Andrea Renda and Moritz Laurer

IOT4SDGS

WHAT CAN THE DIGITAL TRANSFORMATION AND IOT ACHIEVE FOR AGENDA 2030?

In cooperation with

IoT 4 SDGs

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Abstract

Digital technologies can drive growth, connect people and help us protect the environment. At the same time, they can lead to market concentration, fuel precarious working conditions and consume vast amounts of energy. The Internet of Things (IoT) is a perfect example of this tension, and embodies both the promise and the peril of digitalisation. Its emergence offers unique opportunities to achieve the Sustainable Development Goals (SDGs) and the European Green Deal, but policymakers need to be aware of the need for tailored policies and investments, if they want to maximise the benefits of the IoT revolution while mitigating the risks. This report illustrates the key features and evolutions of the IoT, and provides an overview of how the IoT is mostly used today in sectors such as manufacturing, healthcare, energy and smart cities. We conclude that the IoT can massively contribute to several SDGs, especially through its capacity to increase efficiency and save costs. As the IoT is still a relatively young and complex technology, its use is mostly driven by wealthy cities and businesses. Its potential for more vulnerable populations in the global south and the environment remains underdeveloped. This points to an important dilemma for the IoT today from a sustainability perspective: while the main driver for IoT adoption is cost reduction and increased efficiency, sustainability goals such as poverty reduction and environmental protection often remain a secondary thought in its development. The role of public policy and investment will be essential to ensure that IoT solutions contribute to other SDGs in the near future and we outline different approaches for measuring this contribution. This report discusses in particular the policy measures that could be adopted in the European Union to boost the potential of the IoT for sustainability, in light of the European Green Deal and the upcoming 2021-2027 financial framework.

By contract, Hitachi and CEPS have assured that the present study has been conducted by CEPS in full independence.

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EXECUTIVE SUMMARY

The digital transformation fundamentally impacts our economy, society and environment – both positively and negatively. Given monumental challenges like climate change and global poverty, it is essential that both the private and public sector find a way to harness new technologies like the IoT for economic, but also environmental and social purposes. In this context, the United Nations Sustainable Development Goals (SDGs) provide a universally accepted vision and concrete targets, against which the contribution of new technologies to sustainable development can be assessed. The idea of long-term sustainability is also incorporated in emerging visions, such as the one incorporated in the Society 5.0 concept originated in Japan and now endorsed also at the G20 level.

This study investigates this contribution and asks one key question: what can the digital transformation and the IoT achieve for Agenda 2030? After a brief introduction, we explain the different components of the IoT ecosystem: sensors collect data, for example on heat and humidity; antennas transmit this data to a greater system, for example of a global weather monitoring system; actuators can execute commands, for example automated irrigation if an IoT irrigation system registers low levels of humidity. The Internet of Things integrates these 'things' into a broader network and combines them with other technologies such as cloud services or artificial intelligence (AI). We conclude that IoT systems can only be properly understood in relation to other key technologies and that more research needs to be done to tap the positive potential of different IoT architectures.

Chapter three summarises the main IoT use cases in four selected sectors: manufacturing, healthcare, energy and smart cities/mobility. In manufacturing, the IoT can reduce costs and increase efficiencies through predictive maintenance; in healthcare, the medical Internet of Things (mIoT) can enable home healthcare, mobile health and make patients more independent of in-person meetings with medical staff; in the energy sector, the IoT can help integrate sustainable energy sources in the power grid and reduce energy waste through better load management; in smart cities and mobility the IoT can, for example, increase convenience through improved traffic systems, reduce energy consumption through better light management and eventually revolutionise transport through autonomous vehicles. These sectors represent the biggest market share of IoT projects (manufacturing and smart cities/mobility) or are of high social (healthcare) or environmental (energy) importance. The use cases show, that the IoT can be used for diverse economic, social and environmental goals. Despite its potential, the IoT market is, however, still relatively small (but growing) and is slowed down by issues of complexity, interoperability, cost, privacy and security. In addition, negative consequences such as high energy consumption, e-waste, potential job loss through automation and market concentration should be considered. Moreover, despite the IoT's high potential, the main drivers for adoption of the IoT are too often cost savings and increased efficiencies, while its explicit use for environmental and social goals remains underdeveloped on competitive markets with insufficient incentives for sustainable investments.

Against this background, the role of public policy and sustainable investment will be essential to ensure that IoT solutions contribute to SDGs in the near future. Chapter four, therefore, starts by providing an overview of the latest policy developments in the EU ranging from different investment plans, the new strategy for data, the policy framework for artificial intelligence, to

the attempt to mainstream the SDGs in EU policy, sustainable finance and the European Green Deal. These initiatives should steer public and private investments towards the most sustainable use cases of the IoT while disincentivising harmful ones.

In the hope of supporting the search for the most sustainable use cases, we propose a four-step approach for prioritising high potential IoT projects and measuring their impact on the SDGs: (1) Use an 'SDG-first' approach and ask three key questions to identify IoT projects with the highest potential contribution to the SDGs; (2) once a high potential IoT project is selected, choose SDG targets related to the project and translate them into measurable KPIs; (3) measure and monitor the impact of the IoT project; (4) evaluate the project and communicate results. We encourage both public and private organisations to use similar impact measurement approaches and to transparently communicate the results to help others find the most impactful variants of new technologies like the IoT.

As a conclusion, the study provides a mix of policy measures which can help unleash the potential of IoT for sustainable development. First, public investments can support more sustainable IoT projects, which the market would normally neglect, by setting positive economic incentives. These investments should be guided by an 'SDG-first' approach and focus on high impact use cases as outlined in the previous chapter, for example by linking sustainability to the award criteria for Horizon Europe funding. Second, negative economic incentives should be used to reduce negative consequences. The planned revisions of the Emissions Trading System (ETS) Directive and the Energy Taxation Directive, for example, provide an opportunity to put a higher price on energy consumption. Third, innovation-friendly regulation can increase transparency and help reduce negative impacts. A revision of the Non-Financial Reporting Directive can empower investors and consumer groups to scrutinise the non-financial impacts of companies and the planned waste reform should be used to tackle the growing problem of e-waste.

If the right policy environment is created, the market can produce IoT solutions that are both economically viable and contribute to social and environmental goals. The IoT has tremendous potential and can be an integral part of a digital transformation that generates growth and works for the people and the environment. The public and the private sector need to work together to make this a reality.

IoT 4 SDGs

WHAT CAN THE DIGITAL TRANSFORMATION AND IOT ACHIEVE FOR AGENDA 2030?

1 Introduction: From the 'Internet of People' to the 'Internet of Things'

The rise of the digital economy and the internet has already revolutionised the way in which we interact, communicate, and work. The digital transformation is having a pervasive impact on the economy and society: today, online platforms leverage data availability and network effects to develop new forms of service provision, disrupting entire sectors of the economy. The opportunities offered by the internet during the past two decades are so massive that companies that have managed to conquer the attention of end users have reached unprecedented levels of market valuation (so-called trillion-dollar companies such as Amazon, Microsoft, Apple, Alphabet). The need to manage huge amounts of data has also led these companies to invest massively in powerful computers and Artificial Intelligence (AI) techniques such as machine learning, which need huge amounts of data to develop accurate and cost-effective solutions to complex problems (Renda 2019). The role of AI has become so prominent that global superpowers are now competing to retain control of data on their territory, and to lead research and innovation in this domain, which has become a top priority for global competitiveness. Most often, data collected on the internet are stored in the cloud, where they are increasingly analysed through advanced AI techniques such as machine learning.

These developments, however, have not (yet) led to an equally impressive contribution to productivity and sustainability. As a matter of fact, the digital transformation is occurring at a time of rising inequality, accelerating climate change, and a lack of trust in institutions. Emerging digital infrastructure such as data centres and new business models (e.g. fully decentralised blockchains) are creating even more environmental concerns due to outstanding energy consumption; whereas digital platforms are in some cases exacerbating inequality, thereby potentially hampering social cohesion. Commentators have highlighted that information technologies have not provided a significant contribution to productivity, and authoritative scholars have confirmed this view. Others have denounced the rise of market power, and the extreme concentration of data in a few hands. This is also due to the fact that the "internet of people", i.e. the internet that spread across the globe over the past two decades, has led to the mass-development of applications and innovations that do not always make a direct contribution to productivity, for example by changing the way industrial production occurs. At the same time, not all businesses, especially in Europe, have been good at catching up with latest technologies, and this has created a lack of diffusion of innovative technologies, rather than a problem of innovation *per se* (Soete et al. 2017; Ashford and Renda 2016).

All this might change soon, with the rise of new technological paradigms such as the **Internet of Things (IoT)**, which connects cyber-physical objects, rather than end users. IoT, as will be explained in the next sections of this report, interacts with other digital technologies in a brand new ecosystem, which can power new solutions that promise to exert a significant impact on

the achievement of a more sustainable economy and society. In particular, the combination of IoT with more distributed forms of computing (edge/cloud) and the application of so-called embedded AI can revolutionise entire sectors such as manufacturing, healthcare, energy and mobility, increasing efficiency without triggering market concentration. With the IoT revolution, AI and computing developments are expected to reach new levels by generating enormous data availability, and a 'body' (i.e. sensors, actuators) through which to collect data and perform complex tasks.

The impact of this shifting frontier on sustainability will depend, however, on the governance choices that accompany this development. As will be explained below, new digital technologies make it easier to accomplish specific results by adopting either centralised, more distributed, or even fully decentralised governance arrangements. The choice of the governance architecture has consequences for the overall contribution that the technology will make to productivity and sustainability. This is why scholars are studying the role of both technology and policy in enabling a greater contribution of new digital solutions to overall well-being and in particular to sustainable development. Importantly, a focus that goes beyond GDP to encompass all economic, social and environmental aspects of sustainable development requires the adoption of governance arrangements that lead to a widespread involvement of all societal groups, rather than unleashing those same centripetal forces that, in the current digital world, are leading to an unprecedented rise of market power and concentration.

Such a 'beyond GDP', multi-dimensional approach is mirrored in the Sustainable Development Goals (SDGs), adopted by 193 countries in 2015. With the SDGs the international community decided to go beyond economic growth and include social and environmental targets as explicit political goals (see Box 1 for details).

Box 1: The SDGs and Society 5.0

Throughout this report, we refer to the need to use technology as a means, rather than an end in and of itself. This implies that digital technologies should be promoted, funded and supported by policymakers only inasmuch as they provide a contribution to broader societal goals. More specifically, the 'north star' for this paper are the **Sustainable Development Goals (SDGs)**. The SDGs, adopted in 2015 as a universal call to action to end poverty, protect the planet and ensure that all people enjoy peace and prosperity by 2030, consist in a set of 17 goals and 169 measurable targets (United Nations 2019). The SDGs are designed to bring the world to several life-changing 'zeros', including zero poverty, hunger, AIDS and discrimination against women and girls.

The concept of Society 5.0 combines broader goals such as the SDGs with the promise of new technologies. Originally developed by the Japanese Business Federation Keidanren, it is now officially acknowledged by the world's largest powers, in particular within the G20 (2019). Society 5.0 is described as the "Super Smart Society" which aims at creating a society where people can resolve various social challenges by mainstreaming innovations such as AI, robots and big data in the daily life of citizens and businesses. In line with established literature on innovation, Society 5.0 thus echoes the idea that innovation is useful whenever it is able to address societal challenges, and that not all innovation is equally able to do so (Ashford and Renda 2016; Könnölä et al. 2017). Figure 1 shows how Society 5.0 provides a vision for combining new technologies like IoT with the SDGs: the use of sensors for oceanographic data as well as

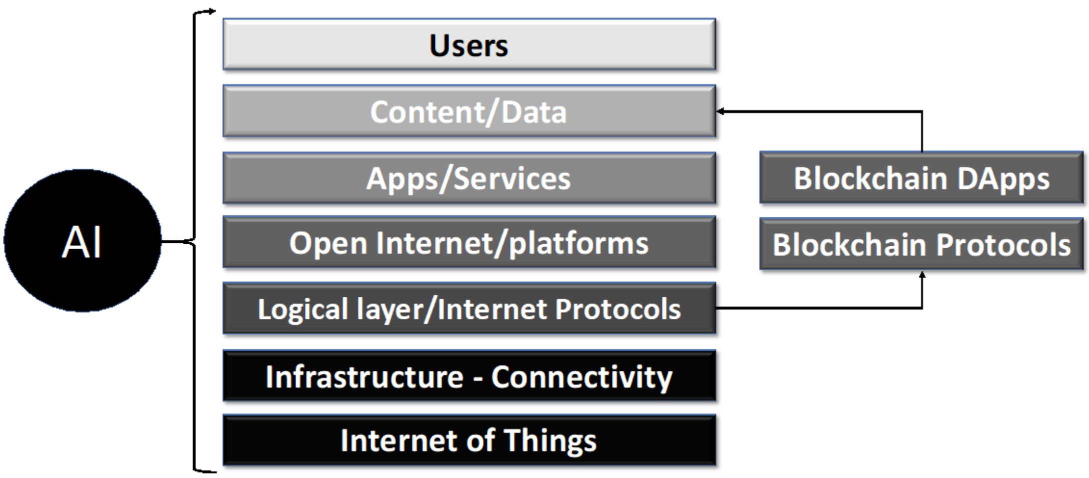
meteorological data, and even more for smart cities, i-Construction, smart grids, early warning alert systems in healthcare and smart agriculture.

Figure 1 – Society 5.0 as a way to realise the SDGs

Source: Keidanren 2019

The latest wave of technological developments promises to revolutionise the digital economy as we know it, bringing it towards an era dominated by dramatically superior computing power and connectivity speeds; a skyrocketing number of cyber-physical objects connected to the internet (IoT);[1] cutting-edge sensor and transmission technologies such as 5G; and the pervasive spread of AI into more and more aspects of personal and professional life. This new stack will be composed of powerful hardware, including faster and smaller processors; distributed computing capacity through cloud, edge (or fog) computing; new, distributed and decentralised ledger technologies such as blockchain, able to keep audit trails of transactions and other asset-backed values; and a pervasive presence of AI-enabled solutions, mostly in the form of data-hungry techniques such as smart analytics, deep learning and reinforcement learning (Renda 2018; 2019).

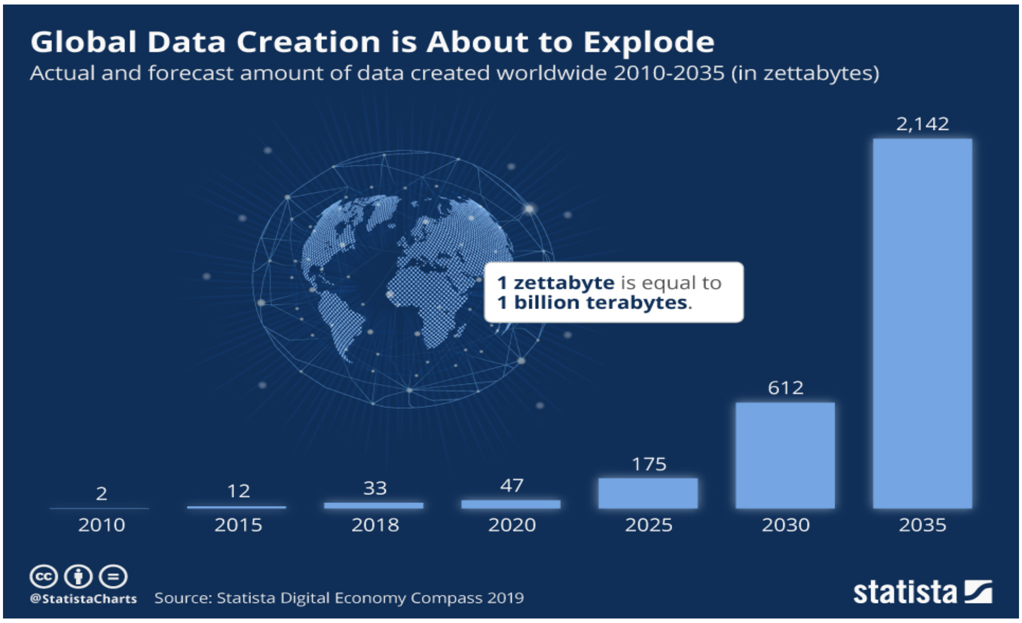
Figure 2 – The new "digital stack"



Source: Renda (2019)

As shown in Figure 2 above, the IoT is one of many layers that compose the new architecture, and an increasingly important one. The expected explosion of machine-generated data is so remarkable that analysts (Statista 2019) have foreseen an increase from 33 Zettabytes to 2,142 Zettabyes (i.e. billion terabytes) of data created worldwide between 2018 and 2035. Likewise, ICT company ARM expects that the number of connected devices, currently between 8 and 10 billion, will reach one trillion by 2035 (ARM 2017). And IoT Analytics expects an increase to 21.5 billion devices by 2025, most of which will be connected through WPAN and WLAN, but also increasingly through new technologies such as 5G (IoT Analytics 2018).

Figure 3 – The explosion of data and devices



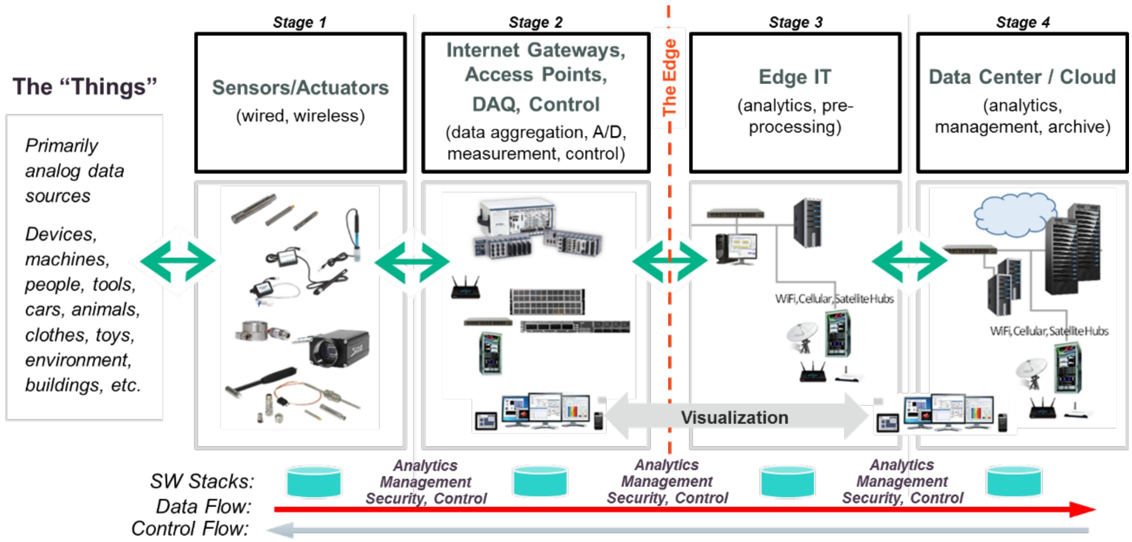
Source: Statista 2019

While this report focuses on IoT, understanding all layers of this emerging stack is extremely important when it comes to scaling up these technologies to the benefit of society: merely focusing on one layer would neither enable a full understanding of the upcoming evolution of this ecosystem, nor provide clarity on which solutions can provide the most valuable contribution to sustainable development. Accordingly, Section 2 below describes the IoT architecture and main technology, as well as the main relationship with complementary technologies such as edge computing, 5G connectivity and AI. Section 3 explores the main use cases of IoT for sustainable development goals (hereinafter, IoT4SDG), focusing in particular on key sectors such as manufacturing and healthcare, energy and mobility and providing an analysis of the strengths, weaknesses associated with IoT. Building on these main use cases, Section 4 discusses what the European Union is doing to promote the deployment of IoT solutions, both in terms of public spending and the development of an *ad hoc* policy framework, and proposes a four-step approach for finding high potential IoT use cases and measuring their impact. We conclude by outlining future policy measures that would help re-orient the development of IoT towards the SDGs.

2 Connecting things: architecture of the emerging 'technology stack' for IoT-enabled solutions

In this section, we 'zoom in' on the layered ecosystem shown in Figure 3 to explore architectural and governance solutions that are emerging in the IoT-enabled world. In order to do this, we explore the main layers of current IoT systems, as in Figure 6 below. As shown, an IoT system is essentially organised around four main layers: directly attached to the 'things' are **sensors, antennas and actuators**, which can take a wide variety of forms (see Section 2.1); these devices must be connected to a **network layer**, which allows the aggregation and basic control of data; above these layers (or, as commonly said, above the 'edge') are a **first layer of intelligence (Edge IT)**, which provides analytics functions and pre-processing of data; and the **cloud**, in which data are stored, analysed, and processed for ultimate action and decision-making.

Figure 4 – The IoT layered architecture



Source: Boyes et al. (2018)

2.1 From things to the cloud, and back: an overview of the basic IoT architecture

The first element to be considered in a full-fledged IoT system is of course the 'things'. Objects of all sorts, including toys, furniture, clothes, implanted devices, wearables, buildings and living objects such as plants, human beings and animals must be known and identified in the system. This is done by attributing to each of them an IP address and/or a universal unique identifier (UUID), which makes the orchestration and integration of things into large-scale networks much easier.[2] Things are then integrated into IoT ecosystems through a variety of technologies, which include RFID, wireless sensor networks (WSN), and mobile computing. RFID, WSNs, and mobile computing contribute significantly to the development of IoT sensing systems.

But things often need technological enhancements that enable them to gather information from the outside world, and implement decisions adopted by either humans, AI, or a combination of

both. This is why **IoT systems typically feature sensors, transmitters and actuators** (Zhang et al. 2018: 510). Local sensors are installed to, for example, measure soil humidity in agriculture or to record location data in logistics. Distant visual sensors on satellites, aerial vehicles (UAVs), or simple cameras generate image data to, for example, estimate the need for irrigation or to count crowds in public transportation during rush hour. There is a plethora of different sensor technologies, but the aim is always the same: create digital data about the physical world. As there are different types of IoT sensors, optimal scheduling and planning algorithms for power and computing resources are needed urgently. The existence of heterogeneous sensing networks also requires seamless information exchange and data communication through different protocols to achieve a high level of interoperability.

After data collection through sensors, the data needs to be **transmitted** to a centralised system, such as a cloud service. To this end, the 'things' are equipped with antennas to transmit data with protocols such as Bluetooth, WiFi, NFC, LoRa-WAN, ZigBee or cellular (5G and earlier generations of cellular network technology). Each protocol has its own advantages and downsides with regards to range, data transmission rates and cost, which means that there is no single, 'silver bullet' solution that dominates the others (see Figure 7). The choice of protocol depends on which protocol is most adequate to transmit data in a given use case (Yang et al. 2019: 5): Bluetooth is commonly used for short-range in-vehicle networking and wearable sensing applications, whereas ZigBee is the most popular wireless sensor network (WSN) protocol with low energy consumption well suited for ubiquitous sensing; Z-wave is suitable for smart home and health applications; NFC is commonly used in contactless payments via smart phones; and while these protocols are used for short-range communication (5cm to 100m), there are long-range and wide-area network protocols such as SigFox, Neul, LoRaWAN, and cellular communication technologies that are commonly used for smart city and environmental applications to transmit data over ranges from 2km to 200km. Independently of the choice of specific transmission technologies, the key is to transmit the disparate data from different 'things' into a central system where it can be stored, cleaned and analysed.

Moreover, some 'things' can go beyond just data collection and transmission. They can receive data and are equipped with **actuators**, i.e. they can receive and execute commands. This means that some 'things' can trigger human or machine action – but only after the data has been processed and analysed by other technologies of the emerging technology stack.

Once the data has been transmitted, they need to be **stored, processed and made available for analysis**. This normally entails the use of cloud solutions such as Amazon Webservices (AWS), Microsoft Azure, Google Cloud Platform (GCP), GE Predix, ThingWorx, IBM Watson, or C3 IoT among others. These platforms provide the software infrastructure to enable physical things and cyber-world applications to communicate and integrate with each other. They enable a variety of solutions such as cloud computing, embedded systems, augmented reality integration, data management, software applications, machine learning, and analytical services.

Once data have reached the location where they will be stored, **analysis**[3] can begin. Different data analytics methods, such as AI algorithms, can start crunching the data collected by the IoT. The most famous type of AI is *machine learning*,[4] a family of algorithms capable of learning patterns from labelled datasets to classify new data (supervised machine learning) or capable of extracting patterns from unlabelled data (unsupervised learning) (Renda 2019). These algorithms have one thing in common: they need large amounts of data, digitally available in an organised format. They are therefore highly dependent on the 'lower layers' to correctly perform their tasks: sensors, transmitters, connectivity.

Figure 5 – Different IoT protocols and their properties

Technology	Frequency	Data Rate	Range	Power Usage	Cost
2G/3G	Cellular Bands	10 Mbps	Several Miles	High	High
Bluetooth/BLE	2.4Ghz	1, 2, 3 Mbps	~300 feet	Low	Low
802.15.4	subGhz, 2.4GHz	40, 250 kbps	> 100 square miles	Low	Low
LoRa	subGhz	< 50 kbps	1-3 miles	Low	Medium
LTE Cat 0/1	Cellular Bands	1-10 Mbps	Several Miles	Medium	High
NB-IoT	Cellular Bands	0.1-1 Mbps	Several Miles	Medium	High
SigFox	subGhz	< 1 kbps	Several Miles	Low	Medium
Weightless	subGhz	0.1-24 Mbps	Several Miles	Low	Low
Wi-Fi	subGhz, 2.4Ghz, 5Ghz	0.1-54 Mbps	< 300 feet	Medium	Low
WirelessHART	2.4Ghz	250 kbps	~300 feet	Medium	Medium
ZigBee	2.4Ghz	250 kbps	~300 feet	Low	Medium
Z-Wave	subGhz	40 kbps	~100 feet	Low	Medium

Source: Vidales 2017

In most circumstances, the working of IoT systems is designed to support human control and decision-making, even if in principle IoT systems could be designed to be fully autonomous. The **level of interaction of the system with humans varies depending on the circumstances**, ranging from mere *ex post* oversight of autonomous systems by humans (or human-on-the-loop) to cases in which the human is fully 'in the loop', and data collection and analysis are performed to support a decision to be adopted by a human. To *support human decision-making*, insights must be presented in an understandable, actionable format such as dashboards, which provide a graphical user interface that make it possible to monitor useful key performance indicators (KPIs) quickly and generate reports for decision support.[5] When *actions are entirely automated* (in particular when IoT devices are equipped with actuators and data reception technology), the user interface will be limited to enabling oversight of key indicators and data visualisation, without providing decision-making tools. A farmer could, for example, decide that his irrigation system should be automatically switched on when the moisture sensors indicate a certain level of dryness. The central system can send a signal to the irrigation system and the actuators can then trigger irrigation. These types of human-machine interfaces can help companies save money and time.

2.2 The Increased complexity of IoT systems, and possible solutions

Thanks to the decreasing costs of data storage, data processing and faster internet connectivity, cloud service providers were able to build global networks of data centres, allowing for remote storage and processing of large amounts of data, 'the cloud'. As already explained, this kind of storage infrastructure is key to enabling IoT, as it provides for a fully managed and flexible IT architecture that can ingest the continuous stream of big data from IoT devices. More specifically, the cloud-based model fully leverages economies of scale, providing on-demand pay-as-you-go services to users and thus dramatically lowering the cost of using IT equipment; it provides elasticity of computing, storage, and networking resources that are flexible and scalable; and it facilitates big data analytics using machine learning technologies thanks to the highly centralised colocation of intensive computation and data (Pan and McElhannon 2018). The cloud also lets companies flexibly subscribe to more/less data storage and use processing hardware (CPUs, GPUs, TPUs) on an on-demand basis (Infrastructure as a Service, IaaS).[6]

But as IoT systems become more complex and numerous, and the tasks they perform become more sophisticated, the 'things-to-cloud' model is increasingly under pressure. There are several reasons why this is the case. First, with the increase in the quantity of connected devices, and in the resulting quantity of data to be processed, the **volume and velocity of data** makes it too costly and inefficient to always send the data to remote data centres. This would still be possible for relatively small and geographically concentrated networks, but not for many of the upcoming use cases, and especially those that are most directly related to SDGs (e.g. agriculture, oceans, energy grids, smart cities).

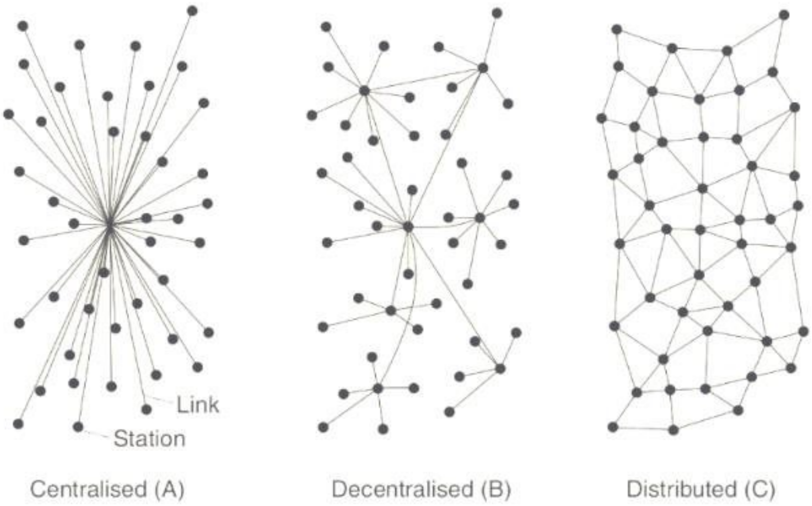
Second, **with distance comes latency**. The farther away a cloud data centre is geographically located, the more latency is introduced. For every 100 miles data travels, it is delayed by roughly 0.82 milliseconds. Depending on the protocol used for data transmission and on the use case, latency will increasingly become a key issue when designing IoT networks. The need to adopt autonomous decisions in a fraction of a second is essential in contexts such as autonomous driving: sending the data for analysis to a remote data centre would simply not do. Accordingly, every time an IoT system involves actuators and real-time decision-making, analysis and action items have to be processed locally, as close as possible to the 'things'.

Third, the centralised IoT model that has prevailed until now has also features important problems in terms of **concentration of market power**. Alongside economies of scale, large intermediaries have been able to accumulate enormous leverage on the whole ecosystem by building a portfolio of services that are almost impossible to replicate: this, especially in the United States but also in Europe, has led to a reduction in competition and rising inequalities, both between winners and losers in the marketplace, and between company shareholders and often independent, precarious workers. Some economists have voiced their concern that with the current centralised model, value creation and value extraction are increasingly separated, thereby exacerbating a phenomenon that had already started with the financialisation of the economy over the past half century (Mazzucato 2018).

Finally, a fully centralised model chiefly depends on the quality of data transmission over long ranges, and this can come with **security problems**, which are also enhanced by the fact that the system has limited redundancy in place, which would otherwise mitigate the risk of system failure. The skyrocketing of the number of connected things and the development of technologies that enable more sophisticated autonomous courses of actions means the 'attack surface' expands massively.

Thanks to the modularity of digital technologies, it is possible to imagine alternative forms of governance, which may address or mitigate this problem. Computer engineers and information systems architects have long been aware of the fact that in layered ecosystems, solutions can be fully centralised, distributed, or even fully decentralised, as shown in Figure 6.

Figure 6 – Centralised, decentralised and distributed computing



Source: Truong et al. (2016)

Looking at different network topologies, the immediate alternative to centralised IoT systems would be the implementation of intelligent solutions closer to things, and in particular 'at the edge'. While a fully decentralised system would entail 'embedded AI' in each of the connected objects, and would therefore be too costly using current technologies, most market analysts consider the so-called Edge/Cloud model to be the most interesting paradigm for the most sophisticated IoT use cases in the near future.[7] In an edge/cloud model, local computing, storage, and networking resources are provided close to IoT devices, and the data generated can be stored and pre-processed by the local edge cloud and only a small volume of processed data are eventually sent to central data centres.

Several attempts have been made at operationalising an edge/cloud model in the past few years. They include projects such as Cloudlet, Nebula, Femtocloud, HomeCloud and Fog Computing. Each of those alternatives has pros and cons, and as occurs for transmission protocols, different solutions may fit different use cases. All in all, the key to realising the full potential of these alternative architectures is in the deployment of new technological solutions that increase the flexibility, scalability and efficiency of previously too costly architectures. For example, the implementation of Network Functions Virtualisation (NFV) and Software-Defined Networking (SDNs) can provide numerous advantages to the dynamic management of edge/cloud systems, especially in the context of 5G deployment, another technology that will be key to IoT systems requiring dense networks and a wide coverage, and a high degree of softwarisation of functions previously performed through hardware. As observed by Pan and McElhannon (2018), "the core concept of Network Softwarisation is called 'Slicing', which turns networks into logically isolated units of programmable resources such as networking, computation and storage. Synergy between NFV and SDN technologies becomes indispensable for such a perspective".

Furthermore, with increased complexity also comes a greater need for complex, even autonomous orchestration, which goes beyond existing models, often run by humans and based on simple 'if-then' instructions. Also, the more a multiplicity of applications needs to be orchestrated, the less likely are existing methods going to prove fit for purpose. Other needs, such as dynamic and flexible offloading of traffic from IoT devices onto the edge layer will become increasingly needed in the future and require further research and market deployment.

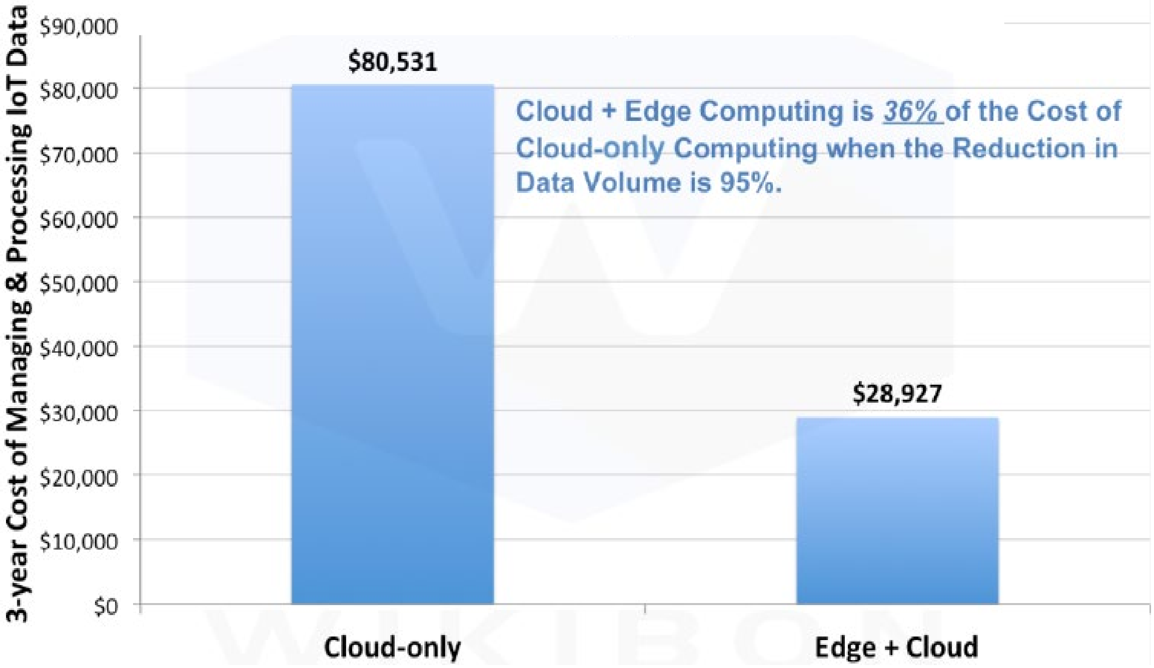
Table 1 – Comparing conventional cloud computing with edge/cloud

Characteristics	Conventional cloud computing	Edge cloud and edge computing
Major applications	Most of the current mainstream cloud-involved applications	Applications on IoT, VR, AR, smart homes, smart cities, smart energy, smart vehicles, etc.
Availability	A small number of large-sized datacenters	A large number of small-sized datacenters
Proximity of services and resources; Data processing location	Usually in remote datacenters and far from users	At the edge close to the users
End-to-end latency	High, due to the distance between the edge and remote datacenters	Low, due to proximity to the users
Backbone network bandwidth consumption	High, since huge data need to be transferred to the datacenters first	Low, since data are locally processed and stored in edge cloud
Scalability	Scalable at center	Scalable both center and edge
Security (e.g., attacks on data enroute)	Data subject to attack due to long-distance transmission; Physical security depends on large facilities	Lower risk for enroute attacks; Physical security varies and different mechanisms needed

Source: Pan and McElhannon 2018: 440

As already explained, the conventional cloud models will remain viable for a number of use cases. However, several emerging applications would strongly require an edge/cloud architecture. The more an application requires low latency (e.g. wearable cameras, industrial monitoring systems, autonomous vehicles) and high data bandwidth (e.g. virtual reality), the higher the number of devices involved (e.g. soil monitoring in agriculture), and the more complex the task to be performed, the greater the need for an edge/cloud solution. Depending on the use case, edge/cloud solutions can offer important cost savings on top of a more distributed structure. In 2015, for example, David Floyer studied the data management and processing costs (see Figure 7) of a remote wind-farm using a cloud-only system versus a combined edge/cloud system. The wind-farm consisted of several data producing sensors and devices such as video surveillance cameras, security sensors, access sensors for all employees, and sensors on wind-turbines. The edge/cloud system turned out to be 36% less expensive and the volume of data required to be transferred was observed to be 96% less, compared to the cloud-only system (Floyer 2015).

Figure 7 – Comparison of total 3-yr management and processing costs of 'cloud only' versus 'edge+cloud' with 95% edge data reduction (200 miles distance)



Source: Wikibon IoT project

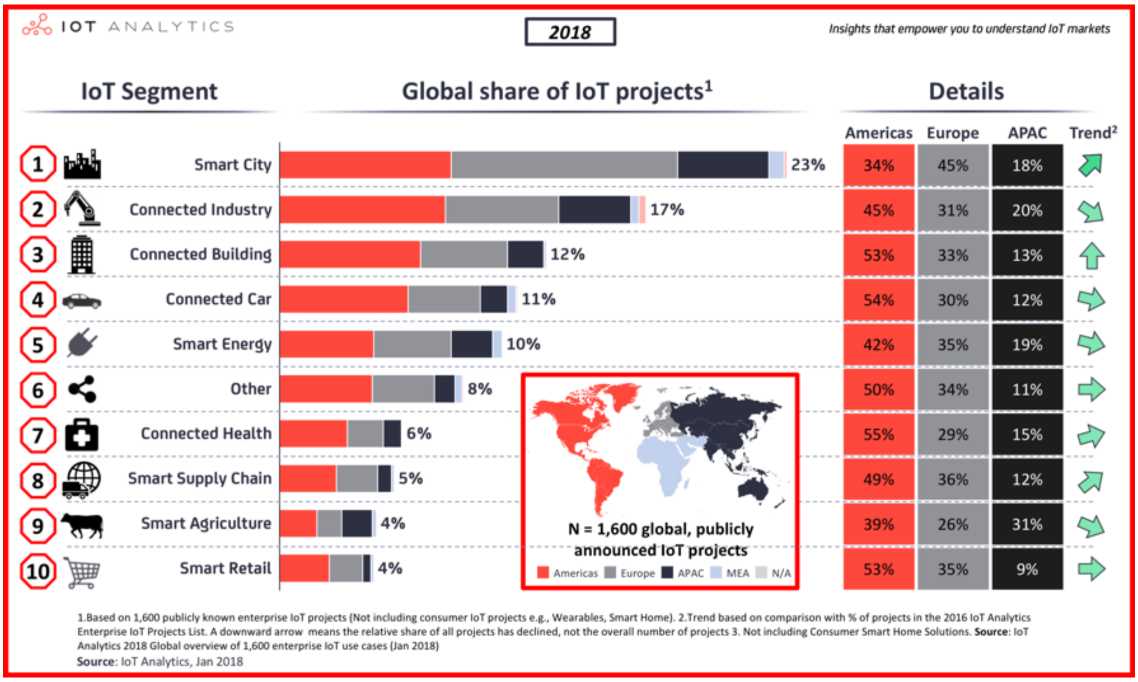
According to existing research, performing computations at the network edge has several advantages:

- The volume of data needed to be transferred to a central computing location is reduced because some of it is processed by edge devices.
- The physical proximity of edge devices to the data sources makes it possible to achieve lower latency which improves real-time data processing performance.
- For the case of data that still must be processed remotely, edge devices can be used to discard personally identifiable information (PII) prior to data transfer, thus enhancing user privacy and security.
- Decentralisation can make systems more robust by providing transient services during a network failure or cyberattack.
- Edge computing increases scalability by expanding compute capacity through a combination of edge and IoT devices.

3 IoT for sustainable development: a look at the most prominent use cases

In which sectors is IoT technology actually being deployed? What does this tell us about future trends in IoT and its potential for the SDGs? Figure 8 breaks down publicly-known IoT projects by sector and region based on comprehensive research into the global IoT market (IoT Analytics 2018a). As shown in the picture, Smart Cities is now the most important segment of the IoT market, mostly due to many smart city initiatives by governments and municipalities for smart traffic, utilities, lightning and environmental monitoring. Connected Industry is the second most important segment for IoT, both with applications inside and outside of factories. Non-factory projects include, for example, asset monitoring and remote control of connected machinery such as cranes, forklifts, or entire mines and oil fields. In-factory projects include automation and control projects, such as production floor monitoring, wearables on the shop-floor, or automated quality control. The Connected Buildings segment has grown the most from 2016 to 2018. Out of all Connected Buildings projects, 61% involve facility-automation to reduce energy costs; 39% are related to building security and 31% to HVAC/Heating/Cooling (IoT Analytics 2018).

Figure 8 – IoT projects by sector and region



Source: IoT Analytics 2018a

Other segments such as Smart Agriculture and Connected Health have grown over the past years but remain relatively small compared to the main segments. One interesting trend in a number of segments is the strong position of Asian countries compared to the US and Europe. More generally, while 'the West' is still leading in most segments, a comprehensive literature review of IoT in agriculture and food revealed that research in the domain is very much dominated by Asian scientists, especially from China: out of 168 reviewed papers, only 14 were from non-Asian authors (Verdouw et al. 2016). This trend will certainly continue over the coming years and

decades, as Asian countries catch up technologically or high-tech countries like Japan invest further. The scale of this trend is hard to estimate, as available estimates often tend to attach more weight to research being published in English language, often ignoring or under-representing other languages.

3.1 IoT use cases in selected sectors

In order to better understand how IoT is used in these segments by companies on the ground, this section zooms in on the most important use cases in four selected sectors: manufacturing, healthcare, energy and mobility.

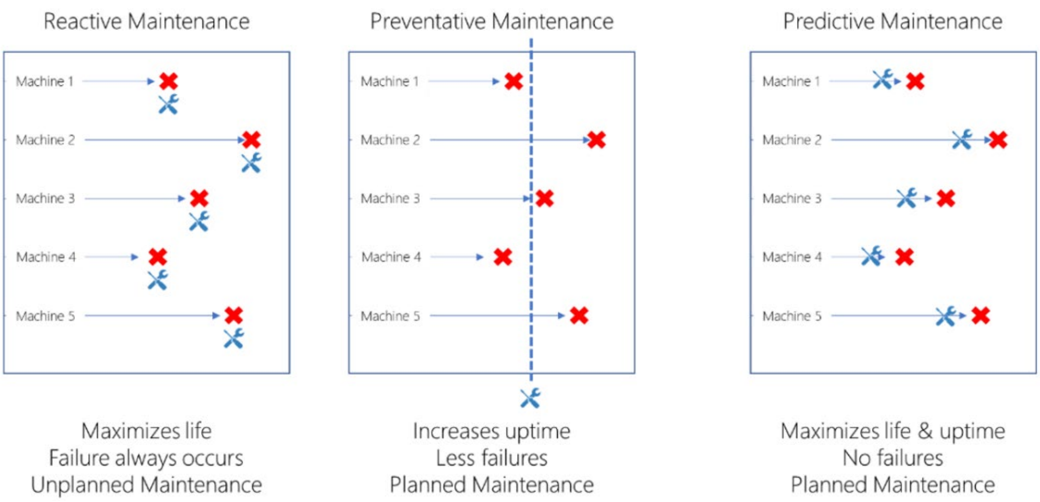
3.1.1 Manufacturing and 'Industry 4.0'

In a highly competitive world market, manufacturing companies are trying to combine IoT, cloud services, big data analytics and advanced robotics to stay competitive – a trend often subsumed under the umbrella term 'Industry 4.0' (Müller et al. 2018; Ibarra et al. 2017; Xu et al 2018; Strange et al. 2017; Nagy et al. 2018; PwC 2016; BCG n.a.; McKinsey 2015). Exploring the benefits and challenges of the most important use cases of Industry 4.0 in general, will allow us to draw conclusions about their potential for the SDGs and Society 5.0 in particular.

3.1.1.1 Predictive maintenance

One of the most important use cases of Industry 4.0 is predictive maintenance. Previous maintenance methods dealt with machine failures as they arose (reactive maintenance) or involved regular asset inspections based on time schedules and experience (preventive maintenance). Predictive maintenance, on the other hand, uses sensor data from machinery to predict machine failure and therefore enables maintenance right before the failure occurs (Seebo 2018: 6). Predictive maintenance providers promise a reduction in maintenance costs of 5-10% (Seebo 2018).

Figure 9 – Reactive, preventive and predictive maintenance



Source: Microsoft 2019

Take the **example of an airplane company** which wants to increase machine uptime and reduce failure risks. Grounded and defective airplanes are a big cost for airplane operators – while an airplane is grounded for maintenance it is not making money and machine failures are significant financial, reputational and security risks. In order to reduce these costs and risks, airplane companies and their suppliers employ predictive maintenance (Microsoft 2016; Rolls-Royce 2018).

First airplane manufacturers install IoT sensor hardware in the machinery to **collect relevant data,** such as the temperature or vibrations in the engine, which can be indicative of approaching engine failure. Today, an Airbus A350 aircraft has 6,000 sensors producing 2.5Tb of data per day to measure the health and performance of its systems and provide insights by tracking diverse data from fuel flow, pressure and temperature to the aircraft's altitude, speed, weather and air temperature (Rolls-Royce 2018). The IoT hardware then transmits these large amounts of data to a central **cloud system for storage and processing**. Cloud platforms provide the flexible infrastructure to store a growing amount of historical data and also provide the computing hardware necessary to crunch the data. Data scientists can then **clean and analyse** the data, in order to find patterns that indicate engine failure. Data scientists have two general approaches for predictive maintenance analysis at their disposal (Seebo 2018). They can manually discover patterns in the data and define explicit data-based rules for maintenance in cooperation with maintenance experts (*rule-based predictive maintenance*). The team could, for example, define a specific threshold value for engine temperature and vibration and if this threshold is exceeded, the system is pre-programmed to send an alert. A more advanced and challenging approach is *machine learning-based predictive maintenance*. Here, the data science team needs to create a labelled dataset containing incidents of past machine failures (dependent variable) in combination with other data (potential explanatory variables). The algorithm can then be trained on this dataset. If the dataset is of sufficient quality (and ideally continuously updated), the trained algorithm can predict future machine failures. The predictions can then be integrated into a **human-machine interface**, such as a dashboard, and help engineers to find the ideal time of maintenance. As a result, aircraft operators can reduce the time their airplanes are not operating and increase safety, therefore saving time and money. Since 40% of airlines' operating expenses are fuel costs, airlines are also trying to use the large amounts of data to optimise and reduce fuel consumption. This can potentially lead to environmental benefits (Microsoft 2016). More research is needed, however, to determine whether this has a net positive effect on the environment given the energy costs of collecting and processing 2.5Tb of data every day.

3.1.1.2 Other use cases of IoT in manufacturing

Stock and inventory management is another business function in manufacturing which can be optimised by IoT. Using IoT sensors to monitor the inventory stock in real time can reduce the risk of stock-out or over-stock and therefore save valuable time, space and labour costs; valuable assets like mobile machinery on large factory floors can be tracked with location sensors to maintain an overview of available assets and reduce the risk of theft; the quality and condition of goods can be tracked, for example with temperature sensors for temperature-sensitive products or vibration sensors for fragile goods (Sensolus n.a.). Similar technologies can be applied in **supply chain management**: incoming supply can be tracked with location sensors, enabling more efficient planning; the location of outgoing goods can be shared with business partners and customers to help them plan and increase their satisfaction (Unleashed 2018). Both inventory and supply chain management can be optimised with **automated vehicles**, a more

advanced use case of IoT. As machines grow more and more autonomous, the incentive will grow for companies to use them to increase efficiency and reduce labour costs (see Section 3.5 on mobility for more details). In addition, the data collected by the IoT could drive innovations like **digital twins**, virtual replicas of physical devices that can be used for lower-resource simulations of manufacturing processes.

3.1.1.3 Impact and drivers for adoption

The above use cases have shown that the **main drivers for adopting IoT** and other new technologies are economic: saving money, time and exploring new business models (see also PwC 2016; BCG n.a.; McKinsey 2015). In competitive markets, companies' primary goal is to stay competitive through lower prices, increased quality or innovative products and services (Porter 2004).

Table 2 shows that Industry 4.0 provides a promising means to achieve these business goals. The table also shows, that there is evidence for not only positive effects on business, but also on workers and the environment. Automation can reduce monotonous work, new technologies can facilitate age-appropriate workplaces and can reduce the environmental impact of production.

Table 2 – Exemplary literature on opportunities of Industry 4.0

Category	Exemplary Literature	Main Contributions
Strategy	Arnold et al., 2016; Arnold et al., 2017; Brettel et al., 2014; Burmeister et al., 2016; Kagermann et al., 2013; Laudien et al., 2017; Rennung et al., 2016	• New business models through Industry 4.0 • New value offers for enhanced competitiveness
Operations	Erol et al., 2016; Kagermann et al., 2013; Lee et al., 2014; Meyer et al., 2014; Oettmeier and Hofmann, 2017; Rehage et al., 2013; Rogers and Trombley, 2014; Rudtsch et al., 2014; Saberi and Yusuff, 2011; Schmidt et al., 2015; Stock and Seliger, 2016	• Increased efficiency • Decreasing costs • Higher quality • Increased speed & flexibility • Load balancing & stock reduction
Environment and people	Berman, 2012; Gabriel and Pessel, 2016; Herrmann et al., 2014; Hirsch-Kreinsen, 2014; Kagermann et al., 2013; Kiel et al., 2017; Oettmeier and Hofmann, 2017; Peukert et al., 2015; Stock and Seliger, 2016	• Reduction of monotonous work • Age-appropriate workplaces • Reduction of environmental impact

Source: Müller et al. 2018: 4

Nevertheless, on competitive markets, the main driver for IoT adoption will be economic. If a predictive maintenance project promises increased productivity, then the increased energy consumption of IoT devices and cloud services and the increased e-waste will play a secondary role in the company's calculations, as long as the costs do not outweigh the benefits.

The impact on the SDGs is therefore mostly relevant in the case of SDG 8 (Decent Work and Economic Growth) and SDG 9 (Industry, Innovation and Infrastructure), but the positive impact on environmental SDGs seem less clear and questions with regards to unemployment due to automation remain open. There is, however, a clear sustainability potential for new technologies. Policymakers can create incentives for companies to invest more in sustainability,

for example through carbon taxation, carbon trading, or incentives for more sustainable products and sustainable finance. Companies are then incentivised to invest in technological solutions such as IoT to reduce energy consumption and waste. By creating a level regulatory playing field for all companies, those who invest more in sustainability will not suffer a competitive disadvantage. We will come back to this argument in Chapter 4, when it comes to policy recommendations and the regulatory environment that needs to be created in order to reconcile sustainability and competitive markets.

3.1.2 Healthcare and the mIoT

Developed healthcare systems are one of the biggest achievements of the modern welfare state. In the past years, however, healthcare systems have come under pressure by budget cuts and an ageing population. IoT and related new digital technologies can provide one answer to these challenges by bringing healthcare to people's homes and into their pockets, promising reduced costs and increased quality of health services.

3.1.2.1 Use cases for the medical Internet of Things (mIoT)

Today, although still in its infancy, the medical Internet of Things (mIoT) has started to be used in three general domains of healthcare (Ahmadi et al. 2018). First, **home healthcare** uses new technologies to limit the need of patients to visit a doctor or hospital in person. Simple consultations can be administered via online video systems; health data can be collected remotely via mobile IoT devices, such as smart watches for vital sign monitoring; sleep patterns can be monitored via sensors in wrist bands; and emergency situations can be identified via sensors for fall detection or seizure detection. These solutions have one thing in common: they limit the need for in-person consultations, which can help save time and money for patients and doctors (Yin et al. 2016: 7; Islam et al. 684 - 690).

Second, **mobile and electronic health** systems use IoT while people are on the move. Different wearable devices can collect health data, such as blood glucose or insulin levels; smartphone applications can incite people to track their eating habits and maintain healthy diets; apps can be used to incite and monitor sport for preventive care and aftercare; the plethora of data collected by these devices can be used for 'predictive healthcare', identifying patterns to alert people of risk factors, similar to 'predictive maintenance' in manufacturing. All of these solutions promise to make people less dependent on expensive medical equipment and allow for more personalised healthcare (Ahmadi et al. 2018; Yin et al. 2016: 7; Islam et al. 684 - 690).

Third, mIoT can improve **hospital management**. In addition to using the above mentioned devices in hospitals, IoT can help improve how hospitals are run and organised: IoT can be used to render logistics and stock management more efficient and liberate money and labour for more relevant tasks, similar to use cases in the manufacturing sector (Ahmadi et al. 2018).

3.1.2.2 Benefits and obstacles

As the mIoT is still in an early stage of adoption, there is only limited academic evidence on the impact of mIoT and a majority of publicly available use cases are distributed by private vendors with an incentive to neglect downsides of their technologies (Wanga et al. 2018). Nevertheless,

a systematic study on big data analytics and IoT use cases investigated the different domains, in which current applications promise to be beneficial (see Table 3). The study finds that most use cases aim towards IT infrastructure benefits (e.g. by reducing system redundancies or reducing IT costs) and operational benefits (improving the quality of clinical decisions, or reducing the need for patients to travel). These benefits can be unlocked by increasing the capability to collect and analyse large amounts of unstructured data; support decision-making; create predictive capabilities; and increase traceability (Wanga et al. 2018: 7-10).

Table 3 – Most cited benefits of big data analytics

Potential benefits of big data analytics	Elements	Frequency	
IT infrastructure benefits	Reduce system redundancy	19	79
	Avoid unnecessary IT costs	17	
	Transfer data quickly among healthcare IT systems	17	
	Better use of healthcare systems	13	
	Process standardization among various healthcare IT systems	9	
	Reduce IT maintenance costs regarding data storage	4	
Operational benefits	Improve the quality and accuracy of clinical decisions	21	73
	Process a large number of health records in seconds	16	
	Reduce the time of patient travel	15	
	Immediate access to clinical data to analyze	8	
	Shorten the time of diagnostic test	8	
	Reductions in surgery-related hospitalizations	3	
	Explore inconceivable new research avenues	2	
Organizational benefits	Detect interoperability problems much more quickly than traditional manual methods	8	13
	Improve cross-functional communication and collaboration among administrative staffs, researchers, clinicians and IT staffs	3	
	Enable to share data with other institutions and add new services, content sources and research partners	2	
Managerial benefits	Gain insights quickly about changing healthcare trends in the market	5	9
	Provide members of the board and heads of department with sound decision-support information on the daily clinical setting	2	
	Optimization of business growth-related decisions	2	
Strategic benefits	Provide a big picture view of treatment delivery for meeting future need	3	5
	Create high competitive healthcare services	2	
Total		179	

Source: Wanga et al. 2018: 9.

Regarding the mIoT's **potential to contribute to the SDGs**, a review of nine use cases investigated the contribution to three groups of SDGs, based on expert judgements (see Table 4). The study finds that their weighted contribution is highest in the domain of Economic Prosperity (45.3%), followed by Quality of Life (31%) and Environmental Protection (23.6%) (Alansari et al. 2018: 682). Interestingly enough, the use cases with the highest potential benefit are 'ultraviolet radiation' (sensors to measure UV rays, which can provide recommendations to reduce UV rays exposure (sun) during certain hours) and 'dental health' (Bluetooth-enabled toothbrushes which collect brushing information to study the person's brushing habits, share the statistics with the dentist and send recommendations via smartphone apps).

Table 4 – Contributions of different use cases to different groups of SDGs

Options	Economic prosperity	Quality of life	Environmental protection
Fall detection	0.109	0.096	0.14
Medical fridges	0.084	0.11	0.039
Sportsmen care	0.069	0.0836	0.153
Patient surveillance	0.117	0.0954	0.121
Chronic disease management	0.079	0.104	0.025
Ultraviolet radiation	0.193	0.132	0.176
Hygienic hand control	0.098	0.094	0.12
Sleep control	0.068	0.143	0.059
Dental health	0.183	0.142	0.167

Source: Alansari et al. 2018

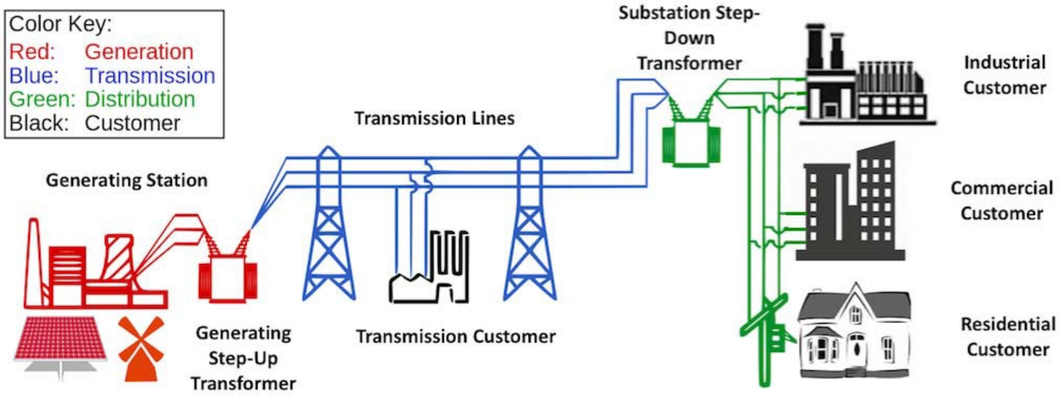
Unfortunately, the adoption of new technologies in the healthcare sector is lagging behind other sectors. This is due to factors such as: budgetary constraints and a lack of basic digitalisation; a conservative culture, lacking data-driven thinking; data protection and security challenges; a lack of trained personnel; a lack of data governance structures, both with regards to available technological infrastructure and explicit rules to incite adoption; a lack of standardisation and interoperability (Wanga et al. 2018: 11; Yin et al. 2016: 7); messy data (Hicks et al. 2019; Dhindsa et al. 2018); and overpromising. IBM's Watson, for example, is a prominent case of a high-tech company promising revolutionary products, but only producing digital assistants that can perform certain routine tasks (Strickland 2019). Similarly, Google's DeepMind is suffering from limited commercial success (Marcus 2019).

3.1.3 IoT in the energy sector

Even if data and IoT are driving many contemporary innovations, the IoT is nothing without energy. In fact, the entire emerging technology stack described in Section 2 depends on energy supply. As these technologies grow, so does their energy consumption, exacerbating existing environmental problems. IoT applications in the energy sector, however, promise to alleviate this problem. As in other sectors, IoT can increase efficiency and cost savings – which, in the energy sector, also leads to energy savings.

IoT hardware can be used in all four elements of electric power and energy systems (EPES): power generation, transmission and distribution (T&D) and consumption (Reka et al. 2018; Bedi et al. 2018). Thanks to IoT hardware, physical signals in energy systems can be translated into digital data, which in turn can be used to detect inefficiencies and optimise the system.

Figure 10 – Schematic overview of electric power and energy systems (EPES)



Source: Bedi et al. 2018: 849

As renewable energy resources become an increasingly important part of the energy mix, integrating these 'distributed power resources' (DER) into existing systems is an important challenge. Since renewable energy depends on, for example, daily sun and wind patterns, renewable power generation is more variable and uncertain (Bird et al. 2013). IoT devices, such as smart metres, intelligent feeders or micro phasor measurement units can collect the necessary data to help adapt to this supply-side variability. The collected data can then be used to improve load forecasting, state predictions, distribution control and optimise system balancing (Bedi et al. 2018: 850). In addition, IoT devices equipped with actuators can automatically execute commands to dynamically adapt the system and increase efficiency (Reka et al. 2018: 96; Aleksandrova 2019).

Transmission and distribution networks face challenges such as outages, power loss and theft and DER integration. IoT can provide new monitoring and control solutions to network providers to address these challenges. The solutions can help reduce the response time to power outages and enable predictive maintenance; help account better for distributed power resource integration; and reduce power loss and theft by adjusting electrical parameters in real time (Bedi et al. 2018: 850; Reka et al. 2018: 97; Aleksandrova 2019).

IoT devices are important drivers contributing to the growth of consumer-facing microgrids and smart homes. Today, **customers** (industrial or residential) can generate power locally from renewable sources to meet their needs and can participate in power exchanges with the electric power network. IoT devices can provide customers with power generation and usage data that helps them utilise power more efficiently and control costs. Smart home occupancy sensors and power monitors can, for example, help adapt energy usage and heating to actual needs (Bedi et al. 2018: 850 - 853; Reka et al. 2018: 98; Aleksandrova 2019).

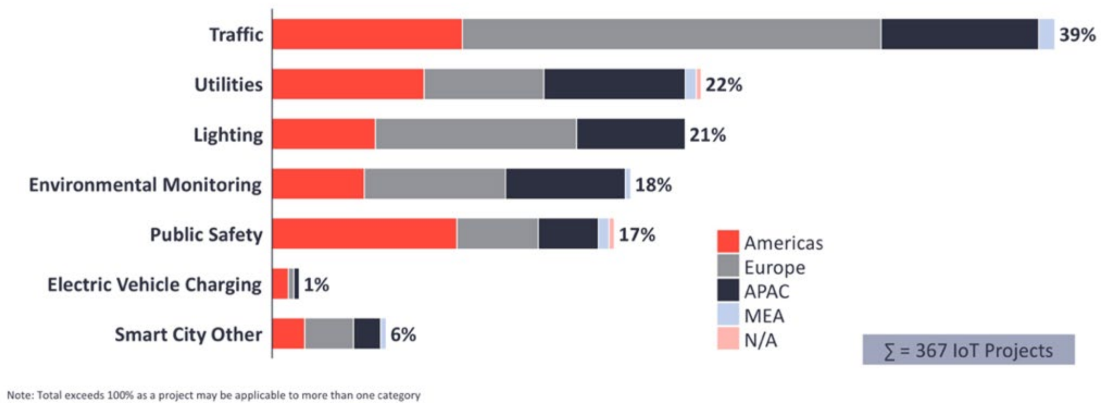
In conclusion, there is a sizeable literature estimating the business opportunities associated with energy systems and IoT at hundreds of millions or billions of dollars (see for example McKinsey 2013; Cisco Systems 2013). While there are fewer studies providing concrete numbers on the environmental impact (Bedi et al. 2018: 854), the environmental benefit of IoT in the energy sector seems nevertheless very plausible. As IoT is designed to increase efficiencies and reduce costs, energy companies have an incentive to use IoT to increase energy efficiency and reduce energy costs (Aleksandrova 2019). Economic and environmental effects are more closely intertwined in the energy sector than in other sectors, given that reduced energy waste and CO_2 emissions are a positive externality of economic optimisation.

As in other sectors there are several constraints for IoT adoption. (1) Increased interoperability and standards are necessary in three domains: first, service-related standards provide common definitions for services to support IoT applications; second, communications-related standards provide common protocols for data transmission and security; third, data-related standards provide for data formats independent of specific technologies or providers. (2) Co-existence challenges: as IoT devices become more numerous and they often share similar frequency bands, transmission can suffer from interference. (3) Cyber security and privacy challenges: as every IoT device is a potential attack vector in the connected system, cyber security is poised to become a more important issue. This particularly true for critical energy infrastructure. (4) IoT functionality: the current IoT devices still lack some important functionalities, such as internal battery management and fault tolerance; detection of abnormal sensor events; or handling of transmission errors (Reka et al. 2018; Bedi et al. 2018: 855 - 864; Aleksandrova 2019).

3.1.4 Mobility in smart cities

Today, more than 4.2 billion people, 55% of the global population, live in urban areas – a number projected to grow to 68% by 2050 (UN 2018: xix). Cities are the backbone of modern society: they house the world's financial centres, are drivers for economic growth and innovation and, at the same time, lead to overcrowding, resource consumption and pollution (GlobalData 2017; Knoll 2014; United Nations 2011). Given cities' economic importance, it is no surprise that the smart city sector is also the most important sector for IoT applications today. Many different applications promise to improve people's lives in cities, ranging from connected streetlights, smart metres for electricity or water measurement, camera surveillance of public spaces to smart bins (IoT Analytics 2018b). The leading use case of IoT in cities is smart traffic (see Figure 11).

Figure 11 – Smart city projects by segment



Source: IoT Analytics 2018c

With thousands to millions of people being crowded in relatively little space and trying to commute to work or meet friends via congested roads or public transportation, IoT-based systems promise urgently needed efficiency gains in traffic. Take '**smart parking**', for example. Operators of parking spaces can use cameras or smart parking metres to monitor the demand and supply of parking space and adjust their offer accordingly. Parking can be made more efficient with licence plate recognition systems or parking assistance apps, which can inform drivers of available space. These solutions increase time efficiencies and convenience to users, while opening new possibilities for monetisation. Providers can combine their data with other

stakeholder's data (such as merchants, city agencies, delivery firms) and increase advertisers' or city planners' understanding of consumer behaviour or driving patterns (IoT Analytics 2018d).

A more advanced use case for IoT in smart traffic are **autonomous vehicles**, ranging from driver assistance systems (level 1) to full automation (level 5). Advances in IoT sensor and transmission technologies are instrumental for enabling vehicles to navigate in complex environments such as streets or warehouses. Autonomous vehicles are equipped with location sensors (GPS), mapping sensors such as LIDAR lasers or radars for measuring distance, and cameras for object detection (Rudolph et al. 2017). Some companies are starting to use automated vehicles to transport parts within warehouses or factories, allowing them to save labour costs and increase efficiency. Further in the future, automated vehicles will also be used to transport goods outside of the (comparatively) controlled environment of warehouses (Accenture 2017). Many leading companies and countries are investing heavily in private autonomous transportation (KPMG 2019), but progress is slower than anticipated (Lohmann et al 2018). A study by RAND Corporation argues that autonomous vehicles could have a positive impact by reducing the accident rate, energy consumption, pollution, congestion and labour costs (Anderson et al. 2014). On the other hand, automation can have a negative impact on employment and increase energy use and e-waste. Future empirical studies will have to investigate the positive and negative impacts, once the technologies are more mature (Sarkis et al. 2018).

Besides autonomous driving, vehicle manufacturers are already installing hundreds or thousands of sensors to better understand their products. These sensors can, for example, be used to monitor ***vehicle health*** and optimise fuel consumption of large vehicle fleets (see the predictive maintenance example in Section 3.1.1.1). In addition, fleet ***logistics*** can be optimised based on a systematic knowledge of vehicle's locations and their use (Cosgrove 2018; Verma 2018). Another use case is ***'geo-fencing***' in (and outside) cities. Smart phones can track the location of their users and trigger actions if the user enters a pre-defined area (the geo-fence). Since locations are primarily tracked via Wi-Fi signals, cell-towers and GPS, the accuracy of these services is particularly high in cities. Geo-fencing can be used for advertising purposes (e.g. building user profiles or sending notifications to users when they are close to a store), asset monitoring (e.g. in logistics when trucks arrive in a defined area or deviate from their path) or crowd control (e.g. for public transportation to dynamically adapt to high traffic, or for surveillance purposes) (White 2017; Verma 2018).

As in other sectors, IoT in mobility has great potential to save time and money for companies and can help achieve environmental and social goals. The examples above have shown that congestion problems can be alleviated, self-driving cars can reduce labour costs and increase convenience, and geo-fencing opens new business opportunities and energy consumption can be reduced. While IoT can help attain sustainability goals the primary goal for adoption by private companies are economic: saving time, money and generating new business (Wilde 2018). These goals can be positive for economic SDGs (8, 9). Recent research on IoT and smart transportation, however, puts into question the environmental benefits of IoT. With a projected 20-50 billion IoT devices by 2020, some researchers are focusing their attention on possible negative consequences of an **'IoT Flood'** (Xu et al. 2018). Taken together, these devices consume large amounts of energy and can create electrical pollution; they cost resources to produce; and they create e-waste when disposed of. These hidden environmental costs need to be taken into account when calculating the benefits and costs of IoT. One estimate suggests, for example, that in 2020, 110 million vehicles will be delivered with 200 sensors per vehicle each roughly consuming 1 watt. These sensors combined could consume 22,000 megawatt-hours, which is the equivalent of 17.8 million energy consumers (Xu et al. 2018).

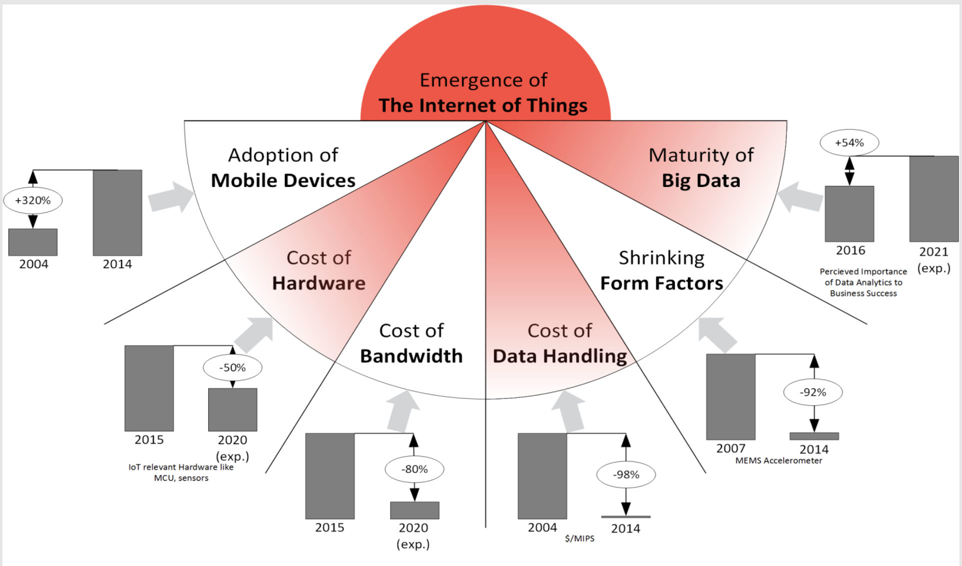
Box 2: The size of the IoT market and barriers for expansion

It is relevant to note that the IoT market is still a comparatively small market. In early 2018, the total number of enterprise projects was estimated to be in the range of 10,000 to 30,000 projects (IoT Analytics 2018a, see also WEF 2018: 6). Why is the IoT market still comparatively small and what is holding back its potential? The reasons why most IoT projects still do not easily scale are technical, commercial and regulatory.

- *On the technical side,* ***interoperability challenges complicate deployment and slow down scalability****. This technological fragmentation will require standardisation efforts by private and public bodies.*
- *On the* ***commercial front, costs and ease of deployment have to improve to convince companies of the commercial benefits of IoT.*** *That is why the budgets for sustainable IoT implementations are currently extremely limited and they mostly come from company funds related to innovation and digital projects. It will be some time before mainstream business P&L budgets – which are substantially larger – can convert these small implementations into large-scale deployments. Decreasing costs have already been an important driver for IoT and costs can be expected to fall further (see Figure 12).*
- *On the* ***policy side, the main barriers are related to security and privacy****. At the same time, there seems to be room for additional effort, especially in the EU, to foster the implementation of digital* technologies *'for good' through various policy means.*
- *Most importantly,* ***these problems must be related to the whole technology stack for the IoT to deliver its full potential****. In particular, the combination of IoT with AI appears to have a very significant potential to help the EU achieve its SDGs, and possibly help other countries do the same via its external action, also centred around the SDGs.*

At the same time, the emergence of IoT is driven by several factors, which will continue to boost the growth of IoT (see Figure 12).

Figure 12 – Drivers for the emergence of IoT



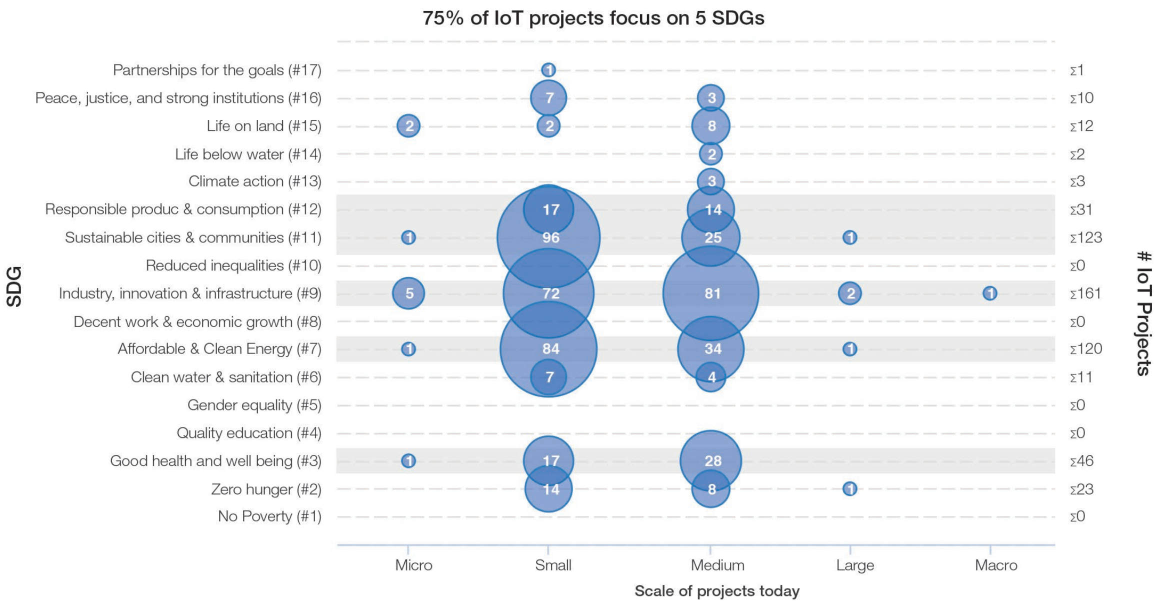
Source: STMicroelectronics, McKinsey, Yole DéveloppementIoT, Analytics

3.2 The reality of IoT and SDGs today

The use cases in Section 3.1 have demonstrated how IoT is primarily used by companies and governments in different sectors today. But is IoT already being linked to the SDGs in particular? A study by the World Economic Form and research firm IoT Analytics analyses 640 IoT deployments and investigates to which SDGs they mostly contribute. They argue that most IoT deployments can address SDGs, but most of them are concentrated on three: #9 Industry, innovation, and infrastructure (25%); #11 Sustainable cities and communities (19%); #7 Affordable and clean energy (19%) (WEF 2018). This focus stems from the IoT's potential to increase efficiencies and cut costs: it can reduce costs in manufacturing industries; increase efficiencies in overcrowded cities; or improve our energy systems.

On the other hand, only a few IoT projects address SDGs such as 'No Poverty', 'Zero Hunger', 'Climate Action', 'Life on Land / Below Water' (see Figure 13 below This shows a key challenge for IoT and SDGs: the current adoption of IoT technologies is primarily driven by rich cities and private companies. Both lack a structural incentive to address SDGs that concern the most vulnerable global populations and the environment (see also WEF 2018: 6).

Figure 13 – IoT projects and their impacts on SDGs



Source: WEF 2018

There is a need to shift gear when it comes to the main IoT applications that can contribute to the SDGs. The current main motivation for IoT adoption is cost saving (54% of projects), while only 35% of IoT projects are used to increase revenue through new products and services, and 24% are aimed at increasing safety through monitoring systems and real-time alerts (IoT Analytics 2018a). This is understandable and positive from a business perspective, as companies search for means to stay competitive in the market and city administrations seek to reduce costs in times of budgetary restraints.

From a sustainability perspective, however, this can have positive, but also negative effects. Cost reductions and efficiency increases, especially in the energy sector can be beneficial for the

environment. On the other hand, the hard- and software infrastructure necessary for running the IoT can have considerable environmental costs, as it consumes non-negligible amounts of energy and produces e-waste. Similarly, from a social perspective, the IoT can create new jobs and increase convenience. At the same time, if cutting (labour) costs is one of the main drivers for IoT adoption, it is unclear whether the net social benefits are positive. To make the IoT a true force for sustainability, the main challenge is to incentivise the private and public sector to internalise these environmental and social externalities.

The current state of IoT begs the crucial question: How could IoT deployment benefit more vulnerable communities and foster the achievement of economic, environmental and social SDGs? In order to answer this question companies and governments first need to investigate which IoT applications have the highest sustainability potential – i.e. which economically viable investments also create a positive social and environmental impact.

4 The EU policy for IoT and for SDGs: current landscape and possible reforms

Our analysis of IoT use cases that can contribute to the SDGs, coupled with a round table with experts organised in January 2020, showed the need for proactive policy and investment initiatives in the European Union. Several areas could be identified for improvement.

First, as a general remark, **the IoT seems to be often addressed indirectly by EU policy, through initiatives that focus on complementary technologies** such as AI, or connectivity. A greater 'salience' of IoT in the policy debate would help the EU find suitable solutions, in a way that reorients the current deployment towards the SDGs.

Second, our analysis and research suggest that **it will be very difficult to achieve the SDGs without a significant contribution of the private sector**, in the form of sustainable business models and a careful selection of investment projects that safeguards and promotes sustainability. Given the emergence of IoT as a major technology segment in the years to come, incentivising the private sector to align their investments and business models towards sustainability appears essential for the achievement of the EU's 2030 goals. This could be done through various types of regulatory incentives and techniques, not only for technology companies but also for investors; however, none of these options would be successful without an adequate framework for measuring and reporting the impacts of investment on the SDGs.

Third, it is of utmost importance that EU institutions achieve **greater policy coherence for sustainable development**. This means that, independently of the budget earmarked for IoT projects, all areas of EU action (both policy and spending) are aligned towards the deployment of sustainable technologies, including, of course, the Internet of Things.

Below, in Section 4.1, we offer a description of the current policy landscape. Section 4.2 discusses possible policy options for the future, and Section 4.3 illustrates a possible framework for enabling the measurement of the impacts of IoT projects on SDGs. Section 4.4 offers some concluding remarks.

4.1 The EU funding and policy landscape: an emerging awareness of the role of technology for SDGs

The EU landscape for IoT has traditionally focused on project funding, largely separate from *ad hoc* policies, let alone sustainability objectives. In the past few years, a set of supporting policy actions have been adopted and proposed by the European Commission to accelerate the take-up of IoT and to unleash its potential in Europe for the benefit of European citizens and businesses.

In terms of funding, while the EU has several different programmes which directly or indirectly relate to new technologies and sustainability (European Commission 2019c), the **most relevant fund for IoT is the research and development programme Horizon 2020**. The programme alone included almost €500 million in IoT-related research, innovation and deployment investments from 2014 to 2021, ranging from healthcare for older adults to autonomous driving.[8] For the period **2021-2027, the follow-up programme Horizon Europe** will probably comprise the bulk of future EU investments in IoT. At the moment of drafting this section, the final funding for Horizon Europe is not yet entirely defined, as negotiations over the EU budget continue. A preparatory document for the Strategic Plan for Horizon Europe (European Commission 2019d)

mentions IoT in various clusters, such as Cluster 3 on "Civil Security for Society", flagging the need to tackle for security and privacy risks; Cluster 4 "Digital, Industry and Space"; Cluster 5 "Climate, Energy and Mobility". The Commission also considers that IoT will be a useful tool for achieving the upcoming Horizon Europe "missions", already launched in five areas including i.a. Smart Cities and "Soil health and food".[9] This shows the cross-cutting nature of IoT research and applications. In general, there seems to be significant room for improvement in the incorporation of the IoT and SDG components in various parts of Horizon Europe (e.g. the Partnerships); and even more in other parts of the EU budget, including the Common Agricultural Policy, InvestEU, and cohesion funds. We will return to this issue in Section 4.4. below.

From a policy perspective, the new European Commission has made important steps towards achieving coherence between digital technologies and sustainability, and indeed set the European Green Deal and the digital transformation (or making "Europe fit for the digital age") as the two main priorities for the next five years. However, more emphasis has been placed on Artificial Intelligence, even if in most cases the EU institutions seem to refer to a broader set of technologies, including IoT: **very often, the debate on AI takes place as if AI were only a software domain, but the need for sensors and actuators is almost always evident in AI applications that are the most impactful for SDGs**. Likewise, all applications of IoT that imply the production of vast swaths of data, to be processed either locally or in the cloud, contemplate some application of AI (or, more specifically, machine learning) to enable the most effective and efficient analysis of the data produced.

4.1.1 The new EU digital priorities

On 19 February 2020, the new European Commission outlined its priorities for the digital agenda in the years to come, showing enhanced attention for sustainability impacts. Specifically, the Commission announced the deployment of new actions in both social and environmental areas.

Regarding environmental measures, the Commission plans to directly tackle a key issue of IoT – e-waste – with a circular electronics initiative, supporting the durability, reuse and recycling of digital devices (in 2021). Moreover, an initiative to achieve climate-neutral data centres by no later than 2030 is planned. In order to tackle the social challenges of digitalisation, a Digital Education Action Plan will be released, and the Skills Agenda will be reinforced, with a particular focus on early career digital skills development (by Q2 2020). Moreover, an initiative to improve labour conditions of platform workers is planned for 2021 and a European health data space to improve safety and transferability of health data is planned for 2020. Cognizant of the challenges digital disinformation can pose for democracy, the Commission also announced a European Democracy Action Plan (by Q4 2020), to support, for example, media diversity. These measures are highly welcome and directly address several key challenges of digitalisation. It remains to be seen, however, how these measures are put into practice and if they receive the necessary financial and political support to achieve their ambitious goals (European Commission 2020e).

More generally, the Commission has committed itself to align all new Commission initiatives in line with the objectives of the Green Deal and promote innovation (European Commission 2019c). What role can the Internet of Things play? A recent Commission communication observed that "digital technologies are a critical enabler for attaining the sustainability goals of the Green Deal in many different sectors", and announced that the Commission will explore measures to ensure that digital technologies such as AI, 5G, cloud and edge computing and the IoT can "accelerate and maximise the impact of policies to deal with climate change and protect

the environment". At the same time, the Communication stressed the need for the digital sector to put "sustainability at its heart". While the measures mentioned above address the negative environmental consequences of digital technologies, at the same time more and more technologies are being developed that can help save the environment. Section 4.2 provides a reflection on how these high potential use cases of IoT can be identified and measured.

4.1.2 The emerging policy framework on AI

The current debate on AI is relevant for the future of IoT and SDGs in Europe. In particular, the EU High-Level Expert Group on AI has set the goal of achieving "Trustworthy AI" in Europe, and has included "societal and environmental well-being" as a key requirement of trustworthy AI.[10] The HLEG specifies that "sustainability and ecological responsibility of AI systems should be encouraged, and research should be fostered into AI solutions addressing areas of global concern, such as for instance the Sustainable Development Goals". Moreover, the group encouraged "a critical examination of the resource usage and energy consumption during training, opting for less harmful choices"; recommended a careful assessment of the impact of AI systems on social agency, social relationships and attachment, social skills, physical and mental well-being, and the impact on society and democracy at large.[11]

On 19 February 2020, the newly elected European Commission set out its future plans for AI in a White Paper "On Artificial Intelligence – A European approach to excellence and trust", strongly building on the recommendations from the AI HLEG. The paper outlines the first elements of an upcoming regulatory framework and announces several action points. The action points include: a public consultation on AI with a view to revising the Coordinated Plan on AI with the member states by the end of 2020; facilitating the creation of excellence and testing centres; establish and support networks of leading universities to attract AI talent; ensuring that a digital innovation hub in every member state specialises in AI; setting up a new public private partnership in AI, data and robotics in the Horizon Europe programme; and sectoral dialogues to facilitate AI development and adoption.

What does the White Paper mean for the SDGs and IoT? The Commission states that "the use of **AI systems can have a significant role in achieving the Sustainable Development Goals**" (European Commission 2020c: 2). Some of the criteria that could be part of the EU's AI governance framework, are clearly related to the SDGs. Non-discrimination and fairness of AI systems is directly relevant for SDG 5 (Gender Equality) and SDG 10 (Inequality). The repeated reference to societal and environmental well-being also indicates that the Commission is aware of both the risks and benefits that AI and IoT can have for the environment.[12] To what extent the SDGs will be an explicit part of the EU's approach to AI will only become clear as the EU takes concrete action in the coming months and years.

4.1.3 The European strategy for data and the new EU industrial policy

On 19 February 2020, the Commission also published the "European strategy for data", a communication announcing four upcoming regulatory measures (European Commission 2020a):[13] it will propose a legislative framework for the governance of common European data spaces (by Q4 2020); adopt an implementing act on high-value datasets (by Q1 2021); possibly propose a Data Act in 2021; and conduct a review of the existing policy framework in the context of the digital services act package (by Q4 2020). In addition, the Commission is planning on

investing up to €2 billion in a high impact project on European data spaces (with a first implementation phase foreseen for 2022); wants to launch a European cloud services marketplace in order to integrate the full stock of cloud service offerings (by Q4 2022); and seeks to create an EU (self-)regulatory cloud rulebook (by Q2 2022).

These measures are, of course, highly important for the IoT, given that the IoT incarnates the physical infrastructure for data collection. The planned 'Green Deal data space' is particularly interesting as it makes a concrete link between data-driven technologies and sustainability. The Commission announced it would: evaluate and possibly review legislation such as the Access to Environment Information Directive to facilitate data access; roll out re-usable data-services; develop a digital 'product passport' containing information to support the circular economy and reduce e-waste; and launch the 'Destination Earth' initiative in 2021, which aims to develop a high-precision digital model of the Earth and forecast natural and human activity on the planet. These measures have the potential to tap the potential of IoT and reduce its risks. Especially the 'Destination Earth' initiative seems like a particularly high potential use case for IoT (see also Section 4.3.1 for the high potential of natural disasters forecasts).

In addition, the Industrial Policy Communication is expected in March 2020. All in all, it has the potential to boost IoT deployment in Europe, through enhanced clarity and availability of complementary technological solutions such as IDS, edge/cloud storage and processing, and embedded AI solutions. These solutions, coupled with legal and regulatory clarity on the treatment and exchange of data, may in turn lead to a more balanced distribution of value across industrial supply chains, avoiding the extraction of value by large digital platforms and cloud providers. These developments are considered essential to guarantee economic and social sustainability: if properly implemented, they could also lead to environmental sustainability, given the energy-saving potential of edge computing and IoT. However, the overall environmental impact of future IoT deployment will depend on the specific solutions identified, since IoT can also consume energy and lead to increased e-waste (Louchez et al 2014).

4.1.4 Mainstreaming SDGs in EU policy. The European Green Deal and the sustainable finance framework

The EU has shown strong commitment towards the SDGs. Since November 2016, a series of communications outlined the future agenda for 2030, centred on SDGs. The Commission presented the new agenda as a joint initiative with member states and "many different actors", aimed at fostering a "stronger, more sustainable, inclusive and prosperous Europe". Most importantly, in the Communication "Next steps for a sustainable European future", the Commission made clear its intention to mainstream sustainable development in European policies: this includes, most notably, the European Semester, the EU budget, the better regulation agenda, and of course the external action strategy. More recently, the new European Commission led by Ursula von der Leyen has relaunched the commitment towards sustainable development, including the SDGs in the mission letters sent to Commissioners and Vice-Presidents, and attributing to the Commissioner for Economic Affairs the responsibility for coordinating the implementation of SDGs in all EU policies, as well as in the European Semester. This patchwork of initiatives, still lacking full coordination, is reflected in the state of advancement of the EU towards the SDGs. Recently, in a stocktaking exercise of progress achieved over the past five years, Eurostat found that progress was strongest for SDG 3 (Good health and well-being), SDG 4 (Quality education) and SDG 1 (No poverty); slow or inexistent for

other SDGs, and even slightly negative on SDG 9 (Industry, innovation and infrastructure) (Eurostat 2019).

When it comes to SDG- and sustainability-related policies, the most important new initiative is without a doubt the European Green Deal (European Commission 2019f). Its annex contains several concrete proposed measures to start in 2020 (European Commission 2019a). They include: a 'Climate Law' to enshrine the 2050 climate neutrality objective; revisions of the Emissions Trading System Directive, Energy Efficiency Directive, Renewable Energy Directive and Energy Taxation Directive. Moreover, the Commission is planning to: propose legislative waste reforms; a strategy for sustainable and smart mobility; a "zero pollution action plan for water, air and soil"; and integrate the SDGs in the European Semester. In addition, new financial tools have been proposed for increased climate action: the InvestEU fund will allocate at least 30% of funding to fighting climate change and a Just Transition fund of up to €100 billion could be proposed. Details remain, however, unclear as the new Commission only took office recently (Greenpeace 2019).

A key challenge for the transition to a sustainable economy is providing incentives to investors to prioritise sustainable projects when deciding what to finance. The Commission estimates that to achieve climate neutrality by 2050, Europe needs between €175 billion and €290 billion in additional yearly investment in the next decades. To this end the Commission is hoping to mobilise large amounts of private funding, notably through the renewed sustainable finance strategy (due in September 2020), building on the existing action plan for sustainable finance (European Commission 2020b). As part of the EU's strategy, financial market participants will, for example, have to disclose to their clients the impact of their investment decisions on sustainability (the obligation will apply from March 2021) and new guidelines and standards will support sustainable investment decisions. These measures are linked to the planned review of the non-financial reporting directive (due in autumn 2020), which already requires large companies with more than 500 employees to disclose non-financial information on their social and environmental impact and its revision will require additional impact reporting (European Commission 2020f).

But how can social and environmental impacts actually be measured? It is easy to call for more information, but in practice there are several challenges linked to measuring social and environmental impacts. In order to further investigate this question, IoT technologies and the SDGs are used as an example to illustrate these challenges. In addition, a four-step approach is developed, which can be used to identify IoT use cases with a high potential to contribute to the SDGs and measure their impact.

4.2 Leveraging the private sector contribution to SDGs: how can the impact of IoT be measured?

A key challenge for the measurement of the impact of IoT solutions in relation to the SDGs is that most of **the existing frameworks for alignment of business conduct with the SDGs are conceived for whole organisations, rather than for individual projects or technologies like IoT.** In order to evaluate the potential of IoT for the SDGs, individual projects and use cases need to be analysed, instead of entire organisations with their broad set of activities. It is therefore important the be aware of **several key challenges related to measuring the potential of IoT for the SDGs**, given that measuring the SDGs alone has been called "an unprecedented statistical challenge" (FES 2018).

First, the **diversity of the SDGs** makes it impossible to assess the impact on the SDGs as a whole. Methodologies for measuring global health (SDG 3) differ strongly from methodologies for measuring climate impacts (SDG 13). In addition, methodologies for measuring the same SDG can vary across countries, given the specific socio-geographic challenges of different countries around the globe. In order to produce concrete results, it is therefore advisable to study the impact on a specific SDG in a specific country or region.

Second, the **diversity of IoT solutions and architectures** itself poses challenges for measuring impact. Given the variety of different IoT devices and use cases, impact assessments become sharper as they narrow down to more specified sets of use cases. In addition, even within one use case, the IoT is always part of a larger technology pipeline – from IoT-driven data collection to cloud infrastructure to (machine learning) analysis to human data-driven action (see Chapter 2). This 'embedded nature' of IoT makes it difficult to measure its specific impact.

Third, even if a specific SDG and IoT application is chosen, it is very challenging to create a clear **causal link** between IoT and the desired outcome. Take, for example, Goal 11 (Make cities and human settlements inclusive, safe, resilient and sustainable) and the associated indicator 11.5.1 (Number of deaths, missing persons and directly affected persons attributed to disasters per 100,000 population). IoT sensors can be a crucial component of an early warning system against extreme natural events like tsunamis. By sensing and transmitting early indicators it can save lives by raising a warning minutes or hours earlier than older systems. The actual number of lives saved depends, however, also on many other factors: sufficient road infrastructure to flee endangered sites, a sufficient communication infrastructure to spread the early warnings, and medical infrastructure to take care of those affected by the disaster, etc.

Fourth, estimates have to be based on **'counterfactual assumptions'**: no one can know what would have happened if the tsunami warning had come 30 minutes later. One can only assume what would have happened without IoT sensors, all else being equal. Distilling the impact of IoT on the lives saved in a disaster is therefore very difficult. In addition, a comprehensive counterfactual analysis would also have to consider the potential benefits of solutions other than IoT.

Fifth, there are **operational and neutrality challenges** for impact assessments. For most impact assessments new data have to be collected, which requires investments in interviews, surveys or impact models, depending on the impact to be measured. In addition, if the study is conducted by or for an interested party, such as a government or IoT device producer, there is an incentive to overestimate the positive impact of the technology (see for example studies on the "political economy of bad data" by Sandefur, Glassmann 2015). This risk can be reduced, but not eliminated, by outsourcing the impact assessment to a neutral third party. These operational challenges require a genuine commitment to invest money in an assessment that might not lead to the desired results.

Sixth, impact assessments entail several **methodological challenges**: *interviews* can be used to discover new information and qualitative assessments, but questions have to be carefully phrased to produce unbiased results; *surveys* can produce larger scale quantitative information, but require prior knowledge and acquiring representative samples is a challenge; *econometric models* can reduce complexity and provide numeric estimates, but the choice of variables and their weights are to some extent based on subjective judgements. The great strength of quantification is also its weakness: quantification reduces complexity and makes it more digestible for decision makers, but consciously disregards certain factors. Moreover, research shows that the trend to measure development targets can lead to overinvestments in

specifically measurable targets, while other, non-measurable targets (e.g. social goals) can be neglected (Fukuda-Parr 2014).

All of these challenges point to a key conclusion: **in order to measure the impact of IoT on the SDGs, the measurement needs to be broken down into concrete IoT applications and specific SDG targets or indicators**. An impact assessment needs to be specific in order to add value. In this vein, the following sections survey the different SDG targets and extracts specific, high potential targets.

4.2.1 Four key steps for measuring the impact of IoT projects on SDG targets

Despite the challenges in measuring the impact of IoT on the SDGs outlined in the previous section, the impact of IoT-related projects can and should be measured. The 17 SDGs are in fact accompanied by 169 targets and 232 indicators, explicitly designed to measure and track progress made towards achieving the goals. But to which SDGs can IoT technology contribute the most? And what concrete steps need to be taken to measure the impact of IoT-related projects on the SDGs? These questions are crucial for public and private organisations, considering to invest in digital technologies like IoT for sustainable purposes. To answer these questions, we suggest a four-step approach.

First, identify high potential IoT use cases; second, choose specific targets and translate them into measurable KPIs; third, measure and monitor impact; and fourth, evaluate and communicate.

Step 1: Identify IoT use cases with the highest potential for attaining the SDGs

Before investing in IoT, it is essential to identify the IoT use cases with the highest potential to help reach SDG targets. Organisations might be tempted to retrospectively link their IoT projects or products to the SDGs. In contrast, we suggest an 'SDG-first' approach, which first assesses the extent to which different IoT use cases can contribute to SDG targets. The purpose of this test is to ensure that organisations choose and prioritise IoT projects with the highest potential for sustainability.

In order to illustrate this approach, we created a 'prioritisation table', testing different IoT use cases for their potential contribution to SDG targets (see table 5). This process was guided by three key questions:

- ***To what extent does the specific IoT use case directly contribute to attaining the target?*** For some targets, IoT is a direct part of the solution, while for others it is only a support for measurement. Regarding target 14.3 (Minimise and address the impacts of ocean acidification), IoT sensors are a useful tool to measure pH levels (Indicator 14.3.1), but IoT cannot directly reduce acidification. For target 7.3. (By 2030, double the global rate of improvement in energy efficiency), IoT can measure energy demand, produce load predictions, help integrated sustainable energy in the network and make transmission and distribution more reliable. IoT therefore makes a direct contribution to increased energy efficiency. For the first criterion, the contribution of IoT was therefore rated as 'high' for target 7.3., but 'low' for target 14.3.
- ***What is the estimated impact of the specific IoT use case on the target compared to alternative solutions?*** It is important to verify whether other solutions are more impactful

or cheaper than specific IoT use cases with respect to the SDGs concerned. Also, solutions may be relevant in developing countries but not in developed countries. For target 3.4 (By 2030, reduce by one third premature mortality from non-communicable diseases through prevention and treatment and promote mental health and well-being), IoT is not an important solution in least developed countries, where a sizeable part of the population is not connected to the internet and much cheaper solutions, such as anti-malaria bed nets or anti-worm tablets, can address more pressing problems (GiveWell 2020). In developed countries, however, IoT can make a valuable contribution to making established health care systems more efficient. We therefore rated the potential impact of IoT for target 3.4 as 'medium'. When it comes to target 1.5 (Reducing the risk of extreme climate-related events), IoT can make a unique contribution to early warning systems both in developing and in developed countries, thanks to its ability to collect data, predict trends and transmit warnings. For this second criterion, the potential of IoT for target 1.5. was therefore rated as 'high'.

- ***Does the IoT use case entail adverse side effects on the target?*** For many SDGs, IoT does not entail particular risks. For targets like 15.1 (Conservation, restoration and sustainable use of terrestrial and inland freshwater ecosystems), however, e-waste and pollution caused during IoT production and disposal can have a negative effect. This third criterion reduced the overall rating of IoT for some targets.

For the first two criteria, we estimated the potential of IoT on a scale from 'low', 'medium' to 'high' based on the experience from the literature review in Chapters 2 and 3. The third criterion could reduce the overall rating through a 'negative side effects' rating. Based on these three questions, we estimated the aggregate potential positive impact on selected targets from all 17 SDGs (see Table 5).

This table is by no means meant to be exhaustive or a final judgement on the impact of IoT on the overarching goals, nor does it cover all IoT use cases. It does, however, provide a starting point for choosing specific 'high potential' targets and exploring IoT's impact more deeply.[14] In addition, it is important to note that there are many different IoT use cases and architectures and the technology is constantly evolving. As different IoT use cases and architectures develop, the assessment might change when there are alternative technology options and governance models within the IoT realm, which could maximise the positive impact on the SDGs.

Table 5 – Prioritisation table: The potential impact of IoT on selected SDG targets

Overarching goals	Selected targets with possible IoT contributions	Added value of IoT	Aggregate estimation of potential positive impact on target	1. Extent of IoT's direct contribution to target	2. IoT's impact compared to other solutions?	3. Adverse side effects?
1. No Poverty	1.5 By 2030, build the resilience of the poor and those in vulnerable situations and reduce their exposure and vulnerability to climate-related extreme events and other economic, social and environmental shocks and disasters	Using IoT sensors to collect and distribute reliable data on e.g. weather in order to predict and quickly react to extreme weather events	High	High	High	/
2. Zero Hunger	2.3 By 2030, double the agricultural productivity (…)	Increase agricultural productivity through precision farming	Medium	High	Medium/low	/
3. Good Health and Well-Being	3.4 By 2030, reduce by one third premature mortality from non-communicable diseases through prevention and treatment and promote mental health and well-being	Use connected health devices to monitor, analyse and treat diseases	Medium	High	Low	/
4. Quality Education	No target directly linked to established IoT use cases	/	/	/	/	/
5. Gender Equality	No target directly linked to established IoT use cases	/	/	/	/	/
6. Clean Water and Sanitation	6.1 By 2030, achieve universal and equitable access to safe and affordable drinking water for all. (See also 6.1.1, 6.3.1; 6.3.2; 6.4.1)	Using IoT sensors to monitor water quality; creating a verifiable and actionable map of water quality in cities	Medium	High/medium	Medium/low	/
7. Affordable and Clean Energy	7.3 By 2030, double the global rate of improvement in energy efficiency	Using IoT sensors for better monitoring, demand and load predictions in order to increase energy efficiency	High/medium	High	High/medium	Energy consumption of IoT devices
8. Decent Work and Economic Growth	8.2 Achieve higher levels of economic productivity through diversification, technological upgrading and innovation, including through a focus on high-value added and labour-intensive sectors	Using IoT sensors and analysis to increase efficiency in agriculture, manufacturing, services	High/medium	High	High/medium	Potential job loss through automation
9. Industry, Innovation and Infrastructure	9.4 By 2030, upgrade infrastructure and retrofit industries to make them sustainable, with increased resource-use efficiency and greater adoption of clean and environmentally sound technologies and industrial processes (…). See also 9.2; 9.5	IoT is part of modern digital infrastructure	High/medium	High	High	Creation of e-waste and CO_2 emissions through IoT

10. Reduce Inequalities	No target directly linked to established IoT use cases	(IoT can increase inequality, by favouring countries and companies with the financial and human capital and infrastructure to use IoT)	Low/negative	/	/	IoT can increase the gap between those countries and companies that have the capital to deploy it
11. Sustainable Cities and Communities	11.6 By 2030, reduce the adverse per capita environmental impact of cities, including by paying special attention to air quality and municipal and other waste management	Use IoT sensors to monitor different environmental indicators (e.g. 11.6.2) to inform action (but only indirect contribution through measurement)	Medium/High	High/medium	Medium/low	Creation of e-waste and CO_2 emissions through IoT
12. Responsible Consumption and Production	12.3 By 2030, halve per capita global food waste at the retail and consumer levels and reduce food losses along production and supply chains, including post-harvest losses	Using IoT sensors to track food waste and enable better supply chain management	Medium	Medium	Medium/low	/
13. Climate Action	13.1 Strengthen resilience and adaptive capacity to climate-related hazards and natural disasters in all countries (see also 13.3)	Using IoT to build early warning and predictive systems against natural disasters	High	High	High	IoT creates CO_2 emissions
14. Life Below Water	14.3 Minimise and address the impacts of ocean acidification	Use IoT sensors to measure the pH levels (indicator 14.3.1) and inform action (but no direct contribution to solution)	Low	Low (only measurement)	low	/
15. Life on Land	15.1 By 2020, ensure the conservation, restoration and sustainable use of terrestrial and inland freshwater ecosystems and their services, in particular forests, wetlands, mountains and drylands	Use remote sensors/satellites to measure forest areas (indicator 15.1.1) and inform action (but no direct contribution to solution)	Low	Low (only measurement)	Low	Creation of e-waste and CO_2 emissions through IoT
16. Peace, Justice and Strong Institutions	No target directly linked to established IoT use cases	/	/	/	/	/
17. Partnerships for the Goals	17.6 Enhance North-South, South-South and triangular regional and international cooperation on and access to science, technology and innovation (…)	Exports of IoT technologies contribute to technology sharing	High/Medium	High	Medium	/

Step 2: Choose targets and measurable KPIs

The ‘prioritisation table’ provides an overview of the potential direct contribution of IoT technology to the SGDs from an ‘SDGs-first’ perspective. If organisations strive to use digital technologies in a sustainable way, they should ideally take these considerations into account when choosing IoT projects. An important challenge is that the SDGs were created as state-level targets and can therefore not be directly transferred to the logic of individual organisations. To enable organisations to contribute to the SDGs at their own level, the targets need to be translated into company-level key performance indicators (**KPIs)**.

A useful quality guideline for creating useful KPIs are the SMART criteria: a KPI should be Specific, Measurable, Attainable, Realistic and Time-bound to be a useful tool for evaluating performance. The SDGs are accompanied by official indicators, which are a good starting point (see UN-stats 2019) for translating the targets into concrete KPIs suitable at the organisation- or project-level. One of the most comprehensive sources of inspiration for sustainability KPIs for individual projects are the **GRI Sustainability Reporting Standards** (2018). The GRI provides a diverse set of 24 economic, environmental and social standards with precise reporting requirements, recommendations and guidance. They range from indirect economic impacts and taxes (economic), to energy and waste (environmental), or employment and training (social) and can be clearly linked to the SDGs (GRI & United Nations Global Compact 2018). Alternatively, other organisations like Nasdaq have also elaborated metrics for ESG reporting that can be used as KPIs (2019).

Take the **example of SDG target 7.3:** By 2030, double the global rate of improvement in energy efficiency. A company cannot attain this global target, but it can take equivalent action at company level: substantially improve energy efficiency or reduce its energy consumption (GRI Standard 301-1). The GRI Standard can be used to translate this target into a SMART KPI: use energy consumption as a specific indicator; quantify and measure it with GRI’s proposed formula (see Figure 14); set an attainable and realistic target given the companies resources; and set timely goals and regular evaluations (see the following steps).

Figure 14 – GRI Disclosure 302-1, Energy consumption within an organisation

Total energy consumption within the organization
=
Non-renewable fuel consumed
+
Renewable fuel consumed
+
Electricity, heating, cooling, and steam purchased for consumption
+
Self-generated electricity, heating, cooling, and steam,
which are not consumed (see clause 2.1.1)
-
Electricity, heating, cooling, and steam sold

Source: GRI Disclosure 302-1: 7

Step 3: Measure and monitor impacts of an IoT project

The KPI then needs to be put into practice through measuring and performance monitoring. As discussed above, the method for measurement strongly depends on the type of SDG and business use case. Organisations have to choose between the different methods described in Section 4.2, ranging from sensor-based measurement (e.g. electricity metres), to assessing perceived impact (through interviews or surveys), to assumption-based models (modelling impact through the simplified relationship of a limited amount of quantifiable variables), to more complex experimental studies.

Take the **example of an IoT project to reduce energy consumption**: an office building might, for instance, want to reduce its total energy consumption with a smart heating system. Heat and movement sensors could be deployed to ensure that only used spaces are heated. In this case, the impact of the project can be measured by comparing the energy consumption as measured with the formula in Figure 14 before and after deployment. In this case, energy consumption data can be obtained from the financial department based on energy purchases in a defined period, the energy provider, or electricity metres. Given the data collecting nature of IoT, it is also well-suited for continuous performance monitoring via sensors.

In other cases, indicators will not be easily quantifiable via sensors and companies will have to invest in different methods. To measure the impact of an IoT-based precision farming system on productivity, a survey among farmers could be conducted to compare their productivity before and after the deployment of IoT (SDG target 2.3 – By 2030, double the agricultural productivity…); to measure the lives saved through an IoT early warning system against natural catastrophes, an assumption-based model might have to be built, estimating the time and lives saved through an early warning; to measure the health benefits of a Fitbit, more complex experimental designs and randomised control trials might have to be designed to measure the impact of IoT on health KPIs such as heart rate (see Section 4.2.1 for different measurement methods).

Step 4: Evaluate the project and communicate results

Creating and maintaining high quality sustainability data is a substantial challenge for many organisations. The World Business Council for Sustainable Development (WBCSD) provides useful guidance for evaluating and improving the quality of SDG-related data following initial trials (2019). While this guidance was developed for company-wide ESG reporting, the recommended steps can also be applied to inform the **evaluation of individual projects and the impact on SDGs**:

(1) **Reassess the original business and sustainability targets**. It is almost inevitable that targets are not perfectly designed. Revisiting them after first trials, and in the light of more experience, is a necessary part of the learning process. As a first step, organisations should therefore make their original objectives explicit and be open to refining them.

(2) In order to understand which improvements are necessary, WBCSD suggests a rich **set of questions to evaluate key issue areas** (2019: 12 – 17): Responsibility and reporting structure (e.g. "Have you determined who is responsible for the metric?"); Definitions (e.g. "Have you defined how metrics should be calculated?"); Scope ("Have you excluded any countries or activities? If so, why?"); Significance to your business model ("Have you considered the significance of individual metrics to your business model?"); Reporting frequency and

format ("How often should the data be reported?"); Information flows and identified risks ("Have you identified the steps in the data collection process that may pose a risk to data quality?"); Established control ("Have you defined and described the controls in place to mitigate the identified risks?").

(3) **Develop a roadmap for improvement**. After asking these key questions, a roadmap for improvement should be developed, which can include: a gap analysis; a review of resources available to implement changes; a manageable timeline aligned with existing internal control and reporting cycles (see WBCSD 2019: 11 for more details); and a review of how data is governed. Putting these changes in place entails **establishing a control environment** with explicit standards of conduct and a culture of quality reporting supported by senior management. Some tools suggested by WBCSD are the creation of an ESG data manual to establish a common understanding of how KPIs are defined and internal best practices for data collection; a chart of accounts can be used to uniformly collect data; a consolidation system can be used to collect and report data, to ensure completeness of information and increase the level of management oversight (WBCSD 2019: 18 – 21). These tools can be an important part of internal reporting and monitoring procedures.

If organisations evaluate and improve data quality through these steps, they can self-confidently report their contribution to the SDGs and **communicate** their results to external stakeholders. The GRI details guidance for reporting and provides several reporting principles (see Figure 15 and GRI 101 2016 for more details). While it is tempting to communicate only success stories, selective and incomplete reporting can be perceived as PR rather than genuine efforts to increase sustainability. It is therefore essential to include stakeholders and adhere to transparent principles when communicating impact.

Figure 15 – GRI Reporting Principles

Reporting Principles for defining report content	Reporting Principles for defining report quality
• Stakeholder Inclusiveness	• Accuracy
• Sustainability Context	• Balance
• Materiality	• Clarity
• Completeness	• Comparability
	• Reliability
	• Timeliness

Source: GRI 101: Foundation 2016: 7

The four-step process described in this section – (1) prioritising, (2) selecting KPIs, (3) measuring and monitoring and (4) evaluation and communication – can be understood as an iterative cycle of constant learning and improving. It is not easy to create an evaluation culture in an organisation and it requires a long-term commitment from all hierarchy levels of the organisation. Starting with an individual project and learning from this experience can be a valuable step towards measuring the impact of IoT projects on SDG targets on the company level.

These reflections on measuring the impact of IoT on the SDGs are, however, not only relevant for individual companies. Decision-makers depend on more data and empirical evidence on technologies with the highest sustainable impact. Such assessments are therefore a precondition, before economic, social and environmental challenges can be tackled effectively.

4.3 An agenda for this decade

We live in times of climate crisis, environmental and biodiversity degradation, persistent global poverty, deteriorating social cohesion and, in some regions, very uncertain economic prospects. At the same time, the awareness of the positive impact that technology can exert in economic, social and environmental terms is mounting. Likewise, the possible risks associated with digital technologies are also increasingly debated. All in all, the role of public policy appears essential in order to maximise the benefits of digital technology, while at the same time minimising the risks. Back in 2015, the international community set itself 17 Sustainable Development Goals, which public and private organisations have committed to reach by 2030. Policymakers, businesses and civil society are now searching for the most effective measures that can make these goals a reality. This report investigates a key emerging technology with outstanding potential to help attain these goals – the Internet of Things. It provides an overview of how IoT is mostly used today in selected sectors: in manufacturing, to save time and money through predictive maintenance, inventory and supply chain management; in healthcare, to enable home healthcare, mobile health and to improve hospital management; in the energy sector, to increase efficiency and save costs in energy generation, transmission & distribution and consumption; in smart cities, to increase convenience and save time through smart traffic and parking or for self-driving cars. We conclude that **IoT can massively contribute to several SDGs, especially through its capacity to increase efficiency and save costs**. Accordingly, it is mostly used in projects related to industry and infrastructure (SDG 9), smart cities (related to SDG 11) and affordable and clean energy (SDG 7), while it is less used in projects related to poverty or the environment. As IoT is still a relatively young and complex technology, its use is mostly driven by wealthy cities and businesses. Its potential for more vulnerable populations in the global south and the environment remains underdeveloped.

This points to an **important dilemma for IoT today from a sustainability perspective**. **The main driver for IoT adoption is cost reduction and increased efficiency**. Especially under the circumstances of competitive markets, poverty reduction and environmental measures mostly remain a secondary reflection in the development of IoT. While no one expects IoT to become a universal tool for all 17 SDGs, more use cases need to be explored for IoT to show its true potential for sustainability as the technology matures. However, public policy choices will be essential in order to ensure that IoT solutions spread beyond leading countries and firms, and reach the least developed countries as well as less technologically-savvy enterprises. The search for more distributed forms of governance and the resulting diffusion of IoT innovation are thus crucial to ensure the achievement of other SDGs such as the eradication of poverty (SDG 1) and the reduction of inequality (SDG 10). The implementation of ethical principles in the deployment of IoT, edge computing and embedded AI solutions will also be essential for the development of human capital (SDG 4).

Against this background, the role of public policy and investment will be essential to ensure that IoT solutions contribute to other SDGs in the near future: the use of smart pills and wearables can provide a significant contribution to good health (SDG 3); the deployment of IoT solutions in agriculture is essential for SDGs 6 and 15 (clean water, and life on land, see Renda et al. 2019); the deployment of sensors, coupled *inter alia* with data from space (e.g. Copernicus), will be essential to monitor and preserve the environment above and below water (SDGs 13 and 14). **So what can be done by policymakers to unleash the sustainability potential of emerging technologies like IoT?** Policymakers in the EU and beyond have at least three types of tools at their disposal: positive economic incentives, negative economic incentives and standard setting.

4.3.1 Positive economic incentives: funding sustainable IoT solutions

The EU has already started investing considerable financial resources in the development of IoT, especially under the Horizon 2020 programme. The €100 billion Horizon Europe follow-up programme will be a golden opportunity to pursue these investments and use them to nudge IoT projects onto a sustainable path. While IoT investments will most likely be concentrated on the 'digital, industry and space' cluster, IoT investments should also be linked to the health cluster and the climate, energy and mobility cluster as well as the different missions. We recommend that these investments concentrate especially on **high potential use cases**, notably energy efficiency in energy generation, transmission and consumption. A means of finding high potential use cases can be to **link environmental sustainability to the award criteria for Horizon Europe funding**. This would be a concrete step to achieve the European Green Deal's ambition to "align all new Commission initiatives in line with the objectives of the Green Deal and promote innovation" (European Commission 2019b) and will incentivise applicants for EU funding to compete for public money by proposing sustainable projects.

In addition, the **European data spaces** announced in the strategy for data contribute both to innovation as well as social and environmental goals. The announced Green Deal data space could provide the perfect opportunity for IoT to show its potential for environmental data collection. A network of globally distributed IoT sensors could become an integral part of a European support system for understanding, mitigating and adapting to climate change. This kind of system could become an important part of the planned 'Destination Earth' initiative announced in the data strategy and is a use case of IoT with high potential for the SDGs. Moreover, the upcoming launch of a **Mission on smart cities** will perhaps be the most obvious opportunity to boost the deployment of IoT 'for good' in an urban environment. Other missions, such as the one on cancer and the one on soil health and food, should also be obliged to look at advanced digital technologies, including IoT. Similarly, the new Partnerships that will result from the ongoing consolidation of funded partnerships under Article 185 and 187 TEU can play a major role in the implementation of IoT solutions. Many of them focus on areas in which IoT can provide an essential set of solutions. For all these research and innovation initiatives, the SDGs provide concrete targets and indicators to measure progress. These indicators can inspire tailored IoT-related KPIs for projects. So-called Key Impact Pathways are already being used at DG Research and Innovation to link funded projects to SDGs. Beyond the Horizon 2020 programme, other funding programmes should also investigate high potential use cases for IoT. At the EU level, they certainly include regional and cohesion funds, as well as the upcoming InvestEU programme. Moreover, the Digital Europe programme, with its expected €10 billion of endowment for the 2021-2027 framework, can also become a key driver of IoT diffusion.

The EU can also contribute to the SDGs through IoT solutions funded as part of development aid. Being the largest donor in the world (if both EU and member states are considered), the EU is now pushing its role to the next level by considering **the creation of a bank for climate and sustainable development**. A recent report by a group of "wise persons", appointed by the European Commission, observed that "the present fragmentation of the system, especially between the EIB and the EBRD, is detrimental to the fulfilment of the EU's priority goals and the achievement of the desired development impact. This argues for the consolidation and streamlining of development finance and climate activities outside the EU into a single entity, a European Climate and Sustainable Development Bank, in order to avoid overlaps, and strengthen the EU's presence, role and long-term capacity to deliver on EU development priorities" (Council of the EU 2019). One key problem in moulding future EU aid policy to further sustainable development is the lack of emphasis on the sustainable use of digital technologies

and on distributed governance arrangements. In reshaping its role in development aid, the EU will be called to blaze a trail in the use of new technologies for good. This is not easy, given that the world is currently dominated by a digital arms race between the two largest economic and political superpowers, the US and China. As a result, many resources that could have been allocated to the development of, *inter alia*, IoT, AI and blockchain solutions 'for good' end up being earmarked in public and private budgets for military or purely consumer applications.

4.3.2 Negative economic incentives: tackling externalities

Another important policy tool available to the EU for incentivising the diffusion of sustainable IoT solutions is so-called **negative economic incentives**, i.e. imposing economic costs in order to disincentivise unsustainable behaviour. Prominent measures include carbon taxation or Emissions Trading Systems. When the EU puts a price on carbon emissions, for example, the private and public sector are disincentivised to increase energy consumption. IoT is one technological tool which the market can then explore for its potential to reduce energy consumption and costs – in some cases it will have high potential, in others it will not.

The key advantage of introducing policies that lead to internalising negative externalities is that policymakers can avoid dictating technological solutions through prescriptive or command and control legislation: this would indeed be a self-defeating choice in the case of ever-changing, constantly evolving technologies such as IoT, which deserve a case-by-case appraisal when it comes to their introduction and the design of their architecture. By holding companies accountable for their environmental and social impacts, EU policymakers can then leave it to the private sector to decide which solutions would lead to improved sustainability and performance, at what conditions, and under what circumstances.

The European Green Deal in particular contains several measures that can help nudge IoT investments towards more environmental applications. A **revision of the Energy Taxation Directive** would be welcome, given that an evaluation of the current directive shows that it is not adapted to the increased environmental ambitions in the Green Deal (European Commission 2019b). By increasing taxation (and therefore the energy price) on the most polluting energy sources, the private and public sector has a stronger incentive to try and reduce these energy costs. The reduction of energy costs and increased efficiency is one of the high potential use cases for IoT as Section 3.1 has shown. Increased energy costs could incentivise more innovation in this domain.

Moreover, it is high time for a **revision of the Emissions Trading System (ETS) Directive**. The ETS is based on the 'cap and trade' principle. It 'caps' the total amount of greenhouse gases that are allowed to be emitted and allows companies to trade emission allowances among them. The literature indicates that an over-allocation of emissions allowances led to only minor stimulating effects on innovation (Joltreau et al. 2018). Here again, the Commission should set ambitious new caps and rules for the ETS to give companies real incentives for investing in sustainability. Other measures like a **carbon tax** are currently politically unrealistic, but would also incentivise investments in energy efficiency and savings. In addition, they can generate new revenues that can be reinvested in SDG-related measures. One such investment should be in reducing inequality (SDG10) in order to avoid putting disproportionate burdens on vulnerable groups.

4.3.3 Standards and innovation-friendly regulation

The third type of policy instrument available to the EU is standard setting, which encompasses a number of possible initiatives, from soft guidance to hard laws. We are hesitant to suggest hard rules specifically tailored for IoT, given that the technology is still relatively young and rapidly changing. Setting general sustainable and ethical standards can, however, provide the right framework to steer the technology in a sustainable direction.

The EU should continue setting **standards regarding privacy, security or the ethical application of AI**, which will also impact the use of IoT. The High-Level Expert Group's Ethics Guidelines for Trustworthy AI or the GDPR are good examples for these efforts. Based on these efforts, the Commission is reflecting on requirements and labelling schemes for AI applications in high risk sectors, which could be controlled via *ex ante* conformity assessments (European Commission 2020c). Requirements to keep records, prove accuracy and human oversight can be useful tools to prevent discriminatory uses of IoT and AI and help reduce discrimination and inequality (SDG 5 and 10).

Regarding the environment, legislative '**waste reform**' and the Commission's "zero pollution action plan for water, air and soil" are important tools to tackle the problem of e-waste during production and disposal – one of the negative consequences of IoT growth. This could, for example, include provisions to limit the export of e-waste to third countries, forcing the EU to bear the full costs of waste and thus inducing mitigating behaviour on the side of European companies and consumers.

Another important opportunity is the upcoming review of the **Non-Financial Reporting Directive.** New sustainability disclosure requirements should empower investors and consumer groups to scrutinise the environmental and social impact of businesses and incentivise them to invest more in sustainability. While new reporting requirements should not be directly linked to IoT, reporting on, for example, energy consumption would reveal if increased ICT uptake also leads to higher energy consumption or energy savings. In addition, IoT can be a useful tool for collecting and monitoring data for reporting.

4.3.4 Concluding remarks

The emergence of digital technologies such as IoT, edge computing and AI offers policymakers a unique opportunity to tackle some of the most pressing issues for the economy and the planet. At the same time, the deployment of these technologies is costly, and their impact often dependent on the extent to which ethical concerns are incorporated in the design from an early stage. The asymmetry of information between policymakers and the private sector also requires enhanced and pervasive impact measurement of technological implementation by private corporations. As digital technologies also create significant risks, especially in terms of market power, inequality, environmental and social externalities (Renda et al. 2019), there is room for public policy to steer their development in a socially desirable way. In this respect, the economics literature has shed light on the positive role that well-designed, well-timed, adequately stringent legislation can play in incentivising responsible innovation (Ashford 1985; Ashford and Renda 2016).

The measures analysed above (positive and negative economic incentives, innovation-friendly regulation and standards) can create a level playing field for all companies operating on the European market, avoiding a race to the bottom for mere revenue growth. By creating the right

policy environment companies should be incentivised to invest in sustainability and compete for the most effective solutions for the sustainability crisis. New technologies are an important (but not the only) building block of the digital transformations necessary for achieving the SDGs. The public and the private sector need to work together to make this a reality.

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Notes

[1] For "things", we intend generically connected (and thus cyber-physical) objects, such as materials, sensors, actuators, wearables, controllers, robots, equipment, implanted devices and many more. The "Internet" refers to a global inter-networking infrastructure that uses the TCP/IP protocol to connect and remotely control "Things".

[2] As the number of "Things" connected to the internet is increasing rapidly, scalability of the protocol has emerged as a major challenge. Currently, IPv4 is the 32-bit address system that is on the verge of being incapacitated, i.e., using up all the IP addresses. IPv6 is the new 128-bit address system that has a capacity of approximately 2128, or 3.4×1038 addresses. IPv6 enables every IoT "Thing" to have a unique IP address in the global Internet network.

[3] As a matter of fact, data scientists spend around 80% of their time on collecting and cleaning the data, and only 20% of their time is actually spent on data analysis (Bowne-Anderson 2018). Data needs to be cleaned and merged with data from different sources to achieve a common format suitable for analysis, such as tabular format ('data wrangling').

[4] It must be noted, however, that artificial intelligence / machine learning is only one tool in the data scientists tool kit - and it is not necessarily the most widely used one. When data scientists are asked about their favorite tool, they often cite classical statistical tools such as logistical regressions, because of their better interpretability and lower complexity. The adequate analytical tool highly depends on the specific puzzle a project tries to solve. See DataCamp (2019): DataFramed Podcast. Available online: https://www.datacamp.com/community/podcast

[5] For example, Azure supports a user-configured dashboard that can include a number of resources from the marketplace such as IoT events, time series insights, stream analytics, log analytics, cost analytics, and reports. Most of these are general-purpose platforms, which are often replaced by domain-specific ones, for example for manufacturing and healthcare.

[6] The use of cloud services is not a necessary requisite for storing IoT data. Data can also be stored in privately managed servers 'on premise' and processed with private processors to increase autonomy or on devices on the 'edge' of the cloud.

[7] A related term, fog computing, describes an architecture where the 'cloud is extended' to be closer to the IoT end-devices, thereby improving latency and security by performing computations near the network edge [49]. So fog and edge computing are related, the main difference being about where the data is processed: in edge computing, data is processed directly on the devices to which the sensors are attached (or on gateway devices physically very close to the sensors); in fog computing, data is processed further away from the edge, on devices connected using a LAN [51].

[8] Funded projects include several large scale pilots (LSPs) for IoT testing and deployment: 'Activage', which aims to "enable the deployment and operation at large scale of Active & Healthy Ageing IoT based solutions and services, supporting and extending the independent living of older adults" (2020); 'Autopilot', which aimed at advancing automated driving (2019); 'U4IoT' for increased user engagement for large scale pilots in IoT (2019); 'SynchroniCity' for smart city pilots (2019); 'IoF2020' for IoT in agriculture (2020); CREATE-IoT to stimulate collaboration between IoT initiatives (2018); 'MONICA' for wearables in smart ecosystems (2019). In addition, the EU also funded several R&D projects to investigate new solutions for security and privacy in IoT (SEMIoTICS, ENACT, SerIoT, SOFIE, SecureIoT, IoTCrawler, CHARIOT or NGIoT). Moreover, the IoT European Platform Initiative (IoT-EPI) was created in order to support the creation of IoT platforms (2018). The initiative includes seven research and innovation projects (Inter-IoT, BIG IoT, AGILE, symbIoTe, TagItSmart!, VICINITY, bIoTope). While Horizon 2020 is the most important funding stream in this context, other EU funds like the European Regional Development Fund also contribute to IoT related projects, for example 'icity.brussels' (2020).

[9] See https://ec.europa.eu/info/horizon-europe-next-research-and-innovation-framework-programme_en.

[10] The AI HLEG is composed of as many as 52 members, including independent experts and academics, alongside with representatives of vested interests. See the composition at https://ec.europa.eu/digital-single-market/en/high-level-expert-group-artificial-intelligence (accessed on September 24, 2019).

[11] The introduction of key requirements in addition to ethical principles already put the AI HLEG at the forefront of the debate on how to encourage responsible AI development. However, the AI HLEG did not limit itself to this already remarkable attempt: perhaps the most innovative feature of the Ethics Guidelines is the attempt to operationalise the requirement through a detailed assessment framework composed of 131 questions. The list walks AI practitioners through the key requirements, asking them whether they have fully considered possible risks, or have procedures in place to mitigate them in case they materialise.

[12] On 19. February 2020, the Commission also published a report on the "safety and liability implications of Artificial Intelligence, the Internet of Things and robotics". The report recalls that there is already an existing EU safety and

liability framework in place and mentions several pieces of legislation which could be revised to adapt to new technologies. See https://ec.europa.eu/info/sites/info/files/report-safety-liability-artificial-intelligence-feb2020_en_1.pdf.

[13] Previous policies included: The Digital Single Market Strategy launched in 2015, which provided a broader strategy for digital technologies. As part of this strategy, the "Digitising European Industry" initiative was launched in 2016, which was accompanied by the "Advancing the Internet of Things in Europe" staff working document. The document detailed the Commission's three visions for IoT: creating a thriving IoT ecosystem, a human-centred IoT approach, a single market for IoT. The key challenges identified by the Commission were: connectivity obstacles, standardisation, interoperability, obstacles to data flow and access, safety and liability issues, the digital divide and trust. In addition, the Commission proposed the "European data economy" initiative in 2017 to help create a single market for technologies like IoT. In the context of this initiative, the EU has passed a Regulation on the free flow of non-personal data which has added to the existing rules on the processing of personal data in the General Data Protection Regulation; the Commission proposed an "Open Data Directive" for public sector data in 2019; has worked on guidance on private sector data sharing; and published a staff working document on liability for emerging digital technologies.13 Moreover, the Commission helped found the Alliance for Internet of Things Innovation (AIoTI) in 2015 as a European network and interest group for IoT-related companies and as a link between the private and public sector. Today AIoTI is the largest European IoT Association.

[14] It should be noted that this represents an 'SDG first' approach: First searching for the highest potential SDGs and then thinking about suitable products to address the target. Companies have an incentive to first develop a marketable product and then think about its potential contribution to the SDGs. The former approach has a higher likelihood of leading to SDG related products, while finding a profitable market for them is more challenging. Ideally, these two approaches should be combined.

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