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DIGITAL CIRCULAR ECONOMY FOR NET ZERO

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Digital Circular Economy for Net Zero

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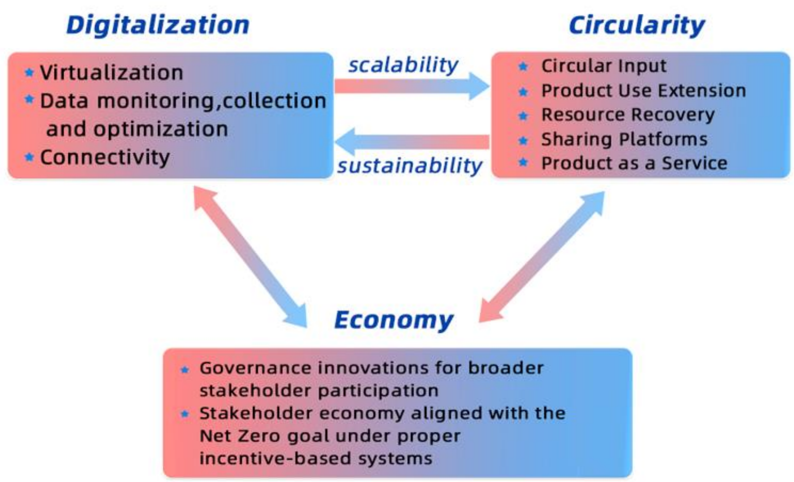
Executive Summary

The climate crisis requires that economies around the world achieve carbon Net Zero by 2050. However, average annual GHG emissions during the 2010s have continued to increase (albeit at a decelerating rate) relative to global emissions in the first decade of the 21st century (IPCC AR6). Most of the emphasis in climate policy has been on accelerating the transition away from fossil fuel energy supply, on reducing carbon emissions from production, and on decarbonizing investment and financial markets. In comparison, relatively little emphasis has been put on the consumption side.[1] This report begins with the analysis of two possible ways to get to Net Zero: digitalization (Chapter 2.1) and a Circular Economy (Chapter 2.2), both of which have recently emerged as essential if we are to reduce GHG emissions as efficiently and effectively as possible.

This report further argues that the key to achieving Net Zero is in promoting both digitalization and Circular Economy (CE) under a new economic system (Chapter 2.3) that is aligned with Net Zero goals, and that is changing our consumption patterns to attain sustainability. Of course, such profound changes cannot simply hinge upon "goodwill". To be able to attain the Net Zero goal the entire socio-economic environment -- incentives, culture, and social norms must also be transformed. We propose a concept called the Digital Circular Economy (DCE) to which society should move to get to Net Zero. We illustrate how such a transformation crucially depends on digital technology, of course, but also on adequate systems of socio-economic governance that induce both the most efficient and effective forms of digitalization and CE through five case studies of recent business and technology innovations (Chapter 3).

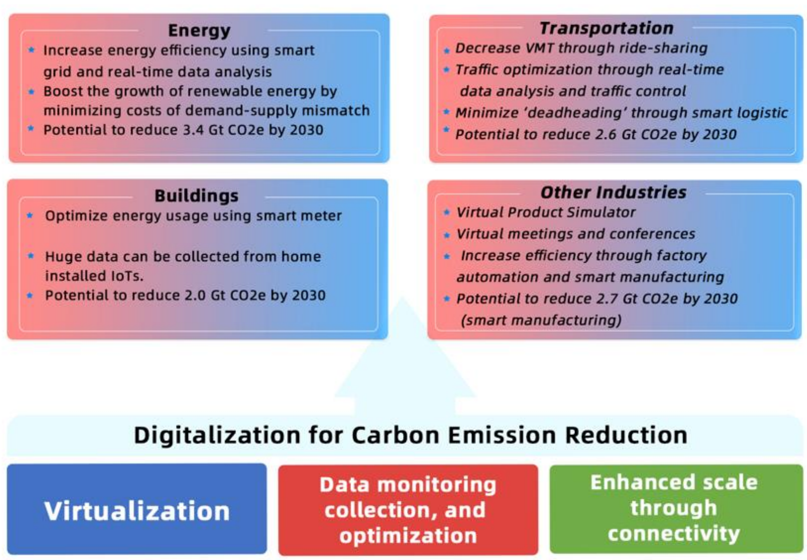
[1] The recent IPCC report (AR6: Mitigation of Climate Change) for the first time highlights the importance of changing individual behavior and consumption to achieve Net Zero. "Demand-side measures and new ways of end-use service provision can reduce global GHG emissions in end use sectors by 40-70% by 2050 compared to baseline scenarios, …" (SPM-44 C.10)

Figure 1. Three pillars of Digital Circular Economy



Chapter 2.1 summarizes the promises of digitalization in sectors such as energy, transportation, buildings, and smart manufacturing. **Digitalization** increases energy efficiency through **virtualization**, **data monitoring, collection, and optimization**, and by **connecting people and firms that otherwise would have not have been connected**. Enhanced efficiency allows the same activity to be completed with less energy, which can be translated into fewer carbon emissions.

Figure 2. Three channels of carbon reduction by digitalization



Source: Data from Global e-Sustainability Initiative (2015). SMARTer 2030

However, despite its huge potential for carbon emission reductions, the digitalization of economic activities has not yet had a material impact on climate change mitigation. There are also concerns that uncontrolled digitalization will further increase energy demand (and ultimately increase carbon emissions) because increased energy efficiency comes with rebound effects in which the lower cost of less fuel intensive products results in higher product demand, offsetting some or all of the per unit reductions in energy consumption. Is digitalization inherently unable to solve the climate crisis? Or do we need a better system to minimize such rebound effects and take full advantage of digitalization's potential?

In this report, we argue that digitalization indeed has a huge potential to reduce carbon emissions on the supply side, but that its full potential can be realized only when guided in the right direction on the demand side. Otherwise, laissez-faire digitalization will probably not help sufficiently to achieve the goal of net-zero emissions by 2050. To attain that goal the entire socio-economic environment, culture, and social norms must be dramatically transformed. The potential of digitalization and the necessity of social transformation have become more than clear by the huge shock caused by the COVID pandemic. Thanks to widespread digitalization, it has been possible to avoid the worst socioeconomic consequences from the necessary lockdowns and social distancing to "flatten the curve" of the pandemic. As a result, economic output did not shrink as much as had been feared -- 2020 was the first time in over a decade when GHG emissions declined (by around 7%, twice as much as the reduction in global GDP).[2]

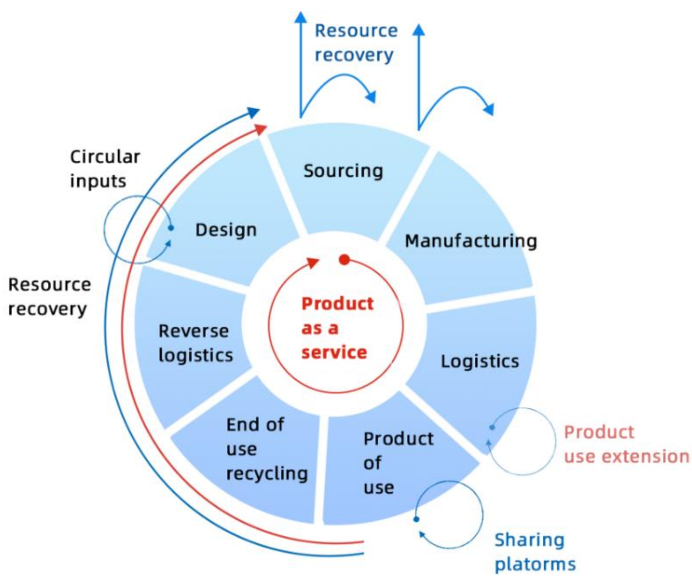
We also propose that the circular economy is a complementary and necessary conceptual framework in which to understand how our current consumption and production habits can be transformed and made sustainable through the application of digitization. **A circular economy** (CE) is one that is "restorative and regenerative by design, and that aims to keep products, components, and materials at their highest utilization potential and value at all times, both

[2] See https://earth.stanford.edu/news/covid-lockdown-causes-record-drop-carbon-emissions-2020#gs.x7f7qo for GHG reduction. See Global Economic Prospects by World Bank for GDP reduction.

through their technical and biological cycles. This new economic model seeks to ultimately decouple global economic development from finite resource utilization (Ellen-MacArthur 2015)."

In Chapter 2.2, we describe five circular business models that can capture the value of the circular economy across a typical value chain. Three center on production: 1) **Circular Inputs**: the use of renewable energy, bio-based or potentially completely recyclable materials; 2) **Product Use Extension**: extending product use through repair, reprocessing, upgrade and resale; and, 3) **Resource Recovery**: the recovery of usable resources or energy from waste or by-products. The other two circular business models are aimed at transforming the relationship between the product and consumers: A) **Sharing Platforms:** that focus on increasing usage rates of products or services through collaborative models for usage, access, or ownership; and B) **Product as a Service:** where the producer retains ownership to increase productivity.

Figure 3. Circular value loop—the five business models



Source: Lacy et al. (2020) The Circular Economy Handbook

The circular economy, however, has its own limitations: it needs to be implemented on a large scale if it is to have a significant impact on global carbon emissions reduction. Currently, the penetration level of circularity is still very low. According to Circularity Gap Report 2020, 100 billion tons of materials enter the global economy every year, among which only 8.6% are cycled back into the economy. Still, the potential is there for CE to achieve the desired economies of scale through the use of digital technology.

Combining the benefits of both digitalization and CE, we propose an integrated conceptual framework we call the **Digital circular economy** (DCE) in Chapter 2.3. It is much more than just a summation of two separate components. each actively impinges on the other, thereby minimizing, or even eliminating the limitations of each when standing alone. On the one hand, the **efficiency** enhancements from digitalization can be translated into **efficacy** gains in CE. On the other hand, CE can achieve meaningful carbon emission reduction by facilitating **scale through digitalization**. Just as importantly, the active interaction of D (igitalization) and C (ircular) E (conomy) is possible only within an **economic system overseen by willing stakeholders and purposeful governance**. We call this system the **Digital Circular Economy** (**DCE**).

Our current socio-economic system must be transformed to help the innovative technologies and business models make maximum contributions to the goal of Net Zero. It should provide people with requisite incentives to adopt the DCE in their daily lives. The solution to the climate crisis depends indispensably on technology (digitization), resources (circularity), and economy (organized with multiple stakeholders steering in the same direction of Net Zero goal). All three elements (D, C, and E) constitute critical pillars of the DCE. Missing any one of the three makes it impossible to achieve Net Zero within the time we have left to save the planet without making huge sacrifices in living standards.

In Chapter 3, we describe five case studies to illustrate how the three pillars of DCE can work together to promote the transition to a Net Zero society, with emphasis on the role of the "economy". Here the meaning of the word "economy" includes all the socio-economic institutions and relationships that govern behavior: market, infrastructure, public policy, social norms, culture, and so forth. Our case studies show that even successful business models such as ride-sharing (Uber, Lyft, and Didi), house-sharing (Airbnb), and re-commerce (Craigslist and

Idle Fish) can fail to contribute to carbon Net Zero without a proper set of "economic" systems that govern people's consumption behavior. This again tells us that the transition to the DCE requires not only a digital technological revolution and innovative circular business model, but also a transformation in the entire socio-economic environment that shapes how people and communities engage with the new digital circular technologies and business models.

Chapter 1. Current Net Zero and Decoupling Challenges

Climate change is the greatest crisis facing humanity: the urgency in confronting the world is growing day by day. The most recent Intergovernmental Panel on Climate Change (IPCC) report indicates that greenhouse gas emissions (GHG) from human activities have been responsible for about 1.1°C of global warming since 1850-1900.[3] The effects of rising temperatures are already visible everywhere, from melting glaciers, to rising sea levels, to the growing intensity of heat waves and droughts, coastal flooding, and more and more intense weather events with more concentrated and extreme rainfall.[4] There have never been more frequent and more intense climate catastrophes than in the last decade.[5] The physical effects of climate change will only increase and intensify in the coming years and decades as the planet continues to warm. And it is the less developed regions of the world that are going to be hit hardest.[6]

Any hope of limiting global warming to no more than 1.5°C requires a major global change in the rate of growth in GHG emissions. According to the latest IPCC report, to attain this goal the total global amount of additional carbon emissions as of 2020 should not exceed 300Gt of $CO2$.[7] According to the International Energy Agency (IEA) 2021 report, global emissions last year amounted to 31.5 Gt of $CO2$.[8] This means that if global emissions continue at the same rate as

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[3] IPCC (2021) "Climate Change 2021: The Physical Science Basis''
[4] IPCC (2021) "Climate Change 2021: The Physical Science Basis''
[5] IPCC (2021) "Climate Change 2021: The Physical Science Basis''
[6] BBC NEWS "Climate change: Low-income countries 'cant't keep up' with impacts": https://www.bbc.com/news/world-58080083
[7] IPCC (2021) "Climate Change 2021: The Physical Science Basis''
[8] IEA (2021) "Global Energy Review 2021"

last year, then the entire carbon budget the world has left will be exhausted in the next eight and a half years.

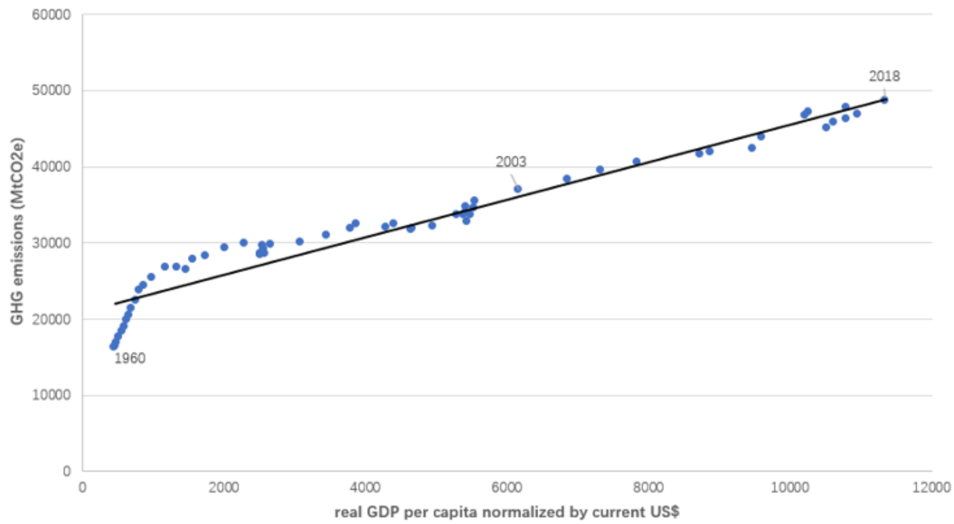
Whether it will be possible to limit warming to no more than 1.5°C (or even 2°C), humanity can change the future trajectory of the climate through its actions. And to avoid the catastrophic impacts of climate change the world must reduce GHG emissions in a sustained way over the next 20-30 years. This will require profound technological and economic change. The main source of energy today—fossil fuels—needs to be replaced by renewable and other non-fossil energy.[9] The way goods and services are produced and distributed must, as a result, undergo fundamental changes. The way society is organized around the new modes and habits of energy use and production must be deeply reshaped. The pathway to Net Zero is narrowing by the day: success depends on a universal ambitious drive to eliminate or capture carbon emissions by all players -- governments, corporations, financial institutions and non-governmental organizations – not just producers and consumers. To be able to maintain our current living standards going forward, indeed, to be able to continue to improve living conditions for the poor, will require a comprehensive decoupling of economic development and the emissions of greenhouse gases.

Is this at all possible? Until recently higher GDP growth could only be achieved through higher GHG emissions, as is shown in Figure 1. Around 35 countries have been able to initiate a decoupling process, but even for these countries total GHG emissions have continued to grow while their ratio of emissions to GDP has started to decline.[10] The transition to a decarbonized economy inevitably involves a cost in terms of lost profits and fewer goods sold in the near term. Otherwise, companies would have already wholeheartedly embraced the transition to Net Zero. In fact, the energy transition will involve huge abatement costs and massive investments in renewable and other non-fossil energy.[11] On the other hand, continuing on a business-as-usual

[9] Out of 59.1 Gt of emissions embodied in each resource group in 2019, fossil fuels account for 38.4 Gt: See page 20 of Circularity Gap Report (2021).
[10] Barth et al. (2019) *Decoupling Debunked* mentions seven reasons why decoupling is not realistic; See Kallis et al. 2018 for a review of the literature on "degrowth".
[11] Gillingham and Stock (2018) summarizes and estimates GHG abatement costs over the past decade.

path is not a realistic alternative. There will be mounting economic and human losses if the climate continues to warm unabated.[12]

Figure 4. Correlation between real GDP per capita and GHG emissions from 1960 to 2018



Source: GDP from World Bank; GHG emissions from Climate Watch Data (World Resources Institute)

These latter costs may well be much higher than the abatement costs and investments required to slow down climate change.[13] Hence, from a purely economic perspective (let alone the environmental implications) the case for climate change mitigation is increasingly compelling as the rising physical costs of climate change become more and more apparent.[14] What's more, investments in green energy, the very process of transitioning the economy away from fossil fuels, themselves generate beneficial economic activity, especially if environmental benefits are

[12] According to Swiss Re Institute (2021), by mid-century, the world stands to lose around 10% of total economic value from climate change if the global temperature follows the current trajectory without achieving the target set by the Paris Agreement.
[13] According to National Oceanic and Atmospheric Administration (NOAA), weather and climate disasters in 2021 have killed 538 people in the U.S. and cost over $100 billion. Moreover, IPCC (2021) points out human-induced climate change to be the main driver of recent increase in the frequency of extreme weather.
[14] According to UN Office for Disaster Risk Reduction (UNISDR), the last twenty years have experienced a rise of 151% in direct economic losses caused by climate-related disasters.

included in its measure.[15] They are sources of sustainable economic growth.[16] Such economic growth will still be needed to alleviate extreme poverty, and to increase human wellbeing in developing countries.[17]

The extent of the tradeoff between GDP growth and reductions in GHG emissions is largely unknown, as so much depends on technological change and on efficiency gains in the reorganization of society and the economy. Another related unknown is the extent of the social shift away from pursuits of purely material well-being to more intangible sources of happiness, which include among others a greater appreciation of what nature can offer. Increasingly GDP, which only measures material consumption, will become a less and less accurate measure of economic progress. As the report on reforming the way economic welfare is measured by Stiglitz, Sen and Fitoussi (2010) emphasizes: "a focus on the material aspects of GDP may be especially inappropriate as the world faces the crisis of global warming." [page xxii in *Mis-measuring our lives: why GDP doesn't add up*, 2010] There may well be far less of a tradeoff between economic progress and the preservation of our natural habitat, if economic progress is better measured and if economic progress takes a more sustainable form, with minimal impact on the environment.[18]

Digitalization

As the climate impact of economic growth worsened over the past three decades another fundamental economic transformation was underway, the digital revolution and the rise of the

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[15] According to International Renewable Energy Agency (IRENA) and the International Labour Organization (ILO), there were 12 million jobs in renewable energy and its supply chains, among which a third of them in solar power sector. Surprisingly, the number of jobs grew from 2019 even under the pandemic. According to *Clean Jobs America 2021* by E2, nearly 3.3 million Americans work in clean energy, which is three times higher than the number of fossil fuel workers.

[16] According to International Renewable Energy Agency (2016), doubling the share of renewables in the global energy mix by 2030 would increase global GDP by USD 1.3 trillion, and increase direct and indirect employment to 24.4 million. Most of the effects are driven by the increased investment in renewable energy infrastructure and developments.

[17] "Climate justice demands that, with the little carbon space we still have, developing countries should have enough room to grow"- India's Prime Minister Narendra Modi in 2015

[18] Regarding Indexes for circular economy, see Platform for Accelerating the Circular Economy (2021) "Circular Indicators For Governments"; See Kubiszewski et al. (2013) for comparison between GDP and other alternative measures such as HDI, Genuine Progress Indicator (GPI), Ecological Footprint etc.

digital economy.[19] This ongoing transformation, far from exacerbating the climate crisis, offers many opportunities for further economic and social progress with minimal adverse impacts on climate change.[20] The migration of physical economic and social activity to digital platforms generally involves a significant reduction in energy consumption and carbon emissions. This digital substitution effect alone entails a major reduction in emission intensity and an essential improvement in the tradeoff between economic progress and the preservation of the planet.[21] And digital technology offers several prospects for combatting climate change even while *advancing* economic development.[22]

It is no coincidence that big tech companies are leading the way in reducing, or even eliminating, their net GHG emissions. Their operations and business models benefit from in-depth use of digital technology, especially with the arrival and expansion of cloud computing, which allows them to reduce their carbon emission intensity to a minimum.[23] Their services can be delivered worldwide online, at once, essentially eliminating the high energy use occasioned by physical travel and transportation.[24] Moreover, most of their energy and electricity needs can be met, as they increasingly are, through renewable energy.[25] And by building excess capacity in renewable energy production, or investing in carbon capture and sequestration, the big tech companies have been able to make ambitious commitments to net zero.[26] They are today among the most valued companies, far exceeding the valuations of oil majors and mining companies (the most valuable companies not so long ago), who are responsible for the largest fraction of carbon

[19] UN Conference on Trade and Development (2021) "Digital Economy Report" documents the global development of digital economy in detail. It also discusses digital inequality. *BEA (2021)* covers the trend of U.S. digital economy.
[20] We briefly introduce benefits of digitalization in Chapter 2-1. For more detailed studies, see GeS "SMARTer 2030" (2015), PwC "How AI can enable a Sustainable Future" (2019), IEA "Digitalization and Energy" (2017)
[21] Faber (2021) for the effect of virtual conference; see Figure 3 in IDC (2016) "Green IT: Virtualization Delivers Energy and Carbon Emissions Reductions" for the effect of using VMware.
[22] We introduce the benefit of digitalization in Chapter 2-1.
[23] Cloud computing is in general more energy efficient than local individual data centers because big companies managing cloud server usually have better technology than small firms. See Masanet et al. (2020). We analyze cloud computing more in detail in Chapter 3-2.
[24] Faber (2021) estimates that virtual conferences of 207 participants emitted around 1.3 tons of CO_2, which is 1/66 of the emissions that would have been produced by a physical conference.
[25] See https://www.wired.com/story/amazon-google-microsoft-green-clouds-and-hyperscale-data-centers/ for information about the current status and future plans of Google, Amazon, and Microsoft cloud in terms of using renewable energy.
[26] "10 Tech Companies Setting Big Goals to Reduce Climate Change" https://www.ces.tech/Articles/2021/May/10-Tech-Companies-Setting-Big-Goals-to-Reduce-Clim.aspx

emissions.[27] What is more, the financial value of the big tech companies is only a fraction of the welfare benefits they provide, as their services are often priced highly competitively.[28]

Besides these important benefits from digital substitution of virtual for physical economic activity, digital technology can offer perhaps an even greater promise, helping to transform consumption habits, thereby minimizing the carbon footprint of the average consumption basket.[29] Most of the emphasis in climate policy has been on accelerating the transition in the *supply* of energy away from fossil fuels, on reducing the carbon emissions from production, and on decarbonizing investment and financial markets. In comparison, relatively little emphasis has been put on the *demand* side, on decarbonizing *consumption* in the direction of a digital circular economy. Yet, there is substantial promise in engaging with consumers, as public opinion on climate change in many parts of the world often leads public governance and corporate commitment.[30]

Circular Economy

However, an important challenge for most consumers is that they have very little information to find and wisely use lower carbon alternatives in their current consumption choices.[31] Digital technology can provide tools and information that empower consumers to discover these alternatives and take practical and simple steps to reduce their carbon footprint.[32] These tools

[27] Except Aramco, no oil and mining companies are in the list of 10 largest companies by market capitalization in 2021. https://www.statista.com/statistics/263264/top-companies-in-the-world-by-market-capitalization/

[28] Even more than that, a large number of digital goods are provided for free. See Brynjolfsson et al. (2020) for relevant argument.

[29] The key is to change the social norm, and to alter individual behaviors through some market-based corrective mechanism. (Note for further researches: Alibaba is redesigning its e-commerce business in this direction. We may have some empirical evidences on how to design a mechanism to alter consumption habits, using the launch of ``green products'' on Tmall as an event study.)

[30] Anderson et al. (2017) for positive relation between public opinion and the introduction of renewable energy policy in European states; See Burstein (2003); Forbes article "Going Green – What's Good For The Planet Is Good For Business"

[31] *Business of Sustainability Index*, GreenPrint: around two-third of American consumers are willing to pay more for eco-friendly products but 74% of them do not know how to identify them. https://www.businesswire.com/news/home/20210322005061/en/GreenPrint-Survey-Finds-Consumers-Want-to-Buy-Eco-Friendly-Products-but-Don%E2%80%99t-Know-How-to-Identify-Them

[32] One useful tool is personal carbon accounting. With the help of digital technology, individual carbon footprints can be measured and recorded in an account. With this account, each individual will be aware of his/her personal carbon emission, and can manage his/her account by adjusting behaviors. Further, the carbon account can be served as financial/saving account. There would be a trading system that allowing individuals to trade their carbon credit and convert it into cash or other green

range from precise and systematic measurement of the carbon footprint of the goods they consume to enhancing the potential of the circular economy.[33] It is becoming increasingly clear that to be able to maintain current living standards in economically advanced countries and to fulfill global development goals, while preventing the planet from further, potentially catastrophic warming, the current *linear* “purchase-and-dispose” model of consumption needs to be replaced by a *circular* “purchase-and-recycle” model.[34] In a nutshell, the circular economy needs to grow and become a fundamental component of the world economy.[35] By fully exploiting the potential of the circular economy the nations of the world will be able to minimize the tradeoff between economic well-being and preservation of the planet.

To fully exploit the potential of the circular economy will require not only new digital technology tools but also changes in consumption habits and socioeconomic systems that better integrate the use of the new digital technology tools into our daily lifestyles. As the literature on socio-technical transition has found (e.g. Geels et al. 2004, 2016, 2017), technological change and the adoption of new tools is closely connected to changing social conventions and norms of behavior. The greater the awareness in society about the climate crisis, the greater the willingness of consumers to change their consumption habits, and the more such changes in behavior are rewarded and valued by society, the greater will be the potential of digital technology for supporting the expansion of a sustainable circular economy.[36] As some socio-technical analyses have shown, it is, for example, difficult to predict the adoption of low-carbon transport technologies without a better understanding of the shifting social norms towards such practices as car sharing, greater reliance on public transportation, and changes in cultural attitudes

products and services. (Note for further researches: Alibaba is currently working on such personal carbon account, and we may be able to collect some interesting data in the near future).

[33] For example, digital platforms of second-hand goods such as Craigslist (U.S) and Idle Fish (China) make purchasing second hand goods more convenient. Personal carbon accounting platforms allow people to easily track their carbon emission from daily activities. We analyze both of them in Chapter 3 of this report.

[34] See introductions of Ellen McArthur Foundation report (2015) and Lacy et al. (2020).

[35] According to Circularity Gap Report 2020 and 2021, our current economy is 8.6% circular. To achieve the climate mitigation target set by Paris Agreement, another 8.6% of circularity is needed, which would shrink global GHG emissions by 29% and cut virgin resource use by 28%.

[36] Joshi and Rahman (2015) reviews 53 researches from 2000 to 2014 that study various factors affecting consumer’s green purchase behavior. They show that knowledge is the most studied variable (18 out of 53). Among the eighteen studies, fifteen find that knowledge of environmental issue positively affects consumer’s intention or actual decision of buying green products.

towards personal transportation (Mattioli, Roberts, Steinberger and Brown, 2020).[37] Changing social norms will not only affect how people travel; enhanced and supported by digital technology they can bring about wide-ranging changes in lifestyles, that help preserve economic well-being while protecting the environment.

This report is organized as follows. Chapter 2 discusses the benefits and risks of digitalization in reducing carbon emissions. As a general-purpose technology, digitalization is a key enabler to achieve the net-zero goal. However, utilizing digital technology is no guarantee of significant carbon emission reductions given the risks of rebound effects. We further argue that CE is the right system under which digitalization can bring its full potential to reduce carbon emissions. Moreover, with the help of digitalization, CE itself is a critical source of decoupling economic growth from carbon emissions. To illustrate the potential of DCE, we analyze five cases of innovative digital technology in Chapter 3 which demonstrate the importance of combining digital technology with changes in the socio-economic system to achieve the desired environmental impact. Chapter 4 concludes the report by suggesting future agendas for research and policy implementation.

Chapter 2. Integrating Digitalization and a Circular Economy

In this chapter we identify the areas where digitalization holds the greatest promise in transitioning towards a low carbon economy, as well as the areas where digital technology has been associated with rapidly rising energy use. As is to be expected with any technological revolution, there is generally both a bright and a dark side in what it has to offer. When it comes to climate change mitigation, and the necessary reduction in future carbon emissions, it is important to make sure that the use of digital technology is channeled towards the bright side,

[37] In chapter 3-2, we analyze how the effect of ride sharing platforms on emission reduction depends on social norms and consumer behavior.

and that the dark side of energy-intensive practices and counterproductive rebound effects is kept to a minimum.

2-1. Digitalization as an enabler of Decoupling

Benefits of Digitalization

Digitalization has often been described as the fourth industrial revolution. This representation has never been more apt than during the COVID pandemic, when thanks to widespread digitalization it has been possible to avoid the worst social and economic consequences from the necessary lockdowns and social distancing to "flatten the curve" of the pandemic. Beyond anyone's expectations, much social and economic activity was migrated almost seamlessly online. Work from home, or even work from anywhere, replaced work at the office. Much education was successfully performed online thanks to Zoom and other online communication platforms. As a result, economic activity did not shrink nearly as much as was feared, and at the same time 2020 was the first time when global carbon emissions declined significantly (around 7%[38]). If there was ever any doubt about the potential of digitalization in fostering more climate friendly economic activity it has been roundly dispelled by the episode of the pandemic. As a general-purpose technology digitalization has had and will continue to have an enormous impact well beyond the information and communication technology (ICT) sector.

Digitalization will open up more and more opportunities to increase energy efficiencies, enhancing all the important adjustments that will have to be made along the path to net zero. For instance, digital technology will be essential if we are to fully harness the capacity of rechargeable batteries available on billions of devices connected to the grid and internet,

[38] See https://earth.stanford.edu/news/covid-lockdown-causes-record-drop-carbon-emissions-2020#gs.x7f7qo. On the other hand, according to Global Economic Prospects (2022), the global economy in 2020 was estimated to have contracted around 3.4 % compared to 2019.

enabling us to better manage the ability of the power grid to manage short-term fluctuations in the demand and supply of electricity. We highlight three primary channels through which digitalization can bring efficiency gains: replacing physical processes using virtualization; optimization through data monitoring, collection and optimization; and increasing coordination through connectivity.

Virtualization has already penetrated into many parts of our lives, directly impacting carbon emissions. The most obvious example is virtual conferences and meetings. Due to virtual meeting applications such as Zoom, people generate lower carbon emissions, reducing travel, reducing the need for heating and cooling of conference venues, and the need to build more of them as time goes on. The "digital twin" is yet another example of virtualization, allowing manufacturing firms to test their products in a digitally simulated world. As digital technology develops, product tests conducted by computer simulation are becoming better and better substitutes for physical tests and even the design of products, often resulting in major reductions in carbon emissions.

Another channel for carbon reduction through digitalization lies in the monitoring, collection, and analysis of data. Data is called the fuel of digital economy.[39] Global data center IP ("Internet Protocol") traffic in 2018 has increased eleven times since 2010.[40] The growth rate is projected to increase even more considering the growing penetration of the Internet of things (IoT) in the future.[41] Compared to virtualization, the impact of data-related technologies on carbon emission is considered to be less direct and less constrained to specific industries. This implies that such data-oriented technologies can be applied to ever wider industry sectors, and that their influence will be increasingly spread throughout society. For instance, data collected from our daily lives will help us minimize carbon emissions through a wide array of optimizing algorithms.

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[39] https://www.forbes.com/sites/cognitiveworld/2019/02/06/data-the-fuel-powering-ai-digital-transformation/?sh=44b37ba1578b
[40] Masanet et al. (2020)
[41] https://www.cisco.com/c/dam/m/en_us/solutions/service-provider/vni-forecast-highlights/pdf/Global_2021_Forecast_Highlights.pdf

"Big data" and machine learning techniques are already extensively used in many industries to optimize production processes. The same techniques can be applied to minimize carbon emissions. The impact will be amplified once households incorporate those techniques into their daily lives to minimize carbon emissions. In addition to optimization, a better system of collecting data allows us to keep better track of emissions from the entire life cycles of products. Current methods of life cycle assessment (LCA) are limited in their ability to keep track of all the emissions embodied in a product, a limitation that is mainly determined by the availability of data. We can have a better life cycle assessment using more detailed data about where the materials come from, how the products are used, and how and where they are destroyed. With a more precise and detailed measurement of carbon emission, both public policies and private initiatives will become more and more efficient and effective in reducing carbon emissions.

Last but not least, digitalization promotes connectivity. The Internet has already brought people together from all around the world, allowing them to engage in an increasing number and variety of activities and contracts. Without help of the Internet, such activities would simply not have been economically feasible. As technology develops, the boundary of connection extends beyond between people, to between people and machine, and even to between machine and machine. This trend of closer connection between machines is a major feature of "Industry 4.0, the increasing use of networked, web-enabled and automated technologies in our society."[42]

Connectivity is important because it allows systems to be scalable. As mentioned in the introduction, climate change is a challenge that demands efforts from every sector of our society. It cannot be restricted to a few agents and locales Digitalization can provides the necessary scale for widespread, all-encompassing solutions designed to reduce global GHG emissions. For example, digital platforms such as Airbnb, Uber, and Idle Fish enable people to share their idle assets with a far greater number of people than just neighbors in the same towns and cities. Connection of household electricity usage to smart meters can form the basis for building a comprehensive, widespread electricity generation system complete with smart demand systems.

[42] https://www.wfb-bremen.de/en/page/bremen-invest/what-does-industry-40-mean-short-definition

Such digitally enabled connectivity can be applied to any sector and system to realize its full potential to reduce carbon emissions.

Although we conceptually define the benefits of digitalization within three categories, they are usually interconnected, and work together to realize their full potential. For example, virtualization helps people meet together more easily and frequently, which increases connectivity. The Internet of things connected to our daily lives prompts more data to be collected, and more data can lead to more connectivity. For the rest of the chapter, we provide examples of how **digitalization can increase efficiency and reduce carbon emissions within different sectors** through the combination of the three channels. Next, we briefly discuss potential adverse rebound effects of digitalization, which are considered to be major obstacles to maximizing their ability to reduce carbon emissions.[43]

Energy

Energy-related emissions account for about two thirds of global greenhouse gas (GHG) emissions.[44] Any net-zero solution, therefore, should involve innovative and viable plans to reduce carbon emissions in the energy sector. As mentioned in IRENA (2020), there are mainly two channels through which digitalization can reduce carbon emissions from the energy sector. First, digitalization can increase energy efficiency using smart grids and real-time data analysis. Combined with data sets collected from the internet of things (IoTs) in both households and industry, smart grids can provide personalized solutions to minimize electricity usage in real-time. Moreover, big data analysis provides better predictions of electricity consumption patterns, which then can be used to smooth out daily electricity consumption using smart demand response systems. Mismatch between supply and demand frequently occurs under the current system, which requires abundant reserve power generation to be on standby. Smart demand systems allow demand to be met with current supply capacity with the least additional reserve power generation on standby. According to the IEA (2017), smart demand responses can provide

[43] See Figure 2 for the summary.
[44] https://ourworldindata.org/emissions-by-sector

185 GW of system flexibility. This increased flexibility can reduce USD 270 billion in new electricity infrastructure.[45]

Secondly, digitalization can boost the growth of renewable energy generation and distribution.[46] Today, fossil fuels (coal + oil + gas) still account for around 66% of electricity generation sources, and the number goes even higher when considering direct usage of fossil fuels. Considering the tremendous impact of fossil fuels on the environment, transitioning to renewable energy systems is not an *option*, but a *necessity*. The good news is that the market share of solar and wind in electricity generation grew 15% annually on average from 2015 to 2020. The cost of wind and solar electricity generation dropped so much that nearly 62% of newly introduced renewable power in 2020 was even cheaper than the cheapest fossil fuel sources.[47] However, the absolute share of electricity generated by solar and wind combined still total only around 10%.[48] One of the obstacles to further growth of solar and wind power-based generation is related to its supply variability. Unlike coal and natural gas, the supply of solar and wind power is heavily constrained by nature and weather. As a result, under the limitations of today's electricity storage technology, heavy dependence on variable renewable energy sources would cause too frequent mismatch between supply and demand, which seriously deteriorates their energy efficiency. Demand smoothing enabled by smart demand responses analyzes customers' energy consumption patterns and optimally encourages them to shift their demand to the hours during which renewable energy sources produce enough electricity.[49] This can mitigate the mismatch problem and maximize the value of solar and wind power. A simulation study by the Rocky Mountain Institute shows that applying demand flexibility solutions to the Texas power system increases the value of renewable energy by over 30% compared to a system with inflexible demand.[50]

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[45] IEA (2017) "Digitalization and Energy", p.91

[46] https://ourworldindata.org/grapher/electricity-prod-source-stacked

[47] https://www.irena.org/newsroom/pressreleases/2021/Jun/Majority-of-New-Renewables-Undercut-Cheapest-Fossil-Fuel-on-Cost

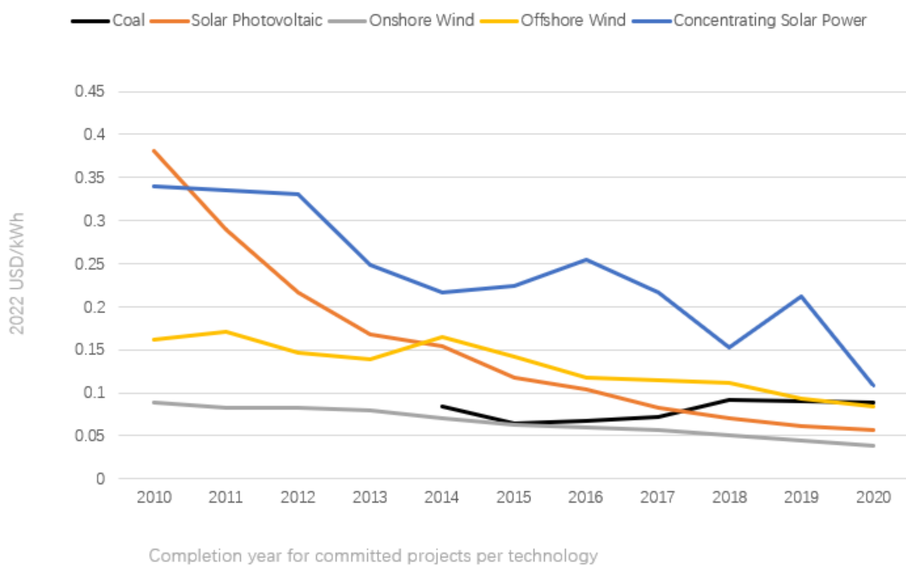
[48] wind (~7%), solar (~3%), hydro (~19%), other renewables (~7%) https://ourworldindata.org/grapher/electricity-prod-source-stacked

[49] Possible behaviors include charging electric vehicle during daytime and running energy-intensive processes like data processing and water pumping during the times of day when renewable energy sources can produce enough electricity. https://www.forbes.com/sites/energyinnovation/2017/03/13/how-a-smart-grid-relies-on-customer-demand-response-to-manage-wind-and-solar/?sh=2ca2e1c31461

[50] https://rmi.org/demand-flexibility-can-grow-market-renewable-energy/

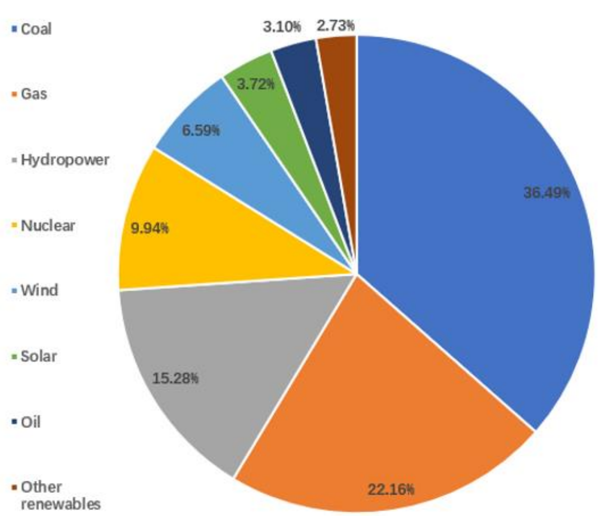
Improved profitability would encourage both governments and companies to increase their shares of solar and wind power-based electricity generation.

Figure 5. Energy price by source



Source: coal price from BloombergNEF; the rest of them from International Renewable Energy Agency

Figure 6. Electricity Production by Source in 2021, World



Source: Our World in Data

Transportation

Transportation was responsible for 24% of global carbon emissions in 2020, of which nearly three-quarters was caused by road vehicles.[51] Despite continuing improvements in energy efficiency and in the adoption rate of electric vehicles (EVs), emissions from road vehicles has stayed constant over the last few years. An IEA (2020) report attributes this lack of progress largely to 1) a change in preference toward larger and heavier vehicles, 2) the growing size of the global middle class, and 3) the increase in ecommerce and fast deliveries.[52] Digitalization, combined with adequate policies, has a huge potential to reduce carbon emissions from this apparently hard-to-abate sector.[53]

Three technologies often mentioned are ride sharing, traffic control and optimization, and smart logistics.[54] GeSI (2015) estimates that the total emissions savings from these three solutions can amount to 2.6 Gt CO2e by 2030 in the best scenario. First, ride sharing can significantly reduce vehicle miles travelled (VMT). Ride hailing platforms such as Uber, Lyft, and Didi are already heavily used in many of the big cities in the world. However, recent studies show that the introduction of Uber or Lyft has increased VMT in some of the big cities in the U.S.[55] To reverse this trend and direct it toward a low-carbon path, people should use more pooled services and use ride-sharing services more as a complement to public transit. Increased real-time availability of data can provide better connections between people with destinations to the same locations and directions, between drivers and passengers, and between public transit systems and private vehicles. Combined with adequate policies, data-enabled connections can enhance the decarbonization of ride-hailing platforms.

Data collected from multiple sensors set up in vehicles can also be used to optimize traffic control and to minimize carbon emissions. The impact will be amplified especially when the usage of

[51] https://www.iea.org/topics/transport Tracking Transport 2020
[52] https://www.iea.org/topics/transport Tracking Transport 2020
[53] https://www.climateaction.org/webinars/the-role-of-heavy-industry-in-the-net-zero-energy-transition
[54] GeS (2015) “SMARTer 2030”. We discuss ride sharing case in Chapter 3-2.
[55] More discussion and details can be found in Chapter 3-2 of this report.

such big data is combined with autonomous vehicles. Fully developed AI driving systems would control vehicles much more precisely than a human driver. They can also be programmed to cut emissions during driving such as eco-driving, platooning, and efficient routing.[56] Despite all these promising benefits, there are still concerns over potential rebound effects from adopting autonomous vehicles; the increased convenience of autonomous vehicles may increase demand for private vehicles, which would then lead to increased carbon emissions. As a result, the net effect of autonomous vehicles is far from settled, and the result will in the end depend on demand-side responses to the technology. For example, Wadud et al. (2016) estimates that autonomous vehicles might plausibly reduce road vehicle carbon emissions by nearly half, or nearly double them, depending on which demand responses it elicits.

Lastly, logistic companies can also leverage big data collected from sensors and adopt efficiency enhancers such as fleet management and route optimization. Digital freight matching platforms such as Convoy, PostBidShip, and Uber Freight provide matching services between small trucking companies and freights, which not only increase space utilization, but also decrease empty runs.[57] All of these contribute to reducing carbon emissions.

Buildings

Direct and indirect emissions from building usage and construction amounted to 10 GtCO2e in 2019, which accounts for around 38% of all energy-related CO2 emissions.[58] Emissions from building sectors has been growing since 2016 despite continuous progress in energy efficiency. The main driver of net emission growth is increased demand for building energy services such as heating, cooling, lighting, appliances and connected devices.[59] Heating, cooling, and lighting generally account for more than 60% of total final energy demand in buildings, and these are exactly where most of the savings would come from the use of digital technology.[60]

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[56] See Wadud et al. (2016) for detailed discuss of environmental effect of autonomous vehicles.
[57] https://www.supplychain247.com/article/the_rise_of_digital_freight_matching
[58] IEA Tracking Buildings 2020 https://www.iea.org/reports/tracking-buildings-2020
[59] IEA Tracking Buildings 2020 https://www.iea.org/reports/tracking-buildings-2020
[60] IEA (2017) "Digitalization and Energy"

As more data are collected through the IoTs used in buildings,[61] people will have better estimates of their current energy usage and carbon emissions. Furthermore, big data analysis and AI models can provide personalized solutions to minimize carbon emissions. According to GeSI (2015), full adoption of smart buildings and the widespread adoption of smart meters can reduce global GHG emissions by 2.0 Gt CO2e by 2030.

As with the energy and transportation sectors, data is critical to realize the benefits of digitalization and the reductions in carbon emissions in the building sector. Yet at the same concerns about the privacy and security of personal data is one of the major hurdles that prevent people from actively adopting IoTs such as smart meters, which are essential for its collection. Data from building usage, especially residence buildings, may contain detailed private information that can be used to infer the patterns of each household's lifestyle.[62] According to Panwar et al. (2019), "security and privacy are two prime concerns in smart home networks."[63] Government policies and company practices should set a transparent standard for data privacy to resolve these concerns, boosting the adoption of smart home systems.

Other Sectors and Industries

IoT and machine-to-machine connectivity lie at the core of the digitization of industry and society, what we called "Industry 4.0" at the beginning of this chapter. This concept of connectivity is not just confined to data analytics and cloud computing. Digitalization in Industry 4.0 implies more active interactions between machines using real-time data and full automatization. Broadly speaking, automation increases resource-use efficiency, and unless the savings are spent on carbon intensive activities, this increased efficiency will reduce carbon emissions. GeSI (2015) estimates that smart manufacturing alone has the potential to reduce global carbon emissions

[61] https://www.businesswire.com/news/home/20200929005109/en/Guidehouse-Insights-Report-Finds-Global-IoT-for-Smart-Buildings-Revenue-Is-Expected-to-Experience-a-14-Compound-Annual-Growth-Rate-from-2020-2029
[62] Amazon Alexa's privacy issue： https://www.theguardian.com/technology/2019/oct/09/alexa-are-you-invading-my-privacy-the-dark-side-of-our-voice-assistants
[63] Panwar et al. (2019)

by 2.7 Gt CO2e. When considering automation in industries other than manufacturing, the amount of carbon emissions reductions can be much larger.

Another avenue that has a high potential for carbon emissions reductions is virtualization. Virtual Product Simulators (VPS) developed by Fujitsu allow companies to test their product development plans with minimal amounts of physical waste.[64] Virtual meetings and conferences also have high potential to reduce carbon emissions. Faber (2021) estimates that virtual conferences of 207 participants emitted around 1.3 tons of CO2, which is 1/66th of the emissions that would have been produced by a physical conference![65] The majority of the saving comes from the emissions from flights, and from heating and cooling conference venues.

All these are examples of the bright side of the digital revolution. If these were the only changes that digitalization has to offer, we should be seeing a greater and greater decoupling of economic activity and carbon emissions, as the share of the digital economy grows. But the evidence on for decoupling has not been so clear-cut, suggesting that there is also a dark side to digitalization that we cannot ignore. The problem is that some enhancements that digitalization has to offer can also invite increased use of lower cost digital technologies, which generate more energy consumption as the demand for their use increases. This phenomenon is referred to as the rebound effect (also known as Jevon's Paradox). We turn next to a discussion of this effect.

Rebound effects (Jevon's Paradox): Energy usage/CO2 emissions from ICT

Several studies have estimated the contribution of information technology utilization to GHG emissions at between 1.8% and 2.8%, based on 2015 data.[66] This would seem to be a reasonably low estimate as of that point in time. But there are still concerns that as society becomes more

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[64] https://www.fujitsu.com/global/about/resources/news/press-releases/2010/0615-01.html
[65] Faber (2021): A framework to estimate emissions from virtual conferences, International Journal of Environmental Studies
[66] Malmodin and Lunden (2018); Belkhir and Elmellgi (2018); Andrae and Edler (2015). Freitag and Berners-Lee (2021) claims the previous authors underestimated the emissions of ICT and adjusted to 2.1-3.9%.

and more digitalized, and as big data processing expands throughout the economy, the carbon footprint of ICT is likely to rise significantly. We know that information and communications technology (ICT) energy consumption is concentrated in data centers, network operations, user devices, and cryptocurrencies. In which of these activities is energy consumption most wasteful? And in which of these activities are rebound effects most pronounced?

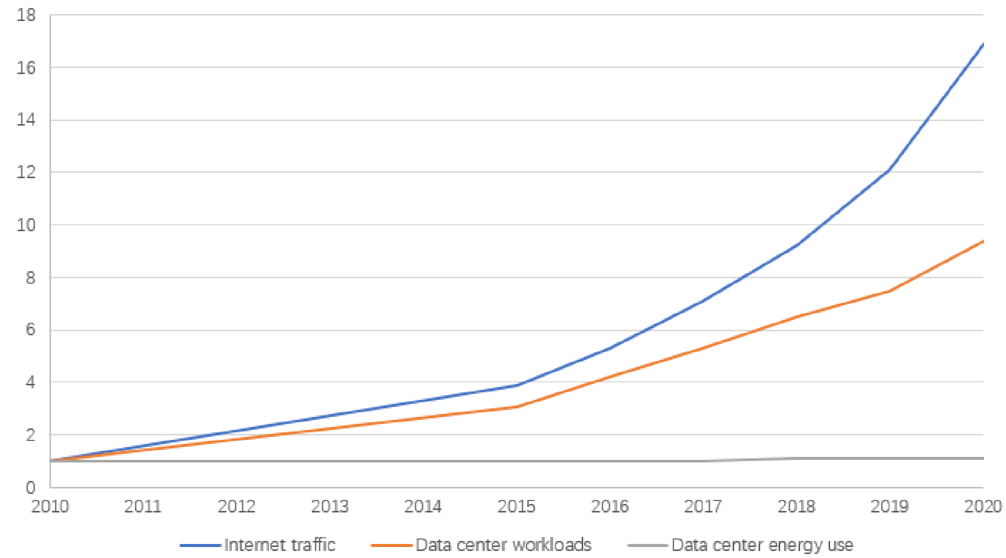
Data Centers

As more and more data become available in digital form, as more and more data are stored, and as more and more data processing generate new data, there is likely to be substantial growth in energy consumption in the use and maintenance of data centers. But how much this energy consumption will rise with the expansion of data centers has been subject to speculation. Some researchers had predicted that energy consumption would increase significantly along with the rapid growth of data traffic under the assumption that data traffic is a key driver of energy consumption of a data center.[67] However, these precautions have turned out to be unfounded. According to an IEA report (2020), the electricity consumption of data centers amounts to 200 TWh, or 0.8% ~ 1% of global final electricity demand.[68] **Interestingly, the energy demand of this sector has remained stable since 2010 even though data traffic has increased twelvefold.** This has been made possible by three major advances in energy efficiency.

First, the energy efficiency of data center servers and storage drives has improved substantially. Second, more data centers are using server virtualization software such as "hypervisor," which allows a single server to run multiple applications.[69] Lastly, the increasing market share of cloud and hyperscale data centers helps to increase the average energy efficiency of the data center.

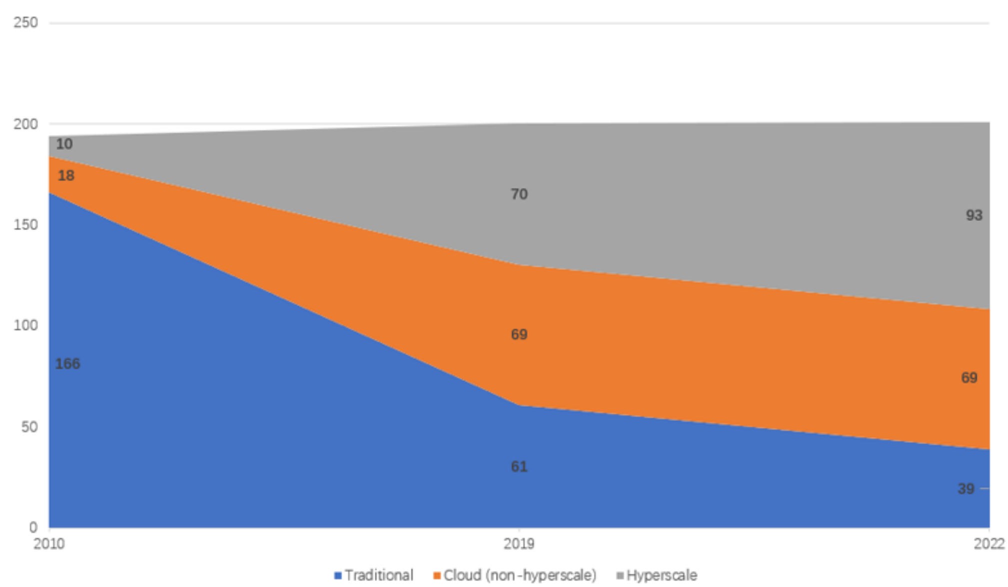
[67] Belkhir and Elmeligi (2018); Andrae and Edler (2015); Bawden (2016).
[68] This can be converted to 141 MtCO2e when applying the converting ratio (1kWh : 0.701 kgCO2e) set by EPA.
[69] https://www.energystar.gov/products/low_carbon_it_campaign/12_ways_save_energy_data_center/server_virtualization

Figure 7. Global trends in internet traffic, data centers workloads and energy use, 2010-2022



Note: Index 2010 = 1
Source: International Energy Agency

Figure 8. Global data center energy demand by data center type (TWh)



Source: International Energy Agency

High-capacity data centers typically have a very low power usage effectiveness (PUE), which is a measure of energy efficiency. For example, Google claims the average PUE of its data centers to be 1.2, which is much lower than PUE 2.0 of conventional data centers.[70] In addition to technological progress, big tech companies such as Amazon, Google, Facebook, and Microsoft invest substantial sums in renewable energy to mitigate their environmental impacts and to protect their data centers from energy price volatility.[71] Those firms buy renewable energies directly from renewable energy developing companies via long-term power purchase agreements (PPA), and the total amount purchased by those firms accounts for about half of global corporate renewable energy procurement in the past five years.[72] Those long-term PPA deals not only green data centers' energy usage: they also help to provide financial stability to renewable energy developers and generation companies.[73]

Despite the huge progress made over the **p**ast ten years, we cannot ignore the potential risks of explosive energy consumption by data centers in the future, especially those caused by rapid development of AI technology and the internet of things (IoTs).[74] To prevent rising energy use of data centers in the future, more investments in next-generation computing, storage, and cooling systems are required. At the same time, more energy use of data centers should be sourced from renewable energy. (Masanet et al. 2020).

Communication Network Operators

ICT telecommunication networks refer to fixed and mobile telecommunication networks, and to their related activities. To avoid double counting, data centers and end-user devices are usually excluded from this category. A fixed-line network connects end users, by means of a cable (e.g. fiber optic and copper cables), allowing them to make phone calls or connect to the Internet. Mobile communication networks, on the other hand, refer to a collection of facilities connecting end-user mobile devices through radio signals transmitted by a large number of cellular towers

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[70] https://www.nature.com/articles/d41586-018-06610-y
[71] IEA (2021) "Data centers and Data transmission networks"
[72] BloombergNEF (2021), 2H 2021 Corporate Energy Market Outlook.
[73] https://www.reutersevents.com/renewables/pv-insider/data-center-demand-juggernaut-creates-new-solar-wind-openings
[74] https://www.technologyreview.com/2019/06/06/239031/training-a-single-ai-model-can-emit-as-much-carbon-as-five-cars-in-their-lifetimes/

(e.g. 3G, 4G, and 5G). Together with data centers and end-user devices, communication networks contribute a significant portion to GHG emissions from the ICT sector. Compared to data centers, it is usually harder to acquire publicly available data sets with detailed network facilities since the information is considered proprietary.

According to Malmodin and Luden (2018 b), who have used the most detailed data, the estimated emissions of carbon from network operators in 2015 was 169 Mt CO2e, accounting for around 0.53% (0.34%) of the energy related (total) carbon emissions. Although the absolute amount might not seem substantial at present, the increasing trend of data traffic led by video streaming, smart phones, and the internet of things (IoTs) do raise concerns over future increases in the emissions generated within this sector. Analysts with the greatest concerns worry that the emissions will follow the same path as the exponential path of data traffic, posing a serious threat under a business-as-usual scenario.[75]

Those who focus more on the rapid progress of data processing technology are more optimistic. They think that technological progress in energy efficiency together with increased reliance on renewable fuels will offset most of the adverse rebound effects from increasing flows of data traffic, allowing the emissions path of communication networks to follow the linear trend in the number of mobile subscribers, not the exponential trend in the growth of data traffic. Malmodin and Luden (2018 b), for example, note that carbon emissions have increased only about 17% since 2010, while data traffic has grown by 280% on average. What's more: they think an absolute decoupling might well take place as the global smartphone market becomes saturated and the growth of smartphone subscribers abates.[76]

[75] See Andrae and Edler (2015); Belkhir and Elmeligi (2018).
[76] More than 80 percent of the world's population now owns a smartphone.
(https://www.statista.com/statistics/330695/number-of-smartphone-users-worldwide/)

User Devices

A major change in the demand for IT devices over the past two decades has been a shift from immobile devices, desktops, PCs, and TVs, whose sales have plateaued, to mobile devices, especially smartphone that have become increasingly popular[77] and that provide most of the uses of the immobile devices at a fraction of the lifetime energy consumption and carbon emissions.[78] As the usage of smartphone continues to outstrip that of immobile devices, we can expect the overall carbon intensity of information technology to decline. However, whether overall carbon emissions from IT devices will decline will depend on the nature and extent of the rebound effect – on how fast the demand for digitized information increases.

Another potential source of carbon emission is the Internet of things (IoT). According to Cisco's Annual Internet Report (2020) IoT has become a prevalent system in which people, processes, data, and things connect to the Internet and to each other. Globally, machine-to-machine (M2M) connections will have grown 2.4-fold, from 6.1 billion in 2018 to 14.7 billion by 2023, at which time there will be "1.8 M - 2M connections for each member of the global population."[79] The consensus forecast among researchers is that IoT will continue to expand dramatically. How much this growth in IoT will translate into net carbon emission growth, however, is not known as the energy efficiency improvements that IoT will help bring about have not as yet been accurately estimated.

Cryptocurrency

If there is one area of the digital economy that is responsible for the greatest adverse impact on climate change it is cryptocurrency with its voracious consumption of energy. It is not easy to measure precisely the energy consumption of cryptocurrency mining, but we know that the scarcity value of major cryptocurrencies (Bitcoin) is built on its extremely high rate of energy

[77] See Figure 7 in Malmodin and Lunden (2018).
[78] See Figure 10 in Malmodin and Lunden (2018)
[79] https://www.cisco.com/c/en/us/solutions/collateral/executive-perspectives/annual-internet-report/white-paper-c11-741490.html#Executivesummary

consumption. This is an extraordinarily wasteful way of building trust in the soundness of the currency. According to IEA, the energy consumption of Bitcoin mining is estimated to be between 20 and 80 TWh (terawatt hours).[80] In another independent study by Stoll et al. (2019) estimates the energy consumption of Bitcoin mining to be 45.8 TWh in 2018, in the middle of the IEA range. Stoll et al. (2019) converted the energy consumption into carbon emission, which amounts to 22.0 Mt CO2e – 22.9 Mt CO2e.[81] Since Bitcoin mining is estimated to account for around two thirds of total energy consumption in coin mining, the total CO2 emissions from cryptocurrencies is estimated to be 33 Mt CO2e-34.35 Mt CO2e.[82] According to Huang et al. (2021), electricity usage from coin mining represents approximately 0.5% of all the electricity consumed globally, or roughly the same amount of electricity consumption in Washington State, more than the electricity consumption in Finland, and seven times more than the electricity consumption by Google.[83] All this energy is consumed for no other purpose than to raise the cost of coin mining, thereby creating a scarcity value. Limiting coin supply can be achieved in other ways that do not require near the level of energy consumption. Constraining the expansion on this dark side of information technology is critical if we are to harness the full benefits of the digital economy to achieve Net Zero.

Rebound effects on other sectors

With the glaring exception of cryptocurrency, the net energy savings from the digitalization of economic transaction and social interaction can be substantial. But how much might these gains be undone by attendant *indirect* rebound effects of digitalization as it fosters an overall increase in trade and commerce? To be sure, while digitalization can reduce carbon emissions through reductions in energy intensity, it can also boost consumption via real income effects, possibly resulting in increased overall carbon emissions.[84]

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[80] https://www.iea.org/commentaries/bitcoin-energy-use-mined-the-gap
[81] Stoll et al. (2019)
[82] Stoll et al. (2020)
[83] "Bitcoin Uses More Electricity Than Many Countries. How Is That Possible?", New York Times September 3, 2021. https://www.nytimes.com/interactive/2021/09/03/climate/bitcoin-carbon-footprint-electricity.html
[84] Real income effect refers to increase in one's purchasing power due to decrease in product prices.

For example, Luo et al. (2019) examine the China Family Panel Studies Survey with county-level e-commerce data from Alibaba. [85] They find that e-commerce development has been associated with higher consumption growth, especially in rural areas. One problem with such an exercise is that it is difficult to isolate the rebound effects. First, one must consider consumer welfare when evaluating the environmental impact. Second, at the aggregate level, consumption tends to grow with disposable income. The faster growth of online consumption tends to reflect the impact on traditional consumption. So long as aggregate consumption does not grow disproportionally with income, higher growth of online consumption will be associated with a more energy-efficient form of consumption.

A complete analysis of rebound effects should in the end be based on empirical estimates of the resulting carbon emission reductions from digitalization. However, calculating the net effect on GHG emissions is usually more challenging than estimating the direct effects on energy consumption. In the first place, we must calculate avoided emissions from online sales rather than traditional brick-and-mortar stores. Second, the change in consumption baskets must be also considered since different categories of consumption differ in GHG emissions intensity. For instance, a dollar spent on additional electricity and gas usually emits much more GHG than a dollar spent on food and clothing.[86] Therefore, and among other things, more accurate estimates of the net effect on GHG emissions requires accounting for changes in consumption baskets. To highlight the importance of changes in the consumption basket, suppose that an individual saved $200 by purchasing a cellphone from a second-hand goods platform instead of a first-hand purchase. Further suppose that the individual spends the savings on d taking plane to travel "across the country." The net effect of using second-hand markets would be determined by comparing the carbon savings from producing and using a new cellphone and the carbon emissions from taking a flight.

[85] Luo and Zhang (2019)
[86] See Figure 1 in Sorrel et al. (2020)

Overall, the above example demonstrates the importance and difficulty of finding a causal relationship between the adoption of new technology and a (net) change in carbon emissions. Identifying such causal links is a demanding task even within the boundaries of a particular sector, let alone for the overall economy. First of all, lack of detailed data on consumption baskets is the most common obstacle to estimate rebound effects. Second, the impact of digitalization on society is very broad and multi-dimensional, which makes it hard for researchers to identify the limits of the impact of digitalization. As a result, even when equipped with detailed data, it is hard to find a causal relation between efficiency gains within one sector (within a "partial equilibrium" analysis) and increases in consumption in other sectors (within a "general equilibrium" analysis).

For these reasons, most previous research on rebound effects has focused on estimating direct rebound effects. Does this lack of evidence allow us to conclude that indirect rebound effects are negligible? We believe that the risk of rebound effects (especially indirect effects) is real. As can be seen in Figure 1, history until now has not provided much evidence of a causal link between energy efficiency improvement and carbon emissions reductions. One might argue against such skepticism by observing that the recent digitalization revolution driven by digital platforms is a new phenomenon and it is hard to predict the rebound effects of this new type of revolution based on history. However, at the same time, there is also no definitive contrary evidence to support the optimistic view of digitalization. Considering the high price of climate change that we may pay, a reasonable attitude for the world is, at least for now, to maintain a skeptical view of the effects of digitalization and to try to find ways to minimize its potential undesirable effects ahead of time.

How to fully capture the benefits of digitalization

Despite the concerns about rebound effects, we cannot ignore the immense potential of digitalization for reducing carbon emissions. The lesson from Chapter 2-1 is that **digitalization in**

itself does not guarantee Net Zero.[87] We also need a new economic system to guide digitalization toward that destination. Put differently, we need to make sure that the savings from the efficiency gains from digitalization are not spent on generating more carbon emissions. In principle, this can be achieved in two ways: reducing carbon emissions from consumption (both directly and indirectly embodied) and reducing emissions altogether by resorting to clean energy.

In the next section we argue that the *circular economy* is the direction toward which digitalization should be guided if we are to achieve Net Zero. CE is a new economic system in which the value of product usage is maximized while the waste from economic activity is minimized. When embedded in a circular economy digitalization can realize its full potential to reduce carbon emissions. At the same time, digitalization helps the circular economy achieve scale and thereby have a significant impact on carbon emissions reductions. CE boosted by D (for "digitalization") is a promising way we can hope to be able to decouple economic growth from carbon emissions. Combining D and CE, we argue that DCE (for "digital circular economy") is a necessary transformation to a world of Net Zero.

2-2. A circular economy will put us on the path to Net Zero

The circular economy is nothing short of a massive transformation from the traditional "linear" "take, make, waste" approach of doing business to a circular model in which products and resources are kept in use for as long as physically possible at which time components and materials are recycled -- looped back -- into the system in zero-waste value chains. In effect, the concept of waste is eliminated, fundamentally altering the way goods and services are produced and consumed.

[87] See the last paragraph in Freitag et al. (2020).

A healthier, thriving ecosystem ensues, continuously *circulating* value throughout the economy and society while *increasing* resource use efficiency and productivity.[88] According to the Ellen MacArthur Foundation, switching to a circular economy could bring a 48% reduction in CO_2 emissions by 2030[89] while strengthening the resiliency of the climate to withstand near-term changes. Adopting a circular economy means acknowledging that we cannot reach net zero by focusing solely on the energy sector.

We can distinguish among five different circular business models that can capture the value of the circular economy across a typical value chain. Three center on production: **Circular Inputs**, the use of renewable energy, bio-based or potentially completely recyclable materials; **Product Use Extension**, extending product use through repair, reprocessing, upgrade and resale, and **Resource Recovery**, the recovery of usable resources or energy from waste or by-products. [90]

The other two Circular Business Models focus on consumption and the relationship between the product and the consumer. **Sharing Platforms** focuses on increasing usage rates of products or services through collaborative models for usage, access or ownership. And **Product as a Service** centers on the offer of a product use, where the producer retains ownership to increase productivity (Figure 3).[91]

The Sharing Platforms model has been growing recently, thanks to the advancement of the platform economy. One of Alibaba's platforms, Idle Fish, the biggest online community for secondhand sales in China, has achieved 24.912 million tons of carbon-emission reduction and contributed 6,278 tons of forest carbon sink in 2019. It illustrates how digitalization can enable circular business models to grow while reducing the rebound effects from digitalization.

[88] Lacy et al. (2020), The Circular Economy Handbook.
[89] Ellen MacArthur Foundation: https://unfccc.int/sites/default/files/resource/Circular%20economy%203.pdf
[90] Lacy et al. (2020), The Circular Economy Handbook.
[91] Lacy et al. (2020), The Circular Economy Handbook.

The way the models are embraced varies, depending on geography, industry, business size and structure, and product type. There is a benefit in leveraging each of the models to gain real scale and impact within the circular economy, and the models can work together to help counteract rebound effects. The whole can be much greater than the sum of its parts: getting all five to work in tandem can create the greatest impact—generating maximum value for the environment -- as well as for the economy.

Circular design is a key enabler for the Circular Business Model

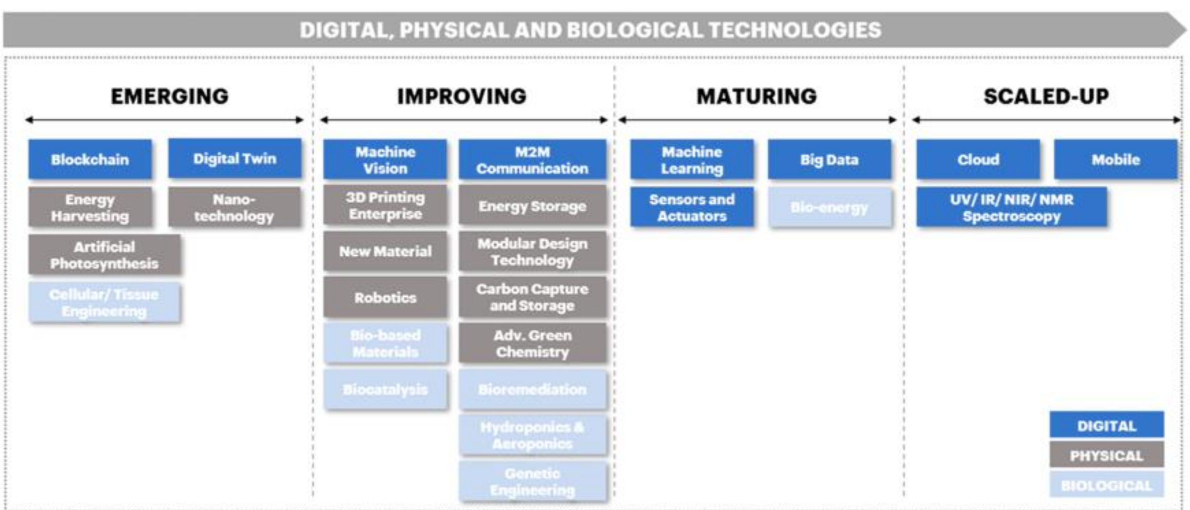
There are many ways to capture the full potential of the Circular Business Model, including consumer and community engagement, reverse logistics, disruptive technologies, innovative ecosystems, and creative designs. Embedding circularity up front at the design stage enables longer use-cycles and greater end-of-use recovery. This can reshape consumer habits, shifting their preferences in a much more sustainable direction. For example, circular design principles, such as redesigning for less material use can cost-effectively extend use of a product, and designing for end of use (e.g., making a product biodegradable) can eliminate waste. If companies apply more circular design to their products or services, it can help to change people's consumption patterns—such as encouraging purchase of a product with reusable packaging that is sent back to the manufacturer to be put back into use.

Digital technology -- another key enabler for the penetration of the circular economy

Let's look at another key enabler for the circular economy: *disruptive* technology. The five circular business models are enabled by a range of "Fourth Industrial Revolution (4IR)" disruptive technologies that are blurring the lines between the physical, digital and biological worlds, ushering in transformational change across global value chains. This includes advances in artificial intelligence (AI), robotics, the Internet of Things (IoT), 3D printing, nanotechnology and more. 4IR technologies are game changers – making it possible, for the first time in human history, to decouple production and growth from the consumption of natural resources. They share in common critical capabilities that enable them to achieve greater efficiency and less waste, to drive innovation by allowing new players to disrupt existing markets and to challenge established companies to pivot to greener business models and markets.

These technologies also increase information transparency. Data can be gathered and analyzed quickly to gain insights that give heightened visibility into the business, enable greater connectivity (between machines, customers and decision makers), and flexibility (making modifications to a device, function or process much easier). Detailed data can also help us track our usage of materials throughout their whole lifecycle to improve their energy efficiency, as well as the efficiency with which other resources are used.[92]

Figure 9. Current and emerging technologies



Source: Accenture

[92] The EU Commission presented in March 2022 a package of European Green Deal proposals to make sustainable products the norm in the EU. One of the key proposals to require all regulated products have Digital Product Passports. "This will make it easier to repair or recycle products and faciilitate tracking substances of concern along the supply chain." See https://ec.europa.eu/commission/presscorner/detail/en/IP_22_2013

Digital technologies are technologies based on the application of the computer, electronics and communication sciences. They tap into the growing volume of information and connectedness of physical resources. Digital technologies are frequently deployed in circular practices, with the IoT and machine learning leading the way. [93] IoT technologies consist of wireless devices with embedded sensors that make it possible to connect assets and products and exchange data generated in a sensor network. An IoT device could be a car, a refrigerator or a piece of industrial equipment—all of which have potential to be monitored and controlled remotely. Machine learning (ML) uses iterative self-learning algorithms that allow rapid prototyping and testing that help organizations design circular products, components, and materials. And by deploying predictive analytics for more precise demand-planning or to analyze usage patterns to optimize asset management, ML also makes it possible to cut waste, resource use, and emissions. In many ways, today's digital revolution and the circular economy go hand in hand.

Digital technologies are an amplifier for scaling and making circular business models more effective and efficient. When companies expand the scale of digitalization, they find new possibilities to tap into the circular business models and optimize scarce resources. When circularity shapes how products and services are designed, it makes possible nearly limitless consumption, since growth is no longer nearly so constrained by resource availability or environmental impact.

2-3. Governance and the transition to a Digital Circular Economy

From Circular Business Models to Digital Circular Economy

[93] Lacy et al. (2020), The Circular Economy Handbook.

The speed with which digitally enabled businesses are tapping into the possibilities of the circular economy is astounding, and it's not just familiar names like Airbnb and Uber. In East Asia, Mercari, a Japanese shopping app that enables people to sell their unwanted clothes securely, raised around $14 million in 2014 alone, only 18 months after its launch. Block Pools, meanwhile, a Singapore-based private social network that allows neighbors to lend and borrow, buy and sell things from one another is now used by thousands. Examples like these abound. According to Accenture, the circular economy represents a global opportunity worth $4.5 trillion by 2030, by redefining the concept of waste as a valuable resource. [94]

Digitalization and circular business models reinforce each other through new forms of economic organization to create value. Digital platforms create value by reducing transaction costs in connecting agents and facilitating exchange. Reduced costs not only increase the volume of existing transactions but also create new transactions that were not possible before. Such increased connectivity is essential to the creation of a full-fledged circular economy because in such an economy a product's value is not constrained to the ownership of a single person. Instead, the value of a product is maximized as it expeditiously moves to the place where it is most needed. As the range of connections broadens, the underlying value of a good or service increases. More and more people are provided with more and more incentives to join the system created by the digital platform.

To be sure, replacing our current linear model with a circular model of production, consumption and the entire economic system will be a monumental task. But by taking the circular economy as our blueprint, enabled by digital technology, it is possible to replace and scale the circular innovations to a Digital Circular Economy (DCE) that we must have if we are to confront its most urgent challenges. **DCE** is not constrained to individual circular business models. It includes a whole set of business models based on digitalization and the entire economic system and society in which economic agents are incentivized toward circular ways of production and consumption. As agents and communities become increasingly motivated to join digital platforms and to

[94] Lacy et al. (2020), The Circular Economy Handbook.

contribute to circular usage of resources, an interdependent, well-organized **digital circular "economy"** is created rather than just a collection of numerous independent **digital circular "business models"** working in every which way and direction. Here the word "economy" includes all social, cultural, technical, and governance dimensions that shape the behaviors and incentives of individuals, their communities, as well as the circular business models themselves. A transition to a digital circular economy cannot be attained merely through the rise of innovative digital circular technologies. What is needed is a systemic socioeconomic transformation that facilitate the creation of a full-fledged circular economy.

Governance challenges

The daunting challenges of Net Zero and the associated socio-environmental crises worldwide compel us to go beyond the conventional governance model based on the separation of policy making by governments from business and social conduct. First, while policies focusing on direct mitigation of GHG emissions, such as carbon taxes, border carbon adjustments, as well as mandatory carbon disclosure requirements are necessary and important, they need to be complemented by other community-based sustainability goals that reduce the harmful effects of human activity on the environment. This requires deep coordination among multiple stakeholders within and across multiple sectors, communities, and government departments. Moreover, the global nature of the GHG emissions externality means that Net Zero can only be achieved as a global goal that covers all countries and people. The transition away from the current fossil-fuel-based economic regime will require both a shift toward a low-to-zero emissions socio-technical system, through subsidies for renewable energies, involving the phase-out of first coal and then oil and natural gas, while encouraging disruptive technologies such as electric vehicles for transportation and carbon capture, utilization, and storage (CCUS).

DCE's potential will be fulfilled through a socio-technical transition that deploys digital technology to enhance circular economy practices, and an even bigger system transformation of which DCE is a critical component. More is required than just the addition of D to CE. Integrating

D with CE is a dynamic process wherein technology and economic behavior actively impinge on one another. This is only possible under an **appropriate governance system that includes and is intended to benefit all stakeholders**. We refer to "governance" here as all the decision-making processes and socioeconomic interactions, through regulatory, fiscal, tax and other governmental policies, evolving social norms, and community engagement (within both formal and informal associations) at the local, regional, and national level. Government, markets, communities, and all social networks must participate in promoting more sustainable forms of behavior in the new Digital Circular Economy. In other words, our current socio-techno-environmental system must undergo major transformations if we are to unleash the full potential of innovative digital technologies and CE business models. The new system must provide everyone with economic and non-economic incentives to fully participate in the DCE -- in work, at play, and in every other aspect of their daily lives. This can happen only through a combination of innovative government policies, market mechanisms, and stakeholder participatory approaches across regions, sectors and social hierarchies.

In summary, whilst global level governance frameworks for climate and sustainability are needed, the dynamics and diverse nature of the distributional effects of these challenges at regional and local levels necessitates multifaceted forms of governance (Ostrom 2005, Jordan et al. 2018). DCE, especially, demands the inclusion of local and sub-national scales of governance that are more sensitive to cultural differences and to local and regional variations in resource endowment and technological readiness.

Chapter 3. Innovation Trends and Emerging Initiatives

In this chapter we present five case studies of technological innovations to illustrate concretely how the DCE might work and to suggest pathways on how to expedite its transition. These five cases have been selected in order to illustrate how the three pillars of the DCE (digitalization, circular business model, and economy) might be constructed. Digitalization and circular businesses provide the essential building blocks, with further, much-needed support by socio-economic governance that helps align their incentives with what's needed to attain a world of Net Zero. After describing each case, we identify and discuss some of the major obstacles in the way of transitioning to a DCE. We employ a concept of a "socio-technical" system in which the meaning and purpose of technological innovation are shaped.

The transition to a digital circular economy requires a systemic shift because it not only involves a digital technological revolution, but also a transformation of the entire socio-economic environment that shapes how people and communities engage with one another and with the new digital technologies. The socio-technical perspective provides us with a holistic view of a social transition that integrates both technological and social dimensions. It views society as a **socio-technical system**, in which "a cluster of elements, including technology, regulations, tax incentives, user practices, markets, cultural considerations, infrastructure, maintenance networks and supply networks. Technology plays an important role in fulfilling societal functions, but its functions depend upon its relationship to the other elements."[95]

3-1. Socio Technical Systems and the Multi-Level Perspective (MLP)

A particularly useful contribution to socio-technical analysis for our purposes is the multi-level perspective (MLP) of Geels et al. (2004). Their MLP distinguishes among three broad layers: i) *niche innovation*, ii) *socio-technical system and regime*, and iii) *socio-technical landscape*. In their analysis, transition to a new socio-technical system involves first a technical innovation, second a transformation of modes of social interaction as the new technology is embraced -- three different forms of adaptation depending on the specific social-technical context, and, critically, the interplay among the three layers. Such a framework is useful to evaluate the degree of integration between circularity, technology, and multi-stakeholder economy. For example, *niche*

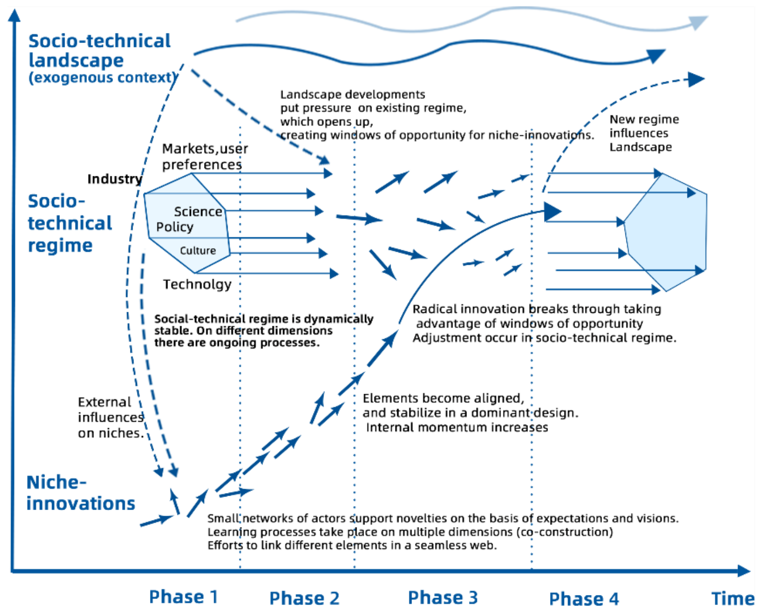
[95] Geels et al. (2004)

innovation could be a new digital platform to enhance second-hand commerce. The impact of this innovation will be through new modes of social interaction and exchange, a gradual transformation of the *socio-technical system* and the more intangible *socio-technical regime*. Finally, the *socio-technical landscape* is the context that shapes the adoption of this circular commerce innovation; that is, it is all the "broader contextual developments that influence the socio-technical regime and over which regime actors have little or no influence."[96]

The figure below represents the main channels of MLP. MLP divides a transition into four distinct phases. In the first phase, niche innovation occurs on the fringe of the incumbent regime. At this stage, the innovation is uncertain, fragile, and experimenting with different design options. In the second stage, niche innovation starts to form a foundation at a localized market with its dominant design. Other associated expectations and rules begin to stabilize. In the third stage as the innovation begins to compete head-to-head with the incumbent regime. The innovation starts to have major conflicts with existing actors: economic competition with traditional business models, and other market entrants, struggles with new rules, regulations, and other public policies, and discursive struggles on how to frame the problems under the new regime. If a new technology survives all these conflicts, it replaces the established regime in the final phase. It becomes a new *socio-technical regime*, and the accompanying rules, regulations, and culture begin to form a new *socio-technical landscape*.[97]

[96] For more detailed explanation of STS and MLP, see Geels et al. (2017).
[97] For more detailed explanation of STS and MLP, see Geels et al. (2017).

Figure 10. Multi-level Perspective on Socio-Technical Transitions



Source : Adapted from Geels et al. (2017)

Niche innovation	Emerging social or technical innovations that differ radically from the prevailing socio-technical system and regime
Socio-technical regime	The current structures which are maintained, defended by incumbent actors, whose actions are guided by deeply entrenched rules and institutions.
Socio-technical landscape	Broader contextual developments that influence the socio-technical regime comprising comprise both slow-changing trends (e.g., demographics, ideology) and exogenous shocks (e.g., wars, economic crises).

In this chapter, we provide five case studies and analyze them through the lens of MLP. Each case involves a digital technical innovation with a huge potential to reduce carbon emissions. Some of the innovations have already passed the third phase of transition and have fully transitioned into a new regime in parts of the world, while others have not yet entered the second phase due to various technical and societal constraints. Our case studies demonstrate the importance of socioeconomic factors by showing that a technological innovation can transit to a regime generating undesired environmental effects when there is a lack of a comprehensive and coordinated set of public policies for its effective application within local communities. The importance of socioeconomic factors is particularly relevant for the “purposive” transition to a net-zero society compared with other historical transitions that remained largely “emergent”.[98] Since the purpose of a technological innovation is not necessarily aligned with Net Zero, the changes it brings can turn out to be harmful for the environment even if the specific technology has a huge potential to reduce carbon emissions.

Technology is value-neutral in general: a it is the socio-economic context that determines the value and purpose of each technology. Therefore, to make full use of digitalization in reducing carbon emissions, we should put huge efforts in not only developing cutting edge technologies, but also transforming socioeconomic environments that can promote the “right,” effective and efficient use of those technologies. Each of the following subchapters contains examples of how various non-technological factors can affect the impacts of a technology on carbon emissions. We also discuss several policy implications and market initiatives that can help digital technology innovations transit in the “right direction” towards Net Zero. This echoes the main theme of this report that the current challenge is **not just a problem of energy and technology, but also a problem of shifting towards more shared consumption habits, and ultimately a problem involving various societal, cultural, and governance factors that shape consumption habits in a community**.

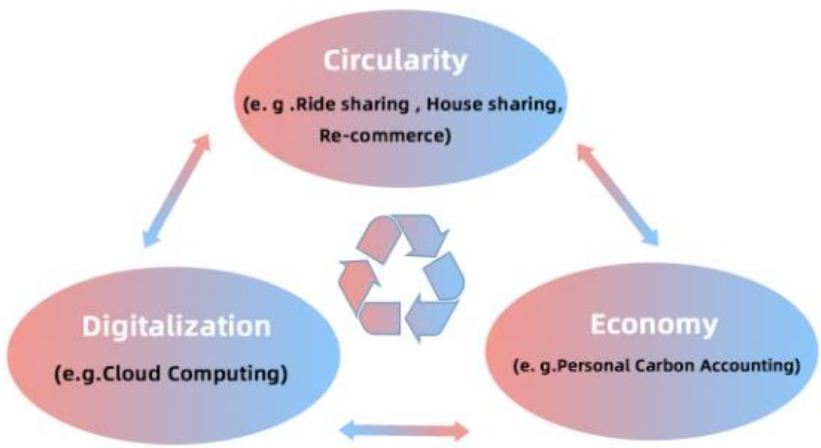
3-2. Technology innovations and the Digital Circular Economy Regime

We begin by describing how personal carbon accounting lies at the foundation of the DCE as an example of an incentive-based economic system that helps to move us towards Net Zero. We then discuss three business models, ride sharing, house sharing, and re-commerce to illustrate how these new business innovations help us scale the circular economy through digitalization. As an example of digitalization, we analyze the influence of cloud computing on Net Zero. We

[98] Geels (2017) p.2

also use these cases to demonstrate that each block of DCE (digitalization, circularity, and economy) is necessary to ensure that the transition is on the right path. We emphasize that to achieve Net Zero requires not just digitalization and innovation in circular business, but also fundamental changes in socio-economic systems that affect people's behaviors, government policies, and social norms.

Figure 11. Digital Circular Economy and five cases



Digitally enabled personal carbon accounting

Economists have described "GHG emissions [as] externalities [that] represent the biggest market failure the world has seen." (Stern, 2008). Indeed, everyone's emissions of greenhouse gases everywhere in the world affects everyone else on the planet. To correct this market failure requires policy interventions such as carbon pricing and tighter limits on allowable emissions. There are two types of carbon pricing: a direct tax on emissions and an emissions trading system (ETS), together with a carbon offset mechanism, designed to minimize adverse externalities that are not considered by transactions between producers and consumers (such as mandatory carbon capture, utilization, and storage for coal-fired generation of electric power, which is not a price, but rather a requirement for doing business).

However, the recent energy crisis has shown that at any point in time there can be conflicts between the goals of carbon reduction and economic growth. On the one hand, a significant increase in energy prices is needed to provide incentives for major CO2 emitters to cut their carbon emissions through investments in the design, construction, and sale of energy-efficient goods and services, that are so essential to the long-term attainment of Net Zero. On the other hand, increases in energy prices that are essential to incentivize green consumption, also raise living costs, particularly for the lowest income groups, who are least able to absorb them and who live in the here and now.

How can society reconcile these conflicting objectives? A very promising direction builds on advances in digital technology, making it possible for individual-level personal carbon accounting allowances (PCA's) to provide incentives for consumers to reduce their emissions. [99] Compared with emissions trading and carbon pricing imposed on businesses, personal carbon accounting focuses more on the demand side, relying on the creation of social and ethical norms to help correct market failures that have led to excessive production of greenhouse gases.

Net Zero is a global policy objective. Ultimately, this goal will have to be implemented at different levels of granularity, from countries, cities and corporations, down to individual buyers and sellers. Nearly half of greenhouse-gas emissions come from households, but the bulk of public policies aimed at reducing emissions target corporations, governments, and other institutions. That must and can change soon. Personal carbon accounting can provide incentives that directly link individual actions (at the very micro level) with the global carbon reduction goals.

Personal carbon emissions are first those that arise from the direct use of energy in the household and for personal transport. Second, they include indirect emissions embodied in the goods and services that an individual consumes. The goal of personal carbon accounting is to empower individual environmental awareness and give individuals agency and motivation to directly

[99] Personal carbon accounting sometimes also refers to personal carbon allowance or personal carbon trading, we do not rigorously distinguish them in this report. Although there are differences to implement them in practice, the general goals are the same.

participate in climate mitigation. PCA also works as a market-based corrective mechanism. Through digitalized market-based carbon emissions matching and trading, PCA incentivizes/subsidies low carbon behavior, while deterring/taxing carbon-intensive activities at an individual level. Furthermore, a well-designed PCA can reduce rebound effects and remedy adverse impacts on the poor.

Here we discuss four cases within a socio-technical perspective that one way or another relates to a PCA: (a) an unsuccessful innovation in the UK in adopting PCA; (b) the CitiCAP project in the city of Lahti in Finland (phase 1); (c) the AMap -Mobility as a Service (MaaS) project in Beijing (phase 2); and (d) the Ant Forest project of Alipay (early phase 3).

UK government's early attempt to adopt Personal Carbon Accounting

In the 2000s, when the UK government explored the adoption of a PCA scheme to reduce carbon emissions by households, the idea was rejected owing to four reasons: (1) low social acceptability, (2) low political priority in a crowded policy agenda, (3) technological barriers and high implementation costs, (4) adverse distributional impacts. In the early 2010s, PCAs were defined as "a big idea that never took off" and "a policy ahead of its time."[100] From a socio-technical perspective this idea was not a successful niche innovation. However, in the 2020s dramatic social and technical changes have made PCA schemes much more appealing. At the political level, a majority of developed countries have now signed up to Net Zero targets. At the technological level, barriers have been reduced substantially with all the recent advances in ITC, AI, machine learning and large-scale digital platforms. Digitally enabled personal carbon accounting is an initiative coming at just the right time, allowing PCA to be scaled well beyond the initial stage of niche innovation.

[100] Fuso Nerini et al. (2021).

CitiCap - Citizen's cap-and-trade co-created in Finland

The CitiCAP project is a pilot program launched in the city of Lahti in Finland. It allows people to earn carbon credits by using environmentally friendly transit. Accumulated balances in carbon credits can then be traded and used for discounts on city services and products. The CitiCAP Project aims to change the behaviors and attitudes of citizens towards mobility. The goal is to promote a shift away from carbon intensive individualized private car usage to sustainable ride-sharing mobility. The lack of mass-transit options in Lahti, and in many other medium-sized European cities, spurred the need to create smart mobility solutions to reduce transport CO2 emissions. Approximately 32% of total CO2 emissions are caused by the transport sector within the city of Lahti.

The CitiCAP Project focuses on co-creating and implementing a Personal Carbon Trading (PCT) scheme for mobility to reduce transportation emissions. This is the first city-wide pilot of PCT performed within the EU. Through the PCT scheme citizens can receive benefits, such as discounted bus tickets or bicycle repair services, in exchange for smart mobility choices. In practice, the personal carbon footprint for mobility will be calculated with a new mobile application based on a transport mode detection solution.

The CitiCAP Project is a successful niche innovation that has been introduced in a small city of Finland. However, the project is still uncertain, experimental, and fragile. It is uncertain whether the CitiCAP Project can be replicated in other EU cities. Also, the sustainability of the project is not as yet clear. Right now, the project is not commercialized and is mainly supported by the European Regional Development Fund (ERDF).

AMap -MaaS (Mobility as a service) project in Beijing

Like Lahti's CitiCAP project, AMap's MaaS project in Beijing seeks to alter the attitudes and behaviors of citizens, and promoting a shift from private car usage to sustainable mobility. It has several innovative and unique features. (1) AMap, like Google map, provides real-time navigation services. AMap also works as a ride hailing platform. As a result, AMap itself connects millions of private car users and riders. It can leverage these economies of scale. (2) The project integrates public transportation data (such as data on subway, bus and train ridership) with private traffic data, offering a complete picture of all types of mobility. It is a private-public partnership. (3) The personal carbon credits accumulated in AMap are linked to an external carbon allowance trading exchange. Certified user carbon reductions will be traded in the China Beijing Environmental Exchange (CBEEX).

AMap's MaaS project is more mature than the CitiCAP project. It involves a much larger user base and it has a more sophisticated and sustainable business model. Because AMap innovation develops a trajectory of its own, with a dominant design now emerging and with expectations and associated rules beginning to stabilize, we classify the AMap project as a phase 2 transition. However, given its complexity and large scale of users, the project requires close cooperation between the private platform and the local government. While much of the system experience can be exported to other cities, exactly how it can be adapted to each particular city remains an open question. Accordingly, the project has not yet reached the third phase of a socio-technical regime.

Ant Forest

The Alipay Ant Forest project, winner of UNEP'S "Champions of the Environment Award" (https://www.unep.org/championsofearth/laureates/2019/ant-forest), launched on the Alipay's mobile app, rewards its users with "green energy points" each time they undertake low-carbon activities, such as biking to work, going paperless, and buying sustainable products. These green energy points grow into a virtual tree on the user's app, which Alipay matches by planting a real tree or protecting a conservation area, in partnership with local NGOs. Ant Forest benefits from the enormous installed user base of China's Alipay mobile payments app, used by more than a billion people.

Ant Forest further encourages use by individuals through "gamification". Users "grow" their earned points into virtual trees on the app. They can share green energy with friends and see how their virtual forests compare with others. For every virtual tree grown, Ant Forest donates – and plants – a real one. This social gamification has real impact given that people tend to adhere to prevailing social norms and are influenced by comparison with others. Thus, the business design of Ant Forest utilizes social network effects and peer interactions to facilitate the fast diffusion of Ant Forest among millions of Alipay users. The success of Ant Forest project relays on two things: (1) the inclusiveness of digital technology allowing large scale participation in the program and (2) the unique business design that incentivizes individual behavior towards the environmental goal.

The Ant Forest project is close to an early "phase 3" of the social-technical transition, where innovation breaks through on a broad scale. Through its unique design, Ant Forest already has had a significant social influence, raising individuals' green consciousness, and motivating their direct participation in climate mitigation by largely reducing the "entry barrier" –reluctance to engage in green activity.

To sum up our cases on digitally enabled PCA, the EU-funded CitiCAP Project was initiated by the government, which has a cap-and-trade system in place and a very clear goal of revolutionizing the participation of citizens in climate change mitigation. However, since it's still an experiential program, the scale of users is relatively small. The MaaS project was implemented at a municipality level, under a private-public partnership. Hence, there has been a greater level of participation though the original purpose of the project has been somewhat diluted. Finally, the Ant Forest project was implemented by a private platform, has a mass of users, and more importantly is a well-designed incentive mechanism to allow the project to be sustainable. However, the business model of the Ant Forest project is not just focused on climate change mitigation; it is also a commercial project.

Overall, these case studies show how digitally enabled PCAs can be a new social infrastructure to trace, measure, and incentivize individuals' carbon reduction activities. Further, PCA can also include people's behaviors within a circular system. While some cases of PCA are still at the stage of niche innovation, some of them have begun to establish themselves as regimes. As a complementary incentive device to an effective system of carbon pricing, a PCA should have at least three basic elements: (1) a digital instrument system to measure carbon activities, (2) an incentive-compatible mechanism to foster stakeholder economy, and (3) a governance system to unify standards and facilitate carbon credit transactions.

Ride-share Platforms

Transportation accounts for around 24% of global CO2 emissions. Within the transportation sector, emissions from passenger and freight road vehicles accounts for 45% and 29% respectively. Many experts believe these two subsectors have immense potential for CO2 emissions reductions through digitalization.[101] GeSI (2015) estimates that digitalization in transportation can save 2.6 Gt CO2e by 2030 in a best-case scenario. Ride sharing is one such area where digitalization can make a big difference. First, shared rides can induce lower private car ownership. Second, shared rides, especially car-pooled rides, can reduce total vehicle miles traveled (VMT) compared to private ownership of vehicles. Third, shared rides can reduce VMT when they complement current public transit system to solve the 'first and last mile' problem, allowing commuters to live and work closer to their first and last subway and bus stops.

Already more than 10 years have passed since Uber launched its business in 2010. During this time, ride sharing platforms have increased their market size globally, having huge impacts on personal lives. For instance, about 25% of the U.S. population uses ride-sharing at least once a month. According to one report, Uber and Lyft account for a non-trivial fraction of total VMT in big cities. In San Francisco County, for example, Uber and Lyft make up as much as 13.4 percent.

[101] Global e-Sustainability "SMARTer" (2015); PwC "How AI can enable a Sustainable Future" (2019); IEA "Digitalization and Energy" (2017).

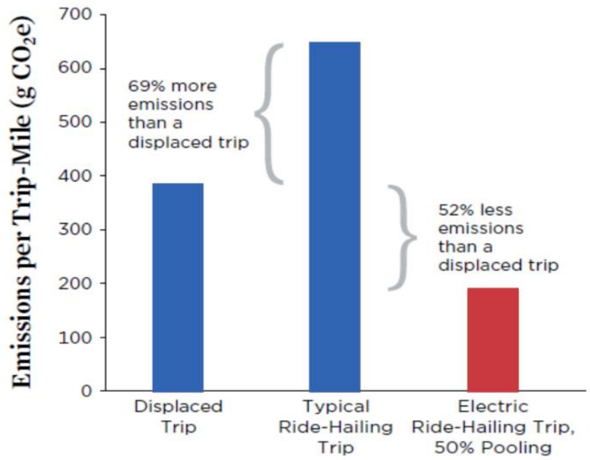
In Boston, it's 8 percent; in Washington, DC, it's 7.2 percent.[102] Didi is the dominant ride sharing platform in China with over 90% of the market. As of 2021, Didi had 377 million annual active users, with an average monthly active user number of 156 million; in the past 12 months, the number of daily active users totaled 13 million.[103] As of 2016, the cumulative mileage of Didi orders has reached 12.8 billion kilometers.[104]

Based on market size, it seems clear that shared ride platforms are already having substantial impacts in many parts of the world. However, the expectations of carbon reductions associated with the growth of shared rides platforms have not materialized. Several recent studies find that growth in shared rides has increased emissions of GHG compared to a scenario of private car ownership. Rodier and Michaels (2019) reviews previous studies between 2015-2017. Depending on the methodology used, the reviewed studies in the paper are categorized either as survey studies or simulation studies.[105]

Despite small differences among the results, interestingly, several conclusions have been drawn. First, usage of shared ride platform barely affects private vehicle ownership (small, if any effect). Second, the increase in total VMT is the result of additional trips that would not have been made without shared ride platforms, and due to "deadheading" of shared ride vehicles (where no one but the driver is in the vehicle).[106] Third, people tend to substitute shared ride services for other modes of transits (bus, subway, bike), instead of using them as a complement to such transportation. Two recent studies (Ward et al. 2020; Union of Concerned Scientists 2020) analyze the effects of Uber and Lyft on major U.S. cities, confirming the findings of the previous studies. According to the Union of Concerned Scientists (2020), a typical ride-hailing trip produces about 69% more carbon emissions than the trips it replaces.

[102] Fehr and Peers report (2018)
[103] https://www.chinaventure.com.cn/news/78-20210706-363040.html
[104] http://www.cs.com.cn/qc/202104/t20210408_6154559.html
[105] **Survey papers:** Smith (2016); Alemi et al. (2017a); Dias et al. (2017); Clewlow and Mishra (2017); Rayle (2016); Crammer and Krueger (2015); Henao (2017); SFCTA (2017). **Simulation Papers:** Faganant et al. (2015); Faganant and Kockelman (2016); Maciejewski and Bischoff (2016); Chen and Kockelman (2016); Martinex and Christ (2015)
[106] Deadheading refers to the part of vehicle trips made without a passenger.

Figure 12. Comparison of emissions between ride-hailing and displaced trips



Source: Adapted from Union of Concerned Scientists (2020) Ride Hailing climate risks

This example illustrates that *niche-innovation* does not necessarily translate to a desired *socio-technical regime*, in the absence of adequate changes in consumer practices, policies (e.g., tax incentives that internalize the externality costs of such behaviors), business models and infrastructures. Ride sharing platforms, especially in the U.S. and China, have already gone through (or have been going through) economic competition between traditional taxi industries, business struggles (Didi vs. Uber in China; Uber and Lyft's market domination in the U.S), and political conflicts (issues of Uber driver's legal status in the U.S). In terms of our multi-level perspective (MLP) approach, ride sharing seems to have already passed **the third phase of the socio-technical transition** in many parts of the world. Especially in major big cities, we may conclude that ride sharing has formed a new *socio-technical regime* for personal mobility.[107] Unfortunately, this new regime does not seem to be compatible with the goal of Net Zero. This demonstrates that the transition path depends on multiple factors of the *socio-technical landscape*, and that we need multiple interventions on the transition path if we want to reach new regimes that are aligned with Net Zero.

[107] Geels (2019)

Many studies suggest three common changes that must be made to change course and correct the current ride sharing *regime* toward a net zero *landscape*: 1) increased car-pooling; 2) higher penetration of electric vehicles; and 3) increased in the use of ridesharing as complements to public transit. Xia et al. (2019) argue that the lack of trust in other passengers and high commuting costs are two major obstacles preventing car-pool activities from prevailing.[108] Platform companies might be able to help passengers to ease these concerns by providing relevant information to each passenger while still protecting their privacy. Advanced data analytics and more efficient matching algorithms can reduce the commuting costs of car-pool trips. At the same time, other measures should be taken to change consumer preferences in favor of car-pool trips. Companies can also coordinate better work from home with ride-sharing to reduce commuting costs.

Increasing the number of EVs, on the other hand, requires more active measures initiated by governments and ride sharing platforms. The current global market share of EVs is only slightly above 1% despite its rapid growth rate since 2010 and the pledges made by major ride sharing companies to be 100% EV.[109] To expedite the roll-out of EVs, especially among the vehicles registered in ride-sharing platforms, governments can build public infrastructure such as charging stations, provide subsidies to EV manufacturing companies and ride sharing platforms, or set regulatory measures promoting rapid adoption of EVs.[110] For example, in 2021, California's Air Resources Board mandated that Uber and Lyft to go all-electric by the end of this decade.[111] In China, generous subsidy policies and tax exemptions have led to rapid growth in the number of both EVs and charging stations.[112] However, measures to increase the share of EVs among ride-sharing platforms will require special consideration, because drivers registered for ride-sharing

[108] Xia et al. (2019)
[109] IEA (2020) Global EV Outlook 2021 "Electric cars, which accounted for 2.6% of global car sales and about 1% of global car stock in 2019, registered a 40% year-on-year increase. Only about 17 000 electric cars were on the world's roads in 2010. By 2019, that number had swelled to 7.2 million, 47% of which were in The People's Republic of China ("China")".
[110] Lyft commits to 100% electric vehicles on the Lyft platform by 2030; Uber commits to zero-emission in Canada, Europe, and the US in 2030, and then globally zero-emission in 2040; The "2020 Didi Platform Green White Paper" shows that in 2019, the mileage of pure electric vehicles on the Didi platform reached 7.09 billion kilometers.
[111] See https://www.greencarreports.com/news/1132348_california-approves-ev-mandate-for-uber-and-lyft
[112] IEA (2020) Global EV Outlook 2021

platforms are not necessarily those who have the highest willingness to pay for EVs.[113] Therefore, they might not be the first ones who will respond to government subsidies.[114]

Governments, in this case, may require special measures favoring either platforms or platform drivers if the priority is to push ride sharing platforms to transit to 100% EVs rather than promoting roll-out of EVs among the general public. On the other hand, platform companies are also responding to increasing public demand for reducing carbon emissions in heavily congested urban areas. Didi has teamed up with a Chinese electric vehicle manufacturer BYD and has already started to produce electric cars for the express purpose of ride-hailing.[115] An U.S. car rental company Hertz recently made a deal with Uber and bought 100,000 Tesla planning to make half of them available to Uber drivers.[116]

Total VMT can be substantially reduced when more people take public transit and use ride hailing services only for the first and last miles of their trips. Such transformation requires changes not only in ride sharing industries but also in other public transit system. Consequently, diverse efforts from different actors are needed to realize a successful transformation. on the business side, the Finland-based company Whim offers subscriptions of multi-modal mobility packages. Alipay in China offers a comprehensive transportation payment system.[117] Both of them provide passengers with services facilitating the use of public transit. Of course, on top of all of this, governments must increase their efforts to maintain the quality of public transportation. For example, Germany has built 62-mile long bicycle roads that connect 10 cities.[118] Netherlands has built 22,000 miles of bicycle paths, and around 27% of all journeys are made by cycle.[119] In 2017, the city of Xiamen, China opened the longest elevated cycling path in the world.[120]

[113] People with high income level usually have higher willingness to pay for EVs: https://www.fuelsinstitute.org/Research/Reports/EV-Consumer-Behavior/EV-Consumer-Behavior-Report.pdf

[114] https://qz.com/2081286/uber-drivers-will-soon-be-able-to-rent-teslas-from-hertz/ "Studies suggest ride-share drivers in cities like Seattle and Chicago earn below minimum wage, and renting a gas car with Hertz for Uber is still cheaper than renting a Tesla."

[115] https://www.theverge.com/2020/11/17/21570016/didi-chuxing-byd-electric-car-ride-hailing-china

[116] https://qz.com/2081286/uber-drivers-will-soon-be-able-to-rent-teslas-from-hertz/

[117] https://www.bloomberg.com/news/articles/2018-10-25/is-helsinki-s-maas-app-whim-the-future

[118] https://www.intelligentliving.co/germany-62-mile-bicycle-highway/

[119] https://www.centreforpublicimpact.org/case-study/focusing-bicycles-transport-urban-netherlands

[120] https://www.archdaily.com/806710/the-worlds-longest-elevated-cycling-path-opens-in-china

Finally, time-of-day congestion pricing, by reducing travel times, can facilitate all of the above, minimizing rebound effects and substantially reducing net carbon emissions -- "by about 22%," in a recent study that found "another 3% reduction associated [with] reduced housing sizes, even as [along with a combination of a carbon tax and land use regulation] it increase[d] social welfare. [121] By eliminating adverse rebound effects, such market-based policies can help digitalization to create wins for the environment as well as for the economy.

House-share Platforms

The Sharing Economy and Environmental Impacts of Airbnb

As one of the most famous applications of the sharing economy, Airbnb is in the midst of transition from niche innovation to mature regime. Martin (2016) identifies three important ingredients for niche innovation: (1) economic opportunity; (2) sustainable consumption; and (3) pathways to a decentralized, equitable and sustainable economy. In response to changing patterns of consumer and worker behavior, Airbnb enables a peer-to-peer sharing model of consumption while creating new forms of work through helping people become micro-entrepreneurs. Botsman and Rogers (2010) argues that a sharing economy facilitates transition from a culture of *owning* assets to a culture of *sharing* access to asset. While Airbnb utilizes idle resources more efficiently, it also promotes individual economic empowerment, which further catalyzes the path from market niche to a full-fledged sharing regime. But there are also factors that can get in the way. Regulatory barriers are often cited. However, too little regulation can transfer excessive risk to consumers, creating unfair competition, establishing illegal markets, and promoting tax avoidance that distort economic decision-making and reduce consumer welfare (Martin 2016).

[121] Domon et al. (2022)

It is important to understand the relationship between Airbnb and traditional hotels. Airbnb can be either a substitute for or a complement to traditional hotel occupancy. Zervas et al. (2017) find that the causal impact of Airbnb's entry on hotel revenue in Austin is a loss of 8 to 10 percent, suggesting that Airbnb is a substitute. On the contrary, because Airbnb is generally more affordable than traditional hotels, it can be a complement to hotels, capturing a class of consumers who would otherwise stay home, while wealthier consumers continue to frequent more expensive hotels catering to their needs. Competitive substitution effects and complementary income effects on the shared accommodation markets are still under-studied. They can have profound effects for energy efficiency and the sustainability of the environment.

The environmental impacts of Airbnb can be twofold. On the one hand, Airbnb may generate lower carbon emissions than traditional hotels. Cleantech (2014) finds that the energy consumption of Airbnb per guest-night is 78-84% less than that of hotels, and the carbon emissions are 88% lower. In addition, Airbnb promotes increased efficiency in the utilization of and accessibility to under-utilized resources and can contribute to the reduction of 9.5 million tons of GHG emissions in the US by 2025 and 20.9 million tons in the European Union by 2030 (Airbnb, 2015 & 2017). Moreover, if Airbnb and hotels are substitutes, it is likely that the growth of Airbnb lowers the demand for hotels, which results in less construction of new hotels reducing longer-term carbon emissions. On the other hand, it can be argued that Airbnb may cause rebound effects on carbon emissions, as people tend to change their tourism habits and travel patterns. The cost reduction in accommodation can lead to more travels, longer stays, further-away visits, for example, increasing the carbon footprints of its consumers. Cheng et al. (2020) find the sum of direct and indirect carbon footprints generated by the Airbnb platform in Sydney increase carbon emissions by 7.27 to 9.39kg per room per night. Their finding challenges the prevalent notion that the sharing economy utilizes idle resources more efficiently, decreasing adverse impacts on the environment.

Whether Airbnb and hotels are substitutes or complements clearly needs to be further studied. Better understanding of the substitution and income effects in this market will help us to quantify the environmental impacts of the sharing economy on sustainability and Net Zero. Whether this niche innovation can be successfully transitioned to regimes will depend on tradeoffs that are yet be fully identified and explained.

Digitalization – a Key to Building Trust

To promote the transition from niche to market, building trust among market participants will be very important. Digitalization can be key to its success.

The shared accommodation platform builds a two-sided platform through the Internet, effectively integrating idle housing, reducing information asymmetry and search costs, and improving the efficiency with which landlords are matched with tenants. Compared with traditional hotels, shared accommodation provides non-standard accommodation products with three main characteristics: diversified housing, personalized services, and socialized user experience. As the largest shared accommodation platform, Airbnb adopts C2C (customer-to-customer) as its main business model, which means that the shared accommodation platform provides a connection channel between the landlord and the tenant to verify the information on both parties. Similar to C2C secondhand markets, trust building is the critical issue in the scalability of the shared accommodation market.

Without an economic mechanism that empowers trust, tenants are likely to see that pictures and texts do not match, the landlord does not abide by the contract, etc., so that the quality of housing and service may not match their expectations. Owners may encounter tenants that don't take care ofr the house, forcing them to raise their rates and even discouraging them from putting their homes on the market. To enhance trust and build a scalable market, digitized economic mechanisms such as systems for credit ratings and for buyer and seller ratings are essential. The Digital Circular Economy plays a vital role in the sharing economy in accommodation, as it enhances efficiency while improving landlord and tenant experiences as they connect with each other in the circular economy.

Digitization and the Proliferation of Re-commerce Platforms

Digital technology reduces the transaction cost of matching people with idle resources. Effective second-hand markets can extend the life of goods and reduce waste and other environmental burdens. Dhanokar (2019) finds that the entry of Craigslist, one of the largest second-hand digital marketplaces in the US, leads to a 2%-6% annual reduction in municipal solid waste per capita generated. Fremstad (2017) documents that the daily per capita solid waste generation is reduced by around one third of a pound by Craigslist.

Idle Fish, the leading comprehensive idle goods trading platform in China, has accumulated nearly 300 million users. There are more than twenty million active daily users and more than one million products are traded every day, covering most cities and regions in the country. A person can not only buy and sell goods, but also communicate with other people with the same interests and hobbies. The various practices of Idle Fish can not only increase user retention and increase the frequency of buying and selling idle goods, but also cultivate a culture of recycling idle resources.

In the era of the digital, “4.0” economy, platform trading models such as Idle Fish have the requisite characteristics of low emissions, high energy efficiency, high-volume recycling, and facilitation of carbon sinks, all of which are in line with the requirements of innovative green development in a circular economy. A new socio-technical regime starts to be established. However, secondhand markets may have some negative impacts. Since secondhand markets increase the liquidity of consumption goods – the ease with which they can be converted into cash - consumers may tend to buy more products from firsthand markets as more money is put into their pockets from secondhand market sales. The rebound effect may once again raise its ugly head, increasing as older and less energy-efficient products stay in service longer as their sale induces an overall expansion of energy consumption on the new products whose sale they finance.

The complementarity between firsthand and secondhand markets raises the question of the overall environmental impact of secondhand markets. If, on the other hand, re-commerce results in a *decrease* in the sale and manufacture of new goods, economic growth and employment can decline raising additional concerns about the ability of society to finance needed steps towards Net Zero. In order for policymakers to better look at this problem, a new measure of economic growth based on the digital circular economy may need to be designed. As we pointed out in Chapter 2, transition to a sustainable economy may not be possible unless this is accomplished.

The social and economic mechanisms of Idle Fish

We've identified three key elements for a successful socio-technical transition for Idle Fish: (1) Digitalization enables niche innovation to evolve into a socio-technical landscape supporting net-zero, (2) Economic mechanisms based on digital technology solve the matching problem, promoting the scalability and enhancing participation of consumers., and (3) Trust building and platform governance.

The core value of the Idle Fish platform is to help buyers and sellers build trust and reach a deal. Effective management of the platform and handling of transaction disputes are also the focus and challenge in managing the Idle Fish platform. These include, for example, efforts to promote buyers' trust in the quality of sellers' goods, and sellers trust in the credit worthiness of buyers, to address both parties' concerns about the fairness of dispute resolution methods, and buyers' trust in the quality of sellers' after-sales services.

The trust problem in the sale of used products – caused by the asymmetry of information between buyers and sellers that give rise to the above challenges – can increases the frictions and costs that they entail, reducing the willingness of buyers and sellers to go on the platform and enter the resale market. Idle Fish, through innovative matching, trading, and governance mechanisms, assists in regulating user behavior, greatly enhancing user friendliness and the satisfaction of buyers and sellers on the platform. It has done so based on Alibaba's corporate e-commerce platform governance model, building a platform-based credit system for users, and improving the transaction efficiency of used and idle items.

Here we have emphasized the role of the economics of the platform business model in helping to build a new socio-technical regime to achieve circularity.

Cloud computing

Cloud computing as a circular business model

By providing scalable and elastic IT-enabled capabilities as a service, cloud computing is becoming the foundation for the ongoing digital transformation. Internet data centers, whether the more traditional ones or the more advanced hyper-scale data centers, together with data transmission networks, are the new critical infrastructure for digital-based societies and economies. Cloud computing is a B2B (business-to-business) service, by nature built on a circular business model, through which energy and resource uses are generally conserved and reduced. At least three service models exist – IaaS, PaaS, and SaaS. ***Cloud infrastructure as a service (IaaS)*** is a standardized, highly automated offering, where computing resources, complemented by storage and networking capabilities, are owned by a service provider and offered to customers on demand. The resources hosted by the service provider or in customers' data centers are scalable and elastic in real time, and their use can be straightforwardly metered. Under the ***Platform as a Service (PaaS)*** model, service providers also provide the operating system and databases, thus giving developers a simple, scalable platform for building applications. PaaS systems, such as AWS Elastic Beanstalk and Google App Engine, enable streamlined workflows and enhanced coordination by allowing multiple users from different locations to simultaneously access their applications. By further providing a variety of applications, ***Software as a Service (SaaS)*** offers the most support and is the simplest of all delivery models for the end user. Without needing to manage software updates, users are only responsible for their data.

Gartner (2021) estimates that in 2022, global cloud revenues will rise to a total of $474 billion, up from $408 billion in 2021, and that cloud revenue will surpass non-cloud revenue for relevant enterprise IT markets within a few years. The rapid growth in Internet traffic, especially through increasing global data flows through videos and streaming, has raised concerns about the energy and climate impacts of cloud computing. In 2017, the Guardian warned that a "'Tsunami of data' could consume one fifth of global electricity by 2025"[122]. By 2018 data centers worldwide consumed around 1% of global electricity use, roughly equivalent to the electricity consumption of Spain or Australia.

Yet, while the volume of data generation and data flows, as well as the resources required to build these infrastructures (including some rare minerals), are still increasing dramatically, globally the overall energy use has not increased nearly as much as expected or estimated a few years ago. Masanet et al. (Science 2020) have estimated that the yearly increase in overall energy use from cloud computing has only been around 8% or so (Figure 7). And in terms of carbon emissions, while there isn't a clear accounting of that, we have reasons to believe that the overall emissions have not increased more than the energy use, given that overall energy systems are greening in major countries where most data centers are located. Nevertheless, the sustainability of cloud computing, and of data centers, is key for the sustainability of digitalization and the major contribution it can make to global decarbonization and environmental sustainability. Creation of capacity for enhanced innovation has become a pivotal dimension along which world leaders in cloud computing services increasingly compete.

[122] https://www.theguardian.com/environment/2017/dec/11/tsunami-of-data-could-consume-fifth-global-electricity-by-2025

Cloud computing for sustainability – A socio-technical transition analysis

The observed evolution of cloud computing development and adoption worldwide is an extremely important example of a socio-technical transition. Over the past dozen years or so, it has emerged from a niche innovation to a major socio-technical regime. Most importantly, cloud computing has overcome some of the earlier perceived obstacles and become a major positive force for sustainability, especially considering the great potential it offers in improving energy efficiency and reducing carbon intensity. Taking MLP as an analytical framework, we further elaborate on the socio-technical dimensions of the rise of cloud computing.

Industry – market consolidation

Major cloud computing providers nowadays offer full-featured platforms with integrated IaaS and PaaS capabilities, or cloud infrastructure and platform services (CIPS), and many also provide SaaS with an increasing battery of applications. Increasing demand for digitalization from emerging and traditional industries for cloud computing drives fierce competition among the hyperscale cloud providers. The most recent forecasts[123] project that by 2023, 40% of all enterprise workloads will be deployed in cloud infrastructure and platform services (integrated and stand-alone), doubling that in 2020. By 2025, it is expected that more than 90% of enterprise cloud infrastructure and platform environments will be based on a CIPS offering from one of the top four public cloud hyperscale providers, Amazon Web Services and Microsoft Azure being the leaders and Alibaba Cloud and Google Cloud their closest competitors.

Worldwide, this consolidation shows no sign of slowing down, while there is some fierce regional competition, especially in Asia. AWS and Microsoft continue to lead in much of North America and Europe, where overall cloud growth rates remain strong. Alibaba is a leading force in China and across almost 30 countries. Emerging Chinese providers such as Alibaba Cloud, Tencent, and Huawei now compete not only in Asia but also in Latin America and other regions, where AWS and Microsoft have a smaller footprint. The world leaders in cloud computing provide a much

[123] Gartner (2021)

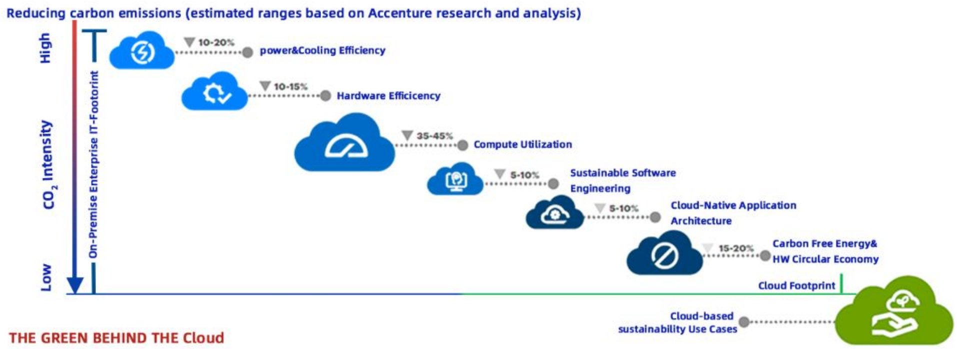
broader range of functionality and faster speed of innovation to meet the growing needs of enterprise workloads, thereby driving smaller regional providers out of the market and accelerating market consolidation. To be sure, taking Gartner's Magic Quadrant for cloud computing as a reference, many of the early players in the cloud computing industry have disappeared.

Science and technology

Technology plays an important role in cloud computing's sustainability performance, and hyper-scale data center technology is one of the factors that differentiate large global and smaller regional service providers. World-leading providers are shifting to hyper-scale data centers with increasingly efficient IT hardware, helping to keep electricity demand flat, despite exponential growth in the demand for cloud computing services. Since 2015, demand for hyperscale cloud computing has doubled while overall energy use has remained flat (Figure 8).

This is but one of the factors that help cloud computing to achieve sustainability. Analysis by Accenture shows *that enterprises migrating from local IT infrastructures to cloud computing reduce their carbon footprint by 84% on average*. Promoting the transition to the cloud is clearly a critical step in decarbonizing the broader economy. According to Accenture achieving cloud computing sustainability involves three levels: IaaS migrations without major redesign, application of sustainable software engineering practices, and application optimization for the "fabric of the cloud". *By designing applications specifically for the cloud, CO2 emissions reductions can be pushed beyond the current 84% —by up to 98 %.*

Figure 13. Estimated carbon emissions reduction by adopting cloud-based computing



Source: Accenture

Market and user preferences

Users also play a key role in cloud computing's pathway to Net Zero. Institutional Investors are increasingly demanding that large technology companies improve their ESG (Environmental and Social Governance) performance, with carbon emissions among their top considerations. The same is true for corporate clients. The increasing prevalence of the adoption of the GHG protocol for corporate GHG emissions reporting is a new factor that is making cloud users look more closely into finding cloud energy savings and carbon emission performance[124]. A recent survey by CloudBolt shows that globally ESG concerns have emerged as a new critical dimension along with computing power and cost when evaluating enterprise cloud decisions. ESG considerations play an increasingly important role in selecting cloud providers based on the provider's environmental commitments and the cloud service's carbon footprint. Out of 256 IT leaders, two thirds indicate that the cloud vendor's sustainability initiatives are taken into consideration in decision making and almost four fifths say that they will pay a PREMIUM to work with vendors who are pursuing and incorporating sustainability into their business models (with 41% saying that premium could be as much as 11 to 15% or more). It's also worth noting that 79% of them say their IT departments are expected to help their companies achieve specific sustainability initiatives driven by their corporate leaders.

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[124] Cloud's mission is part of a corporate user's Scope 3 emission.

Policy

Regional and local

There are naturally regional variations and global-local disparities in the performance of cloud computing[125]. In China overall emissions from IDCs are increasing fast and will continue to increase as its economy keeps growing. The last quarter in 2021 observed a major shift in China's policy towards data centers seeking to turn them from large energy users and carbon emitters to a major mechanism for achieving carbon neutrality, with a focus on overall emissions reductions rather than on energy intensity of specific direct uses. This policy shift recognizes the important role data centers and cloud computing can play in improving the carbon efficiency of the economy going forward.

3-3. Synthesis

The five cases illustrate the three essential building blocks of a successful DCE – social adaptation through appropriate socio-economic mechanisms (e.g., personal carbon accounting), circular business models (ride sharing, house sharing, and re-commerce), and digitalization (cloud computing). The evolution of each case from a niche innovation to a more mature regime illustrates the many different patterns and processes at work. Scaling-up a technology to its best intended use is almost never a simple and straightforward process. The transition towards a more sustainable regime often depends on local socioeconomic contexts beyond the niche actors' influence. A niche innovation must fit in with existing cultural norms and social interactions. When it is possible to adapt current practice and enhance it with digital technology innovations the niche can quickly be transformed into a new regime, as we have observed in the sustainable cloud computing case. The new protocols that emerge with digitalization must be sufficiently flexible that they can be braided into different local evolving contexts, and anchoring in good

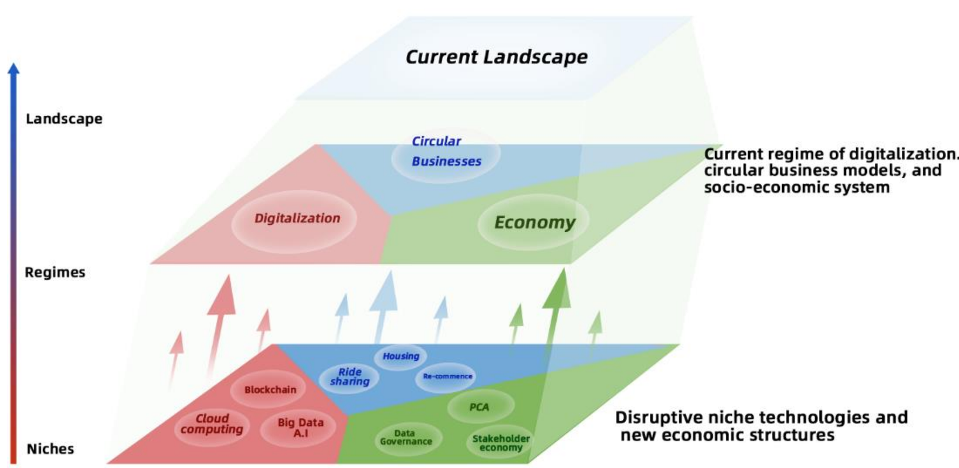
[125] https://www.iea.org/commentaries/data-centres-and-energy-from-global-headlines-to-local-headaches

governance at early stages of the niche-regime transition is important, as we have illustrated in our discussion of personal carbon accounting.

The socio-technical regime framework emphasizes three elements: actors, systems (resources, material aspects) and rules/institutions (Geels, 2011). Often the same rules/institutions may support or inhibit more than one regime. As we discussed in Chapter 3.2, different digital technologies may be in different phases, depending on the local socioeconomic context. For example, riding sharing became a new regime, albeit not as sustainable as expected, depending on how the technology is governed and adapted to local contexts. Similarly, personal carbon accounting takes many different forms around the world and may have a varying impact on sustainable consumption behaviors depending on how it is leveraged and governed by local communities.

For DCE to live up to its promises in achieving net zero and other sustainability goals, systemic changes are needed through supportive governance systems that direct the use of digital technology in a way that enhances the circular economy and achieves the full economies of scale and scope from digitalizing circular economy practices. The diagram below illustrates how we see the multi-regime interaction towards a "whole-system" transition.

Figure 14. Digital Circular Economy and whole-system transitions



Note: Based on Figure 3 from Geels (2002) Technological transitions as evolutionary reconfiguration processes a MLP and a case study

Synergies are obtained through direct interactions between the regimes, and through interactions among the landscapes, regimes, and relevant niches. Interactions between the technologies, actors and networks, shaped by evolving rules and governance mechanisms for the niches and regimes, in turn transform production modes, consumption habits and social interactions. System-wide transition to greater sustainability comes about through landscape pressures, particularly policies, new regulations and shifting norms that destabilize existing regimes. Technological niche innovations that respond to the new landscape pressures are the essential drivers, but they break through into new regimes only when they are supported by changing social interactions, regulatory and tax policies, and governance systems. In the next and final chapter, we discuss challenges and opportunities related to these landscape pressures, specific niches in which Net Zero can be achieved, and the governance reforms that might best put these new practices into operation.

Chapter 4: Prospects and Perils: An Agenda for New Research and Actions

In Chapter 2, we proposed the DCE as an essential transformation to achieve net-zero goals. In Chapter 3 we highlighted the importance of socio-technical environments in developing innovative technologies into a new regime of the DCE. Such a fundamental transition raises numerous issues and can give rise to conflicts between different interest groups. We briefly touch on some of these issues and propose several avenues for future research.

4.1 Digitalization, data ownership, and data privacy: How to build trust

Digitalization has made it easier than ever to collect data from our daily lives: mobile data traffic alone has increased almost 300-fold over the last 10 years.[126] Digital data has not just grown exponentially on the extensive margin, with more and more users of mobile devices, but also on the intensive margin, with more and more screen time spent by users. While enjoying huge benefits from their online activities, users have also been increasingly concerned about the concentration of data in a few hands, with the consequent risks from breaches of data privacy and cyber security. Such concerns are expected to grow as more and more parts of our society become digitalized.[127]

Data privacy and security becomes even more important as we deploy digitization in pursuit of Net Zero. Most of the demand-side solutions discussed in this report require monitoring people's daily lives in order to measure and take account of their detailed and varied levels of carbon emissions. The more accurate estimates of carbon emission we want, the more detailed aspects of our lives must be tracked and recorded. The more detailed emissions data engineers can find, the more accurately and more easily they can tailor their efforts to stimulate demand for energy-efficient goods and services. But if people do not trust the security of the monitoring devices, the levels of digitalization may never encompass a large enough number of users to reach Net Zero.

We have learned during the pandemic how important it is for governments to have enough data to deal with an emergency situation, but at the same time how difficult it is to set a transparent and consistent standard according to which private data of people's lives are collected and used. We've also learned that a standard used in one place may not be applied to other countries since each country has distinct norms and preferences for privacy.[128] All the conflicts between public and private sectors over data privacy during the pandemic offer valuable lessons for future

[126] https://www.ericsson.com/en/press-releases/2021/11/ericsson-mobility-report-mobile-data-traffic-increased-almost-300-fold-over-10-years
[127] Chen et al. (2021) shows that people could develop higher levels of privacy concerns as they experience more of a mobile application.
[128] For example, east Asia countries and regions such as China, Taiwan, and South Korea implemented mandatory schemes of contact-tracing apps from the early stage of the pandemic, and the measures were accepted without significant resistance from public. On the contrary, even weaker measures breaching personal privacy faced strong resistance in western Europe countries and the United States. See Fuso Nerini et al. (2021) for more details.

carbon reduction policies, especially when those policies require balancing data privacy and public policy goals.

Governments must also consider issues related to the interoperability of data and its implications for privacy protection. A daily activity of an individual would generate large sets of carbon emission data, and not every IoT companies would manage the collected data according to the same protocol. To provide a complete solution for reducing carbon emissions, all the data from different sources should be available for analysis by some third party. For example, a household, who wishes to track its energy consumption and to minimize its carbon emissions, needs to have a platform that can combine the data of electricity usage from different brands of IoTs installed in the house. Clear and consistent demarcation of data ownership would streamline the process of combining data sets from different sources. Clearly defined data ownership will become more important when governments implement a personal carbon accounting (PCA) program. Suppose the program provides a certain amount of carbon credit to a person who buys a second-hand product, and the credit can be used to buy a ticket for public transit. To make this happen, the PCA platform first needs to be able to verify the purchase of the second-hand good. What kind of data should be shared to make this happen? Who should own the data? More research and public initiatives should be devoted to answering these types of questions if we are to build public confidence that their digital privacy is adequately protected. Full transition to a digital circular economy will come faster with higher levels of trust in the system of data governance.

4.2 The Corporate Role in Getting to Net Zero: From Shareholder Economy to a Stakeholder Economy

Over 113 countries, representing half of world GDP, have by now made net-zero commitments.[129] The corporate sector has also started to make commitments to reduce carbon emissions.[130] The GHG Protocol established by the World Resource Institute and the World

[129] https://www.visualcapitalist.com/race-to-net-zero-carbon-neutral-goals-by-country/
[130] 10 big tech companies' net-zero goals. https://www.ces.tech/Articles/2021/May/10-Tech-Companies-Setting-Big-Goals-to-

Business Council for Sustainable Development is now the gold standard for corporate carbon emissions reporting. Beside direct emissions (Scope 1) and emissions from the use of electricity and heating (Scope 2), the GHG protocol provides a guideline for corporations to report their indirect emissions, including 15 categories throughout upstream buyers and downstream sellers along their value chains. A company's Scope 1, 2, and 3 carbon footprint accounting thus provides a basis for systematic design and implementation of more targeted and effective decarbonization programs not only for themselves, but also for other companies up and down their value chains.

Obviously, Scope 2 and Scope 3 emissions usually cannot be reduced to a single entity acting alone. The use of such accounting systems makes it clear that companies must work together with others, especially those along their value chains, if they are to reduce their overall carbon footprints. As more and more companies adopt this system, the business world is undergoing a transition toward a more holistic and global view of corporate social responsibility. This is a key part of the ongoing **business transformation from a shareholder to a stakeholder model of economic activity**. The idea is simple – to better live together in a world with a whole set of social, economic, and health crises, the best response will be for all stakeholders, especially the more affluent ones, to consider more than their narrow and short-term self-interest.

Among the most ambitious commitments today are the net zero alignment commitments made by over one thousand companies through the science-based target initiative (SBTi).[131] Corporations increasingly recognize the need to be more proactive -- that they must lead the transition to net zero, rather than content themselves with passively responding to public policies towards climate change mitigation. By being more proactive they can help reduce the risks they increasingly face from the climate change crisis that materialize day by day. They can also better manage the transition by making policy decisions on their own terms rather than having them imposed on them in a haphazard way.[132] An important way to achieve SBTi of a company is to

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[131] https://sciencebasedtargets.org/companies-taking-action#table

[132] "The first phase of business sustainability, […] call "**enterprise integration**," (emphasis added) is founded on a model of

work with their supply chain partners. For example, Walmart, as one of the world's largest retailers, initiated its Gigaton project in 2017 to engage its thousands of suppliers to reduce up to one billion tons emissions by 2030. All participating suppliers were asked to report their emissions explicitly and systematically, in collaboration with the global Climate Disclosure Project (CDP).

While it's encouraging to see more companies adopting SBTi, the effort still does not seem to be in sync with the 1.5-degree goal. It's good to see that the SBTi also encourages companies to go outside the box and consider efforts that could further help reduce emissions beyond those envisioned in Scopes 1, 2, and 3. Some leaders have embarked on journeys in this direction. AT&T has started its Gigaton project, using its stronghold in ICT technologies to help its customers reduce and avoid significant further amounts of carbon emissions.

The increasing digitalization of society and the emergence of platform companies provide new opportunities for such innovative thinking. Recently the Alibaba Group coined the term Scope 3+, which includes all emissions relating to activities on its various ecommerce, logistic and cloud-computing platforms, pledging to reduce a total of 1.5 billion tons of its Scope 3+ emissions by 2035. What is key to Scope 3+ is that platforms with new forms of business structuring and functioning will offer additional opportunities to enlist and connect a much larger quantity of businesses (especially SMEs) and, very importantly, enlist consumers to join in coordinated efforts towards a common goal of decarbonization. Platform operators, with their unique role in the digital economy, can leverage their capacity in both technological knowhow and market insights to gear a faster transition toward low-carbon consumption. Sufficient demand for low-carbon products and services can trickle up and down the value chain, fostering changes on the production side, further increasing the supply of low carbon goods and services. This positive

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business responding to market shifts to increase competitive positioning by integrating sustainability into preexisting business considerations. By contrast, the next phase of business sustainability, what we call "**market transformation**," (emphasis added) is founded on a model of business transforming the market. Instead of waiting for a market shift to create incentives for sustainable practices, companies are creating those shifts to enable new forms of business sustainability" - Andrew J. Hoffman (2018) *The Next Phase of Business Sustainability* feedback loop – this “virtuous cycle” -- is urgently needed to speed up and scale up the transition toward a low-carbon circular economy.

Such private sector initiatives must be supported by governments. As public opinion on climate change increasingly reflects, consumers also want greater involvement in climate change mitigation.[133] They too would like to make commitments, aligning their behaviors with the goal of Net Zero. Often public opinion is ahead of public policy on climate change, but consumers lack the tools to impose change, signal their preferences, and make large scale commitments to reduce the carbon footprint of their consumption baskets. More and more consumers today make purchases online and are comfortable with digital technology.[134] This opens the promise of leveraging digital technology to channel public opinion to more directly and positively affect business operations that embrace a greener world. This view echoes the argument made by Hart and Zingales (2017) in which the objectives of companies are not necessarily to maximize financial market value when shareholders are **prosocial**. They show how seeking to maximize shareholder welfare can line corporate objectives up with those of a **stakeholder economy**, achieving a win-win world in which environmental and economic progress go hand in hand.

Despite growing support from corporate leaders for the stakeholder economy, we still lack enough concrete policies and plans to achieve the transition to a stakeholder economy. To accelerate the transition to Net Zero we must better define the boundaries of stakeholder involvement within different business contexts. Furthermore, more research is needed to establish what legal reforms and changes in social norms will best support the transformation of the current corporate governance model into one that better reflects growing public aspirations for a sustainable planet. Some of the most urgent questions for governance reform and securities regulation are about disclosure, how to standardize corporate reporting of carbon emissions and

[133] About Global Climate Strike: https://www.vox.com/2019/9/17/20864740/greta-thunberg-youth-climate-strike-fridays-future
[134] In 2018, 93% of internet users of U.S., 92% in China, and 97% in the UK made at least one online purchase in the last 12 months (https://www.statista.com/outlook/dmo/ecommerce/china#analyst-opinion); Global smartphone penetration rate is about 78.05% in 2020 (https://www.statista.com/statistics/203734/global-smartphone-penetration-per-capita-since-2005/). As of January 2021, around 59.5 % of the world population are estimated to actively use internet (https://www.statista.com/statistics/617136/digital-population-worldwide/).

other environmental impacts (Bolton et al. 2021), and how institutional investors should engage with companies to induce them to align their business models with the goal of Net Zero. These and other questions deserve further attention from scholars and policy makers.

4.3 Global Cooperation: Building trust between countries in a ***Global*** Digital Circular economy

Finally, *global* cooperation is an essential part of any successful transition to Net Zero. The Paris Climate agreement has set international coordination in motion through the Nationally Determined Contributions (NDCs), national Net Zero commitments and other initiatives. Yet, progress towards full global cooperation is still far too slow. Disagreements between countries over initiatives such as the Border Carbon Adjustment and failures to fulfill the promises of the Green Climate Fund demonstrate just how difficult it is to achieve consensus on a global pathway to net zero and the allocation of decarbonization efforts among countries along the way.[135]

Yet, as highlighted at the COP26 summit, active global cooperation is still a prerequisite for a successful transition to sustainability. This is all the truer as the world economy becomes more and more interconnected. Without global cooperation, a circular economy in one country is at risk of turning into a "spurious" circular economy, with a lot of carbon leakage from rich to developing countries through the global supply chain. Active cooperation among countries is essential to realize all the promises of the Digital Circular Economy.

To be sure, the circular economy can deliver *both* carbon emission reductions and economic growth if it can be fully scaled through digitalization. The problem is that poor countries, who are often the most vulnerable to the climate crisis, are the least equipped to implement a digital circular economy at full scale. The question therefore arises whether it is still possible without

[135] For the conflicts around Green Climate Fund, see https://www.nature.com/articles/d41586-021-02846-3. For the conflicts around Boarder Carbon Adjustment, see https://www.technologyreview.com/2020/07/27/1005641/carbon-border-taxes-eu-climate-change-opinion/.

adequate digital infrastructure to achieve both significant decarbonization through the expansion of the circular economy and economic growth.

Can the circular economy still achieve decoupling of carbon emissions and economic growth without extensive digitalization of developing economies? Poor countries do not have the luxury of prioritizing decarbonization over economic development. If they must sacrifice economic growth at an early stage as they shift to a circular economy model, must this come with financial and economic compensatory support from the more developed countries? Answering these questions is important to be able to estimate the costs of transitioning to a ***global*** circular economy.

Another important area is international politics. We need to examine how to build a consistent and sustainable cooperation system among all the countries of the world. What the poor implementation of the Green Climate Fund has taught us is the importance of building trust between countries in implementing global cooperation for tackling the climate crisis. All the global initiatives and agreements will be of little use without active and long-term participation by both developed and developing countries. But different countries have different stages of economic growth. How should we balance the interests and responsibilities among countries? How should we build trust and design agreements between developing and developed countries that guarantee long-term participation of every nation? Solving those problems will require determined efforts by every nation, large and small, weak and strong. Developed countries will need to answer questions like "what kinds of initiatives should we take to build up trust with developing countries?" Developing countries will need to show their commitments to transitioning to a low carbon circular economy using the support they receive from developed countries. How can we make sure those green loans and grants are being used for the goals we all hold in common? Do we need independent institutions to supervise their effective implementation?

Answering all these questions will require much further research and experimentation. But we cannot afford to wait much longer for the answers. The future is now. Everyone must get aboard if we are to save our precious planet.

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