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Perspective

Digitalisation, sustainable industrialisation and digital rebound – Asking the right questions for a strategic research agenda

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ABSTRACT

Digitalisation is likely to change established economic development processes. This raises questions about the distribution of the potential welfare gains from industrialisation highlighted by, among others, the UN Sustainable Development Goal (SDG) 9 'sustainable industrialisation'. In parallel, industrialisation and digitalisation must be made environmentally sustainable if other pressing sustainability goals, such as climate change mitigation (SDG 13), are to be met. Yet, under the current political and economic system, efficiency gains in material resources and energy associated with digitalisation are prone to aggregate to macro-level growth ('digital rebound') that may exacerbate the ecological harm of industrialisation, rather than alleviating it. In this article, applying the CPERI/CSPK approach (Cultural Political Economy of Research and Innovation/Complex Systems of Power-Knowledge approach), we argue that digital rebound should be a central research parameter in research on digitalisation and sustainability. Thinking strategically about different *models* of digitalization, which we call the 'human-machine associational model' and the 'machinic micro-efficiency model', may enable not only change in the trajectory of digitalisation itself. It could also indirectly address the dominant regime of political economy at the system-level, which will either propel or contain digital rebound. We conclude the article by opening up lines of enquiry, for both research and practice to approach a 'system-questioning' model of digitalisation.

1. Introduction

Digitalisation[1] is likely to change value creation in the global economy, raising questions about its environmental impact and its effects on the distribution of welfare gains from industrial development. Countries in the Global South[2] expect to profit from digitalisation to achieve the Sustainable Development Goal (SDG) 9 'sustainable industrialisation'[3], jobs and rising incomes. In parallel, industrialisation *and* digitalisation need to be made environmentally sustainable[4], if other pressing sustainability goals, such as climate change mitigation (SDG 13) are to be met. An absolute decoupling[5] of the economic growth implicit in industrialisation (and explicit in SDG 8 'Decent work and economic growth') from non-renewable resource consumption, land use and emissions, through a profound industrial transformation, would be necessary to stay within ecological planetary boundaries [5,6]. Many crucial indicators today, however, do not indicate a development in this direction. For instance, Fig. 1 shows the development of global material extraction relative to 1980 values and global GDP development between

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[1] The term 'digitalisation' is understood as the development and application of digital technologies in various realms of society. Additionally, digitalisation includes socio-technical changes associated with the introduction of digital technologies, e. g. changing production and consumption patterns induced by the introduction of digital technologies [1].

[2] The term 'countries in the Global South' refers to low and middle income countries according to the country classifications of the World Bank [2].

[3] We define industrialisation as the process of structural change, i.e. shifting of employment between the economic sectors agriculture and services towards industry [3].

[4] Although sustainability can be interpreted and defined in numerous ways, sustainable or sustainability in this article largely refers to the broader perspective of environmental sustainability targets stated in the UN SDGs 6, 7, 11, 12, 13, 14, 15 (see [4]).

[5] Absolute decoupling of emissions from GDP, for instance, means to not create any emissions with any additional unit of GDP. Relative decoupling of emissions (resource use etc.) from GDP, in turn, means to decrease emissions per unit of value added of GDP.

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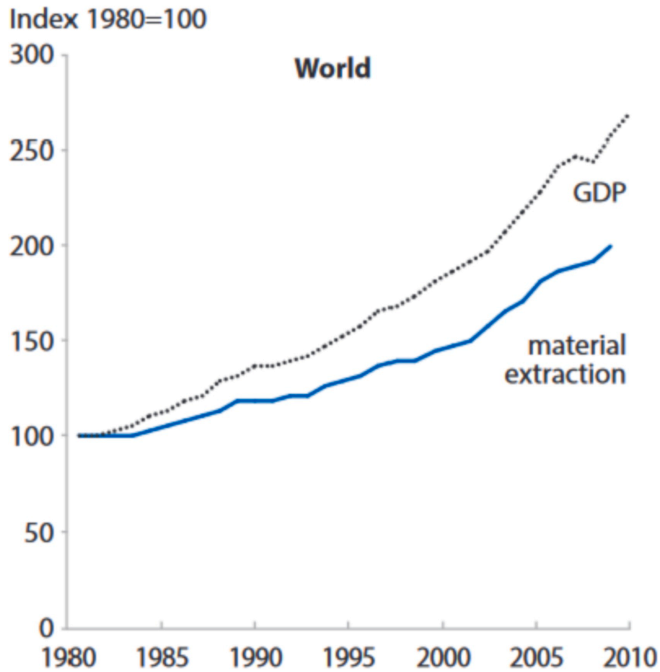

Fig. 1. Development of global material extraction in % and GDP 1980–2010 [8] Note: Relative decoupling between global material extraction and GDP in the last 30 years is reflected in the gap between the curves for GDP and material extraction; absolute decoupling would mean that despite an upward GDP line, material extraction remains flat or bends downwards.

1980 and 2010. Although material extraction grows slower than GDP (relative decoupling), there remains a clear upward trend in material extraction with no signs of reversal (i.e. no absolute decoupling) [7]. Likewise, the Global Footprint Network calculates that in 2020, the ecological resources that can be reproduced every year were used up on 22 August 2020. In other words, demand for resources, e. g. material, land, water, air, was almost 150% of supply, even as half the global population still lives with no electricity and is largely deprived from material wealth.

In pursuit of reconciling conflicting sustainability goals, digitalisation is widely, if tacitly, expected by various stakeholders, like policy makers, private sector and intergovernmental organisations, to contribute to achieving environmentally and socio-economically sustainable industrialisation. For instance, digitalisation is expected to contribute to SDG 9 by reducing emissions and functioning as an enabler of decoupling [5]; and to enable industry to save significant amounts of CO_2 [9] even while raising economic growth [3] and increasing incomes [10], particularly in low and middle-income countries (see also SDG 9c).

Despite these expectations, research on the issues of *both* digitalisation and sustainable industrialisation remains scarce (e. g. [1,11]). While scholars point to the *potential* contributions of digital transformation to sustainable industries (e. g. [12–14]) mainly in developed country contexts, there is little empirical evidence on the concrete mechanisms through which expected positive sustainability effects of digital transformation in industry (such as resource savings) materialize on the macroeconomic level and how far this has already happened, including in countries in the Global South [15]. For instance, applying big data analyses in supply chains to assess sustainability information is considered a promising way to manage large amounts of sustainability-related data across companies and countries [16,17]. The uptake of these technologies, however, is still low [18] and it is yet to be seen whether better and more information on sustainability parameters will lead to significant actions to reduce negative environmental impacts of companies in supply chains.

On the other hand, risks of digitalisation for socio-economic and environmental sustainability in countries in the Global South have been widely documented, e. g. e-waste accumulation [19,20], as have the unequal opportunities for countries in the Global North and Global South to participate in and economically profit from digital transformation. This is discussed using the term 'digital divide' (see for instance [21,22]).

Moreover, indirect environmental effects are under-researched in the digitalisation literature, an important example of which is the rebound effect, or 'digital rebound' [23]. Digital rebound implies that efficiency gains associated with digitalisation might drive the growth at aggregated system level of both consumption of material resources and the production of unrecyclable waste products such that part or all of the efficiency gains are neutralised. If the efficiency gains are more than offset by resulting growth, digitalisation may exacerbate ecological harm, rather than alleviating it.

In this perspective article, we argue that in order to mitigate the risk of digital rebound, alternative ways to think and do digitalisation have to be explored by transdisciplinary research and fostered by policy-makers, businesses and civil society. We first ask what sustainable industrialisation is and how digitalisation is expected to contribute to sustainable industrialisation. We then argue that digital rebound is the default outcome of the way in which digitalisation is currently evolving and that research on the nexus of digitalisation and sustainability fails to provide recommendations as to how to contain the digital rebound. Seeking to advance the debate on alternative conceptions of digitalisation, we apply the heuristic theorization of the CPERI/CSPK approach (Cultural Political Economy of Research & Innovation/Complex Systems of Power-Knowledge approach) to digital rebound and illuminate the key challenge of generating constraints at a global system level to contain it. This, in turn, enables a productive reframing of the questions at the nexus of digitalisation and sustainability, instantiating this change in perspective as a crucial research programme going forward and placing digital rebound in the centre of research and policy agendas. We conclude with some directions for a rebound-centred research agenda.

2. Sustainable industrialisation and digitalisation

2.1. What is sustainable industrialisation?

According to the UN SDG 9, the goal of 'sustainable industrialisation' is to 'promote inclusive and sustainable industrialisation and, by 2030, significantly raise the industry's share of employment and gross domestic product, in line with national circumstances, and double its share in least developed countries'. Industry has traditionally been considered as one of the three major economic sectors, next to agriculture and services (although these lines become increasingly blurry with examples of industrialised agriculture and service-intensive industries). In this longstanding three-sector model, industrialisation can be defined as shifts from agricultural to industrial production [24] and is determined by processes of structural change, i.e. changes of employment between the three sectors.

It can be argued that sustainable industrialisation requires absolute decoupling of economic growth from environmental impact in order to meet several other SDGs, i.e. an absolute decrease in consumption of resources and resulting emissions/waste despite economic growth through industrialisation [25]. If absolute decoupling is to take place, relative decoupling must happen at least as fast as economic output grows. In other words, the emission/resource intensity has to fall faster than the economy grows. Such dynamics go beyond the industrial sector and can be discussed in the context of the *environmental sustainability of structural change*, accounting for the agricultural and service sector as well (e.g. [26]).

To date, industrialisation has led to constant increases in resource and energy use around the world [25]. This is less surprising given the fact that targeted efforts towards sustainable industrialisation can rarely be found in industrial policy documents in countries of the Global South, for instance in African and Southeast Asian countries [27]. Empirical data suggests a correlation between environmental impact and growth in GDP per capita, as illustrated in the case of carbon emissions per capita in Fig. 2. The graph shows that countries with the highest GDP per capita (e. g. US, Canada, Norway, UAE, Saudi Arabia) tend to be among the countries with the highest emissions per head. A 1% increase in industry's share of GDP is associated with an 11.8% rise in emissions per capita [24]. Likewise, Jain & Jain [28], in analysing countries' SDG achievements and looking at causal relationships between SDG Index, Human Development Index and Ecological Footprints, find that global improvements on the SDGs have largely been achieved at the cost of environmental degradation.

It should be noted that there are rare examples of industrialised countries which show periods of absolute decoupling of GDP growth from consumption-based CO_2 emissions[6], i.e. CO_2 emissions when accounting for emissions created in other countries for domestic consumption [30].[7] Equally, it is important to take a counterfactual perspective, asking what would have been the environmental outcomes if observed (relative) decoupling had not taken place. The environmental burden may likely be even higher today.

Nonetheless, staying within planetary boundaries would require continued absolute decoupling in several indicators on a large scale in relatively short periods, which has not yet been observed in any country [31]. For instance, looking at greenhouse gas (GHG) emissions, to the best of our knowledge there is no example of any country in the world that has achieved a (large enough) absolute reduction in consumption-based CO_2 emissions that would exemplify such a rapid decoupling. Thus, for countries in the Global South, there is no blueprint on how to achieve sustainable industrialisation, or even 'leapfrog' into (sufficiently) sustainable production and consumption patterns [32]. This leaves the question of whether 'sustainable industrialisation' is possible and what a viable trajectory from current unsustainable to sustainable industrialisation patterns in the short and medium term could look like.

2.2. *How is digitalisation supposed to contribute to sustainable industrialisation?*

Digitalisation is likely to have an impact on the drivers of structural change [3], e.g. by impacting technology (development) and by facilitating service trade across the globe. This can alter the environmental intensity of industrialisation. However, to date, scientific evidence regarding socio-economic and environmental sustainability effects of digitalisation in industry and, even more so on the process of industrialisation, is scarce [11]. Regarding socio-economic sustainability, scholars analyse productivity effects of digitalisation as a driver for industrialisation in countries in the Global South [33,34]. While new business and trade opportunities can arise through digitalisation, concerns exist about the potential of hitherto employment-intensive industries to absorb a growing workforce in some parts of the world given decreasing labour-intensity due to automation and digitalisation in various industries [35].

Regarding environmental sustainability, digitalisation has direct and indirect environmental effects. On the one hand, digital technologies require energy and resources in their production, use and disposal (direct environmental effect), e.g. manufacturing-related emissions and creation of electronic waste. On the other hand, they have an indirect impact on energy and resource efficiency in manufacturing as well as systemic impacts on consumption and production patterns (indirect environmental effect) [27]. Few scientific studies try to measure or forecast a (potential) net impact of positive and negative direct and indirect effects of digitalisation in industry on a global scale, e.g. whether the potential savings amortize the environmental implementation costs of resource and energy-intensive digital technologies, and the evidence is inconclusive [36–38]. Moreover, several studies originate from industry associations and companies, such as the Global e-sustainability initiative [39,40], AT&T [41] and China Mobile [42]. GeSI [40] finds overall positive savings potential for digital technologies, but the report does not address rebound effects from total 'information and communication technologies (ICT) enabled' savings potential, stating that the rebound would be too difficult to calculate (but expected to amount to between 10 and 30 percent). In a review of various studies, Coroamă & Mattern [23] conclude that 'one of the main flaws of existing assessments [of the environmental impact of digital technologies] is their disregard of rebound effects'.

3. Digital rebound as the default option

3.1. *What is the digital rebound effect?*

The rebound effect is 'an umbrella term for a variety of mechanisms that reduce the potential energy savings from improved energy efficiency' [43][8]. Digital technologies enable energy and other savings that induce rebound effects [23]. Hence 'digital rebound effects' are rebound effects resulting from these digitally-enabled efficiency gains. Digital technologies can be considered general purpose technologies that diffuse across many sectors of society, lowering costs to their users and thus also spreading related rebound effects [46]. Energy efficiency gains through digital technologies have commonly been proposed in areas such as videoconferencing, e-commerce, transport route optimization and smart metering, [47] but these often entailed rebound effects. For instance, in the early 2000s, e-commerce was considered to contribute to energy savings through optimization of logistics and avoidance of individual travel to shops. However, e-commerce led to increased returns through the convenience of sending articles back [48], or increased packaging, e. g. entailing higher energy use per book in the book sector [49]. Looking forward, commentators suggest digital technologies will make industrial production more resource and energy efficient, e.g. through optimisation of robot trajectories designed to lead to more efficient energy use [50], but the potential for rebound effects, such as increasing production, often remains unaccounted for.

3.2. *Reasons for the digital rebound effect*

There are both technical as well as political economy reasons why the rebound effect is not widely accounted for in policy making. From a technical point of view, various popular measurement methods for energy use and energy efficiency are not suited or not adapted to take rebound effects into account. For instance, life-cycle analysis (LCA), partial footprint and the ICT enabling method are the most commonly used methods in measuring indirect effects of digital technologies. However, these methods often neglect wider system dynamics of the application of digital technologies and only look at single cases (LCA, partial footprint) or the positive effects of digital technologies on indirect environmental effects in the application systems (ICT enabling method) [51]. Moreover, it is difficult to determine the system boundaries of the environmental effects of digital technology applications. In addition, the analyses are usually static in that they take consumer behaviour as an exogenous variable. Yet changes in production patterns also cause changes in consumption patterns, associated with

[6] Consumption-based emission accounting refers to the emissions associated with a country's consumption, compared to production-based emission associated with a country's production. For instance, small countries with little industrial activity are likely to import and consume goods and services instead of producing those goods and services themselves and would probably have a larger consumption-based emission per head than production-based emission.

[7] See Haberl et al. [30] for a systematic review of the evidence on decoupling.

[8] Brockway et al. [44] as well as Lange et al. [45] provide two recent reviews on the empirical evidence on (economy-wide) rebound effects [44,45].

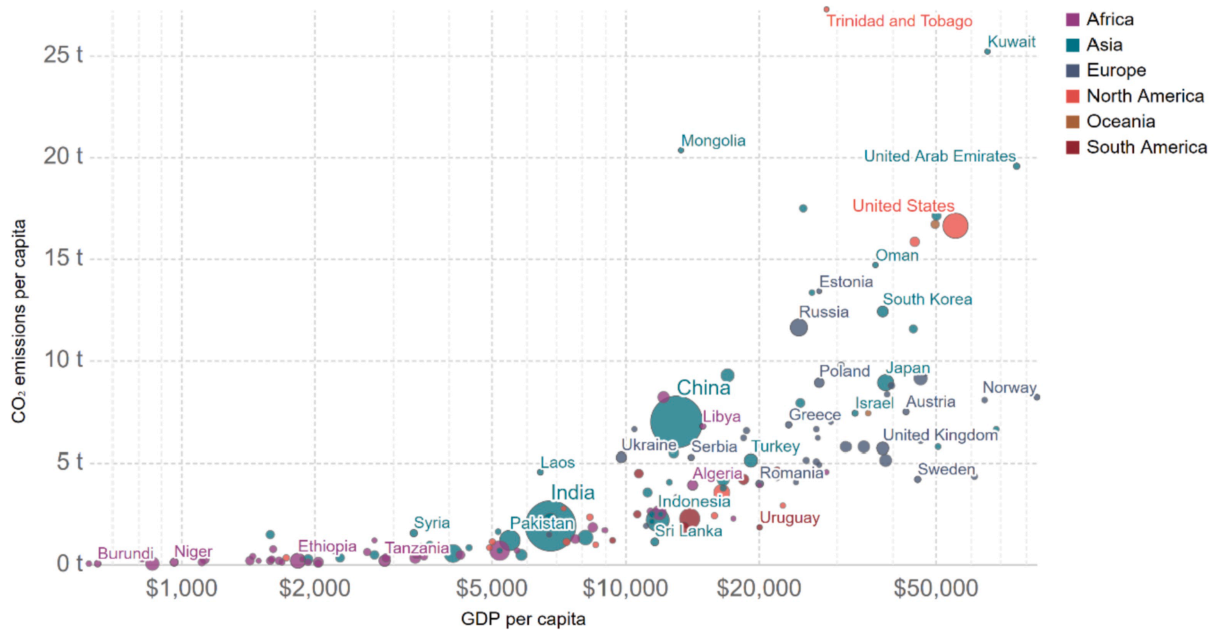

Fig. 2. CO_2 emissions per capita plotted against GDP per capita in 2016 [29]. Note: CO_2 emissions per capita are shown in tonnes per person per year. GDP per capita is measured in international $ in 2011 prices to adjust for price differences between countries and adjust for inflation. The chart was published by Our World in Data under Creative Commons.

environmental impacts. Understanding those changes would be a crucial requirement for understanding the broader environmental impact of digitalisation [51].

From a political economy point of view, there are economic and political interests committed to promoting the positive impacts of digitalisation and drawing attention away from its possible (and already observable) downsides, such as the digital rebound. We would like to point out two aspects.

First, global orthodoxy in policy and business tends to presume that technological innovation is overwhelmingly positive and the primary route to solving societal problems that may arise [52]. Current political-economic power relations thus present only limited incentives to question new frontiers of technological advance. For instance, it is a more compelling story to sell digitalisation as a win–win situation for the economy and the environment, especially for agents excited by new frontiers of digitalisation and the potential to monetize positive visions of the smart home or smart city [53]. In this context, political pressure to consider the potential downsides of digitalisation, especially regarding its widely presumed contribution to pressing societal problems like sustainable industrialisation, tends to come from more systemically-peripheral and/or less powerful sources.

Secondly, the fundamental premise of the economic system, and hence also of its most empowered actors, is that (techno-)economic growth is essential. Yet it is this system compulsion to growth that underpins *both* the competitive dynamics of efficiency gains at the level of the individual firm/agent *and* its (otherwise counter-intuitive) aggregation to growth in the use of the same resource at a system level. Moreover, the competitive environment is such that it encourages concern from individual agents/firms/organizations (however large) to be limited to their own micro level while ignoring emergent system effects as beyond their control. Rebound effects are thus systemically encouraged while so too is a mainstream disinterest in them.

Under the given configuration of the system, it has been argued that preventing rebound effects requires the imposition of system constraints and must be addressed directly at the system level. As Galvin [54] puts it: ‘the history of ICT/electronics shows that energy efficiency increases inevitably lead to increases in energy consumption, hence firm controls on CO_2e emission allowances may offer the best hope of curbing energy consumption and CO_2e emissions in this sector’. Likewise, industry initiative GeSI [40] also acknowledges that ‘in order to capitalize on the […] sustainability potential of ICT, policymakers need to provide the right conditions to ensure that emissions savings from any specific ICT innovation do not lead to rebound effects within the macro-economy, as has been the case in the past’ (p. 92). Conversely, with system-level growth actively contained, e. g. by implementing quantitative emissions limits under an emission trading system [31], it remains an open, empirical question and a significant possibility that new socioeconomic and technological trajectories could arise that divert digitalisation-related growth onto sustainable pathways.

However, this invites discussion about ‘*how*’ such changes at the system level should come about, given significant barriers in terms of the incumbent power dynamics that have blocked such initiatives for many years. Could digitalisation be part of the ‘solution’ to sustainable transition, instead of being part of the problem (of/via digital rebound), not least by enabling this necessary shift in power dynamics? And if so, how?

4. Asking the right questions of digital rebound

4.1. The CSPK/CPERI approach

New ways of thinking about digitalisation are needed if one is to provide strategic recommendations for policy, business and civil society, that can help to limit rebound effects. Digital rebound requires thinking of digitalisation not only as a techno-economic but also as a socio-political process. Specifically, we propose the analytical lens of Complex Systems of Power/Knowledge relations (CSPK) combined with a Cultural Political Economy (CPE) approach to Research and Innovation (R&I, together CPERI) [55,56] to reframe research around digital rebound.

The CPERI/CSPK approach adopts a two-fold shift in perspective from dominant approaches: 1) an explicitly pragmatic and strategic orientation to the issue; and 2) a focus on the parallel shaping of dominant models of socio-technical innovation (particularly digitalisation) *and* the political-economic regime. In particular, these two shifts together offer suggestive insights regarding how a different approach to digitalisation could redirect the uncertain future trajectory of digital socio-technical change such that it supports a growing political momentum of demands for the needed, but improbable, system-level constraints on digital rebound. The dominant approach to exploring digitalisation seeks definitive, universalistic findings in order to identify isolatable problems that can then be tackled with appropriate solutions or patches. This is to ask 'what' and 'why' questions primarily, namely 'what exactly is going wrong, and what is causing it (i.e. why)?' As the advance of digital technologies itself overwhelmingly takes this form and has proven extremely productive, this problem-solving approach is dominant in its research.

By contrast, a CPERI/CSPK approach acknowledges that the problems of digital sustainability and digital rebound are not primarily technological, but socio-technical, complex, dynamic and systemic. This demands shifting to a pragmatic orientation that manifests in research focused primarily on 'how' questions – such as 'how exactly are things currently arranged, and how could they be done differently, leading to different outcomes?' – and inviting strategic insights that are 'good enough', and system characterizations that are 'comprehensive enough', vis-à-vis the practical challenge at hand. This orientation acknowledges that the inquirer is always already situated *within* the complex dynamic systems of interest and as a dynamic part thereof, however small (though potentially significant, e.g. for influential ideas) [57]. This fact is particularly important once it is acknowledged (with CSPK) that these complex systems are constituted of diverse power/knowledge relations [58–60]. The CPERI element of the approach accepts as useful the abstraction of the dominant regime of (global) political economy [55,61]. It can thereby explore the co-evolution of the incumbent model of digitalisation with that dominant regime, with both understood in terms of the relations of power/knowledge discussed above (e.g. [62]).

Conceptualized in these co-evolutionary terms, empirical investigation is opened up regarding how current processes of digitalization are being shaped by, *and in turn are shaping*, the currently dominant relations, actors and beliefs of the (global) political economy. In keeping with the pragmatic stance above, however, this is not in search of an impossible definitive characterization of the dynamic systemic phenomenon, but strategic insights for whatever agent is conducting that investigation.[9] More importantly still, the dominant regime of political economy is the 'system' that will contain, or fail to contain, the dynamics of digital rebound. The CPERI/CSPK approach, however, shows that there are important connections between the dominant model of digitalisation (and its trajectory over time) and the system that is its irreducible context and constant product. In other words, not only is the system context of 'digitalisation' – about which we are primarily concerned regarding digital rebound – thereby 'internalized' into the analysis, and not some separate and external condition impervious to any efforts at the level of digitalisation itself. Instead, digitalisation is also shown to be today an invaluable site of leverage on shaping that system-level reality. Conversely, it becomes possible not only to adopt models of digitalisation that are system-aware, but also for individual 'nodes' in global digital networks, i.e. individual agents and/or organizations, to begin to take responsibility for such system-level emergent effects. Digitalisation thus potentially becomes part of the solution, not a multiplier of the problem, supporting the deliberate transformation (albeit always indirectly and experimentally) of the system itself as the necessary level at which to tackle the threat of digital rebound.

4.2. How is digitalisation currently shaped?

Examining *how* digitalisation projects are currently shaped reveals at least two major groups of contemporary imaginaries. On the one hand, there is the default and dominant form of digital innovation, which we call the 'machinic micro-efficiency model' (MME). This is mainly driven by the widely appreciated potential of digitalisation to replace pre-existing protocols, systems and labour, and to deliver greater (competitiveness-enhancing) efficiencies in time and/or resource input and expense, whether for producers or consumers. With regards to its environmental impact, focusing on the aggregation of the micro-efficiencies this model has been shown to lead to digital rebound. Consider, for instance, the examples above of e-commerce or smart metering [23,46].

On the other hand, there is another approach to digitalisation that understands experimentation with digital technologies primarily as a way to mobilize unprecedented forms of association or organization between individuals or groups. This may enable projects to tackle societal issues in novel ways or creating new personal or collective capacities. We call this the 'human–machine associational model' (HMA), with the emphasis not on *doing things we already do more efficiently* but enabling new inter-personal relations that in turn enable new ways of acting together.

Moreover, a key element of this model is the capacity, when human relations are intermediated by the information and communication capacities of digital technologies, to have accurate and real-time system level data about the emergent totality, e.g. about the impacts of one's actions on any rebound effect. Such information could potentially shape responses and individual actions in previously inconceivable ways. With regards to its environmental impact, this model could thus challenge digital rebound by assuming a form of digitalisation that is explicitly *system-aware* or even *system-questioning*. Such a model of digitalisation would also mark a significant and positive contrast with the current root problem: a model that is tacitly system-perpetuating, system-ignorant or even system-denying.[10]

4.3. Human-machine associational model as a different approach to digitalisation

There are reasons to hypothesize that a growing reorientation to the HMA model of 'digitalisation' would, in turn, cultivate growth in both orientation to and power behind demands to take digital rebound seriously.

Regarding orientation, a key appeal of the HMA model is that it empowers projects and (possibly social) entrepreneurs seeking to deploy digitalisation to enable new, productive (and profitable) forms of repairing the long-neglected collective, institutional and/or public presuppositions of individual action, and even creating new possibilities for action. This would include ways to reduce environmental footprints and to scale those positive impacts. While nothing is guaranteed, the greater success and dominance of the HMA model would tend to support the deeper reshaping of digitalisation by initiatives concerned about the commons, and hence system-level phenomena like the digital rebound. And this is particularly the case as it opposes the incumbent MME model and its tacit driving, and neglect, of that issue.

Regarding power, meanwhile, as the HMA model becomes more common it will be creating new and powerful agents and collectives which are enabled by digitalisation and are self-conscious of the benefits of the HMA model itself for their projects of further empowerment, and against the MME model and its currently dominant actors. This, in turn, would likely encourage further and more ambitious HMA innovations to tackle bigger, tougher challenges and to continually learn, in concrete detail, how to do this better. A spiral conditionality, or positive feedback loop, thus becomes conceivable between growing dominance of the HMA model (*vs.* the MME model) of digitalisation, with new, networked and increasingly powerful digital actors, and the increasing cogency and clarity of political demands for system constraints on the digital rebound.

[9] Here, for instance, this would be in terms of an academic study seeking to explore and illuminate the global public good.

[10] Discussions around different models of digitalisation are already ongoing in the degrowth literature, e.g. under the concept of 'convivial technologies' (e.g. [72,73]).

Moreover, this dynamic is one that is not primarily to be mapped in the abstract but to be actively taken up by diverse agents. An important aspect of the CPERI/CSPK approach is thus that it offers a heuristic conception that enables thinking strategically, and by diverse agents for themselves, about how specific socio-technical initiatives may also reshape power/knowledge relations that constitute the emergent system-level of the political economy itself. Indeed, resituated in this way, even existing MME trends in (demand for) digitalisation may be recontextualized in productive ways, and, in ensuing learning-by-doing, then themselves be further harnessed, building the momentum behind containing digital rebound. Certainly, it would seem that the continued development and aggregation of such incremental micro-efficiency improvements remains of crucial importance for the realization of the increasing system-level efficiencies needed to meet environmental targets.

For instance, both customization and interconnectivity are key top priorities [15] at present regarding industrial adoption of, or shift to, digital technologies. In both cases, though, imaginative engagement with these concerns, resituated within the HMA model, suggests ways in which the latter approach may be particularly effective in addressing customization and interconnectivity. Interconnectivity is likely optimized, not hindered, to the extent the digital innovation in question prioritizes questions of association. Similarly, customization depends upon effective communication with customers (including for feedback or returns) and, to be economic, organisation of the production process to minimize costs of making alterations according to specifications, e.g. through modularization. Both of these are primarily challenges of organisation to enable maximal mutual responsiveness in relations between producers and consumers. It is thus a problem not of doing more efficiently what was already being done, but of using digital technologies to establish qualitatively new interpersonal relations and capacities, i.e. an HMA model issue.

4.4. Questions for a strategic research agenda

A CPERI/CSPK approach thus enables a productive mode of engagement with the key challenge of digital rebound, opening up a strategic research agenda. Specifically, it prioritizes and then progressively formulates ever-more specific ('how') questions that are to be addressed in practical and theoretical projects by as many agents regarding as diverse a set of issues as possible:

1. How do projects of digitalisation shape social power/knowledge relations and get shaped by them in turn?

2. How could the system-questioning human–machine associational model of digitalisation be supported, privileged and prioritized in practice, including at agent level, vis-à-vis the machinic micro-efficiency model? How do projects of digitalisation currently work, and for whom, such that digital rebound arises? How could they be arranged differently, generating different outcomes?

3. How could multi-level social, political and cultural action regarding digitalisation support the growth of a coalition demanding increasingly well-specified global system constraints on digital rebound? How can power momentum for these system-level constraints be strategically cultivated, possibly or preferably working *with* as many stakeholders, including powerful corporate innovation actors and consumers, to expedite social political shifts?

and last, but by no means least,

4. How should one best (action-) research these questions, so as to optimize and expedite practical impact?

4.5. Example: sustainable industrialisation through 'Industry 4.0'?

We illustrate the usefulness of these questions by considering briefly their application to our starting issue: sustainable industrialisation in the Global South. In 2011, an initiative by the German government, including industry associations and representatives, coined the term 'Industry 4.0' to refer to the 'fourth industrial revolution' through digitalisation, but the definition of the term is contested [15]. The concept of 'industry 4.0' has subsequently been taken up in various national policies and governmental action plans in the Global South, such as 'Crafting the Future. A Roadmap for Industry 4.0 in Mexico', the 'Thailand 4.0' strategy, and the 'Making Indonesia 4.0' strategy [63–65]. It is also discussed by the United Nations Industrial Development Organisation as a possible route to economic development for countries in the Global South [66,67].

For countries in the Global South, following the concept of industry 4.0 and fostering digitalisation in industry is a double-edged sword. On the one hand, automation and digitalisation may lead to job losses in industries whose success is mainly based on the comparative advantage of countries in labour-intensive tasks, such as manual assembly of intermediate products that are important export goods. On the other hand, productivity increases through digitalisation might be needed to withstand international competition [3]. Developing a competitive industry 4.0 can turn out to be difficult for many countries in the Global South. For instance, electronics manufacturing is centred around only a few hubs, mainly in Asia. Likewise, there are to date only very few international software / platform firms from countries other than the US and China, creating hardware and software dependence of countries in the Global South on other countries [10]. As such, industry 4.0 seems both inescapable for national governments in the Global South if they wish to remain competitive and to keep 'developing', and yet also a menace, threatening greater structural inequalities vis-à-vis rich countries. In other words, industry 4.0 framed in MME terms seems to augur primarily the digitally-intermediated exacerbation and acceleration of current polarizing tendencies of the global political economy, not their transformation (cf. [68]).

Moreover, despite 'Sustainability' being one of three pillars of the '2030 Vision for Industry 4.0', focus lies precisely on the MME framing of digitalisation's 'potential for resource efficiency' [69] without mentioning potential rebound effects of digitalisation. Thus, efforts of countries in the Global South need to go beyond the visions provided by the Global North, in order to profit from digitalisation without exacerbating harm to the environment and achieve socio-economic advances at the same time. An explicit focus on the HMA framing, supportive policy at system level and their interaction, seem particularly promising. One example of an HMA framing of digitalisation is the open source community. The provision and use of open source software in countries in the Global South has been promoted for a long time [70]. For instance, open source platforms may offer more diverse opportunities for small vendors to sell products while avoiding profit-skimming from international platforms (domiciled elsewhere) such as Amazon, Alibaba and others. The government and public sector, however, will need to play a key role in fostering access to open source solutions and open data – i.e. shaping the system and/or political economy context of digitalisation - as well as fostering local initiatives that give priority to social and environmental sustainability aspects of software/hardware development and application. The public sector can use and provide open source solutions and open data itself instead of relying on costly services and infrastructure from foreign companies.

Such digital innovations would likely be of most value when formulated in HMA terms, seeking to create new and maximally responsive relations between citizens and (new) service providers. In addition to giving preference to software development projects by and for local people, public procurement of HMA digitalisation can take into account other issues of public or systemic concern, including environmental parameters, the energy efficiency of data centres, land use in construction of IT infrastructure, and the degree of recycling and reusing of hardware (including 'green' IT).

Privileging digital innovation that creates new enabling relations also points to a set of other critical success factors for the development of system-questioning digitalisation, and thereby sustainable industrialisation. These include: the strengthening of data protection and the ownership of one's data to retain data in the country of origin and decide independently if and how to use data, which could transform relations with economic entities and hence broaden power relations of the political economy; structures to connect digitally, and so exchange knowledge amongst and leverage communities around the world working on sustainability; increasing digital and environmental literacy in schools and beyond; and movements pressuring private sector companies, including the 'big tech companies', to move towards adopting the system-questioning digitalisation mapped out here.[11]

Finally, initiatives on all these issues are already evident, across the Global South and the Global North. Moreover, there are various initiatives and institutions that try to foster the dialogue on the use of digital technologies and their implications for sustainability and sustainable industrialisation on a global level. To continue the dialogue, and critically contribute to initiatives, we provide readers with a list of some of these resources and initiatives (see Appendix).

5. Conclusion

Great expectations have been placed by policy upon the potential for digitalisation to deliver the 'win-win' of (environmentally) sustainable industrialisation in countries in the Global South and absolute decoupling of economic growth from resource use. Yet there is little empirical evidence on the concrete mechanisms through which expected positive sustainability effects of digitalisation in industry, such as resource savings, materialize, and whether they add up to absolute improvements of the environmental sustainability of industry and the process of industrialisation [15,27]. Consideration of 'sustainable' industrialisation in the context of the ongoing digitalisation suggests that digital rebound is a likely default outcome, absent concerted intervention in research and policy making around digitalisation and sustainability.

In this article, we suggested an approach to reframe research questions at the intersection of digitalisation and industrialisation, namely a Cultural Political Economy of Research & Innovation (CPERI) approach in explicit strategic-ethical examination of Complex Systems of Power/Knowledge relations (CSPK). Turning from 'why' and 'what' questions to 'how' questions, we have set out and illustrated a series of such how questions, thereby offering a strategic research agenda open to diverse agents to tackle digital rebound. Building on the power/knowledge momentum that could be unleashed by such strategic research, it even becomes possible to envisage the global establishment of the system-level constraints needed to contain digital rebound, potentially aligned with systemic measures brought forward by the sustainability community, such as carbon prices and carbon trading [31]. Whether or not this comes to pass depends on how widely and urgently an alternative approach to 'digitalisation', such as outlined here, is taken up in practice.

We cannot close, however, without noting that, even in the best-case scenarios where digitalisation would lead to absolute decoupling of economic development from resource consumption, absolute decoupling would itself most likely be only temporary. Timing here, however, regarding the impact of accelerating digitalisation on climaxing of the climate emergency, is of the essence, and an urgent absolute decoupling would still be a major positive achievement, even if it might eventually be overwhelmed by the continuing quantitative growth of global economic activity. More importantly, though, there is a possibility that the global economy, and the political constituencies dominating it, will have been so profoundly transformed in the interim that what actually happens at the moment of the exhaustion of absolute decoupling is uncertain, and can arguably be left to another day.

As immediate practical recommendations, we call for research funding bodies to make it a condition for (technical) research projects on digitalisation that they explore how (their proposed) digital innovation could be used in ways that at least contain risks of, and preferably reverse, digital rebound. Moreover, transdisciplinary research approaches should be sought, where the private sector, policy makers, civil society and researchers jointly explore the most relevant research topics and questions. Different levels of analysis should also be explored: sustainability of hardware and software itself; software and hardware for sustainability; system-level constraints such as carbon pricing and trading; and necessary changes in the political regime. The goal should be to develop ever more concretely the missing mid-term vision (cf. [71]) that may not reliably lead from the unsustainable 'here' of digitalisation to a promised sustainable 'there' (in the long-term), but that at least cultivates a – digitally-mediated – adeptness at distributed, responsive and system-aware governance of ongoing socio-digital change. This in itself would be moving in the right direction.

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Appendix

List of useful resources at the intersection of digitalisation and sustainability (non-exhaustive)

Research:

- Information and Communication Technology for Sustainability Conference: https://www.ict4s.org/
- Development Implications of Digital Economies (DIODE) Strategic Research Network: https://diode.network/
- UTH Zurich Informatics and Sustainability Research: https://www.ifi.uzh.ch/en/isr.html
- Technical University of Berlin and IÖW; Digitalization and Sustainability: https://www.nachhaltige-digitalisierung.de/en/
- Borderstep Institute, Digitisation & Green IT: https://www.borderstep.org/topic/digitisation-green-it/
- KTH Stockholm Industrial Transformation through sustainable digitalization: https://www.kth.se/en/itm/forskning/iris/vara-verksamhetsomraden/industriell-transformation-genom-hallbar-digitalisering-1.946085
- University Melbourne Institute for Sustainable Industries & Liveable Cities (ISILC):
- https://www.vu.edu.au/institute-for-sustainable-industries-liveable-cities-isilc/research-programs/business-law-research/innovation-digitalisation-change-management-research
- University of Manchester, Centre for Digital Development: https://www.cdd.manchester.ac.uk/

Intergovernmental organisations:

[11] The preceding ideas and notions have mostly been developed during a workshop held by the authors at the Degrowth & International Society for Ecological Economics Conference hosted online by the University of Manchester in 2021 on the topic of degrowth and digitalisation.

- International Telecommunications Union: https://www.itu.int/en/Pages/default.aspx
- Internet Governance Forum: https://intgovforum.org
- UNESCO (AI ethics): https://en.unesco.org/artificial-intelligence/ethics
- UNEP Coalition for Digital Environmental Sustainability (CODES). https://www.unep.org/events/webinar/launch-coalition-digital-environmental-sustainability-codes
- UNCTAD Digital Economy Reports: https://unctad.org/topic/ecommerce-and-digital-economy/digital-economy-report

Communities and initiatives:

- European Framework Initiative for Energy & Environmental Efficiency in the ICT Sector: https://www.ictfootprint.eu/
- Initiative Climate Change AI: https://www.climatechange.ai/about
- Climate Action Tech: https://climateaction.tech/
- Civic Coding: https://www.civic-coding.de/
- Forum for German Information Scientists for Peace and Societal Responsibility (in German): https://www.fiff.de/
- IT for Change: https://itforchange.net/
- Digital for Planet: https://digital4planet.org/
- Exponential Roadmap Initiative: https://exponentialroadmap.org/
- European Green Digital Coalition: https://digital-strategy.ec.europa.eu/en/policies/european-green-digital-coalition
- Dashboard Digitalpolitik: https://www.digital-made-in.de/dmide
- Digitale Zivilgesellschaft: https://digitalezivilgesellschaft.org/

Open Source resources:

- Website to find open source software: https://opensource.com/
- Data-free file system: GitHub – philipl/pifs: πfs – the data-free filesystem!
- CoMSES Net, the Network for Computational Modeling in Social and Ecological Sciences, is an open community developing and sharing agent based and computational models for the study of social and ecological systems. https://www.comses.net/
- Machine Learning CO2 Impact calculator: https://mlco2.github.io/impact/

Data sources:

- ITU ICT Indicators Database: https://www.itu.int/en/ITU-D/Statistics/Pages/publications/wtid.aspx
- EU (International) Digital Economy and Society Index: https://digital-strategy.ec.europa.eu/en/policies/desi
- Global Portal on Environment and Smart Sustainable Cities: https://www.itu.int/en/ITU-T/climatechange/resources/Pages/env-and-ssc.aspx

Companies and initiatives from the private sector:

- GeSI: https://gesi.org/
- Ecochain: https://ecochain.com/
- Betterchain: https://www.bcha.in/
- AI Sustainability: https://aisustainability.org/
- Backmarket (online platform selling refurbished electronics): https://www.backmarket.co.uk/
- As good as new (online platform selling refurbished electronics): https://asgoodasnew.de/

Reads:

- Blog providing information on Green ICT/ Sustainable Communications & Information Technology: https://www.vertatique.com/
- First PC to receive the EU Eco-Label: https://inhabitat.com/wooden-framed-iameco-computer-reduces-environmental-impacts/
- Microsoft Developer Blogs on 'How to measure your application power consumption and carbon impact': https://devblogs.microsoft.com/sustainable-software/measuring-your-application-power-and-carbon-impact-part-1/; https://devblogs.microsoft.com/sustainable-software/carbon-proxies-measuring-the-greenness-of-your-application/
- IT Fixit, 'We told the Copyright Office that Repair should be legal': https://www.ifixit.com/News/49993/we-told-the-copyright-office-that-repair-should-be-legal-period
- Amazon, Elastic and the Fight for Open Source Freedom in the Enterprise: https://thenewstack.io/amazon-elastic-and-the-fight-for-open-source-freedom-in-the-enterprise/
- Practitioner's guide to strategic green industrial policy: https://www.die-gdi.de/en/books/article/practitioners-guide-to-strategic-green-industrial-policy/
- Magazine Issue: A sustainable internet for all: https://branch.climateaction.tech/

References

[1] WBGU – German. Advisory Council on Global Change. Towards Our Common Digital Future. Flagship Report, WBGU, Berlin, 2019.
[2] World Bank. World Bank Country and Lending Groups; Available from: https://datahelpdesk.worldbank.org/knowledgebase/articles/906519.
[3] M. Matthess, S. Kunkel, Structural change and digitalization in developing countries: conceptually linking the two transformations, Technol. Soc. 63 (2020) 101428, https://doi.org/10.1016/j.techsoc.2020.101428.
[4] United Nations Department of Economic and Social Affairs. Sustainable Development: THE 17 GOALS; Available from: https://sdgs.un.org/goals.
[5] J.D. Sachs, G. Schmidt-Traub, M. Mazzucato, D. Messner, N. Nakicenovic, J. Rockström, Six transformations to achieve the sustainable development goals, Nat. Sustainability 2 (9) (2019) 805–814.
[6] UNEP, Towards A Green Economy: Pathways to Sustainable Development and Poverty Eradication, UNEP, Nairobi, Kenya, 2011.
[7] A. Jarvis, C. King, Energetic regimes of the global economy–past, present and future, Earth Syst. Dyn. Discuss. (2020) 1–17.
[8] OECD. Policy Guidance on Resource Efficiency. Paris, 2015; Available from https://read.oecd-ilibrary.org/environment/policy-guidance-on-resource-efficiency_9789264257344-en#page31, based on OECD Environment Statistics (database): "Material Resources"; Available from: https://doi.org/10.1787/env-data-en.
[9] GeSI, Enabling the low carbon economy in the information age. A Report by The Climate Group on behalf of the Global eSustainability Initiative (GeSI), London, UK, 2008.
[10] UNCTAD, Digital Economy Report 2019, United Nations, Geneva, 2019.
[11] G. Beier, K. Fritzsche, S. Kunkel, M. Matthess, S. Niehoff, M. Reißig, et al., A Green Digitalized Economy?: Challenges and Opportunities for Sustainability, Institute for Advanced Sustainability Studies (IASS), Potsdam, 2020.
[12] S. Ford, M. Despeisse, Additive manufacturing and sustainability: an exploratory study of the advantages and challenges, J. Cleaner Prod. 137 (2016) 1573–1587, https://doi.org/10.1016/j.jclepro.2016.04.150.
[13] A.B. Lopes de Sousa Jabbour, C.J.C. Jabbour, M. Godinho Filho, D. Roubaud, Industry 4.0 and the circular economy: a proposed research agenda and original roadmap for sustainable operations, Ann. Oper. Res. 270 (1–2) (2018) 273–286, https://doi.org/10.1007/s10479-018-2772-8.
[14] T. Stock, G. Seliger, Opportunities of Sustainable Manufacturing in Industry 4.0, Procedia CIRP 40 (2016) 536–541, https://doi.org/10.1016/j.procir.2016.01.129.
[15] G. Beier, A. Ullrich, S. Niehoff, M. Reißig, M. Habich, Industry 4.0: How it is defined from a sociotechnical perspective and how much sustainability it includes–a literature review, J. Clean. Prod. (2020), 120856.
[16] B.T. Hazen, J.B. Skipper, J.D. Ezell, C.A. Boone, Big data and predictive analytics for supply chain sustainability: a theory-driven research agenda, Comput. Ind. Eng. 101 (2016) 592–598, https://doi.org/10.1016/j.cie.2016.06.030.
[17] S. Ren, Y. Zhang, Y. Liu, T. Sakao, D. Huisingh, C.M.V.B. Almeida, A comprehensive review of big data analytics throughout product lifecycle to support sustainable smart manufacturing: a framework, challenges and future research directions, J. Cleaner Prod. 210 (2019) 1343–1365, https://doi.org/10.1016/j.jclepro.2018.11.025.
[18] A.G. Frank, L.S. Dalenogare, N.F. Ayala, Industry 4.0 technologies: implementation patterns in manufacturing companies, Int. J. Prod. Econ. 210 (2019) 15–26, https://doi.org/10.1016/j.ijpe.2019.01.004.
[19] C.P. Balde, V. Forti, V. Gray, R. Kuehr, P. Stegmann, The Global e-Waste Monitor 2017: Quantities, Flows and Resources, United Nations University, International Telecommunication Union, Bonn, Geneva and Vienna, 2017.

[20] I.C. Nnorom, O. Osibanjo, Overview of electronic waste (e-waste) management practices and legislations, and their poor applications in the developing countries, Resour. Conserv. Recycl. 52 (6) (2008) 843–858.
[21] R.C. Vincent, The internet and sustainable development: communication dissemination and the digital divide, Perspect. Global Develop. Technol. 15 (6) (2016) 605–637, https://doi.org/10.1163/15691497-12341410.
[22] World Bank, World Development Report 2016: Digital Dividends, The World Bank, Washington D.C., 2016.
[23] V.C. Coroamă, F. Mattern, Digital Rebound: Why Digitalization Will Not Redeem Us Our Environmental Sins. Proceedings 6th international conference on ICT for sustainability, Lappeenranta, 382, 2019.
[24] J. Cherniwchan, Economic growth, industrialization, and the environment, Resour. Energy Econ. 34 (4) (2012) 442–467.
[25] UNEP. Decoupling natural resource use and environmental impacts from economic growth, A Report of the Working Group on Decoupling to the International Resource Panel, United Nations Environment Programme, 2011.
[26] M. Savona, T. Ciarli, Structural changes and sustainability. A selected review of the empirical evidence, Ecol. Econ. 159 (2019) 244–260, https://doi.org/10.1016/j.ecolecon.2019.01.028.
[27] S. Kunkel, M. Matthess, Digital transformation and environmental sustainability in industry: putting expectations in Asian and African policies into perspective, Environ. Sci. Policy 112 (2020) 318–329, https://doi.org/10.1016/j.envsci.2020.06.022.
[28] P. Jain, P. Jain, Are the sustainable development goals really sustainable? A policy perspective, Sustainable Develop. 28 (6) (2020) 1642–1651.
[29] Our World in Data. CO2 emissions per capita plotted against GDP per capita: Based on Global Carbon Project; Maddison Project Database 2020 (Bold and van Zanden (2020)); Available from: https://ourworldindata.org/grapher/co-emissions-per-capita-vs-gdp-per-capita-international.
[30] H. Haberl, D. Wiedenhofer, D. Virág, G. Kalt, B. Plank, P. Brockway, T. Fishman, D. Hausknost, F. Krausmann, B. Leon-Gruchalski, A. Mayer, M. Pichler, A. Schaffartzik, T. Sousa, J. Streeck, F. Creutzig, A systematic review of the evidence on decoupling of GDP, resource use and GHG emissions, part II: synthesizing the insights, Environ. Res. Lett. 15 (6) (2020) 065003.
[31] M. Jakob, W.F. Lamb, J.C. Steckel, C. Flachsland, O. Edenhofer, Understanding different perspectives on economic growth and climate policy, Wiley Interdiscip. Rev. Clim. Change 11 (6) (2020), https://doi.org/10.1002/wcc.708.
[32] D.M. Evans, A.L. Browne, I.A. Gortemaker, Environmental leapfrogging and everyday climate cultures: sustainable water consumption in the Global South, Clim. Change 163 (1) (2020) 83–97.
[33] R. Hawash, G. Lang, Does the digital gap matter? estimating the impact of ICT on productivity in developing countries, Eurasian Econ. Rev. 10 (2) (2020) 189–209.
[34] G. Myovella, M. Karacuka, J. Haucap, Digitalization and economic growth: a comparative analysis of Sub-Saharan Africa and OECD economies, Telecommun. Policy 44 (2) (2020) 101856, https://doi.org/10.1016/j.telpol.2019.101856.
[35] M. Hallward-Driemeier, G. Nayyar, Trouble in the Making?: The Future of Manufacturing-led Development, World Bank Publications, 2017.
[36] J. Romm, A. Rosenfeld, S. Herrmann. The internet economy and global warming, The Center for Energy and Climate Solutions, 1999.
[37] L. Erdmann, L. Hilty, J. Goodman, P. Arnfalk, The Future Impact of ICTs on Environmental Sustainability, European Commission, Joint Research Centre, Seville, 2004.
[38] J. Malmodin, P. Bergmark (Eds.), Exploring the effect of ICT solutions on GHG emissions in 2030, Atlantis Press, 2015.
[39] GeSI, GeSI SMARTer 2020: The Role of ICT in Driving A Sustainable Future, Global e-Sustainability Initiative, Brussels, Belgium, 2012.
[40] GeSI. GeSI SMARTer 2030 – ICT Solutions for 21st Century Challenges, Global e-Sustainability Initiative, Brussels, Belgium, 2015.
[41] Connect to Good: A Roadmap to 2025, AT&T, 2015.
[42] China Mobile. Big Connectivity. New Future 2016 Sustainability Report, China Mobile, 2016.
[43] S. Sorrell, Jevons' Paradox revisited: the evidence for backfire from improved energy efficiency, Energy Policy 37 (4) (2009) 1456–1469.
[44] P.E. Brockway, S. Sorrell, G. Semieniuk, M.K. Heun, V. Court, Energy efficiency and economy-wide rebound effects: a review of the evidence and its implications, Renewable Sustainable Energy Rev. (2021), 110781.
[45] S. Lange, F. Kern, J. Peuckert, T. Santarius, The Jevons paradox unravelled: a multi-level typology of rebound effects and mechanisms, Energy Res. Soc. Sci. 74 (2021).
[46] C. Gossart, Rebound effects and ICT: A review of the literature. In: ICT innovations for sustainability, Springer (2015) 435–448.
[47] J. Malmodin, P. Bergmark, N. Lövehagen, M. Ercan, A. Bondesson, Considerations for macro-level studies of ICT' s enablement potential; 2014 Conference ICT for Sustainability 2014 (ICT4S-14), 2014, https://doi.org/10.2991/ict4s-14.2014.22.
[48] D. Schöder, F. Ding, J.K. Campos, The impact of e-commerce development on urban logistics sustainability, Open J. Soc. Sci. 04 (03) (2016) 1–6.
[49] E. Williams, T. Tagami, Energy use in sales and distribution via e-commerce and conventional retail: a case study of the Japanese book sector, J. Ind. Ecol. 6 (2) (2002) 99–114.
[50] S. Riazi, K. Bengtsson, R. Bischoff, A. Aurnhammer, O. Wigström, B. Lennartson, Energy and peak-power optimization of existing time-optimal robot trajectories, in: 2016 IEEE International Conference on Automation Science and Engineering (CASE), IEEE, 2016, pp. 321–327.
[51] J.C.T. Bieser, L.M. Hilty, Assessing indirect environmental effects of information and communication technology (ICT): a systematic literature review, Sustainability 10 (8) (2018) 2662.
[52] B. Godin, The knowledge-based economy: conceptual framework or buzzword? J. Technol. Transfer 31 (1) (2006) 17–30.
[53] H. March, The Smart City and other ICT-led techno-imaginaries: any room for dialogue with Degrowth? J. Cleaner Prod. 197 (2018) 1694–1703.
[54] R. Galvin, The ICT/electronics question: structural change and the rebound effect, Ecol. Econ. 120 (2015) 23–31, https://doi.org/10.1016/j.ecolecon.2015.08.020.
[55] D. Tyfield, A cultural political economy of research and innovation in an age of crisis, Minerva 50 (2) (2012) 149–167.
[56] D. Tyfield, Meeting the problem of growth in the Anthropocene: The Cultural Political Economy of Research and Innovation, in: L. Pellizzoni, E. Leonardi, V. Asara (Eds.), The Handbook of Critical Environmental Politics, 1st ed., Edward Elgar, Cheltenham, forthcoming.
[57] I. Fazey, P. Moug, S. Allen, K. Beckmann, D. Blackwood, M. Bonaventura, K. Burnett, M. Danson, R. Falconer, A.S. Gagnon, R. Harkness, A. Hodgson, L. Holm, K.N. Irvine, R. Low, C. Lyon, A. Moss, C. Moran, L. Naylor, K. O'Brien, S. Russell, S. Skerratt, J. Rao-Williams, R. Wolstenholme, Transformation in a changing climate: a research agenda, Clim. Develop. 10 (3) (2018) 197–217.
[58] B. Flyvbjerg, T. Landman, S. Schram, Real social science: Applied phronesis, Cambridge University Press, 2012.
[59] M. Foucault, Security, territory, population: lectures at the Collège de France, 1977–78, Springer, 2007.
[60] M. Foucault, A.I. Davidson, G. Burchell, The birth of biopolitics: lectures at the Collège de France, 1978–1979, Springer, 2008.
[61] B. Jessop, N.-L. Sum, Beyond the regulation approach: putting capitalist economies in their place, Edward Elgar Publishing, 2006.
[62] L. Pellizzoni, E. Leonardi, in: V. Asara (Ed.), The Handbook of Critical Environmental Politics, 1st ed., Edward Elgar, Cheltenham, forthcoming.
[63] Mexican Ministry of Economy. Crafting the future: A roadmap for industry 4.0 in Mexico: Mexican Ministry of Economy Mexico City; 2016; Available from: https://amiti.org.mx/wp-content/uploads/2018/01/Crafting-the-future-10-agosto-2016.pdf.
[64] V. Puncreobutr, The policy drive of Thailand 4.0. St. Theresa, J. Human. Soc. Sci. 3 (1) (2017).
[65] N.M. Kuputri, Digital Divide: A Critical Approach to Digital Literacy in 'Making Indonesia 4.0, in: The 2nd Tarumanagara International Conference on the Applications of Social Sciences and Humanities, TICASH 2020). Atlantis Press, 2020, pp. 1–6.
[66] K. Ejsmont, B. Gladysz, A. Kluczek, Impact of industry 4.0 on sustainability—bibliometric literature review, Sustainability 12 (14) (2020) 5650, https://doi.org/10.3390/su12145650.
[67] UNIDO. Industry 4.0: Opportunities behind the Challenge. Vienna, Austria; 2017.
[68] P. Bigger, S. Webber, Green structural adjustment in the World Bank's resilient city, Ann. Am. Assoc. Geographers 111 (1) (2021) 36–51.
[69] Plattform Industry 4.0. 2030 Vision for Industrie 4.0: Shaping Digital Ecosystems Globally; Available from: https://www.plattform-i40.de/PI40/Redaktion/EN/Downloads/Publikation/Vision-2030-for-Industrie-4.0.pdf?__blob=publicationFile&v=9.
[70] S. Weerawarana, J. Weeratunge. Open Source in Developing Countries, Swedish International Development Cooperation Agency (SIDA), Stockholm, Sweden, 2004.
[71] A. Yuille, D. Tyfield, R. Willis, Implementing rapid climate action: learning from the 'practical wisdom' of local decision-makers, Sustainability 13 (10) (2021) 5687.
[72] C. Kerschner, et al., Degrowth and Technology: Towards feasible, viable, appropriate and convivial imaginaries. J. Cleaner Prod. 197 (2018) 1619–1636.
[73] M. Pansera, M.H. Ehlers, C. Kerschner, Unlocking wise digital techno-futures: Contributions from the Degrowth community, Futures 114 (2019) 102474.