Schneider Electric™
Sustainability Research Institute

Digital with Impact:

Towards a systemic approach to digitalization for a sustainable energy transition

Net Digital Impact: Concept Paper

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Introducing the Schneider Electric™ Sustainability Research Institute

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Global awareness for a more inclusive and climate-positive world is at an all-time high. This includes carbon emissions as well as preventing environmental damage and biodiversity loss.

Nation states and corporations are increasingly making climate pledges and including sustainability themes in their governance. Yet, progress is nowhere near where it should be. For global society to achieve these goals, more action-and speed-is needed.

How can we convert momentum into reality? Aligning actions and activities with United Nations Sustainable Development Goals. Leveraging scientific research and technology. Gaining a better understanding of the future of energy and industry and of the social, environmental, technological, and geopolitical shifts happening all around us. Reinforcing the legislative and financial drivers which galvanize more action. Providing clarity on what the private and public sectors can do to make all this happen.

The mission of the Schneider Electric™ Sustainability Research Institute is to examine the facts, issues, and possibilities globally and locally to better understand what business, society, and government can and should do more of. We aim to make sense of current and future trends that affect the energy, business, and behavioral landscape to anticipate challenges and opportunities. Through this lens, we contribute differentiated and actionable insights.

Set up in 2020, our team is part of Schneider Electric, the leader in the digital transformation of energy management and automation, whose purpose is to bridge progress and sustainability for all.

We build our work on regular exchanges with institutional, academic, and research experts, collaborating on research projects where relevant. Our findings are publicly available online, and our experts regularly speak at forums to share their insights.

This report delves into the recent advancements in holistically measuring the environmental impacts of digitalization.

Traditionally, quantifying these impacts proved challenging. However, recent releases of robust methodologies and stronger collaboration between academia and industry are paving the way for more detailed analysis, especially in the field of digitalization for an effective energy transition.

This report proposes a comprehensive framework to evaluate how digital technologies can simultaneously mitigate climate change, bolster socio-economic resilience, and support a transition towards post-growth development.

This paves the way for exciting new research areas where our Sustainability Research Institute will be focusing its energy in the coming years.

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FOREWORD by Pr. Charlie Wilson

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Why is digitalisation important for climate change?

Digitalisation is a global mega-trend transforming activity across the economy and society. Digitalisation centres on Information and Communication Technologies (ICTs) and related applications such as cloud computing, Artificial Intelligence (AI), Internet of Things (IoT), and on-demand platforms and services. For many, digitalisation is inextricably linked to smartphones and other internet-enabled devices which act as interfaces for accessing a proliferation of digital services from e-retail and social media to mobility apps and virtual assistants.

Digitalisation is having far-reaching consequences on the way we live and work. Just as steam engines were the general purpose technology at the heart of the first Industrial Revolution with applications in mining, manufacturing, rail and shipping, now ICTs enable a host of applications across economic sectors and domains of daily life as part of the fourth Industrial Revolution underway. The hallmarks of this Industry 4.0 are increasing interconnectivity, data availability, and smart automation. In parallel in the social realm, digitalisation is transforming how we communicate, interact, exchange, share, move around, and consume goods and services.

Digitalisation is also happening at breakneck speed as the explosive recent growth in generative AI clearly shows.

This rapid and pervasive digital transformation is taking place all around us but without due regard for the most significant challenge of our time – tackling climate change.

The impacts of digitalisation on greenhouse gas (GHG) emissions are potentially large, both for better and for worse.

Energy-intensive activities in buildings, industry and transport systems are responsible for the majority of global greenhouse gas (GHG) emissions. Digitalisation offers countless opportunities to make these activities more efficient, more accessible, more coordinated, and more integrated into energy networks.

Successive high-profile studies by the United Nations (UN), the International Energy Agency (IEA), The World in 2050, and the German Advisory Council on Global Change all agree that digitalisation can be a critical enabler of a global sustainability transformation… if the deployment and use of ICTs can be aligned with decarbonization objectives.

But this promise sits alongside considerable risks from ever-expanding energy-hungry digital infrastructure and the growth-inducing applications and services it enables.

Against this backdrop, **Schneider Electric™ Sustainability Research Institute 'Digital with Impact'** Concept Paper is an important contribution to the mobilisation of firms, industries, and markets to address these twin challenges of our times – digitalising economies and societies in ways that deliver public benefits, and reducing GHG emissions close to zero by mid-century to stabilise the climate system.

How does digitalisation impact energy demand and greenhouse gas emissions?

The impacts of digitalisation on GHG emissions are direct, indirect, and systemic. These impacts increase in both magnitude and uncertainty up through this hierarchy.

Direct impacts are from the manufacturing and use of the physical ICTs themselves. These are the most obvious elements of digitalisation: smartphones, fibre-optic cables, and server farms at scales from individual users up to global network infrastructures. The direct impacts of ICTs combining both embodied and operational emissions are currently around 2-3% of total global GHGs. This is expected to rise as more and more ICT infrastructure is built. The material lifecycle of ICTs – from the mining of minerals to end-of-life disposal – imposes further environmental burdens. E-waste is the fastest growing waste stream in the world.

However, the indirect impacts of digitalisation resulting from what these ICTs are used for are considerably larger but also much harder to reliably estimate. This is partly due to the countless number of digital applications and services, and partly due to the lack of standardised assessment methodologies defining clear and consistent system boundaries.

On the one hand, many digital applications help optimise, control, manage, substitute, balance, and improve the efficiency with which energy is used for a wide range of activities. But on the other hand, by reducing the cost, time, and friction of these activities, digitalisation can lead to an increase in demand – the 'rebound' or induced demand effect. This basic trade-off between efficiency and growth determines the net indirect impact of digitalisation on energy use and so GHG emissions.

At a still higher level, digitalisation as a general purpose technology also has systemic impacts on both the macroeconomy (e.g., employment, income, productivity) and on society (e.g., living and working patterns, political values, social cohesion). These systemic impacts are still harder to pin down in quantitative studies of digitalisation, energy, and GHGs.

Historical analysis of indirect and systemic impacts across countries, sectors and time tends to show the efficiency benefits winning out at the margins; rebound effects are important but do not wholly counteract all the energy savings enabled by digitalisation.

Future projections by industry-led groups like the Global e-Sustainability Initiative (GeSI) or World Economic Forum (WEF) show GHG emission reduction potentials in the order of 10-20% achievable over the next decade, with digitalisation as a positive contributor to decarbonisation objectives.

However, these projections tend to have an optimism bias in scaling up selected best-practice use cases under assumptions of widespread adoption. These indirect energy-saving impacts more than offset the direct impacts of energy-using ICTs on the negative side of the ledger.

What are some of the opportunities for digitalisation to help reduce energy demand in different sectors?

Certainly there are many opportunities for digitalisation to help rather than hinder emission reduction efforts. These have been well documented by the International Energy Agency and other independent bodies. Many of these digitalisation benefits are associated with the increasing electrification of energy use and the move away from direct combustion of fossil fuels in vehicles, buildings, and industry.

In buildings, smart meters, sensors, IoT devices, and control systems exchange and analyse information in real-time to help optimise energy management and enable buildings to flexibly contribute to balancing demand with supply on electricity networks. As buildings increasingly become distributed energy generation and storage assets with solar panels, batteries, and electric vehicle charging, digitalisation allows for pricing signals to incentivise or automate reductions in electricity demand during peak periods. This demand responsiveness helps electricity companies avoid the need for costly infrastructure upgrades. Digital platforms and peer-to-peer networks also enable sharing economies for users to trade or exchange surplus goods, space, and even electricity.

In transport, digitalisation enabled the over-night switch from commuting to remote working forced by the pandemic lockdowns. Teleworking and the virtualisation of physical mobility is now the norm in many places and professions. Digital platforms offer on-demand mobility services from ride-hailing and micro-mobility (e.g. e-bikes and e-scooters) to personalised route planning and multi-modal ticketing that integrates public and shared mobility services. Digitalisation also supports the electric vehicle transition through smart and bidirectional charging technologies that offer vehicle owners a new value stream from shifting demand for charging from peak to off-peak periods. As with the smart building controls, this depends on digital connectivity for exchanging and acting on real-time energy and pricing data between users and electricity network operators.

In industry, digitalisation is widely used to automate and optimise production processes, substituting capital for energy as an input factor to production, and driving resource efficiency and productivity gains. Additive manufacturing or 3D printing using digital designs can also substitute for energy-intensive component or product manufacturing. This allows for more distributed supply chains bringing production closer to the point of consumption, and reducing the need for long-distance freight. As in the building sector, digitalisation also enables industrial plants and facilities to offer flexibility services to electricity networks by making their demand responsive to network needs.

These examples of efficiency-enhancing digital applications in the traditional energy-using sectors – buildings, transport, and industry – all emphasise the importance of increasing integration across digital and electricity networks to manage the increasingly complex system architecture of intermittent renewables, generation, storage, and flexible demand assets distributed but connected throughout the networks. Digitalisation is the lubricant that keeps these electrification and decarbonisation dynamics progressing.

What are the opportunities for Schneider Electric to contribute to low-carbon digital futures?

This sketch of the landscape relating digitalisation to energy and GHG emissions points to the many opportunities for a global technology company like Schneider Electric with their unique expertise, capabilities, data, and experiences developing and applying digital solutions.

First, more and better evidence is needed on digital 'use cases' across applications, sectors, activities, and locations. The evidence base on digitalisation impacts remains patchy, poorly documented and synthesised, and weighted towards either cutting-edge innovations or aggregate sectoral and economy-wide analyses. This leaves a large gap in the knowledge needed to understand how digital applications can deploy, and the impact their scaling up will have on energy demand.

Second, building this evidence base means improving the methods used for assessing digitalisation impacts on energy, materials and GHG emissions. This requires a clear analytical framework for identifying and differentiating direct, indirect, and systemic impacts. It requires standardised assessment methods drawing on lifecycle analysis, and other energy and material accounting tools, with clear recommendations for defining the system boundaries of analysis – what's counted and what's not. The recent standards published by the International Telecommunications Union (ITU-TL.14801[1]) are a welcome step in this direction, and now need widespread testing and improvement.

Third, more realistic future projections of digitalisation impacts are needed to help steer industry activity, innovation trajectories, and regulatory oversight towards low-emission futures… and to avoid a worse-case scenario of unfettered digital innovation intensifying and embedding energy-hungry growth.

In all three of these challenge areas, the contribution of this **'Digital with Impact'** Concept Paper and the internal capacity-building momentum it represents will help position Schneider Electric at the centre of the unfolding digital-energy transformation which is so critical to the challenge of our times – stabilising the climate system to ensure a flourishing future for people and planet.

table of contents

List of tables and figures

List of figures

List of tables

Executive summary

The discussion surrounding the role of the digital ecosystem in facilitating climate change mitigation while ensuring human prosperity has gained significant attention across various sectors, including science and academia, public institutions, and the private sector.

- However, prior to this recent surge in interest, there was a notable lack of comprehensive data available to conduct a thorough assessment of the environmental, economic, and social impacts of digital technologies, encompassing both their positive and negative aspects.
- Despite the newfound opportunities arising from improved data access and processing capabilities, evaluating the impacts of digital technology remains a complex challenge. Therefore, it is crucial to acknowledge that quantifying these effects is currently an extensive, uncharted territory.
- It is essential to establish a clear demarcation between the domains where we possess solid scientific foundations, enabling us to make substantial impacts on markets and policies, and the reality of current frontiers of human knowledge. This dual perspective encourages us to advocate for a responsible approach across our entire ecosystem.

In this concept paper, we will unfold three key elements that have arisen in this context.

1. The rapid development of emerging technologies like AI, IoT, cryptocurrencies and 5G poses a challenge to achieving a comprehensive scientific understanding of the direct effects[a] of digital technologies. **This complexity currently contributes to uncertainty when it comes to accurately provide evidence on direct effects quantification**.

2. Even though many publications from IT think tanks integrating quantified elements are now available, the momentum within the scientific community is not assured, as evidenced by the latest technical report from the IPCC (Intergovernmental Panel on Climate Change)[1], which emphasizes that **neither the indirect[b] nor the systemic[c] effects of digital technologies are scientifically quantified at this time**.

3. As nearly three-quarters of global greenhouse gas emissions originate from energy consumption, and digitalization and electrification are expanding rapidly, carefully examining the Electronic and Electrical Equipment (EEE) sector within the broader digital value chain offers a compelling indication of digitalization's potential to drive the transition towards sustainable energy solutions. While acknowledging the importance of direct impact studies, **a comprehensive assessment and quantification of indirect and systemic effects of digitalization, particularly in regard to its impact on energy demand, is crucial**. This understanding should be grounded in a forward-looking perspective and supported by rigorous analysis of industrial and statistical data.

The primary objective of this research is to provide a comprehensive understanding of these issues and present the Schneider Electric™ Sustainability Research Institute 'Net Digital Impact' framework that will guide our future research initiatives.

(a) Direct effects: These refer to the immediate and tangible impacts resulting from the production, use, and disposal of ICT.
(b) Indirect effects: Indirect effects capture the broader consequences that emerge as a result of changes in patterns of production and consumption in other domains, driven by the adoption of ICT.
(c) Systemic effects: Systemic effects encompass the wide-reaching socioeconomic impacts that occur due to economy-wide adjustments and changes in social practices following the introduction of technology, including ICT.

1 Setting the scene

Does Digitalization hasten activities that contribute to or exacerbate the ongoing crisis, or does it hold the key to building more sustainable, equitable, and resilient societies, or perhaps both?

Although digital technology is part of our lives, its forms and variations have undergone significant evolutions in the past.

It is indeed crucial to differentiate between the ICT sector and the broader phenomenon of digitalization. While the ICT sector has significantly influenced the development of digital technologies, examining digital technology solely within the confines of the ICT sector can result in an incomplete assessment of its multifaceted environmental impacts.

We have identified five steps of the historical interactions between ICT evolutions, energy transitions, socio-economic development, and the environment.

1.1. First Industrial Revolution: The simultaneous emergence of Coal-Powered Industrialism, Environmental Crisis, and Knowledge-ICT.

- Human industrial activities have emerged as the primary drivers affecting a broad spectrum of Earth system factors, leading to the designation of a new era called the Anthropocene[2]. The resulting environmental crisis traces its origins back to industrial transformations that commenced in early 19th-century England and subsequently spread to Western Europe, North America, and East Asia by the late 20th century.[3]
- With the advent of the steam engine and the expansion of Coal-Powered Industrialism, an **emerging knowledge-ICT-based literacy-driven economy became a pivotal cornerstone of the entire new energy system**. These advancements were often facilitated by pioneering ICTs such as accounting and printing techniques[4], leading to subsequent technological breakthroughs and the widespread dissemination of technical literature.[2][5][6]

1.2. 1882 – 1948: The Era of Convergence between Industrialization, Electrification, and Analog ICT: From the first electrical grid to the massification of load management.

- It is noteworthy that Coal-Powered Industrialism not only facilitated the development of extensive infrastructure, including road and railway networks but, more importantly, it played a pivotal role in establishing the indispensable electrical grid (in 1882 the first distribution systems are built in Manhattan and New Jersey), which would prove instrumental for the future evolution of digital infrastructure.[2][3]
- As electrification progressed, the challenge of balancing power to load became ever more closely entwined with the generation of information. Although calculations involving voltage, current, and resistance were instrumental in building electrical systems, they alone could not guarantee optimal efficiency.[7]
- **The demand-side coupling of ICT and electrical system – which opens the era of early load management – served as a feedback mechanism that provided insights for supply management**. Electricity meters also played a crucial role in facilitating the expansion and interconnection of the grid[8], and they later formed the foundation for control engineering what is commonly referred to as the first weak signals of the Third Industrial Revolution.[2][9]

1.3. Post-World War II Great Acceleration revealed the cross-cutting nature of digital.

- While analog models of the electrical grid played a significant role in laying the groundwork for the foundation of modern computers[9][10], a pivotal leap occurred in the aftermath of World War II. During this period breakthroughs in computer design, the emergence of mathematical information theory, and advancements in semiconductor physics, ushered in the era of electronic computation. Simultaneously, post-war collaboration between various sectors and industries, exemplified by initiatives like the 1948 Marshall Plan, facilitated the creation of mutually beneficial markets for each other's sectors.
- **The cross-cutting nature of digital technology began to surface, acting as the primary force binding collaborative efforts, ultimately leading to economies of scale and cost reduction**[12]. Indeed, microelectronics played a pivotal role in introducing the digital era, catalyzing significant advancements in not only the military-industrial complex during the Cold War but also across various domains such as business, accounting, trade, planning, and material design. In hindsight, economic analysis indicates that digital signal processing emerged as a versatile and universally applicable technology, characterized by extensive use, continuous technical enhancement, and the capacity to foster innovation across a multitude of end-sectors[106]. **From this perspective, the early days of Digitalization of the historical ICT sector** – influenced by Claude Shannon's conceptualization of 'digital' in 1948 in the area of telecommunication (referred to as the 'bit')[13] **played a crucial role in synergizing new technologies with industries**.

1.4. The Third Industrial revolution shifted the balance of power towards a Digital-ICT Dependency.

- In the pre-industrial era, the balance of power between labor, energy, and information were essentially in favor of labor[14]. In contrast, the era of industrial expansion allowed for a balancing and synergy of these elements, ultimately leading to the modern era where information becomes the key element.
- Machado and Miller[15] demonstrate that between 1963 and 1987, the US economy experienced a decrease in energy intensity and an increase in information intensity. **They propose the existence of a potential substitution relationship between the development of information-related activities and the utilization of energy**[2]. Their findings indicate that information activities became less reliant on energy, whereas energy became more reliant on information.[16]
- Until 1973, a significant paradigm shift occurred, moving from the 'transforming energy' paradigm to the 'transforming information' paradigm[17]. This shift marked the transition to what is commonly known as the 'post-industrial society'[18], characterized by the 'information economy'[19], the 'information society'[17], or the 'fifth Kondratieff wave'[20]. This transition highlights the profound impact of digitalization and the information age on the course of industrial and economic development in the post-World War II era.

1.5. The digital paradigm and Earth boundaries: from a minor phenomenon to substantial global effects.

- **Initially, the direct economic influence of ICT was irregular, but it began to weight significantly following the consumer electronics revolution in the 1980s**. The quest to uncover Shannon's ultimate communication capacity occupied engineers for nearly five decades but was effectively resolved in the early 1990s.[21]
- The advent of digital methods for processing and disseminating information expedited the extraction and utilization of natural resources, the manufacturing and often inefficient consumption of products, the globalization of trade and financial systems, and consequently, the human-induced effects of these activities on the Earth's ecosystem.[22][23]

The next frontier in Climate Action: five key reflexions on digitization's role.

1.6. Digital everywhere, but for what purpose?

- Greenhouse gas emissions resulting from human activities, the primary driver of global warming, have been on a continuous rise year by year[31]. These emissions amounted to over 2,000 gigatons of CO_2 in cumulative net emissions in 2018, prior to the onset of the Covid-19 pandemic. Although there was a notable 5.8% reduction in energy-related CO_2 emissions in 2020, as indicated by the latest statistical data, marking the most significant annual decline since World War II[32], the rebound in the post-pandemic era is now a recognized evidence.[33]
- The trajectory towards the 1.5°C toward the end of the 21st century remains highly uncertain and a change of scale in the decarbonization of the end-sectors (industry, residential, services, mobilities…) is needed. While the literature is quite dense on how ICT can decarbonize the supply side[34], it is worth noting that despite the pervasive digitalization across almost all energy-related sectors, with its significant scale and rapid pace, **there remains a notable scarcity of comprehensive studies that undertake a quantitative analysis of the potential of digitalization to transform existing energy systems through a demand-driven transition**.
- Recognizing that the current efforts to reduce the environmental impact in the ICT sector fall short of meeting climate goals[24][25] and that there's a lack of comprehensive policy mechanisms to enforce compliance across the sector[23], it's crucial to underscore that ICT could serve as the fundamental cornerstone for achieving substantial decarbonization in other industries through its indirect impacts. Hence, we reaffirm the importance of providing stronger evidence through quantification.

1.7. Rethinking direct effects: Existing digital and energy infrastructures as a common good to mitigate climate change and enabling human prosperity.

- It is worth to be conscious that a significant portion of the digital technology infrastructure has already been established, and digital services are operational, whether we like it or not. Considerable human effort, resources, materials, and energy have been invested in this existing digital ecosystem. **Given the presence of existing infrastructure, it is crucial to investigate its potential to bolster the energy transition and climate change mitigation efforts**[26]. In addition to current research efforts, it is also essential to mobilize resources towards quantifying the decarbonization potential of already established energy and digital systems.
- Indeed, while it is crucial to understand the magnitude of the task to significantly reduce the environmental direct impact of ICT, it is equally critical to comprehend the potential of the existing infrastructure to decarbonize and transform the way we use energy. In the complex digital landscape, **it's essential to prioritize research and action directed at harnessing digitalization's potential to decarbonize various sectors and make our energy systems more efficient and carbon neutral**. Furthermore, the more we decarbonize electricity, the more we decarbonize the ICT sector. Unfortunately, this fact is generally overlooked and lacks the required quantification to provide public authorities, states, and international organizations with a proper understanding to make informed decisions and investments that can fundamentally alter the current climate trajectory.
- A recent research conducted by Lancaster University[23] has emphasized the connection between the growing demand for ICT and its potential to (i) enhance its own efficiency and (ii) enhance the efficiency of economic sectors that would otherwise lack such improvements. It's important to highlight that, despite the well-established narrative framework, there is a significant gap in modeling all the effects related to the energy domains.

1.8. Indirect effects: where do we stand?

- Despite commendable efforts to measure the indirect impacts of digital technology, **we should be mindful that when scrutinizing the indirect effects of digital, recent reports frequently underestimate or disregard the negative impacts of Digitalization.**[27]
- Moreover, we consider there is a gap in our understanding regarding how digitalization influences variations in energy demand. In most cases, digitalization is not comprehensively analyzed, even though several sector-specific studies provide essentially qualitative insights, quantification is missing.
- In the scientific literature, Parviainen et al.[34] explore practical benefits of digitalization, Almeida et al.[35] address potential challenges and opportunities, and Chen et al.[36] delve into environmental sustainability aspects within the context of digitalization for manufacturing.
- Some non-academic think tanks, like 'GeSi'[39] and 'GSMA'[40], have claimed that digital leads to significant positive outcomes, including enhanced efficiency, reduced energy consumption, and lower greenhouse gas emissions. They claim digital technology can inherently reduce emissions by up to 20% – or even more – across various sectors, emphasizing concepts like energy efficiency and equipment substitution. We will discuss this in the course of this report.

1.9. Strengthening existing methodologies.

- While there have been proposed methodological frameworks to facilitate such evaluations[28][29], it is evident that there is a need for more robust quantification of indirect effects. The primary challenge persists in the fact that examined use cases typically rely heavily on context-specific factors (such as a particular technology, country, or usage scenario), making it difficult to extrapolate findings on a global scale.[30]
- **We also need to improve our understanding of the relationships between digitalization, the economy, and the societal transformations it drives**[41][42]. This includes examining its impact on economic growth[43], enhancements in labor and energy productivity, and the profound alterations it brings about in various end uses.[44]

1.10. The imperious need to quantify impacts of Digitalization for a demand-driven energy transition.

- Enabling the construction of a methodology that provides a flexible approach to assess the effects of digitalization and electrification on energy systems at a granular level is fundamental to structure a constructive debate on the potential effects of Digitalization coupled with a sustainable demand-side energy transition.[45]
- The recent research from Xiang Li et al[38] concludes that digitalization is anticipated to have a sweeping influence on all sectors related to energy and to deeply reshape the various layers of the energy system, spanning from production and distribution to end-use demand. From their standpoint, **there is an urgent requirement for (i) quantifying the influence of digitalization on the energy system and (ii) conducting this assessment within a comprehensive framework that encompasses all sectors and treats the energy system as a unified whole**. This approach would enhance the credibility of prospective modeling for energy demand, with sector coupling playing a pivotal role in identifying the requirements and opportunities brought about by the digital transformation of society.

2 Direct Effects: State of the Art

Over the past seven decades, the ICT sector has experienced substantial and rapidly accelerating growth.

Let's examine the current level of knowledge on this front.

2.1. Direct ICT: a historical installed base whose carbon footprint has become significant.

- While there is a substantial body of research exploring various aspects of this field, the most extensive knowledge base primarily focuses on energy demand and carbon impacts. These stages include embodied emissions (GHGs emitted during the extraction of raw materials, manufacturing, and transportation to end-users), operational emissions (arising from energy consumption and maintenance), and end-of-life emissions during disposal[46]. The core of this effort is to estimate the actual size of ICT's carbon footprint, whether it is increasing, remaining stable, or even decreasing due to efficiency improvements and the effects of Moore's Law.
- A significant body of research has explored the energy footprint and carbon implications of information and communication technologies (ICT), however, there remains considerable controversy surrounding the direct consequences of the digital technology, primarily due to three factors[26]:

1. **The cross-sector nature of digital**: digital technology operates as a distinct sector while simultaneously permeating various other industries.
2. **Insufficient open data**: the scarcity of accessible, transparent data hampers comprehensive assessments.
3. **The absence of a universally accepted methodology**, coupled with a lack of consensus among the scientific community, complicates the evaluation process.

The scope of our review is the transfer, processing, and utilization of digital data.[47]

Three main categories of systems are typically identified:
- Data Centers,
- Telecommunication Networks,
- End-User Devices.

Global estimation of various phenomena often relies on a multitude of studies, with some of the most influential ones stemming from distinct research teams that have crafted unique models. Let's take a closer look at these prominent studies:
- Jens Malmodin and Dan Lundén[48] (Ericsson Research).
- Anders SG Andrae and Tomas Edler[49] (Huawei Technologies).
- Lotfi Belkhir and Ahmed Elmeligi (McMaster University).[50]
- Charlotte Freitag (Lancaster University).[23]
- Vincent Petit (Schneider Electric™ Sustainability Research Institute).[47]

Although these investigations all segment ICT into analogous categories, they differ in their adopted parameters and scopes. However, at present, the impacts related to the end-of-life phase are not fully integrated into these assessments, as they are considered marginal in terms of emissions and energy consumption but significant in other aspects such as ecotoxicity and biodiversity.

2.2. The University of Lancaster unification (2020).

The remarkable research produced at Lancaster University[23] showcased the significant variability in estimates of ICT's carbon footprint, and more critically, the discord regarding its projected trend, can be attributed to several factors.
- These discrepancies arise from differences in the chosen scope of analysis, such as whether to encompass new technologies like IoT, cryptos, and services. For instance, the emergence of Machine Learning/Artificial Intelligence (ML/AI) across all sectors of the economy introduces even more intricacy to a subject of study that is already inherently complex.
- Certain assumptions hold significant importance, including aspects such as energy efficiency and the decarbonization of information and communication technology (ICT). Meanwhile, differences in extrapolation methods contribute to various outcomes.
  - For instance, Malmodin and Lundén[48] anticipate a stagnant trend in the carbon footprint, while Andrae[49] predicts an increase. These differences can be attributed to the scope chosen for assessment and assumptions made. Malmodin and Lundén[48] base their projections on equipment sales, which might be too limited in scope to predict future ICT uses and services accurately.
  - Conversely, Andrae and Edler's[49] projections rely on the evolution of data traffic, which has known limitations, as increased traffic doesn't necessarily translate to a proportional increase in the carbon footprint due to advancements in equipment efficiency.

By consolidating the scopes considered in references[48][49][50] **Freitag et al.**[23] **argue that GHG emissions originating from the ICT sector ranged from 2.1% to 3.9% of global emissions in 2020, equivalent to 1.2 to 2.2 gigatons of carbon dioxide equivalent (GtCO$_2$e)**. Freitag et al. conclude that the carbon footprint of digital technology is consistently underestimated by up to 25% due to a poor integration of manufacturing impacts.

Furthermore, they estimate that the carbon footprint of digital technology will continue to increase for three reasons:

1. Historically, the efficiency gains enabled by ICT have been accompanied by increases in energy consumption, but also potential rebound effects, growth, volume and greenhouse gas emissions both in the ICT sector and in the economy as a whole.
2. Current studies make several important omissions regarding ICT growth trends (AI, 5G, IoT, cryptocurrencies).
3. Significant investments are being made to develop and expand the use of these technologies.

Here's a summary of the key findings related to the direct impacts of the analyzed studies.

	Research body	Publication date	Scenario	Carbon footprint $MtCO_2e$ 2020 (w/o media)	Estimated share of Global emissions 2020 (Total $50GtCO_2e$)	Carbon footprint $MtCO_2e$ 2030 (w/o media)	Estimated share of Global emissions 2030 (Total $40GtCO_2e$)
Adjusted on Freitag et al. Perimeter	Belkhir and Elmeligi	2018	Minimum case	1107	2.2%		
			Maximum case	1306	2.6%		
	Malmodin and Lunden	2018	Expected case	1153	2.3%		
	Freitag et al.	2021	Best case	1200	2.1%		
			Worst case	2200	3.9%		
	Andrae*	2020	Best case	1020	1.8%	700	1.8%
			Expected case	1840	3.2%	1700	4.2%
	Petit et al.	2021	Best case	955	1.9%	899	2.2%
			Worst case			1201	3.0%

Figure 1. Summary of ICT 2020 & 2030 Carbon Emissions, based on Freitag et al. harmonization. Schneider Electric™ Sustainability Research Institute.
*Andrae 2020 publication provides perspective on electricity use only, not CO_2, % are based on Schneider Electric interpretation and estimation.

2.3. New technologies high entanglement: Threat or opportunity?

- Digitalization is seen as the next phase of economic and technological advancement, with the potential to contribute to ecological transitions. However, the abundance of technical terms like Artificial Intelligence (AI), Machine Learning (ML), blockchains, autonomous vehicles, smart cities, metaverse, and more can make it challenging to distinguish what truly matters.
- Despite constituting real phenomenons, it is crucial to differentiate firstly their nature: technology (AI, IoT…) and the usage of the technology (Energy Efficiency, prediction and planning…) and secondly their interdependency on the existing ICT infrastructure are frequently mentioned across the literature[51], but studies either remain predominantly qualitative, with few explicit analyses quantifying the impact of digitalization; either focus on small, delineated case studies, or sectoral studies and thus consider solely a limited part of the energy system (e.g., typically only the electricity consumption).[52]

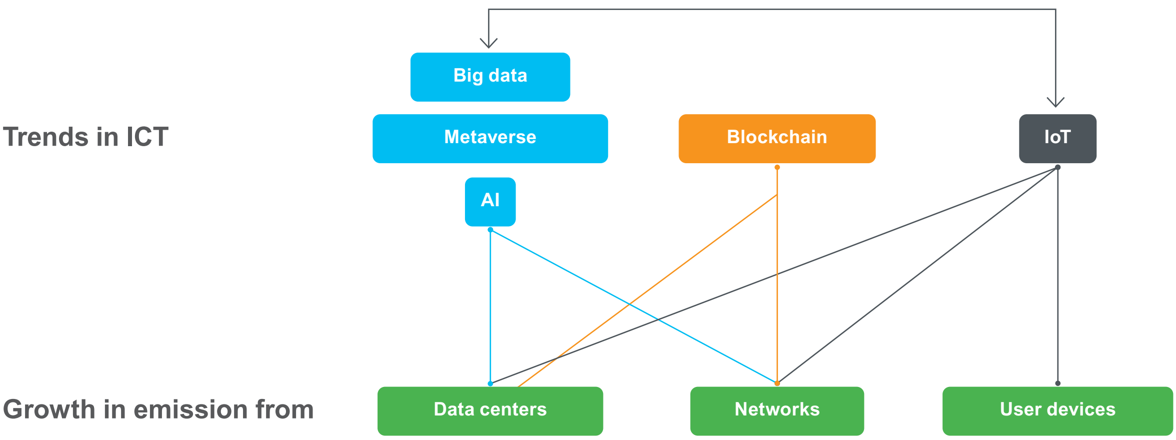


Figure 2. New technologies and existing ICT infrastructure interdependencies. Schneider Electric™ Sustainability Research Institute, based on Freitag et al. and Einstein Center Digital Future.[118]

In this report, we will exclusively discuss the new technologies of IoT and AI. For now, we are excluding other new technologies such as metaverse, big data and blockchain, but they will be part of future analyses.

2.4. IoT dichotomy: Straddling between ICT and digital enablement.

The proliferation of IoT devices is accompanied by a notable increase in the number of devices, device-related data traffic, and the resulting emissions. The quantity of IoT devices and the corresponding data traffic are expanding at a remarkable pace.

IoT as an enabler for end-sector efficiencies…

- IoT technologies have the potential to enhance efficiency in areas beyond the ICT sector. IoT applications are frequently perceived as "smart technology,"(57) particularly when integrated with data science and artificial intelligence to optimize energy utilization on a broader scale.(58)
- This massification of deployment can play as an enabler in most of the end-sectors related to the energy, and it can also support the transition to a better understanding of the demand-side through measurement and feedback loops.(59)

…in certain conditions.

- Nevertheless, although the utilization phase of IoT systems is typically well-documented, and despite the availability of generic IoT device life-cycle models that enhance our comprehension of various critical stages in an IoT device's life cycle, they often fall short in delivering quantitative insights into the direct environmental consequences of IoT devices.

We identify two significant gaps in environmental assessments that remain unaddressed.

1. Embodied carbon: as discussed by Thibault Pirsona and David Bola(56) IoT's carbon footprint is under-explored but will have significant implications for embodied emissions.

2. Rebound effects: it is important to exercise caution when considering IoT applications that may inadvertently result in rebound effects. For instance, smart home technologies hold the potential to decrease energy consumption by enabling remote control of heating and lighting. Still, they could inadvertently lead to what we might term 'energy-intensification' once adopted. This can occur by offering new services, such as pre-heating homes or maintaining continuous security systems, or by intensifying existing services like increased internet connectivity or audio/visual entertainment(60). The latter can contribute to the carbon footprint of ICT through the introduction of more user devices and heightened data traffic.

As a result, we stress the wide array of opportunities presented by IoT in the realm of greenhouse gas (GHG) emission reduction, provided that IoT applications replace carbon-intensive activities rather than simply coexisting with them. **Therefore, it is imperative to embrace a holistic life cycle approach and consider all potential indirect impacts that the deployment of such technology may have**.

2.5. Ubiquitous Artificial Intelligence.

We emphasize that AI should be viewed as a complement to, rather than a replacement for, traditional climate change mitigation strategies. While AI can have impactful applications, it's crucial to understand that there is no single remedy that can completely resolve the issue of climate change. Additionally, it's important to note that while we are focusing on how AI can contribute to climate change mitigation, AI can also be employed in ways that exacerbate climate change. For instance, AI is frequently used to expedite activities like fossil fuel exploration and extraction(61)(62)(63), and some AI models themselves consume substantial energy during their training and operation.(64)(65)(66)(67)

The carbon footprint of AI is still difficult to quantify and even estimate.

- While looking at the direct effects of AI, the integration of AI has the capacity to impact the expansion of digital infrastructures and may result in a heightened global environmental footprint, irrespective of the efficiency of the underlying equipment. Recently, the environmental impact of training natural language processing models has become a source of concern – see, for example, Strubell et al.(68) and Patterson et al.(69) (70). Though these studies generally align with the categorization of data centers, networks, and end-user devices, there are variations in the terminologies used and the specific aspects they emphasize.
- Data science and AI offer additional threats over and above the potential growth of data center emissions. **AI has the greatest potential for impact given the complexity of training and inferencing on big data, and especially so-called deep learning and large-language models**(23). Researchers have approximated that training a single machine learning algorithm for natural language processing can result in the emission of approximately 284,019 kilograms of carbon dioxide equivalent (CO_2e), a carbon footprint equivalent to five times the lifetime emissions of an average car. While this figure has been criticized as an extreme case (more typical model training scenarios may produce only around 4.5 kilograms of CO_2e)(71), the environmental impact of model training is still considered a potential concern, especially given the ongoing trends in AI computation growth(72). Let us remark that a **large model will require more energy to be learned but can then be applied to a broader scope of applications, and hence could provide a higher return on carbon-investment**(115). It's worth noting that AI training computations experienced an exponential increase of 300,000 times between 2012 and 2018, doubling roughly every 3.4 months.(73)

AI literature mostly address a small part of direct impacts and neglects production and end of life, and mostly not following ITU guidelines.(74)(75)

- While some tools today help to estimate the effects of AI(76), the focus tends to center on the training phase typically conducted within data centers, often overlooking the utilization phase on various devices, referred to as the inference phase. Additionally, the manufacturing phase is not consistently considered in these analyses.
- Ligozat et al.(77) contend that the present environmental assessment of AI services is undervalued and suggest that AI research should incorporate Life Cycle Assessment (LCA) to appraise the efficacy of an AI service. Gupta et al.(78) emphasize the increasing part of manufacturing in the life cycle of computing and AI in particular, while Wu et al.(79), Kaack et al.(80), and Ligozat et al.(77) advocate for more extensive evaluations of AI systems, considering the whole life cycle of equipment, the different phases of AI, and its indirect effects.

AI research should use systematically LCA to assess the usefulness of an AI service.

- Recently, Machine Learning (ML) has gained widespread recognition as a highly versatile tool for advancing technology. While there has been substantial growth in using ML/AI for addressing societal and global challenges, there's still a pressing need for a collaborative effort to determine the most effective ways these tools can be harnessed to combat climate change.
- While AI may play a significant role in reducing carbon emissions in various sectors, **there has been, to our knowledge, no comprehensive investigation into the overall environmental consequences of AI solutions within the broader context of environmental goals**, extending beyond the assessment of greenhouse gas (GHG) emissions.(81)

Enablement effects of AI: An outlook on climatechange.ai.

Climatechange.ai is a consortium of researchers which summarized 42 use cases (see in Appendixes) to tackle Climate Change with ML/AI with an evaluation methodology based on 3 levels of impacts[82]:

- **High Leverage** signifies critical bottlenecks identified by climate change experts that are particularly suitable for the application of machine learning tools. These areas hold the potential for ML practitioners to make a significant impact, although it's essential to note that non-flagged applications are also valuable and should not be disregarded.
- **Long-term** refers to applications whose primary effects are anticipated to be realized after the year 2040. While these applications are of utmost importance, they may, in certain cases, be considered less urgent than those with the potential to address immediate climate change issues.
- **Uncertain Impact** identifies applications where the influence on greenhouse gas (GHG) emissions is unclear, potentially due to factors like rebound effects, or where there is a possibility of undesirable side effects or negative externalities.

This approach sets the stage for a discussion regarding the hierarchy of AI impacts within various end-sectors. While platforms like www.climatechange.ai assist in outlining the practical use cases associated with ML/AI implementation, there remains a gap in our understanding that needs to be addressed through a comprehensive life cycle assessment analysis. This is essential to establish concrete evidence regarding whether the effects of AI are positive or negative in the context of climate change.

Enablement effects of AI: AI for Green quantification.

- When proposing an AI for Green method, one should ensure that the overall environmental impact is positive: the positive gain induced by using the AI solution should be higher than the negative impacts associated to the solution. While these use cases represent an important source of potential opportunities, we want to emphasize that such a use case should be tested and validated through the application of a Life Cycle Analysis (LCA) approach, typically as shown in the publication from Ligozat et al.[77]

Enablement effects of AI: AI and energy digitalization.

- The anticipated increase in the electrification of our energy system is set to foster greater connectivity among various elements, including buildings, electricity networks, and the mobility sector. The realization of such interconnected infrastructures hinges on the pivotal role of digital tools. These tools are essential for tasks like data collection, transmission, processing, the creation of comprehensive databases and models, and ultimately, for facilitating optimal decision-making processes. **The emergence of digitalized systems, harnessing the power of artificial intelligence (AI) and capable of making partially to fully autonomous decisions, is a vital component of the ongoing digital transformation within the energy system.**[83]
- This digitalization of the energy system serves as a key enabler of electrification. It holds immense potential to enhance the delivery of essential services such as lighting, thermal comfort, communication, and mobility in a more efficient manner. It also aligns with overarching goals, including providing universal access to electricity, promoting the decentralization of energy generation, accommodating higher proportions of renewable energy sources, and advancing energy efficiency improvements and flexibility.[84]
- Recognizing the imperative of reconciling sometimes conflicting sustainability objectives, digitalization is increasingly, albeit implicitly, expected to play a substantial role by diverse stakeholders. These stakeholders encompass government, private sector entities, and NGOs. The collective aspiration is that digitalization will contribute significantly to achieving environmentally and socioeconomically sustainable development.[85]

3 Beyond Direct Effects: Towards a unified approach

The digital phenomena cannot be oversimplified to one aspect or another: an integrated approach is required, one that is quantifiable and structured by a holistic methodology. This approach should establish a framework that combines analytical rigor and the possibility to scale in some extend.

The Schneider Electric™ Sustainability Research Institute proposes a comprehensive approach, the Net Digital Impact framework consisting of four fundamental layers.

This holistic approach aims a thorough evaluation of the multifaceted impact of digital technologies on the environment, the economy, and society, building potential new valuable insights.

3.1. Clarifying the taxonomy of the issue at hand.

- While there has been a consistent and growing interest in evaluating the overall energy impact of ICT, with a focus on how indirect effects can either offset or amplify the energy consumed directly by ICT equipment, it's crucial to recognize that the scope of potential effects extends well beyond energy considerations. These effects encompass a wide array of factors, including carbon impact, resource consumption, waste generation, water usage, land use, and more.
- These indirect effects can yield both positive and negative consequences, and there is considerable variation in opinions regarding the direction and magnitude of these impacts. Research in this field spans a broad spectrum, ranging from studies that narrow their focus to specific services (such as comparing e-commerce to traditional retail) to extensive macroeconomic investigations aimed at providing a comprehensive understanding of the broader influence of ICT.
- Furthermore, apart from the indirect effects associated with technology utilization, there is a lack of comprehensive modeling for the broader economic and societal systemic effects, even though these factors can, in turn, influence both direct and indirect effects.
- Therefore, **it is essential to have the capability to model the entire chain, incorporating into the modeling process not only the indirect effects related to the environment (such as energy, carbon, materials, water, etc.) but also accounting for the economic and societal consequences**.

Our suggestion is to consider four fundamental layers when constructing the Net Digital Impact model.
- Layer 1 – Technology perspective (direct effects).
- Layer 2 – User perspective (indirect effects).
- Layer 3 – Economic system perspective (economy-wide effects).
- Layer 4 – Social system perspective (society-wide effects).

It's worth to highlight that each of these layers require a distinct approach to quantification.
- Layer 1 might primarily utilize a Life Cycle Approach, which allows for the measurement of effects on energy, carbon emissions, and resource utilization.
- Layer 2 could predominantly employ an enablement/avoided impact methodology.
- Layers 3 and 4 could benefit from the application of rebound effects models such as consequential tree.

Moreover, we will tend to ensure the convergence of the Net Digital Impact Framework and the ITU-T L.1480 recommendations.

3.2. What has been documented in existing research?.

Various categorizations have been put forward to characterize the environmental consequences of Digitalization.

In 2006, Hilty and al. proposed a classification with three orders effects.[(86)]

- 1st-order effects: These are related to the life cycle of a product or service. They typically involve the direct environmental impacts associated with the production, use, and disposal of digital products or services.
- 2nd-order effects: These are related to the efficiency and substitution effects of a service. This category considers how the use of digital services can lead to more efficient resource use and potential substitution of traditional, less environmentally friendly processes.
- 3rd-order effects: These are related to behavioral and structural changes brought about by a service. This category explores how the adoption of digital technologies can lead to broader changes in behavior and societal structures that may have indirect environmental consequences.

Rattle's (2010) framework[(87)] proposes five distinct categories for indirect effects.

- Optimization,
- Substitution,
- Induction,
- Supplementation,
- Creation.

The initial two categories directly correspond to efficiency and substitution, whereas induction, supplementation, and creation can be loosely associated with, or considered as specific instances of, direct, indirect, and economy-wide rebound effects, respectively.

In 2014, Hilty and Aebischer[(88)] introduced a modified classification called the 'LES model':

- L for Life-cycle impact: This focuses on the environmental impacts throughout the entire life cycle of digital products and services.
- E for Enabling impact: This highlights the benefits that come from using ICT services.
- S for Structural impact: This examines the socioeconomic impacts of ICT on society.

In 2016, Horner et al. further summarized more precise categorizations, including[(89)]:

- Indirect effect of a single service: This involves considering the efficiency, substitution, and direct rebound effects of a single digital service.
- Indirect effect of complementary services: This relates to indirect rebound effects, where multiple digital services complement each other, potentially increasing overall consumption and impacts.
- Economy- and society-wide indirect effects: This looks at the broader indirect environmental effects on the economy and society as a whole due to Digitalization.

From our perspective, the work of Horner et al. is the most comprehensive established conceptual framework to assess the potential energy savings, but neglects electrification and has been, from our knowledge, not applied to the energy sector so far.[(90)]

In 2022, the ITU-T L.1480[113] issued a methodology for assessing how the use of ICT solutions impacts greenhouse gas (GHG) emissions on other sectors.

- The methodology provides guidance on the assessment of the use of ICT solutions covering the net second order effect (i.e., the resulting second order effect after accounting for emissions due to the first order effects of the ICT solution), and the higher order effects such as rebound effects. This recommendation applies a hybrid approach including elements of both consequential and process-sum life cycle assessment (LCA) – the scoping considers consequential principles, whereas the quantitative assessment is based on process-sum LCA.

The key principles are the following:

- 3 orders of effects: First order effect + Net second order effect + Higher order effects (which we define as "Systemic effects" on the Net Digital Impact framework).
- 3 depths of assessment: Tiers 1-3: Each of these is associated with specific requirements on data quality and provides specific guidance for the consideration of rebound effects.
- 3 time perspectives:
  - Ex-ante, i.e., a prospective assessment taking place before the assessed operation period of the ICT solution(s);
  - Mid-way, i.e., an assessment of a present situation during the operational life of the ICT solution(s);
  - Ex-post, i.e., a retrospective assessment that takes place after the assessed operation period of the ICT solution(s).

Despite the fact this methodology is essentially ICT-sector based, it has the potential to be extended to the broader scope of sustainable demand-side solutions including the EEE sector. We will use this methodology as a guiding thread for our quantifications combining digital and energy.

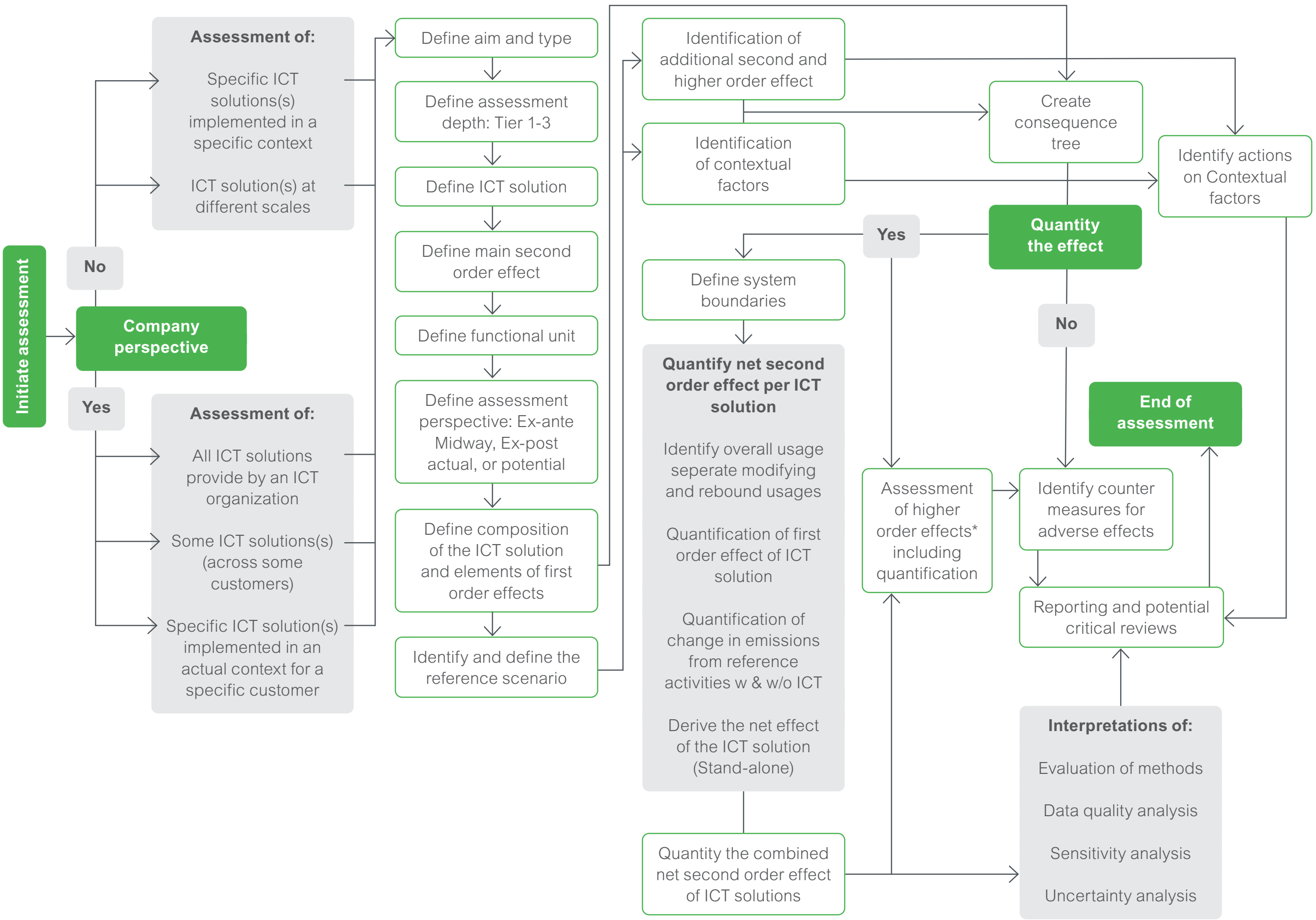


Figure 3. ITU-T L.1480. ICT effects assessment methodology.
*Includes such as data selection, cut-off use of emission factors.

3.3. The Net Digital Impact framework.

Schneider Electric™ Sustainability Research Institute introduces an extension of the Net Digital Impact framework suggests a fusion of the classifications from Horner et al. (direct, indirect and systemic), offering a versatile analytical scope that can encompass various potential impacts, such as those related to energy, carbon emissions, and resource utilization. The proposed framework is essentially based on Horner et al. proposal and aims to integrate the relevant existing and future methodologies, such as, for instance, the ITU-T L1480.

- It's a **multi-criteria framework**, which embarks all potential needed measurement such as for instance CO_2, resources, energy demand, economical, society criterias.
- The **sum of the impacts of each category reflects the Net Impact of digital on the considered criteria**. The result is a physical value, not a scoring.
- The more negative the Net Digital Impact, the more the cumulative impacts of digital technology are positive for the environment. The impact of digital technology on the economy and society needs to be evaluated based on specific chosen criteria. While there might be positive outcomes in some aspects, a comprehensive analysis must acknowledge and address potential drawbacks. It is thus possible that the Net Digital Impact can be negative for some criteria and positive for others, and this for the same field of study.

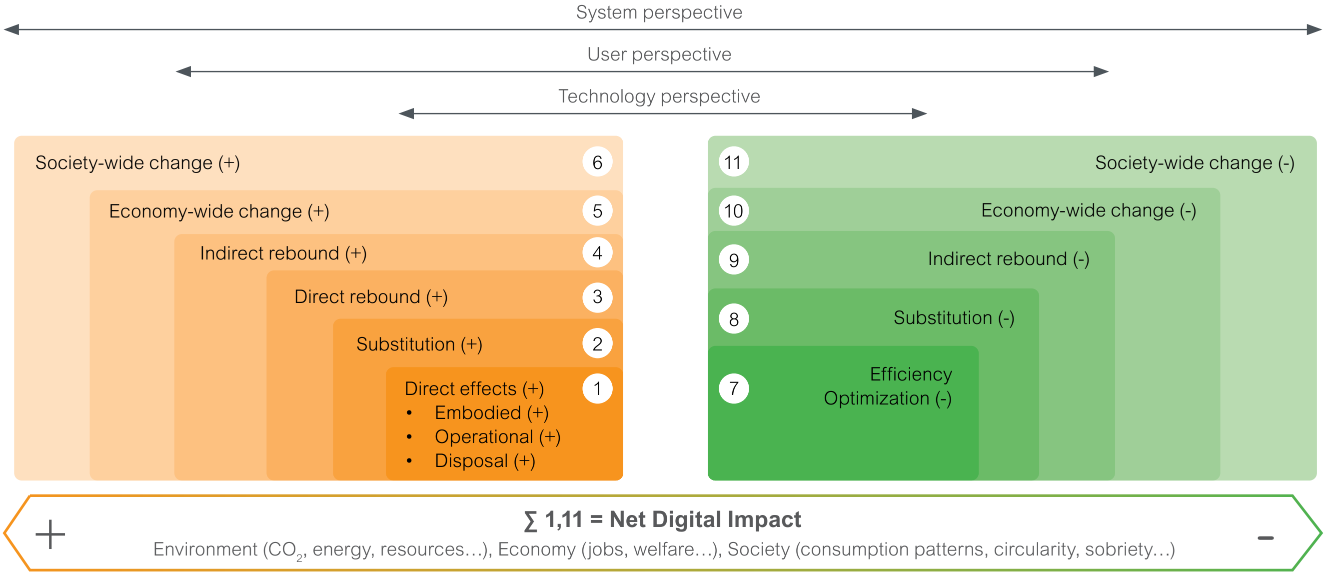


Figure 4. The Net Digital Impact Framework. Schneider Electric™ Sustainability Research Institute, based on Horner et al.

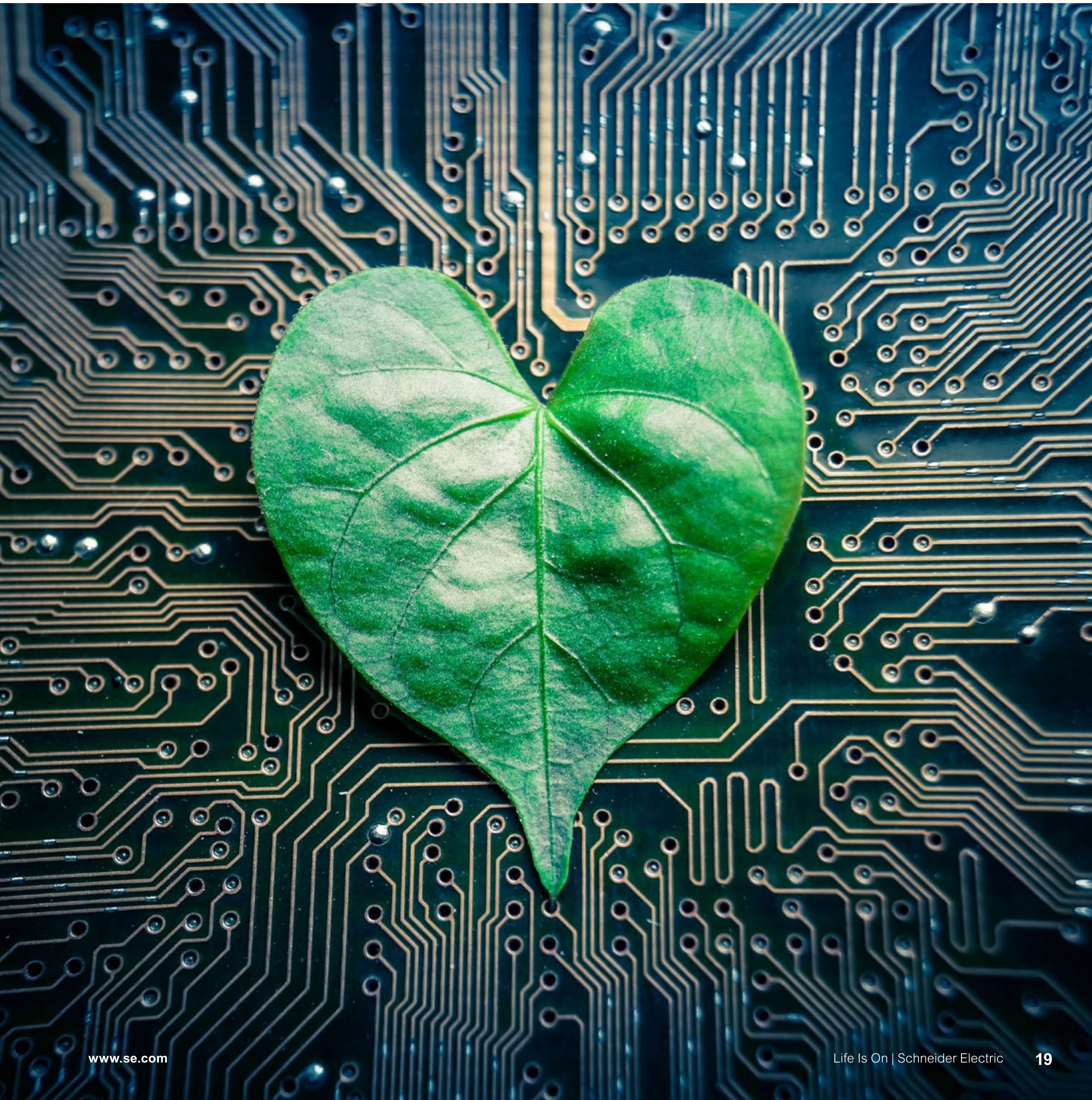
The taxonomy proposed is the following:

- Direct effects (+):
  - Embodied: Impact to design, manufacture and maintain the end-use technology and its associated ICT infrastructure.
  - Operational: Impact to operate the end-use technology and its associated ICT infrastructure.
  - Disposal: Impact to dispose the end-use technology and its associated ICT infrastructure.
- Efficiency/Optimization (-): Positive impacts on other applications (e.g., efficiency).
- Substitution (+ or -): Impact of life-cycle savings from substitution of an existing service/technology with digitalization.
- Direct rebound (+ or -): Impact of additional technology use, stimulated by lower costs and improved utility.
- Indirect rebound (+ or -): Impact of manufacturing and consuming technology, whose demand has increase because of the cost savings from substituting technology.
- Economy-wide change (+ or -): Impact in multiple markets because of the economy-wide adjustments in prices and quantities following the introduction of technology.
- Society-wide change (+): Impact on society and population because of far-reaching changes in industrial and organizational structures and social practices following the introduction of technology.

Combining the Net Digital Impact Framework with the accurate quantification methodologies.

This framework is a conceptual tool that aims to establish an integrated view for the analysis of digital effects. However, it is important to understand that currently, many initiatives led by reputable organizations (ITU, ARCEP, Green IT, etc.) are developing detailed methodologies that can be incorporated into this framework. In addition, it is key to realize that the more we try to model all of the effects, the more the quantification will be subject to assumptions. **Therefore, to effectively measure and analyze the impact of digital technologies, we need to carefully select use cases that strike a balance between feasibility and impact**. On the one hand, we must avoid overly simplistic cases that are easy to quantify but lack the scale to inform meaningful decision-making. On the other hand, we must avoid overly broad cases that introduce too many assumptions and variability, hindering our ability to draw reliable conclusions. This is the challenge that Schneider Electric will be addressing in its upcoming studies.

4 A deeper dive into use cases



Preliminary considerations

It is worth to distinguish between two types of modeling: empirical or econometric models that fit relationships to data, and accounting or simulation models that are used for projections or scenarios. While there are a number of empirical models that quantify the relationship between ICT penetration and energy or CO_2 outcomes (e.g., a recent one is Briglauer, W., M. Koppl-Turyna, W. Schwarzbauer and V. Bitto (2023). “Evaluating the effects of ICT core elements on CO_2 emissions: Recent evidence from OECD countries” [112]), **there is no consensus yet between the scientific community and decision-makers on the ideal modelling to use**.

4.1. Review of the existing literature.

On the side of the scientific publications.
Most publications are taking hypothesis on the potential direct and indirect effects of Digitalization, leading to works which are prospective scenarios. Most of the scientific publications do not rely on real data and fall into the three categories:

1. Macroeconomic.
   The main contribution on that front is the study by Malmodin et al.[91]
2. Techno-economic by end sector [92 – 103].
   Though end-sector techno-economic models can provide detailed insights into the impact of digitalization on specific industries, they can often be fragmented and lack sufficient real-world data from actual users.
3. Techno-economic by technological domain.[104] [105]

On the side of Industry publications.
From our knowledge, the positive impact of digital on transition policies is highlighted by citing two efforts.

- The first, from a GSMA report[40], is that 1g of CO_2 invested in digital represents 10g of CO_2 avoided in other sectors.
- The second, from a GeSI report[39], suggests that digital technology can reduce CO_2 emissions by up to 20% in other sectors.

While the two reports provide valuable insights into the potential emissions reductions associated with digitalization, they acknowledge that further research is needed to develop more comprehensive and reliable estimates. The authors suggest that future studies should focus on improving data transparency and authenticity, refining assumptions, and developing standardized methodologies.

However, and despite mixed results up to now, the world of research and industry have been strengthening their ties very recently (2022 – 2023) and have begun to develop new methods and approaches, typically:

- The creation of a first standard in the sector in December 2022: ITU-T L.1480 (Enabling the Net Zero transition: Assessing how the use of information and communication technology solutions impacts greenhouse gas emissions of other sectors).
- The European Commission has decided to fund a methodological project on the subject in collaboration with the European Green Digital Coalition, a working group of CEOs from major digital companies, and other partners such as GeSI, GSMA, Digital Europe. A publication is set to be released in Quarter 1 2024.[108]
- The World Business Council on Sustainable Development (WBCSD) published, in March 2023, a methodological guide on the calculation of enablement effects.[109]

It is worth noting that the publication by WBCSD represents a significant milestone in how the historical recognition of quantifying the potential enablement effect has traditionally been acknowledged.

Let us note however that the WBCSD considers that these methodologies cannot be applied in the fossil energy sector and related fields, as explained in its guide for selecting solutions with access to avoided emissions calculations[109]:

“The solution has mitigation potential according to the latest climate science and recognized sources and is not directly applied to activities involving the exploration, extraction, mining, and/or production, distribution, and sale of fossil fuels, namely oil, natural gas, and coal.”

4.2. Methodological considerations on the quantification of indirect effects.

Several methodological considerations should be considered when running quantification.

- Defining system boundaries as well as the reference scenario: system boundaries (e.g., which impacts are included, which not) are the biggest source of uncertainty.
- Defining time scale and spatial scale of impact.
- Attributional and consequential life cycle analysis approach.
- The importance to define Digitalization solutions that can have an efficiency, optimization, or substitution impact in the long term, spanning at least 10 years.
- The systemic effects of Digitalization.

Deep dive on the systemic effects of Digitalization.
Considering the quantification of avoided emissions, it’s rare for a digital service or solution to produce the same effect regardless of the conditions.[111]

- A set of conditions must be met beforehand for the studied digital solution to generate significant positive effects (the same logic applies to negative effects). Without these conditions, digital services generally tend to have marginal effects on the business segments or sectors they aim to decarbonize. Typically, a connected and automated heating system will have little impact in a poorly insulated house, and a bike-sharing app will have a marginal effect without sufficient bike infrastructure.
- Hence a digital solution is rarely self-sufficient when it comes to decarbonization; a set of public policies and investments are necessary beforehand. This point serves as a caution regarding the prioritization of investment in the low-carbon transition: digital services are more likely to have significant effects once other key factors (thermal renovation, electrification, etc.) have been initiated.

Overall, **we will tend to ensure the convergence of the Net Digital Impact Framework and the ITU-T L.1480 for the use cases studied in this chapter**. We consider ITU standards (L. 1410, L. 1450, and L.1480) as a good methodological reference point for the quantifications as ITU standard includes the use of consequence trees for mapping out the indirect impact pathways and potential higher order effects.

To gain a better understanding of indirect effects, we will leverage the Net Digital Impact framework, which encompasses both direct, indirect, and systemic effects. **For this initial publication, we will focus essentially on a qualitative assessment rather than implementing the ITU-T L.1480 in full**.

This report focuses on quantifying the direct, efficiency, and optimization effects of digitalization on two use cases. Future publications will explore the other tiers of impacts.

4.3. Digitalization of Energy: Microgrid use case.

Use Case #1: Modelling a Microgrid.
A microgrid is a localized and decentralized energy system that can generate, store, and distribute electricity to a specific area or community, typically on a smaller scale than traditional centralized power grids. Microgrids are designed to operate independently or in conjunction with the larger grid, depending on the circumstances, and they offer several advantages, including increased resilience, reliability, and sustainability. Key components and features of a microgrid include:

- Distributed Energy Resources (DERs),
- Energy Storage,
- Control System,
- Grid Connection.

Purpose of the study.

We assessed the direct and indirect effects, with a focus on the carbon criteria, achieved by a standard microgrid system over the course of one year. The goal is to compare indirect effects with the direct effects associated with the microgrid's Distributed Energy Resources (DERs) and the emissions generated through the use of the microgrid management software EcoStruxure™ Microgrid Advisor (EMA).

In this research, we focus on microgrid archetypes situated in Europe, Asia, and North America. A microgrid system can be categorized into two main components: on-site equipment and cloud-based equipment.

1. ICT-Hardware: the on-site equipment includes key elements such as a Photovoltaic (PV) system, batteries, and power meters.

2. ICT-Networks and softwares: it features a controller, which is a local computer operating continuously to gather data from the on-site DERs. This data is transmitted to the cloud servers, and conversely, the controller receives service orders from the cloud servers. This data exchange occurs through a secure HTTPS protocol using wired communication. On the other hand, the cloud-based equipment comprises the servers responsible for processing data from the DERs, running forecasting and optimization algorithms, and sending back instructions and setpoints at 15-minute intervals. It is important to note that this study assumes the servers are located in Europe.

This case study seeks to evaluate the direct and indirect effects realized by by such a microgrid system, on the carbon criteria. It analyzes the emissions associated with the microgrid's components and operations, addressing the broader question of whether microgrids effectively contribute to reducing carbon emissions over their entire lifecycle.

As presented before, this first quantification does not integrate the systemic effects of the microgrid. This will be done in a next publication.

Methodology.

The case study utilizes the Life Cycle Assessment (LCA) methodology established by ISO 14040 and ISO 14044. This approach is employed to evaluate the environmental impact of a product across its entire lifecycle. Therefore, all the data presented in the following sections encompass the complete lifecycle of the microgrid, with a focus on carbon emissions. A few software components, e.g., for the maintenance of the microgrid elements, have been considered negligible in comparison to the real-time microgrid control, and have not been evaluated.

To address the diversity of microgrid installations, this study calculates an average of carbon savings and emissions of a microgrid archetype based on 46 representative building types and sizes in Europe, Asia, and North America. These 46 instances coincide with those used in the Schneider Electric™ AI Hub Energy Study (analyzing 126 instances)[117] on which a microgrid was economically beneficial. Carbon savings are evaluated by simulation using the Schneider Electric™ Microgrid Design Tool[116]. This approach ensures a comprehensive and representative assessment of the environmental impact across various microgrid configurations.

Summary of results: Applying the Net Digital Framework to the Microgrid.

We have undertaken an assessment of the carbon emissions and savings over the span of one year. To achieve this, we initially estimated the embodied carbon emissions of the Distributed Energy Resources (DERs) and quantified microgrid savings through an extensive energy study conducted across 46 distinct microgrids. The current scope of analysis in only the direct effects and the efficiency/optimization indirect effects.

Our findings demonstrate that our 46 microgrid archetypes provide on average annual carbon savings of 92 tons of CO_2eq. This underscores the significant environmental benefits offered by such microgrid implementations.

Detailed explanations of the outcomes and underlying hypothesis are provided in the next pages.

Net Digital Impact framework: Microgrid use case assessment

Category of effects	#	Impact + / –	Hypothesis & Calculations		Source for quantification	Results ($kgCO_2eq/y$)		
Direct Effect	**1**	Embodied +	Carbon emissions within the Distributed Energy Resources (PV, Battery, Power Meters).	The calculation of embodied emissions within the Distributed Energy Resources (DERs) is executed by leveraging the building dimensions obtained from the Schneider Electric AI Hub Energy Study and the Global Warming Potential (GWP) associated with each functional unit of the PV system and the batteries. The estimation of embodied emissions is calculated by multiplying the dimensions of the DERs by the GWP of their respective functional units and then dividing the result by the lifespan to obtain yearly figures.	Schneider Electric™ AI Hub	10023	10137.1	-92006
		Operational +	Carbon emissions resulting from the utilization of the EMA software in a typical microgrid.	To evaluate the environmental impact of the EcoStruxure™ Microgrid Advisor (EMA) software, we employ the LCIE tool, which utilizes the CODDE database. This tool is adapted to accommodate the specific context of the microgrid. This estimation focuses on the carbon emissions generated during the use of the EMA software, with the emissions associated with the development environment excluded from consideration.		114.1		
		Disposal +	Not estimated	N/A		N/A		
Efficiency/ Optimization	**7**	Efficiency/ Optimization –	Efficiency effects related to the installation of a microgrid. Baseline: DERs without microgrid.	The estimation of microgrid savings is rooted in an energy study conducted by Schneider Electric. This study employs simulations based on ASHRAE standards to gauge the energy savings achieved in various types of buildings, comparing scenarios with and without the installation of a microgrid. These simulated microgrids consist of Photovoltaic (PV) systems and batteries that facilitate the import, generation, storage, and export of energy. The study assumes that the Distributed Energy Resources (DERs) both utilize and generate renewable energy, which holds true in the case of a PV system. Additionally, it is assumed that the energy exported to the grid is carbon neutral. By contrasting imported energy with and without the microgrid for the same building, one can calculate imported energy saving, consequently translated to carbon savings, depending on the carbon footprint of the imported energy. The average carbon savings are determined by averaging the results across all the selected simulations within the study.	Schneider Electric™ AI Hub	-102143		
Substitution	**2**	Substitution +	Additional emissions due to the substitution of a conventional meter with a smart meter.	A smart meter requires the use of other equipment to function: a concentrator, the mobile access network (GPRS/3G), the core network, and servers in a data center.	Jens Malmodin and Vlad Coroama, "Assessing ICT's enabling effect through case study extrapolation – the example of smart metering," Electronics Goes Green 2016+, 2016.	Not quantified		
	8	Substitution –	Avoided emissions thanks to the automation of the information between the DERs.	Emissions related to the change of meter.	Glenn Sias, "Characterization of the Life Cycle Environmental Impacts and Benefits of Smart Electric Meters and Consequences of their Deployment in California," UCLA Thesis, 2017.			
Rebounds	**3**	Direct Rebound +	Additional emissions due to changes in behavior.	Quantifying the impact of changes in behavior.	Fateh Belaïd, Adel Ben Youssef and Nathalie Lazaric, "Scrutinizing the direct rebound effect for French households using quantile T regression and data from an original survey," Ecological Economics, 2020.	Not quantified		
	4	Indirect Rebound +	Additional emissions due to the new equipments and services generated by the installation of the microgrid.	Considering the purchase of additional equipment to enhance the operation and benefits of a microgrid.	Jens Malmodin and Vlad Coroama, "Assessing ICT's enabling effect through case study extrapolation – the example of smart metering," Electronics Goes Green 2016+, 2016.			
	9	Indirect Rebound –			Veronika Kulmer and Sebastian Seebauer, "How robust are estimates of the rebound effect of energy efficiency improvements? A sensitivity analysis of consumer heterogeneity and elasticities," Energy Policy, 2019.			
Economy-wide change	**5**	Economy-wide change +		Macroeconomic rebound effects involve looking at the scale of a sectoral or national economy. It is typically an observation made after the fact when a given economy has adapted to a new situation of efficiency and price changes. Depending on the publications, macroeconomic rebound effects can encompass all other rebound effects, so one must be cautious about the risk of double counting.	CGE (Computable General Equilibrium) Model Paul Brockway, "Energy efficiency and economy-wide rebound effects: A review of the evidence and its implications," Renewable and Sustainable Energy Reviews, 2021.	Not quantified		
	10	Economy-wide change –						
Society-wide change	**6**	Society-wide change +						
	11	Society-wide change –						

Table 1. Net Digital Impact of a Microgrid. Schneider Electric™ AI Hub.

Detailed Results – Direct Effects.

Embodied carbon emissions.
The calculation of embodied emissions within the Distributed Energy Resources (DERs) is executed by leveraging the building dimensions obtained from the Schneider Electric™ AI Hub Energy Study and the Global Warming Potential (GWP) associated with each functional unit of the PV system and the batteries. These GWP values are sourced from 'PEP ecopassport®[(a)]', a globally recognized program for environmental declarations of products within the electric, electronic, and heating & cooling industries. PEP ecopassport® conducts product Life Cycle Assessments (LCAs) in accordance with ISO 14025, covering the entire product lifecycle – from production and distribution to installation, use, and end-of-life considerations. Similar to the carbon savings estimation, the carbon emissions estimation is carried out by averaging data across the selected simulations from the Schneider Electric™ AI Hub Energy Study.

- For the assessment of the PV system's GWP, the Solar panel "Photowatt" from 'EDF ENR PWT'[(b)] is employed as a reference. This PV system has a lifespan of 25 years and is composed of components manufactured in China, France, and Norway. According to its PEP, it is evaluated at 524 kgCO_2e/kWh. In the absence of data enabling to establish the sourcing of the solar panels depending on the geography, we used this number as reference.
- To evaluate the GWP of the battery system, the study conducted by J. Sadhukhan et al. – as detailed in "An In-Depth Life Cycle Assessment (LCA) of Lithium-Ion Battery for Climate Impact Mitigation Strategies"[(114)] – is utilized. This battery has a lifespan of 10 years and is evaluated at 25.8 kgCO_2e/kW in the referenced article.
- For the assessment of power meters GWP, the Energy Sensor Powertag NSX from Schneider Electric serves as the reference. These power meters are manufactured at a Schneider Electric production site certified under ISO 14044 standards and have a lifespan of 10 years. The PEP for these power meters evaluates them at 162 kgCO_2e/kW/asset.
- The estimation of embodied emissions is calculated by multiplying the dimensions of the DERs by the GWP of their respective functional units and then dividing the result by the lifespan to obtain yearly figures. On average, the embodied emissions associated with the DERs amount to 10.023 tons of CO_2e per year.

Operational carbon emissions.
To evaluate the environmental impact of the EcoStruxure Microgrid Advisor (EMA) software, we employ the LCIE (LCIE is the Bureau Veritas tool to quantify the environmental impact of your products and services throughout their life cycle), which utilizes the CODDE database. This tool is adapted to accommodate the specific context of the microgrid. This estimation focuses on the carbon emissions generated during the use of the EMA software, with the emissions associated with the development environment excluded from consideration.

- The EMA version 5 (v5) architecture consists of several key components. These include a one-site controller, essentially a local computer, responsible for collecting data from on-site equipment and transmitting it to the EMA cloud server. Conversely, it relays service orders from the EMA cloud server to the on-site Distributed Energy Resources (DERs). The connection between these components operates through a secure HTTPS protocol using wired communication.
- Within the EMA v5 architecture, Model Predictive Control and forecast algorithms play a central role. They process and analyze data from the DERs, providing instructions and setpoints back to the system every 15 minutes. These computations are executed on Azure servers, which are located in Europe.

In essence, this assessment focuses on the carbon emissions linked to the operational use of the EMA software, while development-related emissions are not considered in this estimation.

As per the LCIE methodology, when considering the "Scenario 1: Collecting and managing sensor data," there are three primary sources of carbon emissions within the scope: terminals, network, and servers.

- Within the terminals category, the sole component fitting this description is the on-site controller, which operates on a standard PC computer with a lifespan of 10 years.
  - Type: IPC – EMA Controller
  - Quantity: 1
  - Lifespan: 10 years
- In terms of network-related emissions, the data transmitted to and from the controller flows through wired communication and, on average, amounts to 4.5625 gigabytes over the course of a year.
  - Network Type: DERs to EMA Controller to EMA Cloud (Fixed at 100%)
  - Quantity of data flowing over the network over a year: 4.5625 gigabytes

The server infrastructure encompasses two main functions: computation and storage. In the computation category, there are three distinct server types, each serving specific purposes. These include servers dedicated to Matlab computations, servers hosting the forecasting and optimization component on the Azure platform, and servers for more general computational tasks, also hosted on Azure.

As for storage, data is housed on the Atlas platform. In most cases, data is transmitted to servers located in the Netherlands for the forecasting and optimization components. For a first-order approximation of carbon emissions, we used the Mix-Continental Europe electricity mix for all 46 microgrids, i.e., gCO_2e/kWh. Given the small values obtained in comparison to the embedded emissions, it was not considered necessary to further detail, including any consideration on the expected evolution of the mix in the coming years.

These elements constitute the key sources of carbon emissions within the specified scenario.

Utilizing the LCIE tool, we have conducted carbon emissions estimations for the three primary sources: terminals, network, and servers. Considering the assumptions and numerical data provided, the LCIE tool projects that the carbon emissions resulting from the utilization of the EMA software in a typical microgrid amount to 114.1 kilograms of CO_2 equivalent over the course of one year.

The findings presented in the table below highlight that the utilization of cloud servers represents the most substantial contributor to these emissions.

(a) https://www.inies.fr/en/inies-and-its-data/pep-building-equipment/
(b) https://www.photowatt.com/en/

Note: in the table below, "Optimization ECA/A2S" corresponds to "AI based forecasting and optimization".

LCIE tool results		GWP (kg CO_2 eq.)
Energy Mix		Mix continental, Europe
Terminals		0.74
Network		0.28
Servers	Computation (Matlab) (1 small)	0.65
	Storage (Atlas) (1 small)	4.24
	Optimisation (ECA/A2S) (2 small)	1.6
	Largest EMA Servers (1 big + 2 medium)	41.6
	Other Azure services	65
Total emissions		**114.1**

Table 2. Operational carbon emissions of a Microgrid. Schneider Electric™ AI Hub.

Detailed Results – Indirect Effects: Optimization/Efficiency effects.

The estimation of microgrid savings is rooted in the Energy Study conducted by Schneider Electric. This study employs simulations based on ASHRAE standards to gauge the energy savings achieved in various types of buildings, comparing scenarios with and without the installation of a microgrid. These simulated microgrids consist of Photovoltaic (PV) systems and batteries that facilitate the import, generation, storage, and export of energy.

The study assumes that the Distributed Energy Resources (DERs) both utilize and generate renewable energy, which holds true in the case of a PV system. Additionally, it is assumed that the energy exported to the grid is carbon neutral. By contrasting imported energy with and without the microgrid for the same building, one can calculate imported energy savings, consequently translating to carbon savings. The overall carbon savings are determined by averaging the results across all the selected simulations within the study.

- Out of the 126 simulations in the Schneider Electric Energy Study[117], 46 were selected, i.e., the cases in which a microgrid was economically beneficial. These simulations encompass a range of building sizes, spanning from midrise apartments to secondary schools to strip malls. On average, these buildings consume approximately 3579 MWh of electricity and 123 MWh of thermal energy annually. The PV system sizes range from 12 kW to 999 kW, with an average of 349 kW, while the battery systems range from 38 kWh to 4300 kWh, averaging at 1028 kWh.
- According to the energy study, without the microgrid, the average external energy consumption totals approximately 959 MWh per year, whereas with the microgrid, it drops to around 603 MWh. This signifies an average reduction in consumption of 355 MWh.
- The assumption of a fixed carbon cost is applied to both electricity and thermal energy to estimate the carbon savings attributed to the microgrid. This means that the real savings may be greater than calculated, as the emission factors are conservatively estimated.

Summary of results: Applying the Net Digital Impact Framework to the Microgrid.

The analysis is done per functional unit. The current scope of analysis in only the direct effects and the efficiency/optimization indirect effects.

- Embodied emissions: 10023 kgCO_2eq/y
- Operational emissions: 114.1 kgCO_2eq/y
- Avoided emissions: -102143 kgCO_2eq/y
- **Total Net Digital Impact = -92000 kgCO_2eq/y**

4.4. Digitalization of Energy: Advanced Building Management System use case

Use Case #2: Modeling an Advanced Building Management System (ABMS)

An advanced Building Management System (ABMS), also known as a Building Automation System (BAS) or Building Control System (BCS), is a sophisticated and integrated network of hardware and software that allows for the centralized control and management of various building systems and functions. These systems are primarily used to optimize the operation of commercial, industrial, or institutional buildings, with the goal of improving energy efficiency, comfort, safety, and overall building performance.

Key components and features of an advanced Building Management System may include:

- Sensors and Actuators,
- Control Software,
- Integration,
- Energy Management,
- Fault Detection and Diagnostics (FDD),
- Remote Monitoring and Control,
- Reporting and Analytics,
- Occupant Comfort.

Scope of study: Advanced Building Management vs. standard BMS.

I this use case, we are studying and advanced BMS solution, which aims to provide more savings than a standard BMS thanks to IoT (providing service when and where it is needed in a sufficient way).

As the ABMS adds an added/delta IoT Hardware & IT infrastructure, we compared:

- Extra carbon emissions of the ABMS during use vs. standard,
- Extra carbon emissions embodied in the ABMS vs. standard,
- Extra carbon savings of the ABMS vs. standard.

Methodology.

The study is based on data from physical zones (functional units) from two actual buildings, each physical zone corresponding to 2 windows, 4-6 desks, and about 17 square meters. The average difference in energy consumption per zone is multiplied by the EU electricity carbon footprint to obtain the CO_2 carbon savings per zone in a typical Europe location.

Zone data stem from 2 buildings in Grenoble, France, for which we were able to compare the use of the ABMS (class A) with a standard BMS (class B).

- Building#1 building – 10600m^2
- Building#2 building – 26000m^2 with 4000m^2 PV

Building control architecture made of physical zones (Functional Units).

- Each zone is fitted with 2 combined light level/occupancy sensors and 1 Temperature relative Humidity and CO_2. (no occupancy sensor in class B)
- Each zone includes 1 zone controller (RPC)[a], the zone controller is identical in Class B and Class A BMS.
- One zone/FU ~ "2 windows " equivalent to 4-6 desks ~Functional unit covers ~17m^2
- For Building#1 building: 5 FU per open space, more than 600 Functional Units on site
- For Building#2: 24 FU per open space
- Analysis at FU allows for extrapolation at any building given its size is provided
- Data consultation on server is 30min/year
- Life cycle of 10 years

(a) RPC SpaceLogic™ Controller (formerly known as SmartX IP Controller -- RP-C) is a modular, freely programmable BACnet/IP room controller that helps create smart buildings.

Net Digital Impact framework: Advanced Building Management System use case assessment								
Category of effects	**#**	**Impact + / –**	**Hypothesis & Calculations**		**Source for quantification**	**Results ($kgCO_2eq/y$)**		
Direct Effect	**1**	Embodied +	Carbon emissions from the additional IoT and software layer.	I this use case, we are studying and advanced BMS solution, which aims to provide more savings than a standard BMS thanks to IoT (providing service when and where it is needed in a sufficient way. As the ABMS adds an added/delta IoT Hardware & IT infrastructure, we compared: • Extra carbon emissions of the ABMS during use vs. standard • Extra carbon emissions embodied in the ABMS vs. standard • Extra carbon savings of the ABMS vs. standard	Schneider Electric™ AI Hub	1.01	1.013	-11.287
		Operational +	Carbon emissions resulting from the utilization of the Advanced BMS.			0.003		
		Disposal +	Not estimated	N/A		N/A		
Efficiency/ Optimization	**7**	Efficiency/ Optimization –	Efficiency effects related to the installation of an Advanced BMS.	The Advanced Building Management System (ABMS) demonstrates its ability to achieve carbon savings, even becoming carbon positive, in a remarkably short timeframe – just under one year – for an average European all-electric building using a reversible heat pump heating system. • The key to this achievement lies in the Advanced BMS Solution, which features sensors that enable efficient management of lighting and HVAC services precisely when and where they are needed. For instance, it can automatically turn off lights and heating in unoccupied meeting rooms. While a standard BMS, equipped with controllers and meters lacking spatial and temporal granularity linked to sensors, already delivers savings, the objective here was to showcase the additional benefits gained by adding the digital layer, which includes both hardware and local IT infrastructure. • Real data from the Building #1 over several years revealed energy savings brought about by the solution. A detailed analysis segmented energy consumption by function (heating, cooling, non-weather-dependent loads) and illustrated energy (electricity) savings attributed to the solution, further categorized by usage. The deployed solution achieved a remarkable 15% energy savings (equivalent to 55 MWh) during the 2019-2021 period, surpassing EU targets for energy consumption reduction.	Schneider Electric™ AI Hub	-12.3		
Substitution	**2**	Substitution +	Additional emissions due to the substitution of a conventional BMS with a Advanced BMS.	A smart meter requires the use of other equipment to function: a concentrator, the mobile access network (GPRS/3G), the core network, and servers in a data center.		Not quantified		
	8	Substitution –	Avoided emissions thanks to the optimized automation of the information between the devices.	Emissions related to the change of meter.				
Rebounds	**3**	Direct Rebound +	Additional emissions due to changes in behavior.	Quantifying the impact of changes in behavior.		Not quantified		
	4	Indirect Rebound +	Additional emissions due to the new equipments and services generated by the installation of the Advanced BMS.	Considering the purchase of additional equipment to enhance the operation and benefits of an Advanced BMS.				
	9	Indirect Rebound –			Veronika Kulmer and Sebastian Seebauer, “How robust are estimates of the rebound effect of energy efficiency improvements? A sensitivity analysis of consumer heterogeneity and elasticities,” Energy Policy, 2019.			
Economy-wide change	**5**	Economy-wide change +		Macroeconomic rebound effects involve looking at the scale of a sectoral or national economy. It is typically an observation made after the fact when a given economy has adapted to a new situation of efficiency and price changes. Depending on the publications, macroeconomic rebound effects can encompass all other rebound effects, so one must be cautious about the risk of double counting.	CGE (Computable General Equilibrium) Model Paul Brockway, “Energy efficiency and economy-wide rebound effects: A review of the evidence and its implications,” Renewable and Sustainable Energy Reviews, 2021.	Not quantified		
	10	Economy wide change –						
Society-wide change	**6**	Society-wide change +						
	11	Society-wide change –						

Table 3. Net Digital Impact of an Advanced Building Management System. Schneider Electric™ AI Hub.

Detailed Results.

The Advanced Building Management System demonstrates its ability to achieve carbon savings, even becoming carbon positive, in a remarkably short timeframe – just under one year – for an average European all-electric building using a reversible heat pump heating system.

- The key to this achievement lies in the Advanced BMS Solution, which features sensors that enable efficient management of lighting and HVAC services precisely when and where they are needed.
- Real data from the Building#1 over several years revealed energy savings brought about by the solution. A detailed analysis segmented energy consumption by function (heating, cooling, non-weather-dependent loads) and illustrated energy (electricity) savings attributed to the solution, further categorized by usage. The deployed solution achieved a remarkable 15% energy savings (equivalent to 55 MWh) during the 2019-2021 period, surpassing EU targets for energy consumption reduction.

Regarding emissions, it was demonstrated that the upgrade from a standard BMS to an Advanced BMS solution reaches a carbon "break-even point" in less than one year for a European all-electric office building.

- This assessment considered energy savings converted into avoided emissions and the emissions associated with the solution, including embodied contributions (derived from Product Environment Profiles of hardware and internal analysis) and operational contributions, which were found to be negligible.
- A specific focus on heating at the Building#1 during the 2020-2021 period revealed a striking 35% energy savings (equivalent to 60 MWh), even with increased occupancy in 2021 and higher consumption in other areas, such as IT equipment. This translated into significant avoided emissions.

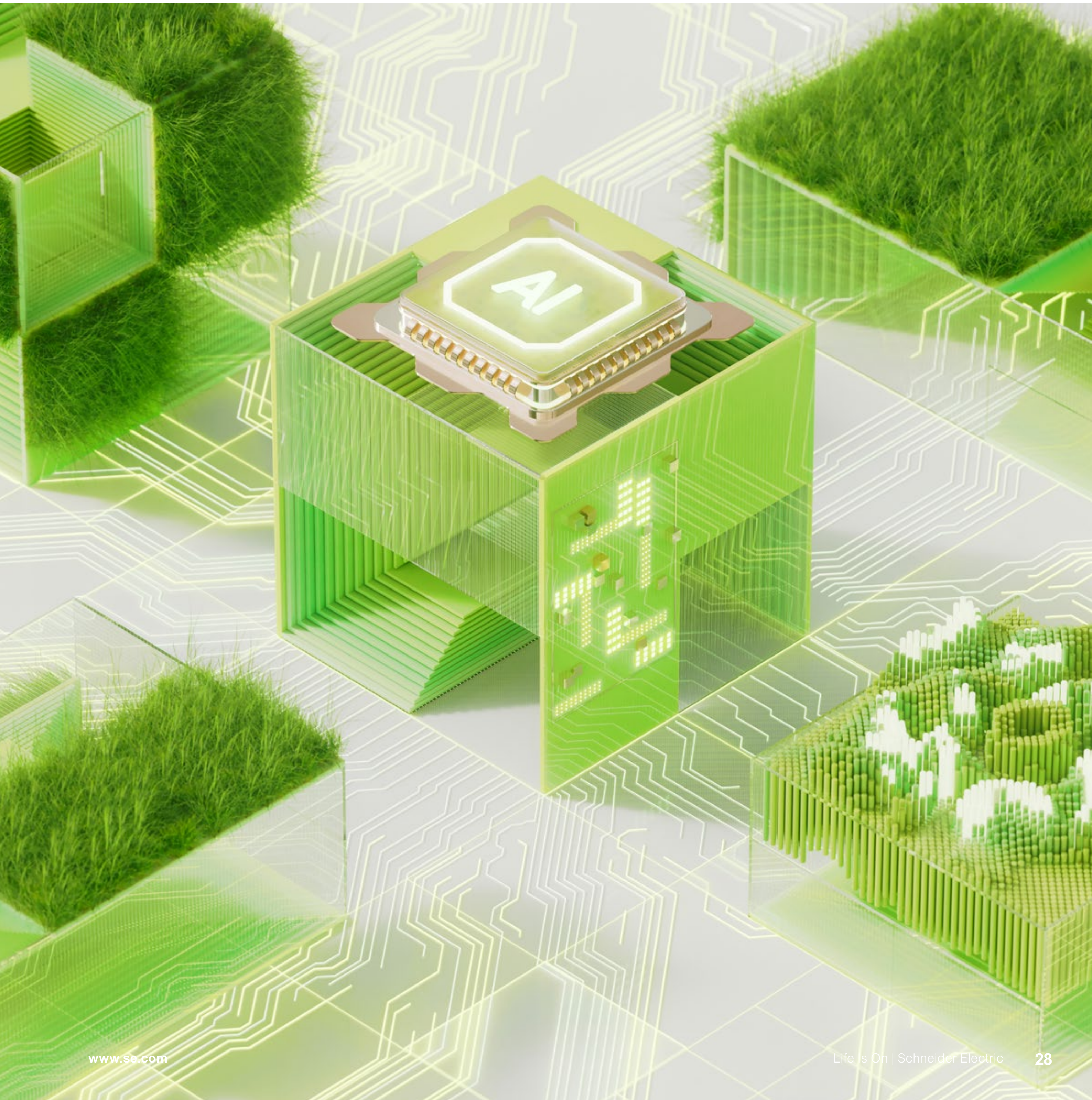
In conclusion, it is evident that implementing an Advanced BMS in gas-heated buildings and all-electric buildings in Europe is a highly effective strategy for rapidly reducing CO_2e emissions while simultaneously contributing to substantial energy cost reductions.

Summary of results: Applying the Net Digital Framework to the Advanced BMS.

The analysis is done per functional unit. The current scope of analysis in only the direct effects and the efficiency/optimization indirect effects.

- Embodied emissions: 1.01kgCO_2eq (hyp:10y lifetime products)
- Operational emissions: <3.10^{-3} kgCO_2eq/year (EU)
- Avoided emissions (avg. EU) vs. EU All Electric building: -12.3kgCO_2eq/year
- Total Net Digital Impact = -11.287 kgCO_2eq/year

5 Considerations for future research and conclusion



Encouraged by the findings presented in this research, Schneider Electric™ Sustainability Research Institute will embark on a series of focused investigations to further probe the following areas of interest.

Research Series 1:
Direct Effects: An updated quantification.

- This research series aims to enhance our understanding of the direct environmental consequences of ICT, particularly in the context of emerging technologies like cryptocurrencies, Artificial Intelligence (AI), the Internet of Things (IoT), and 5G. The series will delve into the latest trends in ICT, such as the ever-expanding volume of digital data driving data center expansion, the challenges of predicting future data center trends, and the importance of efficiency improvements and stricter regulations in curbing data center energy consumption.
- Additionally, the research series will explore emerging areas with the potential to enhance ICT efficiency and reduce energy usage. The research series will also consider the challenges of data collection in distributed systems and propose solutions such as the rollout of smart meters. In terms of research scope and methodology, the series will encompass the entire lifecycle of ICT infrastructure and services, including additional environmental impact indicators.
- It will also examine latest infrastructure advancements (Edge, IoT/IIoT, network deployment…), emerging services (AI/ML life cycle, AR/VR, blockchains), and the environmental impact of the EEE (Electronic and Electrical Equipment) sector.

Research Series 2:
Digitalization of Energy: The imperative to quantify the impacts of Digitalization for a demand-driven energy transition.

- The integration of digital technologies into energy systems holds the potential to revolutionize how we produce, distribute, and consume energy. However, to fully realize the transformative benefits of digitalization and ensure a sustainable energy transition, we need to rigorously quantify its impacts and consider the broader energy ecosystem.
- The research series “Digitalization of Energy” builds upon the methodological foundation established in the current paper, which introduces the Net Digital Impact framework. Guided by this framework, we seek to fill a knowledge gap by developing a database of digital energy use cases and systematically quantifying their impact on various aspects of the energy transition (environmental, social, and economic)
- In term of scope and methodology, the series will also integrate the potential negative effects of digitalization, incorporating counterfactual scenarios, time perspectives, external conditions hypotheses, conservative extrapolation methods, and rebound effects analysis.

Research Series 3:
Digitalisation as an enabler of Circular Economy

- This research series examines the intersection of digital technologies and circular economy principles. It delves into how digitalization can be harnessed to build resilient, interconnected ecosystems that support circularity objectives, leading to enhanced efficiency, cost savings, and innovation. The series will explore key aspects of this integration, including breaking free from reliance on finite resources, adopting ecosystem-centric approaches, digitizing business ecosystems, creating value within circular economies, and identifying the imperatives for transitioning to a digital circular economy.

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Terminology

AI: Artificial Intelligence
EEE: Electronic and Electrical Equipment
ICT: Information and Communication Technology
ISO: International Organization for Standardization
IT: Information Technologies
ML: Machine Learning
GHG: Greenhouse Gas
GSMA: Global System for Mobile Communications Association
GeSI: Global Enabling Sustainability Initiative
GWP: Global Warming Potential
LAN: Local Area network
LCA: Life Cycle Analysis
OECD: Organisation for Economic Co-operation and Development
IPCC: Intergovernmental Panel on Climate Change
WRI: World Resources Institute
IoT: Internet of Things
IIoT: Industrial Internet of Things
AR/VR: Augmented Reality/Virtual Reality

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