Digital Transformation and the 2030 Sustainable Development Agenda

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Nirupam Bajpai and John Biberman

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Center for Sustainable Development
EARTH INSTITUTE | COLUMBIA UNIVERSITY

Abstract

The Digital Revolution may not have made its way in any meaningful respect into the 2015 SDG Agenda, but over the past few years, it has become overwhelmingly clear that recent advances in digital technology will be core to realizing the possibility of sustainable development around the globe. These cutting-edge innovations have the potential to revolutionize the design of infrastructure and urban environments, lay the groundwork for equitable, quality health and education systems, and redefine how resources are consumed and distributed between ecosystems and human environments. But the Digital Revolution shows signs of high risk in addition to these high rewards. If poorly managed, this societal transformation could instead deepen inequality, harm the prosperity of the most vulnerable, and kneecap the cause of sustainable development for generations. These consequences are already becoming visible; while technological advances have allowed billions to continue their normal lives relatively undisturbed during the COVID-19 pandemic, they have also enabled the rise of an intransigent digital underclass in developed and developing economies alike without the protections afforded to more traditional workers.

Understanding the theoretical linkages between digital technology and sustainable development is a simple task, but it is far more complicated to translate these insights into actionable policy which will further sustainability rather than hindering it. Some sustainable applications of digital technology are still undergoing research, while other approaches have been developed but wait on greater institutional backing to scale and thrive. Therefore, specific uses of digital technology which synergize with the SDG Agenda must be explicitly identified, outlined, and prioritized as destinations for key investments. Only by doing this can the new, transformative technological advances of the 21st century be leveraged to launch sustainable development into a new trajectory impossible under current Business-As-Usual practices.

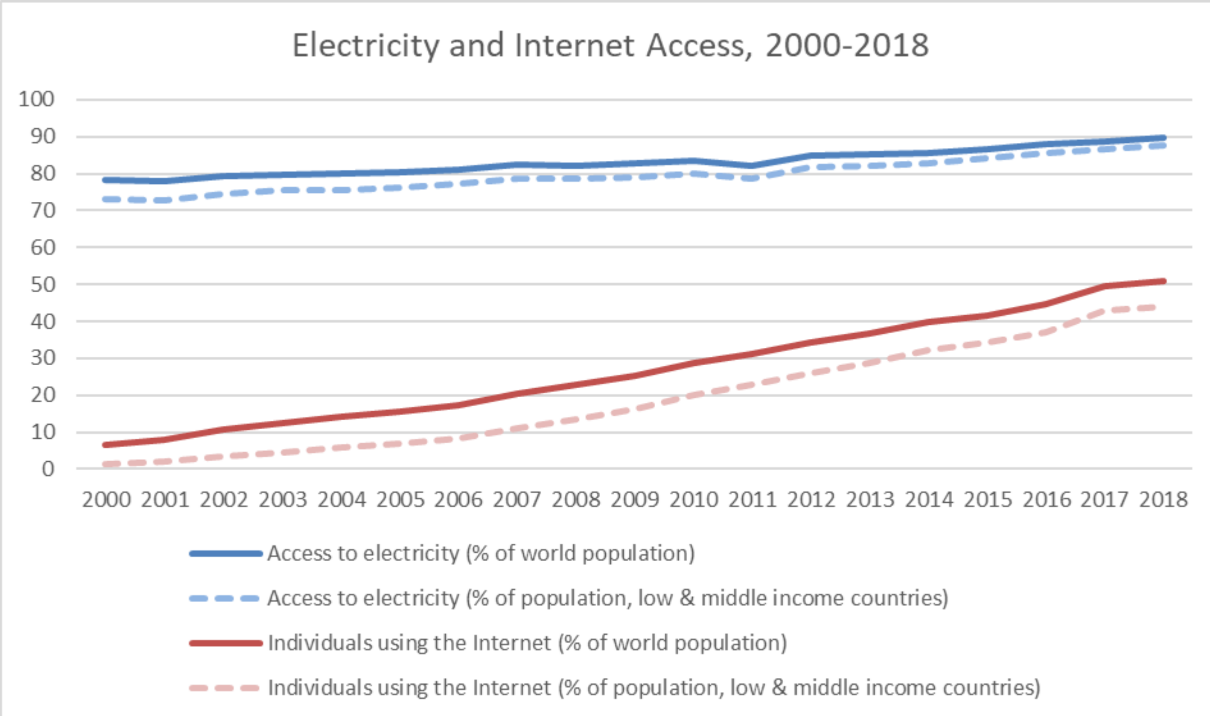
Introduction

In the history of societal transformation, the most consequential changes have often come from unexpected places. In 2000, the Millennium Development Goals (MDGs) were established by the United Nations, laying out a framework for global progress covering critical issues including eradicating extreme poverty, achieving universal primary education, promoting gender equality, and reducing child mortality. The MDGs had been largely achieved by their official conclusion in 2015, but it was the rise of a new development almost entirely outside of the MDG framework – namely, the advent of widespread electrification in the developing world – which was disproportionately responsible for much of this progress, far more than any investments tied directly to the MDGs themselves. In the 20th century, the automobile was at first dismissed as a novelty for the rich of little consequence. But fast-forwarding to the present day, automobiles define urban geography, social mobility and access to economic opportunity in ways their inventors could scarcely have envisioned. From the invention of the steam engine in the 18th century to the invention of the printing press in the 15th, and going even further into the past, every significant transition between historical eras has been sparked by the emergence of a singular, transformative technology which enabled the radical transformation of how human beings interacted with each other to define the structure of their society.

These epoch-defining innovations have been termed General Purpose Technologies (GPTs), so named because they are discrete and universal innovations which interact with social and economic structures in a way that exponentially increases productivity at the national or global level, making the development of new modes of interaction beneficial and feasible. While GPTs may take some time to by refined to the point of feasibility, their many potential different uses eventually lead to their universal incorporation across the economy. Additionally, the unexpected positive spillover effects they generate lead to societal benefits beyond those which their inventors had ever anticipated or even imagined. Using universal electrification as an example, policymakers recognized many of its positive benefits from the beginning of the 20th century, but it wasn't until this century, well into the era of the MDGs, when its full transformative potential impact was realized and understood.

Digital technology, whose many applications collectively comprise the world's next great GPT for human development, has followed a very similar trajectory. In the field of sustainable development, the digital revolution's vast prospective contributions towards inclusive economic growth, social mobility and equity, and environmental preservation were largely unrecognized as recently as the adoption of the Sustainable Development Goals (SDGs) in 2015. Despite the transformative impact these new technologies had already had across the developing and developed world alike by that time, the Digital Revolution went almost entirely ignored in the version of the SDGS adopted by the UN General Assembly, being mentioned in just one of the SDGs' 169 targets across 17 overlapping topics covering economic, social, and environmental goals.

In a manner similar to the MDGs, sustainable development planners have largely so far chosen to focus investments on the most tangible manifestations of poverty, injustice, and environmental destruction in the pursuit of a more just and inclusive future. But in doing so, they have all too frequently ignored the untapped possibilities of a new GPT whose impact is now ascendant around the world. If planners do gain the vision to fully recognize the digital revolution's promise for accelerating sustainable development, then they will be able to mainstream it within new, future-resilient initiatives which tap into global economic and technological undercurrents to multiply the impact of these programs far beyond their initial anticipated scale. But if the digital revolution's potential in the world of sustainable development continues to remain underappreciated, then planners at the national and international level risk missing a transformational opportunity in the same way that so many MDG-era investments, by ignoring the power of tapping into an emergent GPT, failed to realize much of their promise.



Access to electricity has become near-universal since 2000, powering the achievements of the MDG era in a way not anticipated by the drafters of those goals. As internet access rapidly becomes more widespread and digital technology takes its place as the foundation of new global standards of communication, it will likewise contribute to sustainable development in ways which, while not anticipated by the authors of the SDGs, can nonetheless be harnessed to vastly accelerate their achievement. Data Source: World Bank.

The 2030 SD Agenda

The 2015 adoption of the SDGs was intended to herald a new era for global, cooperative and inclusive development. For the first time, every member state of the UN had reached an agreement to, at least in theory, pursue a joint set of goals to meet the environmental, social, and economic challenges certain to face countries of all types over the course of the young century. Encompassing both a broad range of interconnected topics and many of the granular details integral to achieving these goals, the SDGs have collectively formed an impressive initial framework, outlined below, for understanding what planners aiming for sustainability should aim for around the world.

The Sustainable Development Goals, in brief. Detail on targets, indicators, and direct investments associated with each goal can be found at https://sdgs.un.org/goals .

Goal 1: End Poverty in All its Forms Everywhere

Goal 2: End Hunger, Achieve Food Security and Improved Nutrition and Promote Sustainable Agriculture

Goal 3: Ensure Healthy Lives and Promote Well-Being for All at All Ages

Goal 4: Ensure Inclusive and Equitable Quality Education and Promote Lifelong Learning Opportunities for All

Goal 5: Achieve Gender Equality and Empower All Women and Girls

Goal 6: Ensure Availability and Sustainable Management of Water and Sanitation for All

Goal 7: Ensure Access to Affordable, Reliable, Sustainable and Modern Energy for All

Goal 8: Promote Sustained, Inclusive and Sustainable Economic Growth, Full and Productive Employment and Decent Work for All

Goal 9: Build Resilient Infrastructure, Promote Inclusive and Sustainable Industrialization and Foster Innovation

Goal 10: Reduce Inequality Within and Among Countries

Goal 11: Make Cities and Human Settlements Inclusive, Safe, Resilient and Sustainable

Goal 12: Ensure Sustainable Consumption and Production Patterns

Goal 13: Take Urgent Action to Combat Climate Change and its Impacts

Goal 14: Conserve and Sustainably Use the Oceans, Seas and Marine Resources for Sustainable Development

Goal 15: Protect, Restore and Promote Sustainable Use of Terrestrial Ecosystems, Sustainably Manage Forests, Combat Desertification, and Halt and Reverse Land Degradation and Halt Biodiversity Loss

Goal 16: Promote Peaceful and Inclusive Societies for Sustainable Development, Provide Access to Justice for All and Build Effective, Accountable and Inclusive Institutions at All Levels

Goal 17: Strengthen the Means of Implementation and Revitalize the Global Partnership for Sustainable Development

Transformations for Sustainable Development

The SDGs are impressive for their astonishingly comprehensive survey of what the ends of sustainable development should be, but they go into far less detail concerning the means of achieving these ambitious goals. Only one goal is dedicated to enabling the achievement of the remaining 16, Goal 17, which unsurprisingly for a UN document, calls for greater international financial, technical, scientific, economic, and political cooperation in pursuit of the goals without further elucidating what such cooperation would look like or require. Part of this strategic ambiguity is undoubtedly intentional to provide signatories with the space to pursue their own pathways to achieving the goals, and a certain level of compromise is necessary in any international resolution, let alone one garnering unanimous support in the General Assembly. But this same ambiguity, absent clearly articulated pathways to sustainable development, serves as a permission structure for countries to maintain their current, Business-As-Usual (BAU) practices These will do little to meaningfully shift the global trajectory towards sustainable development in time for catastrophe to be averted.

In recognition of the need for such concrete implementation pathways for sustainable development, the global research initiative The World in 2050 (TWI2050) has defined six discrete integrated governing pathways that all societies must follow in order to permit the long-term achievement of the SDGs. Five of these “societal transformations” directly concern the targets and goals of the SDGs themselves, while the sixth, the Digital Revolution, serves as a universal catalyst which, if properly applied, will accelerate the achievement of the prior five transformations.

Transformations for Sustainable Development, as identified by TWI2050.

Human Capacity and Demography

For societies and the people who comprise them to achieve sustainable levels of inclusion and economic opportunity, policy must pay explicit attention both to encouraging the demographic transitions which will enable the achievements of these goals and anticipating the downstream effects of this unavoidable transition. Although quality health is seen as one of the ends of the SDG agenda, it is in fact an inseparable prerequisite for poverty reduction and the reduction of health, education, and income inequalities. Likewise, quality education may be an end goal of the SDGs, but a sustainable society cannot be achieved without training people from all walks of life in the skills necessary for a sustainable society to function. Furthermore, investments in improving health and education outcomes will alter long-term economic trajectories in ways which societies aiming for lasting, sustainable development must anticipate, just as more concrete investments in sustainable development will impact the settlement, movement, and education patterns of people in ways which sustainable development planners must predict.

Education is often valued on its own both for its intrinsic value and as a human right, but the demographic impacts of education extend far beyond this important, yet narrow conception. Education is a primary source of the increased productivity which drives economic growth, one of the pillars of sustainable development. In fact, more equal access to education has also been found to encourage income growth and discourage income inequality across society.[1]
One of the strongest mechanisms by which equal access to education promotes such equality is its well-documented impact on improved gender equality, which additionally manifests itself via reduced fertility rates. Not only do the children of these smaller, more educated households have

[1] Coady, David and Dizioli, Allan. "Income Inequality and Education Revisited: Persistence, Endogeneity, and Heterogeneity." IMF Working Paper 17/126. May 26, 2017. https://www.imf.org/en/Publications/WP/Issues/2017/05/26/Income-Inequality-and-Education-Revisited-Persistence-Endogeneity-and-Heterogeneity-44854

improved mental and physical health, they contribute less to a high and growing global population at a time when resources are increasingly strained. In addition, more educated populations are both more respectful of and more resilient to environmental challenges. A smaller population is one with easier universal access to clean energy, water, and healthy diets, without straining planetary boundaries or excessively endangering biodiversity. More educated households have also been found to have higher disaster preparedness and to experience less harm from negative shocks, such as those which could be caused by climate disruptions. Finally, higher-education societies generally experience greater civic engagement, social cohesion, and political participation, supporting a virtuous cycle of beneficial and transparent institutions which further improve societal welfare.[2]

Improving health outcomes across society results in an equally consequential chain reaction of positive effects via the demographic transition. For example, an improved public health and healthcare system weakens poverty traps and encourages social mobility by preventing premature removal from school for health reasons or to care for family members. Stronger public health systems which prioritize equality of preventative care also give poorer households freedom to invest for the future, rather than saving money to be consumed by inevitable health crises. If societal violence is also viewed as an aspect of public health, then public health initiatives seeking to reduce gender-based violence and violent conflict also promote the demographic transition by reducing risks of mental health disorders and violence against children, the harms of which are likely to last through adulthood.

Consumption and Production

Building sustainable consumption and production systems through a model circular economy is explicitly called for in SDG 12, and a sea change in global manufacturing, trade, and industrial and household practices is necessary if this is to be realized. Under BAU practices, inefficient usage of raw materials and unsustainable levels of pollution threaten to sap nonrenewable resources and choke communities and ecosystems alike. To facilitate this transition, policymakers will first need to improve efficiency within production systems to reduce the waste generated as a byproduct of current resource demand. Over time, they will also need to restructure the delivery of major services so that their provision is less resource-intensive, a process which engages both production systems and consumer tastes. Finally, major production practices will need to be rethought in order to synergize their outputs with the required inputs of other processes and to reduce the stress their outputs place on planetary boundaries. Converting to renewable energy or waste-to-energy from fossil fuels, promoting a shift to a plant-based diet, and increasing recycling of urban waste and wastewater within cities are all excellent examples of what this transition will look like. Ultimately, the circular economy will require a life-cycle approach to products and the resources that comprise them, ranging from fertilizer to the rare earth components within digital technology,

The transition to responsible consumption and production patterns depends on measuring well-being not by resource inputs, but rather by the material outcomes resulting from the services

[2] Mayer, Alexander. (2011). Does Education Increase Political Participation?. The Journal of Politics. 73. 633 - 645. 10.1017/S002238161100034X.

these resources are intended to provide. Those aiming to be food secure should not aim to produce the most food; rather, they should work to provide every member of the population stable access to a healthy, balanced diet and identify what changes in production, distribution, storage and consumer preferences are necessary to achieve this goal. In transportation discussions, particularly within urban environments, rather than aiming for the types of headliner projects which infrastructure debates have traditionally revolved around, planners should consider the purpose of these investments – namely, to meet the population's need to move between work, home and leisure in the most time and resource-efficient manner possible. Asking whether present investments further this goal, and redesigning projects to make infrastructure more efficient and just, will likely require interfacing with planners to reshape the landscapes of many cities, rather than doubling down on inefficient legacy networks. Techniques for improving efficiency of resource consumption can be summed up in the heuristic "avoid/shift/improve:" avoid unnecessarily resource-intensive means of providing a service when an alternative mean exists (telecommuting over physical commuting), shift to providing a different service with a similar output if a certain service is unnecessarily resource-intensive(bicycle infrastructure over car infrastructure), and improve the efficiency of resource consumption for services where neither type of substitute exists(electric vehicles and public transit over cars and fossil fuels).[3]

Related to the question of responsible consumption is the social inclusion implications of irresponsible consumption. Overconsumption of basic resources excludes millions from access to those same resources, if not in the present, then certainly in the future. Rationalizing resource consumption so that resources and the opportunities they provide are not hoarded according to geography or generation is therefore inseparable from the goal of affording the same chance for well-being and mobility to all. This becomes even more serious when one considers that overconsumption by the Global North alone has created the current unsustainable paradigm. Were the Global South to aspire to levels of consumption similar to those in North America, the planet's resources would be drained impossibly quickly. It is therefore imperative that wealthy countries seek to reduce their resource footprint as rapidly as possible, if not for the sake of improving their own contribution to sustainability, then for the sake of providing a model for how a high standard of living can be maintained without the corresponding drain on resources to match it. Such a template will be necessary for all countries to eventually follow, regardless of what stage of development they currently find themselves at.

Decarbonization and Energy

Decarbonizing the energy system, and providing safe, clean, and affordable energy to all, are key building blocks to meeting climate action goals, building human capacity in a socially inclusive fashion, and designing livable urban environments. With climate-related disasters looming, global carbon emissions continuing to accelerate, and over a billion people still without access to electricity, the present need could not be greater. However, managing the process of this transition will require significant technological advancements and infrastructure investments, revolutions in distribution and energy storage technology, and a population with the skills to design and maintain this new system.

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[3] Creutzig, F., Roy, J., Lamb, W.F. *et al.* Towards demand-side solutions for mitigating climate change. *Nature Clim Change* **8,** 260–263 (2018). https://doi.org/10.1038/s41558-018-0121-1

The clear first step in separating energy production from carbon emissions is the rapid replacement of fossil fuels by carbon-neutral energy sources such as wind, solar, geothermal, nuclear, and hydropower. Certain renewable sources, namely wind and solar, can be decoupled from central distribution networks for household and local production. This distributed energy generation has already revolutionized access to power in many parts of the world, aided by technological advances and vast resulting improvements in efficiency and affordability. Regions more dependent on power networks will require new innovations within the grid to reduce transmission losses, more accurately measure and adjust to fluctuating demand, and incorporate greater sharing of distributed production. Finally, production and new storage techniques for decarbonized alternative fuels, such as hydrogen, will likely make a significant contribution in applications where electrification of existing services is not feasible.

Decarbonizing the energy sector would yield great benefits beyond its direct climate impacts. It would greatly reduce indoor and environmental air pollution, reducing the prevalence of serious respiratory diseases whose negative impact is only now being fully understood. Advances in efficiency are likely to align with more efficient production practices across the spectrum, accelerating the adoption of more sustainable resource usage patterns. Furthermore, this transition, if started now, could generate great economic opportunity for those with the skills to contribute to it at minimal public cost. One recent study estimated that decarbonizing the global energy sector at a pace which would avert the worst impacts of climate change would cost a mere 2.5% of annual global GDP.[4] In doing so, a decarbonized global energy system would contribute to reduced vulnerability to poverty and hunger, better health outcomes, improved access to clean water and sanitation, and preservation of biodiversity, among other positive SDG-related implications.

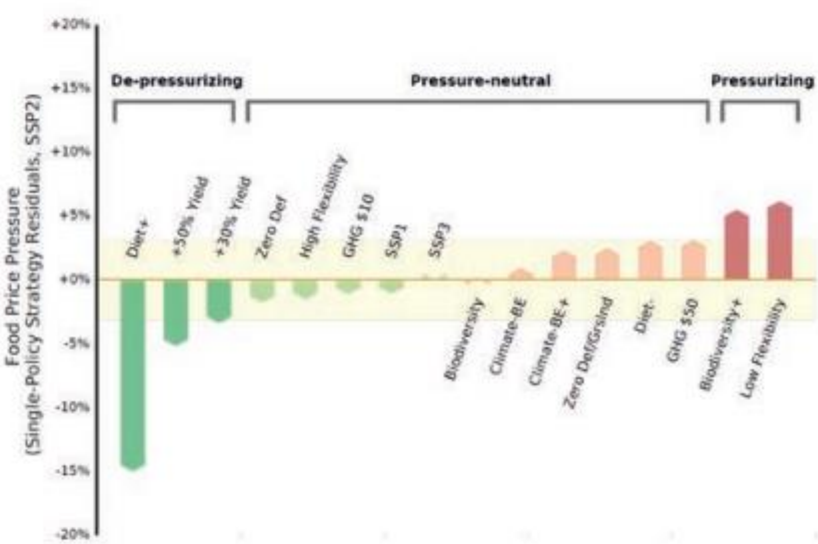
Food, Biosphere, and Water

Regardless of how carefully natural resources are stewarded and planetary boundaries are respected, the health of the world ecosystem forms the foundation for human prosperity and well-being. Unfortunately, current land use patterns and practices threaten the continued viability of the delicate balance between nature and human needs. BAU agriculture practices directly contribute to climate change through excessive meat production, habitat and biodiversity loss through eutrophication and deforestation, and water pollution through poor management of chemical agents. Modern agriculture is not only actively harmful to the ecosystem it relies upon, it is also highly fragile and vulnerable to degradation and climate-related changes. Desertification threatens vast swathes of grazing grounds across Africa and South Asia, and rainfall patterns are becoming more volatile and unpredictable. In the world's oceans, formerly rich fisheries are on the brink of collapse due to overfishing, and acidification from excessive atmospheric carbon dioxide threatens to sever vital links in the food chain. Lastly, despite all these shortcomings of an unsustainable, excessively resource-intensive food system, 800 million people remain undernourished and two billion are overweight or obese, meaning modern

[4] McCollum, D.L., Zhou, W., Bertram, C. *et al.* Energy investment needs for fulfilling the Paris Agreement and achieving the Sustainable Development Goals. *Nat Energy* **3,** 589–599 (2018). https://doi.org/10.1038/s41560-018-0179-z

agriculture has failed to deliver healthy, nutritious outcomes to over a third of the world's population. The time has come for a reimagining of agriculture such that damage to the ecosystem can be mitigated, resilience to changing conditions can be enhanced and benefits to human health and well-being can be maximized.

To halt the advance of this environmental degradation, several land use regulations must immediately be put into place. One such change should be the massive expansion of protected areas, particularly those housing habitats vital to the production of ecosystem services. This should proceed in lockstep with the limiting of all agricultural production to previously developed land, which would replace extensive growth of food production taking place on undisturbed ground with the intensification of existing farmed space. To ensure that this intensification is sustainable itself, existing techniques that boost efficiency of resource consumption such as precision irrigation and fertilization and no-till farming must be paired with innovations that reduce waste, such as improved post-harvest handling and pest-resistant crops, and diffused across the globe. A significantly more restrictive approach will be required in global fisheries, where new technologies will need to monitor and contribute to enforcing strict limits on catches, bans on illegal fishing techniques, and flows of pollutants from inland waterways and the coast. Finally, consumer preferences will need to shift along with agricultural production patterns towards healthier, less resource-intensive alternatives, a shift which climate and health advocacy has already begun to prompt. This sweeping transition will need to be managed in a fashion which does not place undue financial pressure on the most impoverished, who are already the most food-insecure as well. A poorly functioning food system threatens economic viability, social cohesion, and environmental resilience, but a sustainable one can contribute to health and well-being across all walks of life without infringing on the ecosystem which makes this prosperity possible.



Various contributors to agricultural intensification are likely to impact food prices in different ways. In poor regions where yields fail to rise and little space for making diets more affordable remains, special attention must be paid to improving the function of food markets, likely through the use of digital technology, to avoid price increases while still maintaining a sustainable food system. Source: TWI2050.

Smart Cities

Cities today already house 55% of the world's population and 70% of its economic output, and over the course of the century, their footprint on the world stage is only expected to increase. Indeed, by 2050, cities could comprise 70% of the global population and 85% of world GDP. With cities an increasingly central stage for human development, enhancing cities as environments to promote sustainable development has become increasingly vital. Cities can be more than a site where the SDGs are achieved; if managed properly, they can contribute exponentially to inclusive economic opportunity and social cohesion while dramatically reducing the environmental impact of human settlement compared to other population patterns.

But many cities today, rather than contributing to sustainable development, are hindering its achievement instead. Growing inflows of migrants, rather than being directed into interconnected neighborhoods with safe and adequate infrastructure, are often funneled into informal settlements where basic power and water infrastructure, hygiene and sanitation, digital connectivity, and transit linkages to hubs of employment are all lacking. Other cities have attempted to dodge the pressures created by a growing population by fighting all new development, which has only served to constrain internal access to opportunity while contributing to a wide and growing gulf between the rich and the poor. Still other cities have welcomed development to meet the growing demand to live in urban areas, but in a way which has retrenched sprawl and unsustainable urban settlement patterns which limit the potential of cities. With urban areas increasingly serving as the center of gravity in the 21st century, cities must strive to direct their development along lines which promote inclusive economic opportunity, social engagement and stability, and environmental sustainability.

The accelerating urbanization trend of the 21st century makes it more imperative than ever for cities to meet the needs of populations who will be unable to thrive long-term absent an approach grounded in sustainable development. To do so, cities will need to foreground the livability of communities while transforming their physical environments to serve as a springboard to opportunity. This transformation will take many forms, but first and foremost, it will require investment in a dense, low-carbon infrastructure network which provides essential services to all inhabitants in a resource-efficient manner and allows all inhabitants to fully take advantage of cities without undue time or monetary expense. Further reforms in housing policy will be required to prevent segregation, and subsequent limiting of opportunity, of excluded groups on this basis of class or race, while communities will need to be intentionally designed through the judicious use of mixed-use development to stave off the social exclusion prevalent in many modern-day cities. Finally, technological advances have recently revolutionized the way in which people live and work in urban areas, potentially eliminating commutes entirely for white-collar workers. The impacts of these innovations on the physical layout of smart cities is still to be fully understood, but cities will likely have to work harder than ever to maintain dense, efficient infrastructure networks and communities in light of the outward pressures on population these changes are likely to prompt over the medium term.

Digital Revolution: The Unifying Transformation

Astonishingly, over 17 goals and 169 targets, the SDGs make only two brief direct references to the Digital Revolution. Target 9.c, as part of the broader goal of building resilient infrastructure, calls for significantly increasing access to ICT, with a particular focus on universal and affordable internet access. Target 17.8 advocates in the abstract for the greater use of ICT as an enabling technology in the context of international partnerships with least-developed countries, with few details on the specifics of what role these enabling technologies would serve. Needless to say, the SDGs broadly overlook the great potential of digital technology to contribute to sustainable development initiatives across the board, treating ICTs mostly as an end separate from the rest of the goals rather than as a crucial catalyst for achieving the goals which must be mainstreamed into SDG initiatives in order to provide the greatest possibility of success.

The Digital Revolution is the single societal transformation which makes the remaining five possible, uniting them as a whole. As a collective, interconnected suite of new advances and new applications of existing technologies, Artificial Intelligence (AI), Virtual Reality (VR), Machine Learning, and the Internet of Things (IoT) will come to saturate the economy and society. As the impact and spread of these technologies increases exponentially, they will converge with the new institutions, lifestyles and settlement patterns emerging from them to generate a wholesale societal transformation to rival the Industrial Revolution, as well as anything envisioned in the SDGs.

This great transformation holds the potential for great success as well as great harm. As an example of early success, 80% of the world population now has access to mobile phones, including up to a billion phone users without access to electricity. The widespread diffusion of this game changing technology has nearly erased the cost of communication compared to ages past, flattening barriers to transactions and setting the stage for productivity growth in what had been some of the world's most excluded communities. Mobile technology, and the services which have sprung forth from them, are but one example of how ICT has allowed some regions to leapfrog the developed world in terms of provision of services for which soft and hard infrastructure had previously been lacking. On the flip side of this example, the disruptions in service provision, manufacturing, and agricultural production which the Digital Revolution is likely to prompt could tremendously increase social and economic inequality in the absence of deliberate policy to counteract this effect. Automation, for instance, could make existing livelihoods more precarious while shifting the distribution of income further from labor to capital. Even if these jobs are replaced, the new positions that emerge are not guaranteed to improve the earnings and working conditions of employees.

The Digital Revolution and Societal Transformations

The Digital Revolution's potential for contributing to the achievement of sustainable development is undeniable. However, so are the threats these new technologies have opened society to, such as digital identity theft, invasion of privacy, cyberattacks, mental health issues, and automated statistical discrimination by an AI. Therefore, continuing the rapid expansion of physical infrastructure and digital systems to ensure the benefits of the Digital Revolution can be felt by all communities will not be the only pressing need. New normative and regulatory frameworks will need to be drafted in order to capture the benefits of these new technologies while avoiding their dangers. When it comes to the transition to sustainable development, innovation and technology roadmaps will need to be individually formulated in order to guide the Digital Transformation in the direction of sustainable development for each of the other five major societal transformations discussed above.

Human Capacity and Demography

Healthcare

Technology has always served an important role in medical systems, but the portability of new devices has made it more personalized and accessible than ever before. Smartphones and smart devices have allowed for personalized care to reach a new frontier, with heart rate and exercise tracking, diet monitoring, and even rudimentary ultrasounds now made possible through what has become an everyday piece of household technology.[5] Across the medical space, this technological revolution has enabled advances such as new modes of telemedicine, individualized manufacturing of medical devices, robotic surgery, genetic sequencing, gene therapy, and computer-assisted diagnoses.

Digital telemedicine has already begun reducing inequalities in access to modern medicine in developed and developing countries alike. Smartphones can deliver real-time patient data to doctors and specialists who would otherwise be unable to access them, bridging long-standing shortages in health systems. These doctors can then analyze and return their feedback to patients entirely remotely, erasing distance which previously would have excluded many from the best medical care. Implanted IoT devices can add to the efficacy of the new digital telemedicine by directly transmitting specialized health data to doctors, while advances in drone technology can further smooth the delivery of pharmaceuticals to hard-to-access patients. Finally, health and preventative care apps, which could be further improved by these same advances, have increasingly seen voluntary adoption by those wishing to make healthy living a habit. Collectively, these advances in the area of remote medicine have the potential to eradicate shortages throughout overburdened health systems while concurrently increasing savings.

At the bleeding edge of innovation, prosthetics and living tissue can now be manufactured with the aid of 3D printing. Whole organs will likely be made available for surgery within the next decade or two, greatly diminishing the likelihood of complications from rejection prevalent in organ transplants today. Robot-assisted surgery, which offers greater precision and accuracy than human hands with minimal invasiveness during delicate and complex operations, is also on the rise. Medical advances in the near future are not limited to hardware; computer modeling and big data applications within the field of synthetic biology open the door to personalized and affordable gene therapy. With the cost of sequencing an individual's entire genome now below 1000 USD, these breakthroughs could allow specific cancer-causing mutations to be targeted for treatment, or even the elimination of certain genetic diseases.

Yet all this promise does not come without risk. Regulations must walk a tightrope between individual, business, and government interest alongside the rapid progression of these

[5] Refer to Butterfly Network, Inc. as an example of a company manufacturing smartphone-powered home ultrasound equipment.

advancements in order to balance incentives for innovation with the sustainable imperatives of just, affordable healthcare and the informed consent of patients. This need becomes particularly acute when considering the issues of inequality of advanced treatments and corporate access to personal information. While the technological elimination of serious sicknesses and genetic disorders is an unambiguous good, the same technology could likely be used for the genetic enhancement of the wealthy and well-connected, encoding inequality into our very DNA. Insurance providers, which are provided legal rights to patients' genetic information upon the signing of a contract by some countries, must also be prevented both from using this information to discriminate against patients and from selling it to outside entities, such as potential places of employment. If this can not be immediately accomplished, patients must be made aware of the risks of voluntarily sharing their medical data and encouraged to treat it as any other type of sensitive, personal information. Finally, certain challenges are unlikely to go away regardless of how advanced medical technology becomes. For highly advanced treatments coming at prohibitive cost, such as the monoclonal antibodies currently used on rare occasion to combat COVID-19, governments will need to lever their patenting and licensing system to balance the need for universal public provision of lifesaving treatments with the ongoing need to incentivize innovation.

Education

Since the advent of its use in the 1950s, ICT has played a steadily increasing role in providing access to quality education, a trend which the Digital Revolution is likely to extend. Digital education platforms offer access to opportunities that would otherwise be out of reach to all but the most privileged students; through MOOCs, any student with fast enough internet can experiences courses from the world's best universities, and VR allows for the simulation of excursions and field trips to distant sites without leaving the home. If the Digital Revolution in education is fully realized, educational outcomes will no longer be gatekept according to school admissions or geographical location, allowing for the opening of the entirety of the skilled global labor market to the best individuals available regardless of origin or background. But before this revolutionary degree of inclusion can be realized, substantial hard and soft investments will need to be made to make certain first that adequate broadband infrastructure exists across the world, especially remote areas of the developing world, and second, that education personnel are capable of taking advantages of the possibilities of this new technology.

Education's overlapping impact across the entire spectrum of sustainable development is undeniable. In addition to its strong impact on encouraging female empowerment already mentioned, better education is associated with higher economic growth, higher innovation and labor productivity, reduced population growth, better nutrition and health outcomes, higher life expectancy, greater environmental awareness and outcomes, societal promotion of good governance, and more. Additionally, digital curricula offer unprecedented room for students to personalize their own education according to their own interests and needs, at dramatically reduced costs compared to traditional education. Finally, digital education platforms open new possibilities for students to take advantage of collaborative learning opportunities between classrooms around the globe, strengthening international bonds and global cooperation.

The transition to a digital education model will require substantial adjustment by teachers and will create significant impacts on broader society which must be accounted for. Teachers will need to become fluent in a dramatically different skillset from what the present day demands, as new digital classrooms will require new levels of technological literacy many simply do not yet have. In addition, new digital curricula will need to mature alongside technological advances in society both to engage students in the learning process as digital society evolves and to meet the rapidly evolving needs of the workforce. Furthermore, as e-learning becomes more predominant, centralized physical campuses will dwindle, with commensurate impacts on urban spaces, college towns, and student interpersonal relationships. This will contribute to sustainability in some respects, freeing land for alternative uses and reducing GHG emissions. But smart cities and communities will eventually need to identify alternative means for children to fulfill their needs for physical and social interaction which online education cannot provide. Finally, most significantly in the developing world, public education systems must strive to ensure that all can utilize new technologies that provide access to a quality education. Digital technologies must reinforce education's role as the great equalizer, rather than erecting yet another barrier to opportunity.

Consumption and Production

The Digital Revolution is likely to improve the sustainability of consumption and production patterns in two ways. First, it will allow many services to be provided near-universally at no additional cost, expanding the affordability and inclusivity of such services while minimizing the resource outlays necessary to achieve the same level of well-being. Second, digital systems will improve the distribution of scarce resources by more closely aligning supply with demand in real time. This principle, the basis of the "sharing economy" which underlies so many digital services platforms today, holds great potential for improving service while reducing resources spent maintaining idle assets. Through both these pathways, the Digital Revolution is likely to succeed not just at streamlining the delivery of real services, but by replacing real services with virtual services as well. This would have broad implications for the development of urban environments, the reduction of GHG emissions, and the wider dematerialization of consumer demand preferences. On the whole, digitization is likely to result in more affordable, higher-quality services, aiding in the reduction of poverty and inequality. Improved resource efficiency due to digitalization will also likely reduce the environmental footprint of human society.

But digitalization of the manufacturing and services sectors is absolutely not without its risks. If digital infrastructure is not accessible to segments of the population, then the services provided through it become part of the digital divide and contribute to increased inequality. This becomes especially concerning if essential public services, such as public transit or payment systems, only become accessible through mobile devices which not all can afford. In addition, as big data from consumption of digital services accumulates and is shared by corporations or public agencies, data privacy concerns will become increasingly prominent, and information sharing will encourage the rise of natural monopolies. Finally, if consumer preferences durably shift away from the consumption of material resources, employment in the manufacturing sector is likely to decline. The same will happen in the services sector if digitalization leads to automation on the front or back end. If these changes shift the comparative advantage in the services and manufacturing sectors back to developed countries, then developing countries intending to follow the historical export-oriented industrialization model may find that the markets they had relied upon will no longer exist.

Ultimately, considering the Digital Revolution's impact on consumption and production requires contemplating just what the future of work will look like around the world.[6] The business processes adopted during the pandemic already show signs of sparking a new era of rapid productivity growth, and historians could look back on the present crisis as the inflection point in the emergence of the automated workplace.[7] Is automation destined to displace all but the most highly-educated professionals and "last-mile" service workers? Or will the remainder of the labor market simply be forced to transform beyond the point of recognition? At the frontier of current technology, the latter appears to be holding true; in Norway, one of the world's most highly automated economies, the labor market has largely evolved to prioritize jobs with highly social components, emphasizing management roles which machines are currently incapable of doing.[8] Regardless, the decline of low-skilled jobs is likely to happen with unprecedented speed compared to prior societal transformations once the automation of services and manufacturing achieves full viability, considering the level of globalization in the modern world economy. Governments must begin formulating policies today to cushion the landing for these disproportionately vulnerable groups. This necessarily requires first attempting to identify what skills will be in demand in the future labor market, and predicting the future is a tall order for a world we have not yet seen.

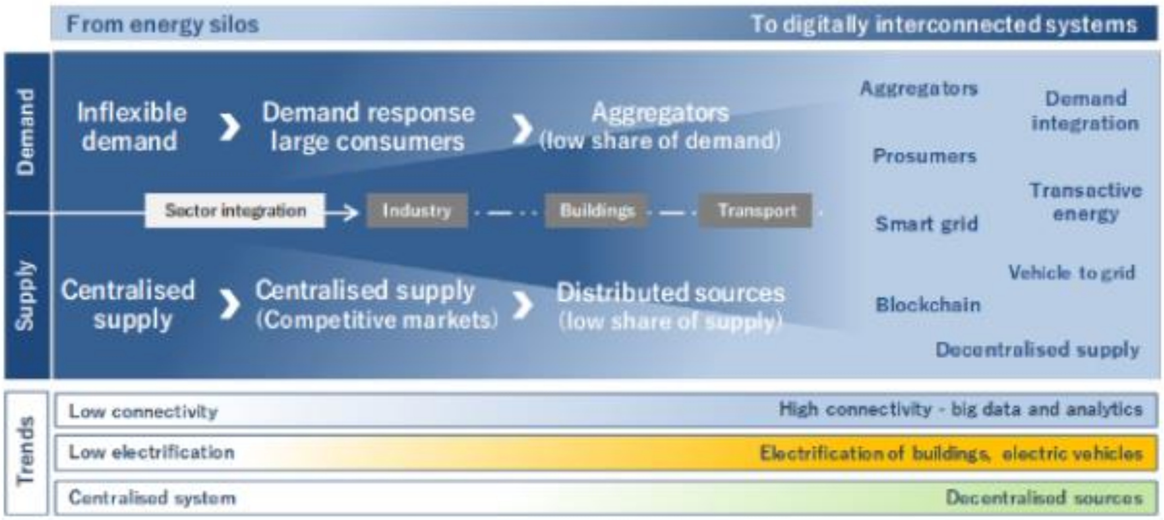
Decarbonization and Energy

The carbon intensity of energy production has been falling since the onset of the Industrial Revolution, but modern technologies offer for the first time the real promise of permanently decoupling energy production from carbon. However, if carbon emissions are to be reduced in time to meet targets under the Paris Agreement, decarbonization of the energy system and improvements in energy efficiency must proceed in lockstep at a far faster pace than we have seen to this point. As of 2019, decarbonization was proceeding at a mere 0.3% per year, while carbon emissions continued to rise by 2% on an annual basis. The Digital Revolution has a major role to play in accelerating both aspects of this transition. First, digital systems are enhancing the interconnectivity of energy and transportation systems, with benefits for flexibility, efficiency, and reliability. Second, digital systems permit far more sophisticated monitoring of carbon control schemes, enhancing the efficacy of efforts to reduce emissions. However, in both cases, attention must be paid to mitigating the security and privacy risks invited by a fully digitalized energy infrastructure, if possible.

[6] For further discussion on ICTs and the future of work, please review ICT India Working Paper #11, "The Future of Work in India: Adapting to the Fourth Industrial Revolution." https://sustainable-development.site.drupaldisttest.cc.columbia.edu/sites/default/files/content/docs/ICT%20India/Papers/ICT_India_Working_Paper_11.pdf

[7] "The pandemic could give way to an era of rapid productivity growth." *The Economist*, December 10, 2020. https://www.economist.com/finance-and-economics/2020/12/08/the-pandemic-could-give-way-to-an-era-of-rapid-productivity-growth

[8] Nedelkoska, Ljubica and Quintini, Glenda. "Automation, skills use and training." *OECD Social, Employment and Migration Working Papers*, #202. https://www.oecd-ilibrary.org/docserver/2e2f4eea-en.pdf?expires=1611118003&id=id&accname=guest&checksum=D2F8D318D308016125B7F2D6FAEF279A



Pathways for the Digital Revolution within the energy system. Source: IEA (2017).

Digitalizing the energy sector is likely to result in efficiency gains up and down the entire energy supply chain. Real-time data monitoring is estimated to reduce energy usage in buildings by 10%, with further gains arising from the use of smart meters and devices which moderate their energy demands according to environmental conditions. On the generation side, digitalization will lead to reduced operating and maintenance costs, greater network efficiency, fewer unscheduled power cuts, and improved durability for plants and other energy assets. Collectively, these improved efficiencies are expected to shave 5% off of annual power generation costs, or $80B per year.[9] Furthermore, digitalization will likely accelerate the integration of distributed renewable production into the broader energy grid by enabling smarter response to fluctuating demand, improved tracking of output from notoriously variable renewable sources of production, and improved coordination of distributed energy resources as a whole. The result, if accomplished to its full potential, would amount to nothing short of a fundamental transformation of the energy system.

Beyond the benefits accruing to the fight against climate change from the renewable energy sector, improvements in agricultural land use, and smarter infrastructure, the Digital Revolution can also be brought to bear to directly improve monitoring of climate data and emission control efforts. For example, advanced sensor technologies allow for the generation of real-time geolocated environmental data, allowing scientists and policymakers to precisely measure the origins of carbon and methane pollution from the manufacturing, transport, and agriculture sectors, among others. These improved means of data collection will allow for the identification and pursuit of those making the worst contributions to a problem which is otherwise, by its nature, diffuse and challenging to track. Taking one example, a recent flagship study using cutting-edge sensor technology successfully flagged high volume undisclosed methane leaks from natural gas facilities in Texas, identifying targets for future regulatory enforcement.[10] On a large scale, such technology could paint a full portrait of the effectiveness of mitigation efforts

[9] IEA World Energy Outlook 2017. https://www.iea.org/reports/world-energy-outlook-2017
[10] Tabuchi, Hiroko. "It's a vast, invisible climate menace. We made it visible." *The New York Times*, December 12, 2019. https://www.nytimes.com/interactive/2019/12/12/climate/texas-methane-super-emitters.html

under the Paris agreement, providing valuable information on where these efforts can be improved. A further recently prominent novel application of ICT, the blockchain, holds great potential for improving the tracking, reporting, and verification of national and subnational emissions across a decentralized international system. With accurate and granular reporting of emissions in place, this data would allow for the strengthening of emissions and permit markets while increasing the transparency of climate data within industry supply chains.

There is, however, a clear vulnerability to outsize reliance on digital devices to solve our energy problems: the energy requirements of the devices themselves. Data centers and networks already consume 2% of global electricity production, although efficiency gains are likely to cause this level to remain steady or decline over time. The digital economy, on the other hand, already consumes 12% of global electricity production as of 2020 and increases its consumption by 7% annually. Bitcoin, one of the most famously wasteful uses of energy in the digital ecosystem, already consumes more electricity than many small countries. If energy grids are to rely as heavily as anticipated on digital technology, then either these devices will need to become more efficient or energy systems will need to find a separate means of rapidly decarbonizing. Otherwise, the increased burden of all these devices could easily backfire. More prosaically, increasing the integration of IoT devices in major power grids via distributed systems is likely to increase household and global vulnerability to cyberattacks and data theft alike. Significant security protections will need to be put in place and enforced to maintain the safety and trust of those who rely on these systems.

Food, Biosphere and Water

The sustainability challenges of feeding a world population soon to exceed eight billion are unquestionable, especially considering the historical relationship between greater development and less sustainable dietary preferences. Without the expansion of new, sustainable forms of agriculture, status quo food systems are certain to continue contributing to land and water degradation, deforestation, and biodiversity loss around the world. At the same time, unacceptable levels of food waste under the current system will continue to contribute to GHG emissions while underscoring the food system's failure to provide a universal acceptable baseline of nutrition to the entire world.

Under these conditions, digital advances can contribute to agriculture's transition to sustainability in one of two ways. The first path lies through optimizing digital contributions to precision agriculture, which relies on data from GPS and remote sensing, local IoT sensors, and remote consultations to optimize outputs while minimizing resource usage. This intensification-oriented approach, which applies unique data concerning individual plots to dynamically adjust inputs such as water and fertilizer, represents current agricultural techniques at peak efficiency. By automating farm equipment to minimize labor inputs, planting and harvest costs, the precision agriculture approach can further improve efficiency in a way which synergizes with other aspects of the Digital Revolution.

However, precision agriculture still largely adheres to the monocrop standard of modern agriculture, based in long-standing pesticide, herbicide and fertilizer practices, which has little alignment with a different approach which would promote biodiversity and resilience. Alternate approaches such as agroforestry and ecosystem-based forest management, falling under the umbrella of holistic agriculture, have a proven track record of preserving the biodiversity of fragile ecological systems while contributing to the demands of the modern food system. While the overall intensification potential of such approaches remains unproven, digital advances can contribute to their output by tracking and optimizing the performance of biological systems within these agricultural microhabitats.

No matter the approach taken to sustainably intensifying agriculture, Digital Revolution-related advances ranging from remote sensing to improvements in synthetic biology and gene editing also hold great potential both for improving outputs and preserving biodiversity. New GMO and laboratory advances are increasingly allowing for the emergence of scalable mass production of lab agriculture, a particularly valuable development when it comes to the replacement of carbon and land-intensive agricultural products such as meat and dairy products. Closer to existing agricultural communities, novel partnerships between biotechnology companies and conservation organizations have combined ICT insights, such as machine learning-powered genomic analysis, with access to endangered habitats to identify new pharmaceutical compounds from these habitats as a first step to providing an economic justification for their preservation. And technologies such as LiDAR are providing data for computer models which can accurately describe shifting habitat conditions and modes of land use in even the most remote environments. Such information will likely prove highly useful in future biodiversity management projects, which rely far more on knowledge about local conditions than any specific technology.

When it comes to the world’s oceans, remote sensing offers unprecedented access to a habitat once nearly invisible to human eyes. The improved mapping of underwater habitats made possible by new digital advances will likely expand knowledge about sensitive biological zones on the ocean floor which will directly lead to their formal protection. Aquatic habitats can also be mapped by new computer models which forecast fish migrations and behavior, as well as emerging DNA analysis techniques which analyze the presence of fish population on the basis of tissue shed into the water. These modes of analysis could bolster the efficient and sustainable management of fisheries and oceans while avoiding excessive bycatch of vulnerable and endangered species – provided these predictive and analytical models are properly governed. If their powers fell into the wrong hands, they will instead likely expose sensitive fisheries to illegal exploitation.

Finally, digitalized monitoring enables the tracing of numerous types of agricultural products in compliance with conservation, health and quality guidelines. DNA analysis kits can be used to spotlight and intercept illegal catches at the point of sale, discouraging the continued abuse of fishing rights to harvest and sell threatened species. Digital databases can also improve the certification chain for organic and sustainable products, providing customers with more detailed, accurate information about the environmental impact of their food habits.

Smart Cities

Transit and Interconnectivity

Aside from the automobile, arguably the single invention from the Industrial Revolution with the greatest impact on the evolution of cities was the elevator. While the car forced populations outward, generating congestion in dense environments while making commutes from distant suburbs feasible and commonplace, the elevator made living and working in tall, dense urban centers attractive and inviting. The two technologies have existed in unspoken opposition since their invention, pulling in opposite directions until the uniquely diverse built landscapes of today's cities emerged. In North America, the car mostly won, leading to the characteristic, unending sprawl which has done so much harm to natural habitats, control of carbon emissions, and social cohesion in these cities. Today, the antagonistic link between modern urban landscapes and sustainability has become abundantly clear, as has a growing conviction that cities must once again work to build up, rather than out, in the pursuit of sustainable development. Far less consensus exists, however, on just how to accomplish the goal of reshaping our sprawling metropolises into dense, interconnected, and above all, smart cities.

First of all, smart, sustainable cities are simply incompatible with car-centric transportation systems. Even with an entirely electric, zero-emission fleet, the land use demands both of car infrastructure and of the habitation patterns which result both lead to substantial GHG emissions in and of themselves and prevent the emergence of the walkable, accessible communities common in the world's smartest cities which yield such benefits for economic growth as well as mental, physical, and social health. Car infrastructure can certainly supplement urban transportation infrastructure under certain conditions in which ICT can play a significant role. For example, autonomous and self-aware vehicles will make roadways substantially safer than they currently are, especially when paired with smart road infrastructure which dynamically interacts with vehicles according to traffic and congestion conditions. But these technologies, appropriate as they are for intercity travel, have little role to play in dense urban environments.

Rather, in the long term, smart cities will need to build themselves around dense mass-transit networks, whose stations and hubs create natural gathering spots for the formation of communities and economic clusters. To bridge the gap from now to then, cities can start by encouraging the evolution of car usage in cities from private ownership models to shared services, particularly those powered by mobile digital platforms. This approach would substantially reduce land usage dedicated to parking, urban congestion, and GHG emission, with a low barrier to entry and without relying on significant behavioral changes or unrealized technological advances. As car usage declines, transportation investments can transition from pursuing movement through a space to facilitating interaction within a space. ICT advances such as Communications-Based Train Control (CBTC), autonomous trains, and demand-based scheduling can also be implemented to improve the throughput of mass transit while dynamically adapting to shifting ridership. Such a system would fully realize the goal of an urban transit system which embodies sustainability in all its dimensions.

Smart Human Environments

Transit is part of the equation for designing the ultimate smart city, but it is incomplete unless complemented by smart spaces and buildings designed around sustainable consumption patterns.

As is, buildings are already responsible for 51% of worldwide electricity consumption, and needless to say, a far higher proportion in urban areas. 80% of energy in urban areas continues to be sourced from fossil fuels, necessitating the shift towards renewables with the aid of digital tools discussed above, while new construction will need to incorporate energy efficiency principles from the ground up. Fortunately, digital innovations provide a great amount of room for efficiency improvements. Smart homes, using the smart energy infrastructure mentioned earlier, can adjust settings such as temperature and lighting without human intervention in real time by monitoring occupancy or other variables. As many as 38% of homes in the US now have enough connectivity to qualify as smart homes, a figure only expected to grow. Yet designing buildings for sustainability, including connectivity, is best done from the outset, meaning cities moving towards sustainability will likely require substantial new construction in order to boast of a building stock which can meet these needs, along with continuous retrofitting to match buildings with the latest technology for improving efficiency.

More passive systems grounded in digital technology can also help moderate the energy usage of buildings. Building Energy Management Systems (BEMS) and Building Information Modeling (BIM) systems, which dynamically adjust buildings according to environmental factors such as shading, wind, outside temperature and light, can harmonize the energy consumption of buildings with their surroundings. Self-sufficient waste management systems, which leverage digitalization to restrict energy consumption to when and where it is required, can turn these buildings into closed, cycles for water and food waste in a way which serves as a model for the circular usage of waste products in a sustainable society as a whole. Smart buildings can also further interact with a distributed grid, especially one based on renewables, to further improve the collection of intelligent meter and climate data, optimize energy demand, and take the reliability and efficiency of the citywide grid to the next level. Finally, with the rise of home workspaces during the pandemic, the outlook for smart cities structured around shared mixed spaces, rather than separate home and office buildings, looks increasingly optimistic. Such spaces would substantially reduce costs associated with transportation and construction as well as demand for energy and resources, making the smart city even more sustainable than previously conceived.

Guiding the Digital Transformation

Through the mechanisms identified above, the digital revolution serves as the single unifying innovation with the potential to effect the remaining five transformations required for the achievement of sustainable development. With this great power, however, comes significant risk. The digital transformation demands that policymakers explicitly guide its trajectory towards the sustainable, lest the powers unleashed by these new technologies instead contribute to the increasing fragility of the modern social contract. In addition to promoting the pathways explicitly described, agents of change would do well to aim for shaping a digital revolution which, in the broader sense, upholds the three core principles of sustainable development: economic prosperity, social inclusion, and environmental preservation.

The economic growth potential of the digital revolution cannot be questioned, but policymakers must investigate the impact these new technologies will have on how much of this new prosperity workers and the general population are actually able to capture. Historically, even as new technologies have boosted the productivity of capital, long-term job displacement has not occurred as the new shape of the economy made space for new forms of employment. However, although current innovations do not yet seem to have generated unprecedented job loss, cutting-edge advances now entering the market in fields such as cognitive computing possibly do have the potential to fully revolutionize economic production by eliminating the need for any human component at all. If the digital revolution seems to be heading in this direction, leaders must support social cohesion in the short term by cushioning this transition for workers while building permanent social support structures which will promote the general welfare in the new, post-labor scarcity world.

Digital technologies theoretically have the potential to create a new era of societal inclusion for marginalized groups, but inattentiveness on the part of the public and private spheres alike has instead so far given rise to a digital divide between the included and the excluded. As differences in skills, wages, professional and technical knowledge, and national infrastructure accumulate, the digital future will increasingly look like an entrenched world of haves and have-nots in the absence of immediate remediation. On the global level, closing this divide will require investments both in infrastructure and human capital, the latter of which invokes the demographic transition. Well-designed public platforms, such as the suite of services running through India's Aadhaar identification system, can also rapidly expand universal access to services.

Finally, the transformation of the global economy will likely create unprecedented demands on the environment and ecosystems of all types. Accelerating growth will stress existing wasteful production and consumption systems, especially regarding the recycling of the electronic equipment which will exponentially proliferate throughout the digital revolution. Alongside this technological uptake, biodiversity loss, increased pollution, and worsening climate change will likely accompany the otherwise promising digital revolution unless these technologies are explicitly mobilized for the preservation of Earth systems.

To fortify these three pillars, achieve the transformations necessary for sustainable development, and realize a livable and prosperous future for all, innovators at the local, national, and international level will need to pave the way for comprehensive governance systems which are capable of guiding not just the digital transformation, but holistically incorporating it into a long-term plan for a thoroughly sustainable future. If societies are unable to do this, these pathbreaking technologies are likely to go towards the fulfillment of another purpose: the destruction of public trust, the elimination of social mobility, and the erosion of a future which is both possible and necessary. Avoiding the emergent slippery slopes of power concentration, neglect of human rights, rising inequality, and declining governance capacity has never been more important; the time to conceptualize the norms, institutions, and guardrails which will underpin the evolution of this new society has come.

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