeb, A., Xia, E., Saud, S., Ahmad, A., Khurshid, H. (2019): Does information and communication technologies improve environmental quality in the era of globalization? An empirical analysis, in: *Environmental Science and Pollution Research*, 26(9), 8594–8608, URL: https://doi.org/10.1007/s11356-019-04296-x.
Hedberg, A., Šipka, S. (2020): *The Circular Economy: Going Digital*, Brussels: European Policy Centre, URL: https://www.epc.eu/en/Publications/The-circular-economy-Going-digital~30c848.
Hein, E. (2014): *Distribution and Growth after Keynes: A Post-Keynesian Guide*, Cheltenham, UK and Northampton, MA: Edward Elgar Publishing.
Hilty, L.M., Köhler, A., Von Schéele, F., Zah, R., Ruddy, T. (2006): Rebound effects of progress in information technology, in: *Poiesis/Praxis*, 4(1), 19–38, URL: https://doi.org/10.1007/s10202-005-0011-2.
Holt, R.P.F., Pressmann, S., Spash, C. (eds) (2009): *Post Keynesian and Ecological Economics: Confronting Environmental Issues*, Cheltenham, UK and Northampton, MA: Edward Elgar Publishing.
ILO (ed.) (2013): *Wages and Equitable Growth*, Geneva: ILO.
Jackson, T. (2016): *Prosperity Without Growth: Economics for a Finite Planet*, 2nd rev. edn, Abingdon, UK: Taylor & Francis.
Jackson, T., Victor, P.A. (2014): Does slow growth increase inequality? A stock–flow consistent exploration of the 'Piketty hypothesis', PASSAGE Working Paper Series, No 15-03.
Jackson, T., Victor, P.A. (2015): Does credit create a 'growth imperative'? A quasi-stationary economy with interest-bearing debt, in: *Ecological Economics*, 120, 32–48, URL: https://doi.org/10.1016/j.ecolecon.2015.09.009.
Jackson, T., Drake, B., Victor, P.A., Kratena, K., Sommer, M. (2014): Foundations for an ecological macroeconomics: literature review and model development, Working Paper for the Research Project WWWforEurope, 65, URL: http://www.foreurope.eu/fileadmin/documents/pdf/Workingpapers/WWWforEurope_WPS_no065_MS38.pdf.
Jacobs, M. (2013): Green growth, in: Falkner, R. (ed.), *The Handbook of Global Climate and Environment Policy*, Hoboken, NJ: John Wiley, 197–214, URL: https://doi.org/10.1002/9781118326213.ch12.

Kaldor, N. (1955): Alternative theories of distribution, in: *The Review of Economic Studies*, 23(2), 83–100.
Kaldor, N. (1957): A model of economic growth, in: *The Economic Journal*, 67(268), 591–624.
Kaldor, N. (1961): *Capital Accumulation and Economic Growth*, New York: Macmillan.
Kalecki, M. (1987): *Krise und Prosperität im Kapitalismus: Ausgewählte Essays 1933–1971*, Marburg: Metropolis, URL: http://scholar.google.com/scholar?q=krise+und+prosperit%C3%A4t&btnG=&hl=de&as_sdt=0%2C5#0.
Kallis, G., Kostakis, V., Lange, S., Muraca, B., Paulson, S., Schmelzer, M. (2018): Research on degrowth, in: *Annual Review of Environment and Resources*, 43(1), 291–316.
Kern, E., Hilty, L.M., Guldner, A., Maksimov, Y.V., Filler, A., Gröger, J., Naumann, S. (2018): Sustainable software products: towards assessment criteria for resource and energy efficiency, in: *Future Generation Computer Systems*, 86, 199–210, URL: https://doi.org/10.1016/j.future.2018.02.044.
Koomey, J., Berard, S., Sanchez, M., Wong, H. (2011): Implications of historical trends in the electrical efficiency of computing, in: *IEEE Annals of the History of Computing*, 33(3), 46–54, URL: https://doi.org/10. 1109/MAHC.2010.28.
Kopp, T., Lange, S., Nabernegg, M. (work in progress): The climate effect of digitalization in production and consumption in OECD countries, Article, Under Review.
Kümmel, R. (2011): *The Second Law of Economics: Energy, Entropy, and the Origins of Wealth*, New York: Springer, URL: http://nbn-resolving.de/urn:nbn:de:1111-20110624122.
Lange, S., Santarius, T. (2020): *Smart Green World? Making Digitalization Work for Sustainability*, London: Routledge.
Lange, S., Pütz, P., Kopp, T. (2018): Do mature economies grow exponentially?, in: *Ecological Economics*, 147, 123–133, URL: https://doi.org/10.1016/j.ecolecon.2018.01.011.
Lange, S., Pohl, J., Santarius, T. (2020): Digitalization and energy consumption: does ICT reduce energy demand?, in: *Ecological Economics*, 176, No 106760, URL: https://doi.org/10.1016/j.ecolecon.2020.106760.
Lu, W.-C. (2018): The impacts of information and communication technology, energy consumption, financial development, and economic growth on carbon dioxide emissions in 12 Asian countries, in: *Mitigation and Adaptation Strategies for Global Change*, 23(8), 1351–1365, URL: https://doi.org/10.1007/s11027-018-9787-y.
Lucas, R.E. (1988): On the mechanics of economic development, in: *Journal of Monetary Economics*, 22(1), 3–42, URL: https://doi.org/10.1016/0304-3932(88)90168-7.
Magdoff, F., Foster, J.B. (2011): *What Every Environmentalist Needs to Know About Capitalism: A Citizen's Guide to Capitalism and the Environment*, New York: Monthly Review Press.
Malmodin, J., Lundén, D. (2018): The energy and carbon footprint of the global ICT and E&M sectors 2010–2015, in: *Sustainability*, 10(9), No 3027, URL: https://doi.org/10.3390/su10093027.
Malmodin, J., Moberg, Å., Lundén, D., Finnveden, G., Lövehagen, N. (2010): Greenhouse gas emissions and operational electricity use in the ICT and entertainment and media sectors, in: *Journal of Industrial Ecology*, 14(5), 770–790, URL: https://doi.org/10.1111/j.1530-9290.2010.00278.x.
Marx, K. (1867 [1980]): *Das Kapital: Kritik der politischen Ökonomie. Erster Band – Buch I: Der Produktionsprozeß des Kapitals*, Hildesheim: Gerstenberg Verlag.
McAfee, A. (2019): *More from Less: The Surprising Story of How we Learned to Prosper Using Fewer Resources – And What Happens Next*, New York: Scribner.
Petschow, U., Lange, S., Hoffmann, D., Pissarskoi, E., aus dem Moore, N., Korfhage, T., Schoofs, A. (2020): Social well-being within planetary boundaries: the precautionary post-growth approach, Report, No 234, 180 pp., Environmental Research of the Federal Ministry for the Environment, Nature Conservation and Nuclear Safety, German Environmental Agency (UBA).
Proske, M., Jaeger-Erben, M. (2019): Decreasing obsolescence with modular smartphones? An interdisciplinary perspective on lifecycles, in: *Journal of Cleaner Production*, 223, 57–66, URL: https://doi.org/10.1016/j.jclepro.2019.03.116.
Rezai, A., Stagl, S. (2016): Ecological macroeconomics: introduction and review, in: *Ecological Economics*, 121, 181–185, URL: https://doi.org/10.1016/j.ecolecon.2015.12.003.

Rezai, A., Taylor, L., Mechler, R. (2013): Ecological macroeconomics: an application to climate change, in: *Ecological Economics*, 85, 69–76, URL: https://doi.org/10.1016/j.ecolecon.2012.10.008.

Romer, P.M. (1986): Increasing returns and long-run growth, in: *Journal of Political Economy*, 94 (5), 1002–1037.

Romer, P. (1990): Endogenous technological change, in: *Journal of Political Economy*, 98(5), S71–S102.

Sacom (2010): Workers as machines: military management in Foxconn, Report, Hong Kong: Students and Scholars Against Corporate Misbehaviour, URL: sacom.hk/wp-content/uploads/2010/11/report-on-foxconn-workers-as-machines_sacom.pdf

Salahuddin, M., Alam, K. (2015): Internet usage, electricity consumption and economic growth in Australia: a time series evidence, in: *Telematics and Informatics*, 32(4), 862–878, URL: https://doi.org/10.1016/j.tele.2015.04.011.

Salahuddin, M., Alam, K. (2016): Information and communication technology, electricity consumption and economic growth in OECD countries: a panel data analysis, in: *International Journal of Electrical Power and Energy Systems*, 76, 185–193, URL: https://doi.org/10.1016/j.ijepes.2015.11.005.

Salahuddin, M., Alam, K., Ozturk, I. (2016): The effects of Internet usage and economic growth on CO2 emissions in OECD countries: a panel investigation, in: *Renewable and Sustainable Energy Reviews*, 62, 1226–1235, URL: https://doi.org/10.1016/j.rser.2016.04.018.

Scholz, T. (2016): Platform cooperativism: challenging the corporate sharing economy, Report, Berlin: Rosa Luxemburg Stiftung, URL: http://www.rosalux-nyc.org/platform-cooperativism-2/.

Seidl, I., Zahrnt, A. (2010): Argumente für einen Abschied vom Paradigma des Wirtschaftswachstums, in: Seidl, I., Zahrnt, A. (eds), *Postwachstumsgesellschaft: Konzepte für die Zukunft*, Marburg: Metropolis, 22–36.

Serrenho, A.C., Sousa, T., Warr, B., Ayres, R.U., Domingos, T. (2014): Decomposition of useful work intensity: the EU (European Union) – 15 countries from 1960 to 2009, in: *Energy*, 76, 704–715, URL: https://doi.org/10.1016/j.energy.2014.08.068.

Shehabi, A., Smith, S.J., Horner, N., Azevedo, I., Brown, R., Koomey, J., Masanet, E., Sartor, D., Herrlin, M., Lintner, W. (2016): United States Data Center energy usage report, Lawrence Berkeley National Laboratory, Berkeley, California, LBNL-1005775.

Shift Project, The (2019): Lean ICT: towards digital sobriety, Report, Paris: The Shift Project, URL: https://theshiftproject.org/wp-content/uploads/2019/03/Lean-ICT-Report_The-Shift-Project_2019.pdf.

Solow, R.M. (1956): A contribution to the theory of economic growth, in: *The Quarterly Journal of Economics*, 70(1), 65–94, URL: https://doi.org/10.2307/1884513.

Solow, R.M. (1974): The economics of resources or the resources of economics, in: *The American Economic Review*, 64(2), 1–14.

Solow, R.M. (1987): We'd better watch out, in: *New York Times Book Review*, 12 July, 36.

Sorrell, S. (2007): The rebound effect: an assessment of the evidence for economy-wide energy savings from improved energy efficiency, Research Report, London: UK Energy Research Centre London.

Spash, C.L., Schandl, H. (2009): Challenges for Post Keynesian growth theory: utopia meets environmental and social reality, in: Holt, R.F., Pressman, S., Spash, C.L. (eds), *Post Keynesian and Ecological Economics: Confronting Environmental Issues*, Cheltenham, UK and Northampton, MA: Edward Elgar Publishing, 47–70.

Staab, P. (2017): The consumption dilemma of digital capitalism, in: *Transfer: European Review of Labour and Research*, 23(3), 281–294, URL: https://doi.org/10.1177/1024258917702830.

Staab, P. (2019): *Digitaler Kapitalismus: Markt und Herrschaft in der Ökonomie der Unknappheit*, Berlin: Suhrkamp Verlag.

Stiglitz, J. (1974): Growth with exhaustible natural resources: the competitive economy, in: *The Review of Economic Studies*, 41(Symposium on the Economics of Exhaustible Resources), 139–152.

Swan, T.W. (1956): Economic growth and capital accumulation, in: *Economic Record*, 32(2), 334–361, URL: https://doi.org/10.1111/j.1475-4932.1956.tb00434.x.

Trapp, K. (2015): Measuring the labour income share of developing countries, Working Paper No 2015/041; WIDER Working Paper World Institute for Development Economics Research.
Van den Bergh, J.C.J.M. (2011): Environment versus growth: a criticism of 'degrowth' and a plea for 'a-growth', in: *Ecological Economics*, 70(5), 881–890, URL: https://doi.org/10.1016/j.ecolecon.2010.09.035.
Van den Bergh, J.C.J.M. (2017): A third option for climate policy within potential limits to growth, in: *Nature Climate Change*, 7(2), 107–112, URL: https://doi.org/10.1038/nclimate3113.
Van Heddeghem, W., Lambert, S., Lannoo, B., Colle, D., Pickavet, M., Demeester, P. (2014): Trends in worldwide ICT electricity consumption from 2007 to 2012, in: *Computer Communications*, 50, 64–76, URL: https://doi.org/10.1016/j.comcom.2014.02.008.
Von Finck, Z., Manhart, A. (2016): Das Geschäft mit dem Schrott, in: *Internationale Politik*, November/December(6), 108–115.
Warr, B., Ayres, R.U. (2012): Useful work and information as drivers of economic growth, in: *Ecological Economics*, 73, 93–102, URL: https://doi.org/10.1016/j.ecolecon.2011.09.006.
WBGU (German Advisory Council on Global Change) (2019): Towards our common digital future, Flagship Report, Berlin: WBGU.
Wolter, M.I., Mönnig, A., Hummel, M., Weber, E., Zika, G., Helmrich, R., Maier, T., Neuber-Pohl, C. (2016): Wirtschaft 4.0 und die Folgen für Arbeitsmarkt und Ökonomie: Szenario-Rechnungen im Rahmen der BIBB-IAB-Qualifikations-und Berufsfeldprojektionen, IAB-Forschungsbericht No 13/2016, Institut für Arbeitsmarkt- und Berufsforschung.
Zuboff, S. (2019): *The Age of Surveillance Capitalism: The Fight for a Human Future at the New Frontier of Power*, London: Profile Books.