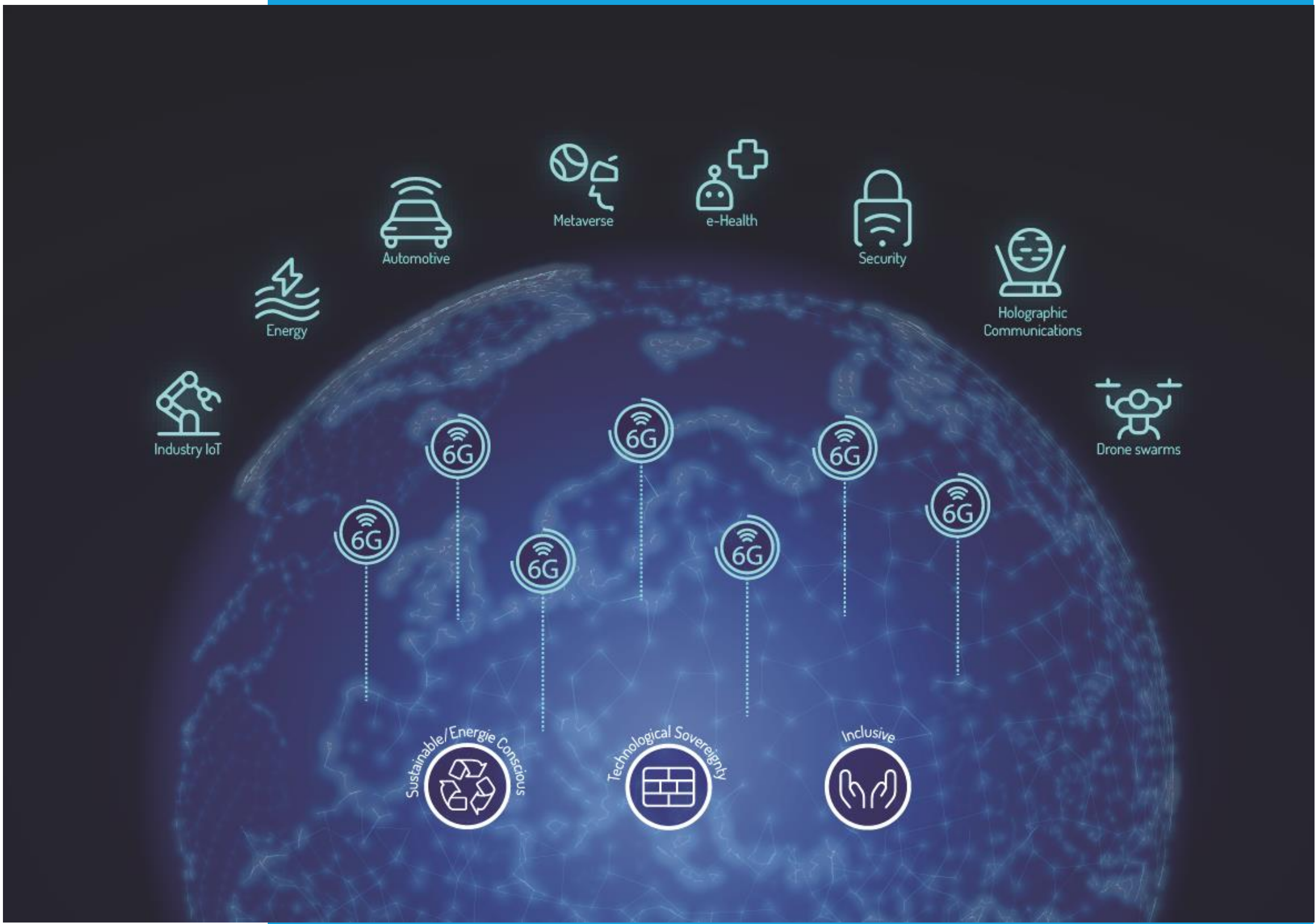
6G-IA Vision and Societal Challenges Working Group



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WHITE PAPER

SUSTAINABILITY OF 6G: WAYS TO REDUCE ENERGY CONSUMPTION

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EXECUTIVE SUMMARY

This document is the first whitepaper of the 6G Infrastructure Association (6G-IA) dedicated to the *technological* questions of sustainability of future mobile telecommunications systems (6G). Produced as a collaborative effort within the 6G-IA Vision and Societal Challenges Working Group (VSC WG), it results from work at the involved partner organizations in both their internal and collaborative research activities, most notably within several running research projects of the Smart Network and Services Joint Undertaking (SNS JU).

This whitepaper identifies main challenges in the area of operational Sustainability of 6G by contrasting the consensual 6G vision of the European Industry and the expected evolution of services and the mobile ecosystem with the lessons learnt from 5G, in the sense of the main energy consumers and the reasons for the latter. Trying to address these challenges, it identifies several candidate enabling technologies and more general approaches for energy consumption and carbon dioxide emission reduction and possible current research and standardization gaps, to be considered in the future work on the way towards more sustainable 6G.

This whitepaper lays out a possible path towards more sustainable 6G operations along the following concrete recommendations for technological advances:

- Agree on a small set of *universal, ICT-suitable energy consumption and carbon emission metrics*, fit for cooperative ICT service provisioning characterized by multitenancy, open interfaces and service and system composition.
- Continue investing into successful optimization work, both on system and service energy efficiency, supported by explicit full-service-scope *green KPIs*. The whitepaper underlines the high saving potentials of dedicated energy efficiency measures, yet it also identifies intrinsic limitations of the latter facing the expected increase in loads.
- Improve the maturity of our profession by measuring and providing data on energy consumption and carbon footprints, i.e., ecodata, of current systems and services. *We need reliable, agreed benchmarks today* to be able to improve systems and services in the future.
- Introduce *native, integrated, service-level energy consumption metering capabilities in 6G*.
- Create an agreed industry methodology for the *attribution* of measured ecodata to the service instances responsible for them at each level of service usage and resource abstraction.
- Specify trustworthy, *per service session ecodata exchange* (forwarding, aggregation) among the (sub)service providers and users involved into a (sub)service function chain.
- Position *service user involvement* as a new green technology family, consisting of service user awareness, service user incentivization and service user enablement. *Raising service user awareness* is key to greening 6G.

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1 INTRODUCTION

1.1 WHAT IS THIS DOCUMENT

This document is the first whitepaper of the 6G Infrastructure Association (6G-IA) dedicated to the technological questions of 6G sustainability.

This document is a whitepaper produced as a collaborative effort within the 6G-IA Vision and Societal Challenges Working Group (VSC WG). It results from work at the involved partner organizations in both their internal and collaborative research activities, most notably within research projects and different initiatives of the Smart Network and Services Joint Undertaking (SNS JU).

The idea for this document came up in late 2022, and concrete work towards this document was endorsed by the 6G-IA Governing Board as part of the 6G-IA VSC WG work plan for 2023, leading to the subsequent specification of the purpose, scope and positioning of the planned whitepaper, the establishment of an editing team within the technology-oriented subgroup of the VSC WG, call for contributors, establishment of a contributing team and the kick-off of the actual writing in November 2023. The main text contributions were received during spring 2024, change requests were sent and incorporated during summer, final editing and message alignment took place in autumn 2024.

1.2 WHY THIS DOCUMENT

The European Commision's Green Deal has elevated ecological considerations, along with the relevant methodologies and approaches, to the highest political agenda level striving to make Europe carbon-neutral by 2050. Ever since, the European Commission has been active on defining concrete measures, programmes and directives towards this goal, all of which have a non-negligible impact on the European economy, e.g. Circular Economy, Sustainable Product Initiative (SPI), the European Union's Green Claims Directive oriented against greenwashing, etc.

In this context, Information and Communication Technology (ICT) is regarded as one of the most promising enablers to achieve the challenging societal goals. Under the defined political programmes and directives, as its contribution towards the decarbonization of the society, the European industry at large is currently considering innovative measures to reduce the overall Greenhouse Gas (GHG) emissions through an increased reliance on ICT methods, such as virtualization, cloudification, digital twinning, predictive operations with artificial intelligence, generic industrial control solutions, advanced generic communications over future networks with private or public networking, etc. Various such approaches, spanning over all phases of the lifecycle assessment methodology (LCA) [1] can be generally classified as "sustainability with ICT". In spite of the relative openness (interfaces, APIs), flexibility (software) and the universality of the ICT domain, the economic feasibility, the exact form of the overall system integration and the actual field deployments of relevant methods and tools have to be introduced, fostered, tested and adopted by the respective stakeholders from the target domain. Hence, technologically speaking, ***sustainability with ICT* is mostly not an ICT problem**.

At the same time, some recent, interesting developments in the ICT domain have moved the technological boundaries. Distributed consensus of the distributed ledger technologies (DLT), automatic adaptations and software development with artificial intelligence toolboxes, even some kind of common sense with the newest Artificial Intelligence and Machine Learning (AI/ML) tools (e.g., using large language models), together with super-fast communication networks and deep edge integration of distributed computing provide entirely novel technological means for many sectors but also call for some prudence, when it comes to ecological fitness: in particular, data centres, proof-of-work blockchains and AI model training are known to be extremely energy intensive. To create, evaluate, integrate and deploy performant yet eco-friendlier alternatives in these fields, research in the ICT field is required. Generally speaking, with its paramount role for decarbonization, as the ICT becomes the self-proclaimed nervous system of the society**, the relative weight of the ICT sector in the GHG emissions continues increasing**, and this, in spite of the increasing energy efficiency of ICT operations. **To make ICT domain at large eco-friendlier requires serious efforts from the ICT sector itself and is sometimes referred to as "*sustainability of ICT*"**.

The ICT domain is currently working towards the definition of 6G systems, prospectively integrating super-fast and super-reliable mobile communications, local environment sensing, DLT, distributed computing and AI/ML methods, with the deployment start planned around 2030. Hence, 6G may play a crucial role in the achievement of the ecological targets of the European Union (EU). Therefore, looking closely at what and how 6G could be doing, and notably what it should be doing differently from previous mobile system generations, is a highly relevant and very timely question for sustainability.

Trying to address this question, different relevant streams of work have emerged in the 6G-IA VSC WG. From this ongoing work, joined by the SNS JU research projects, the WG plans to publish a series of sustainability-related whitepapers, providing insights of the 6G-IA community into technological, economical and societal aspects of 6G sustainability. In particular:

- The Societal Needs and Value Creation Sub-Group (SNVC SG) of VSC WG has considered the general question of value of technology for the society. It produced a methodology for the evaluation of technologies under different relevant angles, including sustainability.
- The Business Validation, Models, and Ecosystem Sub-Group (BMVE SG) of VSC WG currently works on business models and economic validation, and looks specifically into the question of economic sustainability and sustainable business.
- The Smart networks and Services Vision Sub-Group (SNSV SG) looks into the technological aspects of sustainability of 6G.

Initiated by the SNSV SG, the document at hand is the first 6G-IA document dedicated to 6G sustainability.

1.3 POSITION OF THIS DOCUMENT

This first in the planned series of sustainability-related 6G-IA VSC WG whitepapers treats the question of the **sustainability of 6G** per se, and not of other sectors or domains. This whitepaper will not treat questions related to the potential improvements achievable through digital transformation and use of mobile telecom systems by other sectors.

The approach to a sustainable 6G network discussed in this document is mainly **technology-driven**. This implies the development of a technology framework, as part of the 6G system development work, composed of robust methodologies, guidelines, mechanisms and protocols that provide structured approaches and best practices for integrating sustainability considerations into the design, implementation, and operation of the 6G network. This should not be confused with energy efficiency alone. Energy efficiency is important, yet insufficient. In spite of the important improvements in the energy efficiency of mobile systems, so far, we had to witness, generation after generation, how the ever-growing data traffic has increased the overall energy consumption. As a concrete, highly relevant example: even though 5G has increased the energy efficiency of the air interface by up to factor 10, the overall energy consumption of 5G-related infrastructure has increased. While this can be interpreted as a typical example of the well-documented *rebound effect*, the reality is even more complex. For instance, 5G pursues a strong opening towards so-called vertical sectors, which should bring not only way more usage, but also results in completely different usage patterns and raises new requirements. Beyond the mere rebound effect, 5G also relies on a different set of enabling technologies, which, on the one hand, certainly promise more flexibility, yet, on the other hand and depending on the concrete situation and specifically in the uptake phases of the technology, may result in a considerable increase of required resources. **Hence, with the growing importance of 6G for the society, it becomes paramount for the ICT in general and the mobile communications sector in particular, for the involved researchers, engineers, economists and practitioners, to start producing concrete proposals contributing to the inversion of the trend above and reducing the total energy consumption in spite of the expected increase in system loads.** The proposals in this document are not limited to the question of energy efficiency, let alone to the energy efficiency of products, which can be adequately answered/achieved in the design phase.

In the context of the LCA methodology, the main accent of this document is on the **use phase**; in other words, beyond the product design, we look specifically at the reduction of energy consumption in operations, for the same or comparable service provisioning.

Hence, what matters most to this document are the following questions:

- How will 6G look like, and what are the probable impacts of these projections on energy consumption and the greenhouse gas (GHG) emissions of 6G systems?
- What are concrete environmental costs that can be attributed to different features and system components from the existing experiences? Beyond that, where do we see main saving potentials for energy consumption in the mobile systems today and in the future?
- Which are major challenges to realize these savings?
- What are concrete ways forward to achieve such savings in spite of the expected increase in system loads? Which additional requirements emanate from these? Which concrete novel solutions, mechanisms, protocols and network functions are required in the 6G system?

Since in the use phase, all 6G-relevant components without exception use electrical power, the question of GHG emissions in this document becomes directly related to the question of electrical energy consumption (EC) under the given energy mix. For a known energy mix, it is straightforward to calculate the expected GHG emissions (e.g., Carbon dioxide equivalent - CO_2e) from the energy consumption. Therefore, this document insists on the operational energy consumption as its main preoccupation.

Figure 1 clarifies the overall position of this whitepaper combining the progress drivers, industry branches and LCA phases. It also underlines that the overall problem of sustainability cannot be addressed by 6G technology alone and requires a more global effort. However, given that ICT and mobile systems in particular play a crucial role in the decarbonization of all other industry sectors and the society at large, and given the large amount of deployed infrastructure in particular in developed countries of the EU, addressing this particular subspace of the overall hypercube is expected to have a strong network effect, positively influencing all others. In other words, the size of each individual slice in the illustration in Figure 1 is not to be confused with its potential impact.

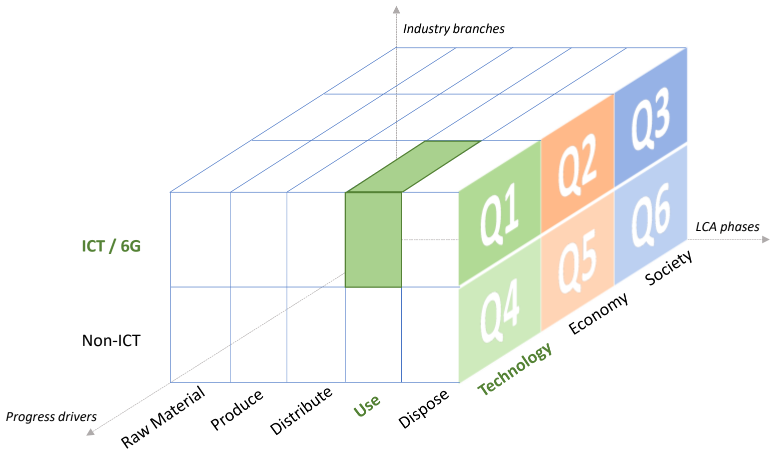

Figure 1: Position of this whitepaper

Beyond resource optimizations and methodologies for resource footprint reduction, this document specifically discusses ICT-suitable methodologies and solutions for CO_2e reduction of future 6G systems. To address the mentioned rebound effects, this document strongly supports the idea of user involvement and notably explores ways to raise service user awareness of the ecological impact of the use phase.

The objectives of this document are closely related to this positioning:

- Create community awareness of the relevant technological problem spaces;
- Create community awareness of service level sustainability considerations;
- Identify saving potentials of system parts and components;
- Assign responsibilities for reduction of the service-level energy consumption including operators, vendors and end-users;
- Identify, justify and initiate research on systemic sustainability considerations in 6G.
- Justify and motivate sustainability related metering activities in the deployed networks.

1.4 DIFFERENCES TO OTHER INITIATIVES

This whitepaper stands out in its comprehensive approach to 6G sustainability by integrating ecological considerations into technological 6G development, contrasting it with other key initiatives and efforts that focus on different aspects around telecommunications systems' sustainability:

- **Sustainability with 6G:** This whitepaper does not address decarbonization through ICT, i.e., sustainability improvements possible in other sectors through the broader usage of ICT or 6G in the future. However, we acknowledge the increasing energy consumption due to the increasing demands on ICT and 6G stemming from such decarbonization.
- **Energy estimation of 5G Usage:** Various groups (energy lobby, scientific research) have highlighted significant energy consumption of 5G, particularly in base stations and data centres. This whitepaper differentiates itself by not only addressing these concerns but also proposing specific measures to foster energy consumption reduction in 6G through explicit user involvement, but also through the use of innovative technologies like runtime scheduling, zero-waste computing and adaptive edge processing.
- **NextG Alliance:** The NextG Alliance, prioritizing economic and technological North American leadership in 6G and beyond, has published a noteworthy and highly interesting Next-Green whitepaper that discusses ecological impact of mobile networks by focusing on the manufacturing phase. It attributes the ecological impact (e.g., in tons of GHG) to different materials and manufacturing modalities. In contrast, our whitepaper concentrates on the use phase of deployed mobile systems in typical operational conditions.
- **ETSI:** The European Telecommunications Standards Institute (ETSI) has developed frameworks for network energy efficiency, such as the ES 203 228 specification for assessing energy efficiency in live networks. This whitepaper extends these principles to 6G, emphasizing end-to-end energy efficiency, including terminal equipment, RAN, and core network operations.
- **ITU-T Recommendations:** The whitepaper aligns with the International Telecommunication Union's (ITU-T) L.1470 recommendation for emission reduction, pushing for comprehensive metrics to measure the carbon intensity of network infrastructures.
- **3GPP Efforts:** Until Rel. 18, 3GPP work on energy considerations was "inwards" oriented, targeting to satisfy user experience while achieving energy efficiency improvements. Key Performance Indicators (KPIs) like bandwidth, latency, data volume and metrics to estimate the EC of the whole mobile system have been standardized in 3GPP TS 28.550. Starting from Rel. 19, 3GPP (cf. TR 22.882 and TR 28.880) considers exposing energy as a service criterion. This document, albeit stemming from an independent stream of work, is aligned with this new thinking and extends the 3GPP development roadmap.

An up-to-date overview of these and other relevant initiatives can be found in Green ICT DIGEST [2].

Overall, this whitepaper presents a technological approach to operational 6G sustainability, integrating energy consumption and CO_2e emission considerations deeply with the system operations, service provisioning, quality of service and KPIs, hence distinguishing itself from other initiatives that may focus more narrowly on domain energy consumption, energy efficiency or economic competitiveness.

2 TELECOM SERVICE EVOLUTION: FROM 4G OVER 5G TO 6G

The evolution of telecommunications is marked by decadal intervals of innovation, each introducing new capabilities that redefine the way we connect and communicate. From analogue voice communication (1G) in the 1980s, to digital voice and basic data services (2G) in the 1990s, to mobile internet access and video calling (3G) in the 2000s. The 2010s were dominated by 4G LTE which provided broadband-level speeds and improved network efficiency and ushered in a new era of mobile video consumption and data-driven services.

2.1 4G TO 5G: PHYSICAL NETWORK TO VIRTUALIZED NETWORK

The evolution from 4G to 5G has been marked by a shift from physical network infrastructure to a more virtualized network environment. Software-defined networking (SDN) and network functions virtualization (NFV) have emerged as key technologies, enabling a level of flexibility, scalability, and efficiency in network management and operations previously unattainable with hardware-reliant 4G networks. Through SDN and NFV, operators now enjoy unprecedented interoperability, programmability, and reconfigurability that is essential for the future of telecommunications.

Following 3GPP specifications work, the LTE standard and related 4G standards have been published in Release 8 onwards (in 2008), while standardization of 5G started with Release 15 in 2018 onwards. 5G has been developed taking into account the very different data transport needs of applications to be served, which led to the division of three main 5G use case families: enhanced mobile broadband (eMBB), massive machine-type communications (mMTC), and ultra-reliable low-latency communication (URLLC). In this regard, a few main 5G enabler technologies are briefly summarized in the following.

For the core network of a mobile communication system, traditionally the network functions have been realized in the form of special-purpose hardware that needed to be upgraded/replaced, when new network functionality had to be implemented. This was slow and expensive, which contradicted the ever-shorter development cycles in other ICT domains. Through NFV, network functions including Access and Mobility Management Function (AMF), Session Management Function (SMF), and Unified Data Management (UDM) are implemented as a software/microservice running in a virtual machine/container on commercial off-the-shelf hardware (e.g., industrial standard high-volume servers) or even in the cloud. These virtualized network functions lead to the cloud-native 5G core network, offering increased flexibility in the network architecture and elasticity in the infrastructure. This move also means that less functionality is hosted within operators' premises but is bought and integrated as a service.

In order to replace previous generations static networking deployments and hardware having very specific and rather monolithic functionality, a new approach called software-defined networking (SDN) is pursued in 5G. In SDN, central networking functionality such as routing, link/path configuration is now realized as flexible software application (control application – cApp), which indirectly controls the basic and efficient network hardware (packet switches). Hereby, network control can be centralized and is decoupled from naturally distributed network forwarding functions (switching devices), which enhances flexibility and reconfigurability. In 5G practice, a special cApp can be coupled with particular network functions to redirect some particular traffic to them or to enforce their orders on the infrastructure.

While NFV and SDN are complementary, they both together enable another 5G feature: network slicing. In order to serve the heterogeneous needs of above-mentioned different use-cases, it is desirable to run multiple virtual networks – each fulfilling dedicated quality of service (QoS) – on one and the same shared physical infrastructure. A virtual network is one logical entity that combines different hardware and software resources in a flexible manner. Running multiple virtual networks can be realized by 5G network slicing building upon SDN and NFV and put into place by an intelligent NFV management and orchestration (NFV MANO) framework. Mutually isolated network slices can then be created with respect to the specific application requirements, each representing a logical E2E network by itself and each having its own control and management.

2.2 5G TO 6G: FROM TELCOCLOUD TO AN INTELLIGENT USERCLOUD

With 5G currently being rolled out, industry and academia are working towards creating concepts that go beyond cloud-native systems and automation, to decentralized and user-centric approaches and end-to-end KPIs for the next generation mobile network, namely for 6G. In parallel, sustainability targets have come into focus and are greatly impacting current 6G research projects initiated around the globe. The Paris agreement [3] and the adoption of the 17 United Nations' Sustainable Development Goals (UN SDGs) [4] in 2015, as well as the European Green Deal [5] from 2020 have set out broad goals for a green transition. For the European Green Deal, the ultimate goal is to reach climate neutrality by 2050, with an intermediate milestone in 2030 to reduce GHG emissions by 55% (compared to 1990). As first roll-out of 6G is envisioned for ca. 2030, this coincides with the green ambitions and must be considered for 6G development and definition now. As a result, current 6G research projects from SNS JU, such as Hexa-X-II [6], 6GREEN [7], BeGREEN [8], and EXIGENCE [9], but also other European research project such as NATWORK [10], are balancing the technological opportunities with sustainability requirements of future stakeholders including operators, consumers, verticals and other decision-makers, such as regulators.

As we move from 5G to 6G, the vision outlined by the EU Industry for 6G emphasizes a transition from TelcoCloud paradigms, where telecommunication services revolve around centralized infrastructure managed by operators, to an intelligent UserCloud approach, evolving from pure cloud-deployed functions/capabilities mainly for operators, to broader and more democratized concepts placing the user at the center of the network. This evolution is characterized by decentralized and distributed intelligence across the network allowing user devices, edge nodes, and cloud resources to collaborate seamlessly and dynamically adapt services to individual needs. Edge computing, user-centric security mechanisms, and network optimization become pivotal.

In this concept, a network extends beyond mere access means to services; rather, it is here envisioned as a full-service platform that seamlessly combines compute and network resources to cope with combined payloads. The full integration of AI is central to this vision, enabling self-optimization and making AI an intrinsic part of the system and service offers. The resulting system is built with more capable, agile, evolvable, responsive, and dynamic elements. Zero-touch principles automating maintenance, fault detection, and optimization, as well as AI-driven network orchestration, will help to rapidly adapt to changing conditions. Here, responsiveness gains prominence: 6G systems will enable rapid activation/deactivation of elements with minimal observability and transition times.

With applications such as augmented reality, autonomous and connected drones and vehicles, and intelligent and automated machines requiring data rates in the range of Terabits per second and a number of connected devices around 50 billion by 2030 [6], digitalization of our society will be pushed to unprecedented levels. All this will be enabled by a multitude of significant technological advances, such as Non-Orthogonal Multiple Access (NOMA), mesh networks, distributed massive Multiple-Input Multiple-Output (D-mMIMO), beamforming, reconfigurable intelligent surfaces (RIS), and the exploration of terahertz (THz) frequencies. The integration of artificial intelligence and machine learning (AI/ML) at the physical layer (PHY) is poised to revolutionize how networks operate, leading to unprecedented levels of performance and efficiency.

While energy efficiency remains a priority in usage phases, 6G aims for E2E energy efficiency, minimizing power consumption in both hardware and software. This is especially critical for energy-intensive AI workloads. Broader E2E KPIs are equally essential. While 5G focused primarily on wireless transmission, 6G’s KPIs should span the entire service function chain (SFC). Quality, security, and user experience matter holistically. Since 6G systems aim to enable the integration of networking and computing in a cloud-to-thing continuum, the data processing demands increase inside the network, leading to higher energy consumption in data centres and edge devices. In this context, zero-waste computing approaches, including energy-efficient algorithms, data compression, and edge computing, can mitigate energy consumption in data processing. For instance, edge computing allows data to be processed closer to the source, reducing the need for centralized data centres and can lead to more energy-efficient operations.

While terrestrial networks (TNs) form the backbone of existing networks, integrating non-terrestrial networks (NTNs) in 6G systems extends coverage to the most remote corners of our planet. The harmonious coexistence of TNs and NTNs will redefine how we experience wireless communication. Mutualization of network infrastructure plays a key role in maximizing coverage.

In consequence, this 6G vision would drastically change the way the network system is used and open up new opportunities for different stakeholders. Among them, just to briefly sketch a few possible evolutions, vertical use-cases might be realized by highly customized network slices, potentially with specific control via Common API Framework (CAPIF), or different users/subscribers might consume compute services (and naturally compute resources) provided by the system. Also, different AI-specific offerings could be provided in the same way by 6G to a broad consumer base. Novel services such as localization and sensing would feature precise positioning and situational data, enabling context-aware data exchange and location-bound in-network computing services.

In summary, in 6G, the panoply of new services will lead to the abundance of novel types of resources, which might drastically change the distribution of energy consumption both over system parts/segments and geographically. Currently used data-volume-based models for energy consumption and CO_2e emission estimation would be pushed at their limits; they would become useless for arbitrary, user-definable compute payloads. The diversity of services expected to be supported in the 6G era and provided directly from the 6G system will lead to more and more dynamic infrastructure sharing. Hence, merely measuring energy consumption at the infrastructure level will become rapidly insufficient, as what will actually matter is the attribution of the consumed energy to a particular logical instance, e.g., to an entire slice, to a type of service, to a service instance provided to some customer, or ultimately to a single phone call.

3 SUSTAINABILITY OF MOBILE NETWORKS

3.1 IDENTIFYING MAIN ENERGY CONSUMERS

Preliminary observations regarding the envisioned technological transition from 5G to 6G have raised concerns regarding the sustainability of 6G technologies, stemming from studies on the energy consumption and carbon footprint ascribable to 5G [11][12].

As per Section 2, in comparison to 5G, 6G core is expected to have a way bigger share of the overall energy consumption, not only because of the continuing proliferation of the cloud-native paradigm with its impact on datacentres but primarily because of the probable deployment of compute-intensive services such as image and video processing, AI model training and advanced situational awareness. More generally, many noteworthy emerging innovations mentioned above such as Artificial Intelligence (AI) and Reconfigurable Intelligent Surfaces (RIS) are expected to be widely adopted in 6G, also to increase the efficiency of the system yet come with the threat of draining more energy than the one that can be saved in the controlled system, if not adopted carefully.

Nevertheless, looking at the main energy consumers in the existing mobile networks is necessary for becoming able to optimize all aspects of the future system generations:

- First, one could expect that at least the first deployments of 6G will be built on top of the current mobile networks, with the basic transport services continuing to play an important role. In this case, the insight how much of this energy can be saved where in 5G, would still be relevant for 6G as well.
- Second, and probably more importantly, **we need to start gathering concrete numbers on the energy consumption of the currently deployed mobile systems to use them as benchmarks and reference figures** later, to be able to even talk about savings in 6G.

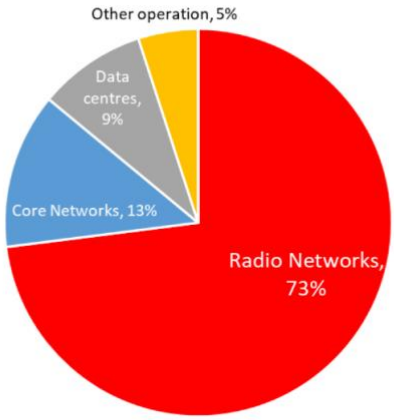

Figure 2: Energy consumption in the current generation of mobile networks [14]

As depicted in Figure 2, the major energy consumer element in the current mobile networks is the RAN with an energy consumption of 73% of the network's total energy consumption, and then is the core network as the second energy consumer with 13% of the total consumption [12][15]. The remaining 16% or so account for data centres and other operations, which are beyond the scope of this whitepaper.

Note that these figures from operators only cover the "use phase" and ignore manufacturing phase consumption and emissions. While the latter is out of scope of this document, interested audience is referred to Next G Alliance Green G Working Group[1] analysis, which identifies the manufacturing phase as the LCA phase responsible for the most of the overall CO_2e emissions.

3.1.1 ENERGY CONSUMPTION IN THE RADIO ACCESS NETWORK

The big share of RAN in the network energy consumption creates the following important questions: i) why RAN consumes so much more energy than other network domains; and ii) whether this figure can be reduced (or if not, then why this number matters at all?). To answer the first question, the reason why RAN consumes more energy than other parts of the mobile networks is because the equipment in RAN, i.e., base stations (BS), absolutely outnumber the equipment in any other part of the network. Also, the number of BSs increases in proportion to service coverage expansion, which is not the case for the core network. In addition, main equipment accounts for 50% of the total energy consumption in a BS, followed by air conditioning equipment that consumes 40%, power supply, and others [12]. To answer the second question, it seems the community believes firmly in energy efficiency improvements introduced by the current and upcoming technology progress. Part of the next sections are delving into this aspect.

In general, 5G equipment consumes more energy than previous generations due to its increased number of transmitters in the case of mMIMO, which is 8 to 16 times more than LTE, and to its increased channel bandwidth, which is 5-10 times broader than in LTE [14]. Hence, although 5GNR is more energy efficient than LTE, it is inevitable that equipment's output power increases to improve its performance and, hence, simultaneous efforts to reduce energy consumption are required to reduce carbon emissions [15].

It is observed that in a base station, most energy is consumed in its radio unit (RU). 5G RU main energy consumers are:

- The RF board power amplifiers.
- The analogue to digital and digital to analogue converters.
- The SoC/FPGA on the baseband processor.

Furthermore, it is also observed that even in densely deployed networks, as in city centres, the network traffic load can fluctuate very much during the day, with significant periods of almost no traffic in the base-stations [16]. When further examining the traffic patterns, it appears there are many short gaps in the data transmissions even during highly loaded times, as shown in Figure 3. This raises an obvious question: if the base stations are spending so much of their time not transmitting user data, why are they still consuming energy all the time? To understand this, it is necessary to have a closer look at the base-station power consumption characteristics. Figure 4 shows that there is significant energy consumption in the base-station even at the times when there is no output power, i.e., when the base-station is in an idle state. The reason for this is that most of the hardware components remain active so that they can transmit mandatory idle mode signals that are defined in the 4G standard such as

[1] https://nextgalliance.org/working_group/green-g/

synchronization signals, reference signals, and system information. So, how can we use this knowledge to create features for energy saving in 5G NR and beyond?

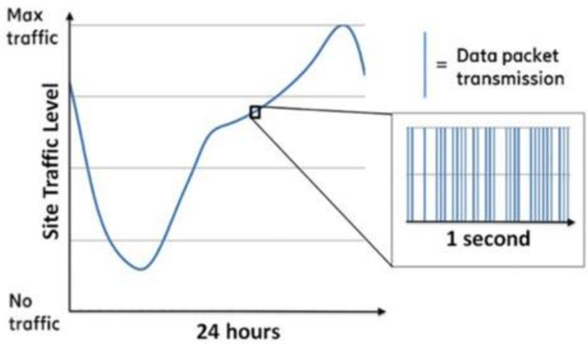

Figure 3: Varying network traffic load during the day. The highlighted part shows the gaps in data packet transmissions during a high-traffic situation

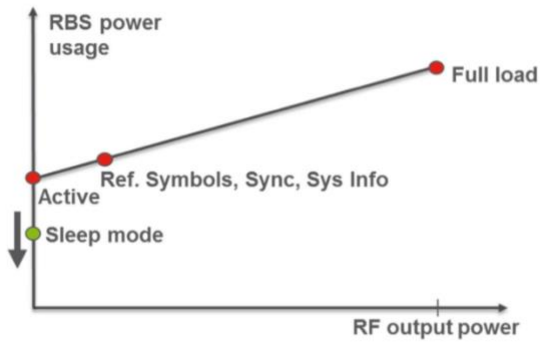

Figure 4: Base station power model. Parameters used for the evaluations with the cellular base station power model described in [17]

The 5G NR standard is designed based on the knowledge of the typical traffic activity in radio networks as well as the need to support sleep states in radio network equipment. By putting the base-station into a sleep state when there is no traffic to serve, i.e., switching off hardware components, it will consume less energy. With more components switched off, more energy will be saved (shown on the y-axis in Figure 4).

In previous network technologies, such as LTE, there are frequent transmissions of always-on signals, such as cell specific reference signals (CRSs). These are needed to secure cell coverage and good connection with users. As a result, there are only very short durations (less than 1 ms) for the base-station to sleep until the next required signal transmission occurs and only a small number of components with very fast reactivation times can thus be switched off when the base station is in idle mode, and this limits the possible energy savings of LTE.

NR, on the other hand, requires far less transmissions of always-on signalling. This, in turn, allows for both deeper and longer periods of sleep when there are little or no ongoing data transmissions, which has a significant impact on the overall network energy consumption as shown in Figure 5.

3.1.2 ENERGY CONSUMPTION IN THE CORE NETWORK

As discussed above, energy efficiency and saving problems have been mostly related to the radio access part, as the RAN so far is the most energy-consuming part of the network. Yet, with 5G's technological choices in the core network, we already witness the impact on the resources and energy consumption at the datacentre (DC) level, ascribable to the deployment and operations of the virtualized 5G core (5GC). As future generations are unlikely to abandon this technological path, it is worth analysing the main culprits for consumption of the current technology.

The energy consumption of the 5G core network (5GC) is a noteworthy aspect that significantly varies based on the specific implementations and deployment options considered. Recent research work and operators' efforts extended the analysis scope to the whole 5G system, ensuring that the actual core network services and the underlying infrastructure are holistically optimized in terms of energy. While 5G has opted for a very flexible underpinning with a set of enabling technologies allowing essentially any service provisioning, the actually provided functionality in 5GC is rather limited to network forwarding, control and management tasks; the expected leap to 6G described above rapidly reveals a transformative scenario, where the core network evolves into a comprehensive system hosting arbitrary ICT services within the system boundaries. This evolution implies edge computing, advanced applications, machine learning-powered systems and other functionalities that would emphasize the role of the core network. Thus, understanding and addressing the energy implications of different DC and typical cloud technologies is crucial for the development of 6G networks.

In a nutshell, three main aspects are worth investigating when it comes to evaluating the footprint of the mobile network core: (i) the virtualization technology, (ii) the datacentre resource manager, and (iii) the design of the core network function (NFs) themselves.

Although comparisons of mobile cores implemented with different virtualization technologies are hard to find (see Section 3.3.2 for some references), there is ample literature on resource and energy consumption of virtual machines (VMs), containers and bare metal deployments. Some scholars [23] focus on resource consumption of VMs, containers and unikernels, highlighting different features such as Central Processing Unit (CPU) utilization and throughput. Particularly, VMs show a higher idle CPU utilization compared to Docker containers, unikernel and Kata containers. VMs consume an average of 4.3%, while containers and unikernels remain below 1%. Conversely, unikernel experiences the highest CPU utilization (above 60%) when processing requests, but at the same time gives the highest throughput. Notably, while Docker container has the lowest CPU occupation with 10.12%, its throughput turns out to be better than Kata alternative and VMs (143.4 req/s against 101 and 130, respectively). Unfortunately, this paper does not specifically address energy consumption.

Instead, energy consumption is tackled in other works [24], where authors compare energy and resource consumption, in idle and active states, of two hypervisor- and two container-based technologies, with the latter emerging as best performing (Docker in particular). The difference is particularly visible in the presence of multiple virtual entities running simultaneously, in which hypervisor-based technologies consume up to 20 W more than container-based ones both when sending and receiving TCP traffic.

This behaviour is also noticeable in another work [25], which shows consumption figures for containers that are comparable to those of bare metal systems, being 18 and 37% lower than KVM and XEN, respectively.

The analysis of virtualization technologies alone is not sufficient to assess the actual impact on an infrastructure. Especially when exploiting the edge-cloud continuum [26] to leverage on low latency and improved security, service placement becomes a crucial and non-trivial problem, as the improved performance and flexibility is counterbalanced by the different costs, heterogeneity of infrastructure and increasing number of owners characterizing the continuum. The proposed methodology for optimal placement of services in a varying number of facilities has acceptable execution times, under 23 seconds, for up to 10 services in four facilities, but it grows too rapidly from there on. In this respect, different orchestration solutions have been proposed in the last several years. Two relevant surveys on edge-cloud deployments can be found in [27][28]; while the former only briefly mentions that fog computing improves energy efficiency with respect to cloud, the latter presents a mathematical model for energy consumption in nano-datacentres that accounts for both time- and flow-based models. Other noteworthy publications include the work in [29], which proposes an orchestration solution based on an optimization algorithm for service-based joint request mapping and response routing that achieves near optimal performance in maximizing users' satisfaction with minimum operational cost, and allows reducing the CPU and bandwidth energy costs with improvements of up to 50% depending on the tier. Others [30] deal with the problem of having multiple stakeholders and proposes a federated optimization algorithm for multi-domain scheduling of fog-native microservice workflows that improves the fraction of workflow "greenness" by around 15% with respect to the state of the art. Finally, in [31] authors apply a federated deep reinforcement learning system, based on deep Q-learning network (DQN), for energy-aware workload distribution in a fog ecosystem that shows over 50% reduction in failed allocations.

3.2 CHALLENGES

Future mobile telecommunications systems like 6G must take on the ultimate challenge of reducing energy consumption and carbon emissions in operations in spite of the expected increase in usage intensity and system loads in the future. Main related challenges will lie in the definition of precise baselines for such reduction, the precise scope of that challenge, an estimation of future system loads and the known problems with relevant technological approaches.

3.2.1 BENCHMARK REFERENCE POINTS

To be able to speak about the reduction of energy consumption, we need to agree on a baseline reference point as a benchmark for future evaluations.

Two notable challenges arise from this. The first is related to the existing 5G systems, the second stems from the uncertainty of what 6G will ultimately become.

Indeed, the expected evolution, described in Section 2, lays out how future mobile communication systems like 6G might not just increase the performance but profoundly change the nature of provided subscriber service from telecommunications to remote computing, sensing or augmented reasoning. Chiefly, with 6G we will see better performance at well-established, known use cases, but we will also see utterly new use cases in 6G, unsupported by previous generations.

For the first situation (i.e., better performance), **it becomes paramount to establish energy consumption baselines *today***, to be able to compare the posture of the future system later. These baselines must include precise typical service setup but also typical deployment descriptions, e.g.:

- bulk data access (eMBB) over the 5G system with a particular amount of data sent at some QoS level, e.g., with some particular data rate, and potentially, with a particular mobility scenario of the user equipment (UE), number of base stations, antennae, used, with configurations, modes, core network form, transport, etc;
- telephone calls, of some particular type (Voice over LTE or over NR – VoLTE/VoNR, with parameters) with a duration, potentially, with some particular mobility assumption, configuration and form of RAN, Core, IP multimedia subsystem (IMS), etc;
- narrowband Internet of Thing (NB-IoT or RedCap) service, for a number of devices within an area and number of exchanged messages, as well as number and distance to available NB-IoT/RedCap base stations, core network support, etc.

These are just some examples. **A real benchmark catalogue should be actively worked on and requires concentrated efforts starting already today**. A benchmark should include typical energy consumption values for diverse types of equipment (e.g., from different vendors), its precise configuration and should come along with standard deviations and statistical errors. Good 5G field knowledge is required for that work, but understanding of 5G business and 6G visions is required to avoid use cases likely to become obsolete in the upcoming decade.

For the second situation, **the biggest challenge is to establish baselines for the services that do not exist today**. For some such use cases, this might be simply unfeasible before the first 6G implementations are available. Note how this severely shrinks the possibilities for the idea of "sustainability by design", as long as we speak about the use phase of the LCA. Still, for some few of these novel use cases, it might be possible to implement the use case by using 5G systems along with some additional external systems as a starting baseline. For instance, we might be able to approximate integrated network computing (INC) by using edge computing features of 5G systems. Another potential feature of 6G, AI-as-a-Service (AIaaS), might be approximated by using a dedicated platform combining 5G networking and AI compute elements. These insights could be added to the catalogue above.

3.2.2 SCOPE OF CHALLENGES

As explained above, we do not treat larger scope societal issues in this document, and specifically, we are not interested in how a broader adoption of 6G might compensate for decreased carbon footprint of something else. On the other hand, the goal of this document is much more challenging, as, ideally, we would like 6G per se to consume less (than 5G) while providing all 6G services as expected. Generally, in this document, we concentrate on the technological aspects, however there can be indeed many hurdles of different nature on the way to achieving this purely technological challenge:

- Technological hurdles with either optimization or information exchange, such as lack of suitable methods, in the state of the art, or simple unavailability of data, or lack of possible command and control mechanisms, potentially because of lack of relevant interfaces. Often, the sheer system size and the need for explainable behaviour and rapid convergence of command loops uses good engineering practices such as separation of concerns, which prevent information and commands from spreading through the entire system. In particular, high algorithmic complexity of formal optimization mechanisms is known to result in unrealistic runtime expectations, when it comes to the input data availability (historical data, runtime states of large systems), practicable system size limits, unacceptable duration, etc.

- Administrative / legal hurdles related to the technology, creating other reasons for unavailability of data/inputs, impossibility, or unwillingness to share and/or to cooperate due to various boundaries and concerns. These can be both by regulation and by contract.
- Economic hurdles leading to difficulties with the implementation of technological measures, e.g., a lack of a clear business model, business secrecy considerations (e.g., unwillingness to reveal business partners, direct/indirect cost increase without obvious corresponding gains, or, generally, prevalence of externalities, etc.)
- User behaviour: more responsible usage is key to the net reduction of energy consumption in future systems. Creation of user awareness of the actual energy consumption related to service usage (of subscribers, verticals, business partners, etc.), is paramount if we want to achieve the goal stated above. Besides, novel mechanisms in the deployed systems to let respective users act on their particular service behaviour will need to be considered.

In the usual practice, a technological issue is defined through some combination of the hurdles above. For this reason, even though this document is dedicated to the sustainability of 6G, some of the considerations will have to go beyond pure technology, touching upon other constraints related to the applicability, success and acceptance of technological measures in practice. What is relevant though is to state concrete technological goals and to translate these into viable technological measures, acknowledging, wherever applicable, that these might only work under certain regulatory, economic and user behaviour assumptions.

3.2.3 REBOUND EFFECTS

Note that the ultimate challenge formulated above includes energy efficiency aspects but goes way beyond that; the reason for this is that the envisioned reduction of the overall energy consumption must work in spite of the rebound effect [44]. With optimization and energy efficiency increase alone that would not happen: when burden of use goes down, be it financial or non-financial, an increase in utilization is triggered, resulting in a net increase in consumption, dwarfing the benefits achieved by trimming per unit consumption categories. The rebound effect has been observed in many different business areas. In the ICT and telecommunications areas, this effect has been confirmed several times: Wirth's Law for the software/hardware development, and data from the previous generations and other telecommunications systems shows that the increase in performance does not result in the decrease of the overall consumed energy. Among others, this has also been observed for 5G systems.

Policy instruments for all involved stakeholders, including for service users and service providers, might help to curb the rebound effect. Typical effective instruments are some forms of carbon or data tax [43][47] yet their usage in the mobile telecommunications so far can be deemed to be exotic at best. It is a challenge to find realistic and working methods, how to implement such mechanisms in the area of mobile telecommunications systems.

3.2.4 PROMISE, CHALLENGES AND SHORTCOMINGS OF ENERGY EFFICIENCY MECHANISMS

Optimization is a popular approach to claim energy efficiency, e.g., for a given energy budget we can transfer more bits (bits/Joule). Optimization is immensely powerful in the sense that it achieves the same service with less resources, very often so through pure brain power, i.e., application of mathematics, formal models, best known algorithms, etc., within the domain of interest. Through its repetitive application, even a small gain (e.g., in percentage of a module) can result, e.g. through network effects, in huge societal gains. For this reason, optimization remains an obvious possible way forward and should always be considered.

Technologically speaking, optimization is very complex, both algorithmically and in the implementation. Typical generic optimization methods, such as Integer Linear Programming, are known to be computationally intensive, but also hard to handle operationally (due to required customizations and assumptions on the availability of input data).

As of today, there is hardly any dedicated **green orchestration**, i.e., the state of the art on the optimization of energy and/or carbon footprint of large-scale ICT systems is quite recent. **Existing orchestration mechanisms with the goal of reducing resources required for a given service provision might be a suitable starting point but would require quite some customization first**.

In general, optimization bears an inherent problem, namely to run into the rebound effect. Whether and how we could break out of this dilemma depends on the implementation of strategies that encourages change of end-user and organizations' behaviour leading to sustainable outcomes rather than increased resource consumption and closing the "Attitude-Behaviour Gap". Herein, pricing models may play a substantial role, by affecting end-user behaviour, investment decisions and even policy decisions. Current flat rate pricing models do not contribute to responsible behaviour. Furthermore, choice is directly affected by the transparency of the impact of service use. For example, information about the footprint of a service allows an organization that uses 6G services to better calculate its own overall footprint. Whether and how we can limit unnecessary and irresponsible ICT service use is one of the most difficult questions and heavily depends on the acceptance of the authority that would be defining what is unnecessary or irresponsible.

3.2.5 MISSING MEASUREMENTS, MISSING COMMON METRICS

One particular challenge in the ICT sector is a relative immaturity, when it comes to the actual measurements of energy consumption of operational ICT systems in general and of ICT services in particular.

Consider as an example the recent prominent debate between the experts from the International Energy Agency (IEA) and the French Association "The Shift" about the energy consumption of video streaming[2]. While the debate per se was well covered by the international press, what remains in the aftermath of obvious error corrections and rectifications, is the ascertainment of an about factor 7-8

[2] https://www.iea.org/commentaries/the-carbon-footprint-of-streaming-video-fact-checking-the-headlines

(!!!) difference in the claimed, well-reasoned results of both camps, none of which is from the ICT sector. **It is up to the ICT sector to establish more sound methodologies and to provide methods and interfaces for more reliable operational measurements to avoid such discrepancies in the future.**

This is also true for mobile telecommunications systems. While one hears very often which part of the deployed mobile system consumes more, it is much more difficult to get operational, measured data on the actual consumption. Relevant standards for domain-level measurements have existed for about a decade, owing to the work in ETSI. More complicated are energy consumption measurements involving several different technology domains because the relevant standards often employ different metrics (e.g., different units, incompatible measured objects, time periods, etc). Even more complicated are measurements of virtual, allocated objects such as virtual machines or flows, as their "usage" of the actual executing hardware varies in time, and their energy consumption is per definition a time-proportional attribution of the consumption of the executing hardware at the moment of execution. Similarly, the biggest challenge is a correct measurement of the energy consumption of an ICT service instance involving a mix of several such allocations in addition to some physical devices.

Carbon emission measurements reveal additional challenges. A typical operational CO_2e measurement approach is to translate the measured consumed energy into the amount of CO_2e given the knowledge of the energy mix. However, field experiments reveal that the energy mix is not homogenous in time and place; to avoid too approximate estimates, the current energy mix at the moment and place of energy consumption would be required. For a general solution, this would require a programmatic runtime interface to the energy provider, e.g., an integration of the "Advanced Metering Infrastructure" (AMI) of the smart grids in the ICT sector considerations.

3.2.6 DISTRIBUTED SYSTEMS, MULTI-STAKEHOLDER SYSTEMS: SHARING ECO-DATA

In modern ICT systems, shared resources, cooperative execution, composed services and multi-stakeholder systems are the new normality. In the Internet, an IP packet habitually traverses infrastructure elements not contractually bound to either sender or recipient; in the Cloud infrastructure, a compute task of a user A may be scheduled on the fly to be executed on the best available worker of provider B, processing data of user C and delivering results to user D – all this, potentially, without transparency to either A, C or D. The mobile telecommunications systems are no exception to this trend: even in traditional telephone systems, the caller and the callee were not necessarily served by the same network operator, making cooperation a must; today, less and less infrastructure is physically owned by the service provider. Even major mobile network operators (MNO) have long implemented business practices involving usage of non-private transport, cloudification and infrastructure sharing. **Therefore, in today's practice, it is insufficient to measure the owned equipment, as it would hardly reflect a representative part of the overall infrastructure involved into service provisioning.**

Rather, to understand the ecological impact produced by a given service provider, this service provider:

- Must measure the energy consumption of the physically owned resources;
- Must get the energy consumption data of all outsourced components of the overall service implementation.

While the first part is a classical measuring/monitoring problem, the latter part is an open and relatively new challenge, as it goes beyond the classical control boundaries and would require eco-data exchange over the authority domain boundary, which is an issue characterized not only by technological, but also by economic and regulatory hurdles. Yet, without a solution to this problem, in the way how today's ICT services are typically provided, no reasonable measurements can be obtained. This latter point coincides with and underlines the general trend recognized in this document, notably **the need to measure the eco-impact of the service instances, as opposed to infrastructure parts**.

3.3 ENABLERS FOR REDUCED ENERGY CONSUMPTION IN 6G

3.3.1 APPROACHES FOR RAN

Implementation of standalone power saving features (PSFs) to adapt energy consumption to traffic demand is a promising green candidate technology. In this regard, implementation of C-SON and AI/ML platforms to automate and improve energy efficiency is an attractive solution. Specifically, the implementation of deep dormancy/hibernation mode functionalities, as well as intelligent RU/gNB/eNB on/off switching or energy saving modes control based on traffic predictions and actual RAN status that can be implemented by O-RAN based rApps (direct control through O1 control or indirect through A1 policies) is a good candidate to achieve a more energy-efficient network.

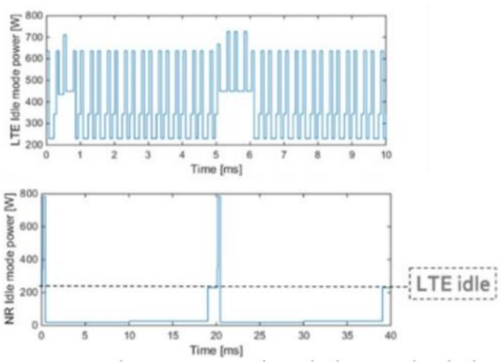

Figure 5: Example of base station energy consumption during idle mode signaling in LTE (top) and NR (bottom). NR is configured to send signal blocks (SSB) every 20 ms

With an efficient sleep mode functionality, the consumption of energy-hungry components, e.g., of power amplifiers, can be drastically reduced. In addition, RU power blanking modules can be used to turn off the RF power amplifiers power supply when there is no data to be delivered by the RU (checked slot by slot). Also, RF power amplifier efficiency can be improved by using an efficient digital predistortion (DPD) module, while employing an envelope tracking module could reduce RU overall power consumption by improving power amplifiers' DC supply. **Overall, efficient and innovative analogue front-end design (filters, amplifiers, etc.) of the RF boards needs to be accounted for.**

What would be the cost of these potential solutions? Very briefly, some of these costs can be listed as:

- Deep dormancy/hibernation mode can be achieved in low cost, it should be developed at software level and be applicable as a software functionality to shut down logical component(s), when there is no traffic.
- PSFs are low cost, usually agreed in operator's RAN contract, although there are some difficulties to activate them due to some radio hardware restrictions.
- AI/ML incurs mid-level cost. For it to operate properly, more aggressive thresholds triggering without KPIs impact is necessary. It is useful to avoid dependency on only existing PSFs, facilitate orchestration, data access, and rollback procedures.
- The cost in O-RAN-based RU control schemes is moderate. Implementing manageable on/off switching or energy-saving modes could have an impact on hardware development. Exposing these capabilities to the DU through M-plane, or to the SMO through O1, is something being considered by O-RAN.
- The DPD module is complex; therefore, it must be implemented mainly in high power amplifiers (> 4 Watts).
- Envelop tracking has a moderate cost and can be implemented in all types of RF modules.
- RU power blanking could be implemented at low cost, as it can be implemented in SW and, therefore, should always be considered.

While **RU is by far the main energy consumer**, layer 1 (L1) algorithms in DU are also power consuming. As an example, massive MIMO (mMIMO) has many advantages in increasing coverage and capacity; however, due to its increased number of antennas, its RU can be a very big energy consumer, but also its L1 design requires high computational complexity algorithms such as maximum likelihood (ML) detectors and low-density parity check (LDPC) decoders that are also consuming energy. Potential solutions in this case could be for example (other than RU solutions mentioned above), using just the needed number of elements in mMIMO deployment depending on the number of UEs that need to be multiplexed, and switching off the redundant elements. Paths to be explored here include an efficient implementation of DU algorithms, the usage of low power architectures such as ARM® processors and offloading the computationally demanding algorithms to GPU and accelerators. As it was mentioned above, rApps can be used in CPU on-off schemes as well. Implementing rApp-based solutions could be done at low cost, although it depends on the capabilities of the managed RAN components.

Radio Network Planning using Reconfigurable Surfaces

Another note regarding the energy consumption optimization is on the network planning. The mobile network is complex, and the operational environments are diverse. As mentioned above, policies such as cell on-off switching could be considered as ways to improve network planning. In case the granularity of the control scheme permits, sector on-off technique or mMIMO antenna elements grouping (and using on-off schemes on the transmissions) can be deployed. Technologies such as reconfigurable intelligent surfaces (RIS) and relays can be used to improve network planning, coverage extension, and consequently improving energy consumption (an RU can turn off, if the user in its coverage area can be covered by a RIS). Current RIS infrastructure has a moderate cost, as the technology is in its early stages. However, it is expected that next generation RISs have lower costs and better performance (higher accuracy/gain). The implementation of a RIS control scheme can be done at a low cost, as implementing RIS control mechanisms could be done by the same vendor in conjunction with the base station products, or it could be based on O-RAN and, thus, components and interfaces may be reused.

RIS energy efficiency involves optimizing their design and deployment to reduce energy usage without compromising communication quality. This is particularly relevant in the context of sustainable and green communication technologies, where the goal is to achieve high efficiency in data transmission, while minimizing the environmental impact. RIS can dynamically change to reflect, absorb, or polarize incoming signals, thus providing a more controlled and efficient propagation environment. This ability to intelligently manage the propagation of electromagnetic waves leads to several benefits, including reduced energy consumption in wireless networks, enhanced signal strength and quality, and improved coverage at the expense of an additional physical object that needs manufacturing, delivery, phase out and hence results in quite some costs in all other life cycle assessment phases. **Overall, integrating RIS into existing and future wireless networks is expected to play an important role in developing energy-efficient communication systems.** By intelligently redirecting signals to areas with weak coverage or optimizing signal paths for lower energy consumption, RIS can significantly reduce the overall energy requirements of wireless networks. In [18], extensive computer simulations have shown that communication supported by RIS can attain an energy efficiency up to threefold higher than that of relay-assisted communication. Additionally, the energy efficiency performance of RIS has been investigated for multicast [19] and device-to-device communication [20].

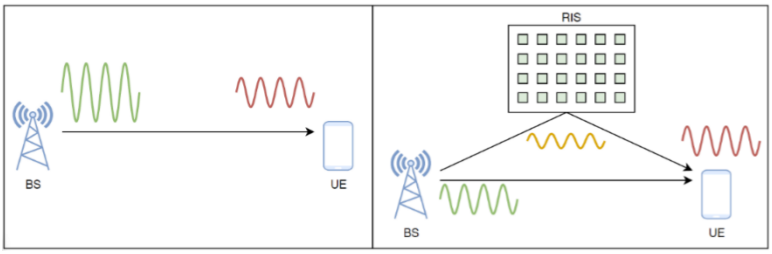

Figure 6: A representative wireless communication without RIS and with RIS

In comparing two communication scenarios involving a BS and UE in Figure 6, the inclusion of a RIS in the second scenario significantly improves energy efficiency, showcasing its superiority over the first scenario without RIS. The core advantage lies in the RIS ability to intelligently manipulate electromagnetic waves, thereby improving the signal's path and enhancing the received SNR at the UE. This improvement means that the BS in the RIS-equipped scenario can maintain lower transmission power while achieving the same or even better communication quality than the traditional setup. **This ability to optimize signal quality with less power output is a game changer in terms of energy efficiency.** It does not only reduce the energy consumption of the BS but also contributes to the overall sustainability of the communication network. However, to fully capitalize on this potential, it is crucial to undertake a holistic life cycle assessment that considers not only the current benefits but also the long-term viability. This includes ensuring the compatibility and adaptability of the installed RIS technology with various upcoming frequency ranges anticipated in new generations of wireless communication. Without such foresight and adaptability, there is a risk that RIS, along with BS, might become outdated and require phasing out, thereby diminishing the long-term sustainability gains. Hence, the implementation of RIS should be done with a strategic vision that encompasses future technological evolutions and environmental impacts to ensure its prolonged utility and effectiveness in enhancing network sustainability. The RIS scenario's enhanced efficiency and reduced power requirements establish its superiority, marking it as a considerable advancement in pursuing energy-efficient and environmentally friendly wireless communication technologies.

In [21], an experiment has been performed where the impact of RIS is investigated in a practical scenario. It is demonstrated that the received signal power is dramatically increased when a proper codebook is selected for RIS configuration compared to the scenario without RIS (see Figure 7).

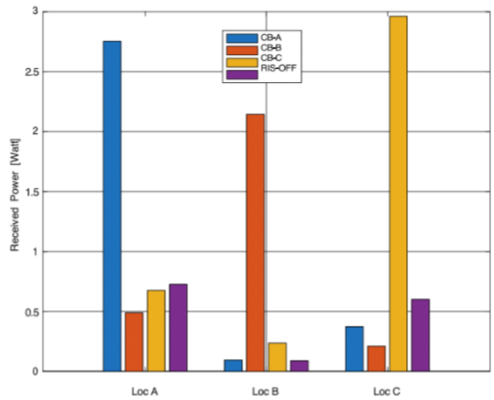

Figure 7: Codebook performances at different locations [21]

Understanding the energy consumption of RIS is vital for efficient integration into communication networks. These surfaces, which control electromagnetic waves for improved communication, must be energy efficient. The focus lies on modelling their power needs and validating these models through measurements. This step is critical to ensuring RIS technology enhances communication efficiency and aligns with sustainable and eco-friendly network goals. Efficient power management in RIS is crucial for advancing more sustainable wireless technologies. In [22], a general power consumption model and measurement validation for RISs have been conducted using different RIS structures. In this study, the authors divided the RIS hardware into three basic parts, as in Figure 8.

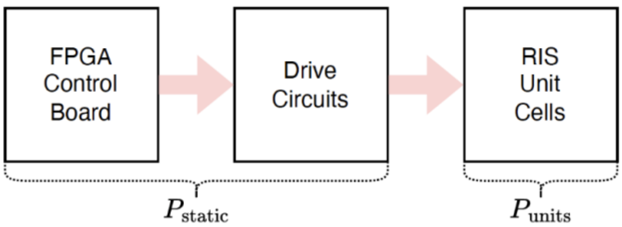

Figure 8: Three basic parts of a general RIS hardware [22]

As seen from Figure 8, the total power consumption of RIS hardware can be given as:

$$P_{RIS} = P_{static} + P_{units}$$

where P_{static} and P_{units} are the static power consumption and power consumption of RIS unit cells, respectively.

In conclusion, exploring energy efficiency and consumption in the context of RIS is an emerging area of research with far-reaching implications for the future of wireless communication. It offers a promising pathway towards achieving more sustainable and environmentally friendly communication systems, a crucial aspect in our increasingly connected world.

3.3.2 APPROACHES FOR THE CORE NETWORK

5G Core (5GC) solutions have to meet the demanding requirements of low latency and high data rate. However, achieving these performance goals often comes at the cost of energy efficiency. A survey for energy-saving options for the 5GC [32] asked operators, what actions can most help to reduce energy consumption. It concluded that the leading initiative to achieve this goal is to "move as many functions as possible to a common infrastructure platform". From a core network perspective, consolidating a common lightweight cloud platform is probably an ideal move to reduce energy consumption, since it provides better elasticity to dynamically (re-)allocate resources at any given moment. Conversely, dedicated devices (e.g., optimized UPF device) lack this flexibility, but with the potential for enhanced energy efficiency when significantly loaded. Therefore, additional improvements for energy efficiency can be considered in terms of CPU efficiency at edge locations to minimize infrastructure footprint, hardware offload/accelerators investigation (e.g., P4) and optimized cooling. **In particular, programmable hardware accelerators offer a convergence of benefits**. They provide software control while leveraging the efficiency of dedicated hardware circuits, essentially encapsulating the best of both worlds.

The 5GC's features and capabilities can foster energy efficiency also via network analytics and network capability exposure via APIs, like those of the Network Exposure Function (NEF). The exposure of APIs can enable operators to become open technology platforms for other parties. A typical example is the Network Data Analytics Function (NWDAF) [34], which allows the exploitation of different data-based and AI/ML-powered approaches to improve energy consumption, for example driving NWDAF selection for providing insight for optimizing and improving 5GC deployment or proactively managing energy issues/failures. The potential of integrating NWDAF with 5GC resides in its capability to process 5GC metrics via ML-based data analytics methodologies, which use them to provide analytics-based statistics and predictive insights to 5GC network functions. Some of these analytical and predictive methodologies could consider energy contexts and make actions for network consumption optimization. Moreover, the Management Data Analytics Function (MDAF), which retrieves Operations, Administration and Maintenance (OAM) data and to perform analytics, as well as provide predictions, on a per-NF or per-slice basis, can be exploited not only to improve the efficiency of the 5GC, but even to reduce the carbon footprint ascribable to the applications relying on the core itself. While the current MDAF definition already contemplates predicting resource usage according to the load level or resource utilization associated with the SBA NFs, [35] proposes an extension, allowing the collection of metrics coming from both the infrastructure and the management, to estimate the current and the future carbon/energy footprint induced to the computing and offloading resources in the edge-cloud continuum, and even the availability and the use of green energy sources and hardware offloading engines. Such research aspects are actively treated within the ongoing SNS JU research projects such as 6Green [7] and EXIGENCE [9].

The flexibility of 5GC can contribute to energy efficiency not only in terms of deployments, but also in terms of functionality and actions. With the introduction of specific energy-aware or green orchestrators and/or intelligent optimization tools, some of the core functionality can be deactivated or brought to idle state when not needed, saving a significant amount of energy.

Table 1: 3GPP Technical Specifications focused on energy efficiency and models

Standardization Reference	Title	Description
TS 28.310	Energy Efficiency of 5G	Basic concepts, services, KPIs and possible solutions for energy optimization and savings of a 5G network.
TS 28.541	5G Network Resource Model (NRM)	Information Model and Solution Set for the NRM. In Section 6.3.30, EnergyEfficiency data type has been defined.
TS 28.552	5G Performance Measurements	Definition and calculation of the performance measurements and aggregated indicators for every NF of the 5GC and RAN.
TS 28.554	5G End to end Key Performance Indicators (KPI)	Related KPIs definition for measurements defined in TS 28.552.
TS 28.622	Generic Network Resource Model (NRM)	Generic network resource information exchanged between MnS producer and MnS consumer for telecommunication management. ENERGY_EFFICIENCY management data category has been defined in Section 4.3.50.
TR 28.813	Study of new aspects of Energy Efficiency for 5G	Technical report investigating the possibility to define KPIs related to energy efficiency and energy saving solutions (last update in 2021)

Another way to reduce energy consumption is the strategy called local caching [36], which exploits the use of localized storage at edge sites to reduce traffic load on backhaul links. In this way, any shared content can be stored at the edge, potentially increasing energy efficiency thanks to the reduction of transmissions of the same content from/to centralized instances of the 5GC's user plane.

Network function virtualization has paved the way for a unified network architecture spanning data centers, carrier networks, and edge, enabling dynamic service creation using distributed resources. Efficient and dynamic end-to-end scheduling of network services, with packets processed through orchestrated network function chains, could significantly reduce the resource required to be deployed in the system to provide services, decreasing also the energy and carbon footprint of the system. Called **runtime service scheduling,** these novel ideas from research exhibit amazing potentials for the reduction of required resources by 30%-60%, compared to the existing static or coarse-grained dynamic scheduling solutions, while providing similar service quality to the users [37][38].

Focusing on virtualization aspects, the energy requirements of a virtualized core network are closely tied to the choice of virtualization framework and the underlying hardware of the specific deployment. Operators must carefully consider trade-offs between performance, flexibility, and energy efficiency when selecting virtualization frameworks and hardware for their 5G core networks in light of the specific use cases. This is due to the distinct requirements posed by the deployment use case. The nature of 5G networks, with the sheer endless slicing possibilities in the 5GC supported by diverse radio modes ranging from enhanced mobile broadband to massive machine-type communications and ultra-reliable low-latency communication, justifies a more nuanced approach to network architecture design. Virtualization frameworks and hardware must be capable of delivering the necessary functions with the required assurance, while supporting throughput and responsiveness to ensure a seamless user experience. However, achieving high performance may come at the expense of flexibility, as specialized frameworks and configurations optimized for specific tasks might be less adaptable to varied use cases, and, thus, not particularly oriented towards optimizing energy efficiency. In this context, Figure 9 shows an example of the difference in energy consumption (W = J/s) between the same 5GC software deployed but leveraging three different virtualization technologies [34]. This result illustrates the importance of the underlying infrastructure management and its optimization according to different scenarios.

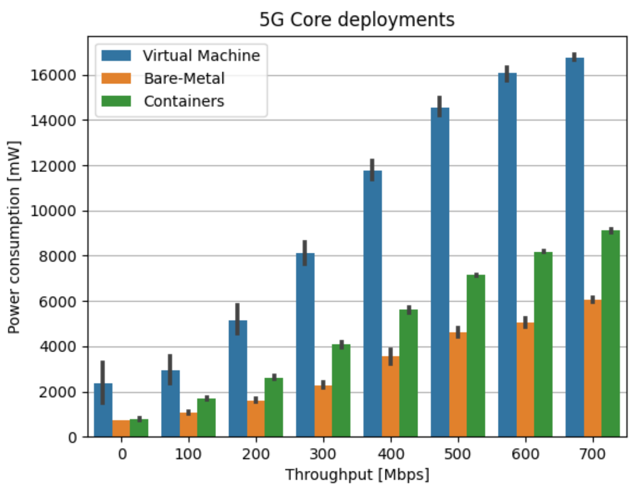

Figure 9: Energy consumption (in mW) for three 5GC deployments leveraging different virtualization levels and technologies

3.3.3 INTEGRATION OF AI/ML BASED AIDS AND TOOLCHAINS

AI/ML is the major candidate technology for the 6G systems. It can be used both to provide services to various subscribers, and in the optimization toolchain, including for energy aspects [35].

Targeting a global environmental sustainability solution, AI/ML's own energy consumption has to be also considered and optimized. AI/ML energy costs need to be considered at multiple levels: models, data management, platforms, etc., whereas the most energy consuming ML phase is the training process, in which a significant computing process takes place. Once the ML models are trained, there is no clear difference in incorporating ML as part of the decisions loop or not from the energy consumption perspective. There are some numbers in this regard in the literature:

- NVIDIA trained MegatronLM (smaller than GPT-3) over 9 days consuming ~27648 KWh, almost 3 times the average consumption of US homes/year [41].
- GPT-4's training energy consumption is estimated to be between 51,772,500 and 62,318,750 KWh [42].

Therefore, the first insight is that it is not always the best approach to opt for the most powerful AI/ML model so as to be more energy efficient in operations, as the energy cost of ML itself might overshadow the operational gains. Hence, there can be cases, in which it is not worth using ML to replace traditional methods, when, e.g., a known approach may reach an acceptable energy performance; this has to be evaluated on a case-by-case basis.

Second, such optimizations should not stop at energy-efficiency but should target the overall energy consumption reduction, since the potential rebound effect needs to be considered with AI/ML as well. The network can be very energy-efficient, but if, in turn, this leads to an increased usage and an increase in energy consumption, the sustainability target will be missed.

Third, beyond the overall energy consumption, more importantly the focus should be put on the actual carbon footprint and CO_2e emission reduction, so the use of green energy should be prioritized when using AI/ML.

As stated in [43], there are some main mechanisms that need to be considered in order to reduce the carbon footprint associated with AI/ML:

- Selecting efficient ML model architectures, such as sparse models. This measure can reduce energy consumption by a factor between 3x–10x.
- Using processors and systems optimized for ML training, versus general-purpose processors. The expected reduction can be by a factor between 2x–5x.
- Computing in the Cloud, rather than on premise, reduces energy usage and therefore emissions (reduction by 1.4x–2x). This postulate should not be taken for absolute truth: these numbers reflect the assumption of a higher *power usage effectiveness* (PUE) in the modern, professional data centers and do not take into account local competencies or potential transport costs.
- Location with the greenest energy mix (reduction by 5x–10x).

One of the most powerful measures is the use of green energy sources for the ML training phase. It is envisioned that novel mechanisms could be applied in order to move the training phases dynamically, in time and location, during runtime, towards available greener energy sources for carbon footprint optimization.

Furthermore, specific energy consumption reduction measures are envisioned to be investigated for the ML models themselves. First, it will be key to re-utilize computation whenever possible for the training of potential similar ML models; second, depending on the computation, memory, and network link state, training and inference can be offloaded by using ML split-learning mechanisms.

3.3.4 TOWARDS MORE PRECISE MEASUREMENTS

Energy and carbon emission reduction in the future generation mobile systems is strongly related to the capability to precisely measure and attribute the incurred consumptions and emissions in operations. This is required both to be able to better optimize the systems as well as to correctly attribute the consumption and emission to the respectively causing users. The latter is absolutely required in the era of infrastructure sharing and cooperative execution, as has been discussed in the Section 3.2 above. In addition, existing and upcoming legislation requires MNOs in many EU countries already today to show subscription-relevant consumption and emission numbers.

Overall, such measurements should not be done at the infrastructure level alone, but at the service level in the near future, as also recognized by major industry-led groups such as Next Generation Mobile Networks alliance (NGMN, cf. Green Future Network) and in the 3GPP.

3GPP acknowledges this trend in its ongoing Rel. 19 and planned Rel. 20 work (cf. TR 22.882, TS 22.261, TR 23.700-66). However, current 3GPP releases (in the 5G era) advocate model-based estimations of service-level consumption and emission figures, e.g., by data volume for eMBB service. The advantage of doing so lies at hand: these methods can be relatively simply implemented in the 5GC architecture, without bigger changes and within the existing separation of concerns. Indeed, one problem with service-level ecodata measurements in 3GPP systems is due to the architecture per se, as recognized and studied in SNS JU EXIGENCE [9][72]: while the resource view is in the management plane, the session view is in the control plane. The current 3GPP approach of model-based estimations, albeit pointing in the right direction, comes with intrinsic limitations:

- Per-volume or other execution-unrelated (e.g., per time, per service type, etc.) estimations are not helpful to trigger targeted optimizations in the owned infrastructure. For optimizations, the precise cause of accrued consumption needs to be determined and acted upon.
- Data-volume based estimations are in principle inadequate for tasks, where a relatively short request can result in high infrastructure involvement. This can be the case for many compute-intensive tasks, e.g., high complexity tasks, such as AI tasks, generation of particular content, but also for classical database requests, where a relatively simply formulated database lookup request may result in a plethora of different operations at different nodes. 6G is believed to have a richer service capability. Integrated sensing and communication (ISAC), AIaaS, INC, storage services are not very suitable for data-volume based estimations.
- Such estimations are intrinsically imprecise, as they yield the same amount of consumption or emission regardless of the actual energy mix, the optimizations in the deployed devices or in the system. To an extent, they might make optimizations useless, as a super-optimized provider and a sloppily managed infrastructure would yield the same ecological impact. As soon as it comes to reattribution of such numbers to the causing user's legal entity, maybe in form of a monthly bill or carbon consumption certificate, usable at the regulatory carbon market such as EU emissions trading system (EU-ETS), these numbers must be auditable and hence, precision, accuracy, and truthfulness requirements apply.

Hence, while 5G systems now confirm the trend to service-level ecodata assessment, 6G systems will have to feature more potent energy consumption metering, capable of reconnecting resource views with logical task/session views, to obtain truthful, accurate and verifiable data.

3.3.5 SERVICE ENERGY CONSUMPTION AWARENESS

In the world of shared resources, cooperative task execution, e.g., outsourced core networks running on 3rd party cloud platforms, etc., all players in the value chain will need to be aware about the energy consumption caused by and attributed to their service instance execution.

This awareness of the ecological impact of own service execution is a straightforward requirement just to be able to correctly evaluate the ecological impact of the current service deployment manner and the potentially available alternatives, e.g., to be able to judge the impact of switching to om premise platforms or to an alternative service provider. Hence, it is easy to see, how **such awareness is important to service providers, whenever part of the service realization is outsourced to some other service provider.**

However, **it is just as important for service users to be able to act on their own service consumption.** Indeed, as many other telecommunications systems, 6G systems and in particular telecommunications services of 6G systems underlie some form of network neutrality regulations. For this and other regulatory reasons, an MNO generally will not be able to block or throttle traffic of paying subscribers, some specific and rare exceptions put aside (e.g., illicit type of access, behaviour against or beyond the service contract). This means that in the general cases only the user as such will be able to act on the own service consumption. However, to be able to achieve ecological gains, **the user must be aware of the ecological costs of the current service execution, and, ideally, of the costs of existing alternatives.**

Such alternatives could be postponing service (use it later), changing service parameters (such as reducing resolution, switching video off, etc), switching service providers and many combinations of the above. Service requirements generally have significant impact on resource utilization and the consequent energy footprint, in terms of consumption, cost, greenness and CO_2e emissions [45][46].

To be able to attribute the available ecological costs to the service instances, **a solid and accepted eco-data attribution methodology is required first**. Besides, exposure interfaces for such information would be needed. While on the latter point, there has been quite some work in the 3GPP recently, the first point is largely unexplored. Further, to be able to produce service alternatives, novel research work on **green service configurations** would be helpful.

The overarching point here is to recognize that within the scattered, cooperative ICT ecosystem, achieving end-to-end energy consumption and carbon emission reduction requires cooperation amongst said stakeholder in the sense of the energy consumption and carbon emission measurements, both to achieve local optima and to reach consensus towards global optimization. **Consensus-based global optimization is increasingly showing potential.** The recent work of [28][50] shows how energy objectives can be optimized on end-to-end service level.

3.3.6 OPTIMIZATION ALGORITHMS

Optimization algorithms play a crucial role in reducing data transmission and storage requirements and improve the overall efficiency of 6G networks. So far however, the state of the art of concrete usage of such algorithms in the area of network consumption reduction is relatively thin.

To optimize resource allocation, minimize data redundancy and improve goodput, following approaches have been developed for different areas:

- *Swarm-based optimization* - Particle Swarm Optimization (Kennedy and Eberhart, 1995) [56], Ant Colony Optimization (Dorigo and Di Caro, 1990s) [57], Bee Algorithm (Pham et al. 2005) [58], Cuckoo Search (Yang and Deb in 2009) [59], Firefly Algorithm (Yang, 2010) [60];
- *Evolutionary-based techniques* -- Genetic Algorithm (Holland in the 1960s) [61], Differential Evolution (Storn and Price in 1997) [62], Multi-Factorial Evolutionary Algorithm (2016) [63], Multi-Tasking GA (2019) [64], Genetic Programming (Koza, 1992) [65], Evolutionary Strategies (Rechenberg and Schwefel, 1960s and 1970s) [66], Biogeography-based Optimization (Simon, 2008) [67], Artificial Immune System (Farmer et al., 1980s) [68];
- *Stochastic optimization algorithms* such as simulated annealing, tabu search and random search;
- *Mathematical programming-based algorithms* – linear programming, integer linear programming, quadratic programming and convex optimization.

The latter has been extensively used to solve the problem known as **virtual network embedding**, which tries to minimize the resource footprint for an expected service allocation (of whatever kind), as a planning approach. Sometimes used as part of the orchestrator, concrete applications to energy as a fluctuating, changing resource are still missing and could be probably better exploited.

Besides, **runtime service scheduling** has been recently advocated as a promising method in literature [37][38]. Employed in data centers and shown to have high potential for general resource footprint improvements, it should be applied more often to energy and/or CO_2e emission reduction problem.

Last but not least, for dynamic adaption to network conditions and, thus, to ensure optimum performance with minimum resource utilization, recent advances in AI/ML algorithms could be exploited. AI/ML methods such as Reinforcement Learning for Resource Management, Q-Learning and Deep Q Networks , Online Gradient Descent and Online Random Forests, Adaptive Learning Rate Algorithms such as Adagrad, Adadelta and RMSprop, AutoML frameworks such as Google AutoML and TPOT, Transfer Learning, Meta-Learning, Dynamic Time Warping, Self-Organizing Maps and Deep Reinforcement Learning such as Proximal Policy Optimization or Soft Actor-Critic can be used in different offline/online/hybrid setups for **energy-aware service and application provisioning**.

3.4 PATH FORWARD: REQUIRED NEXT STEPS

In future telecommunication systems, **it will be necessary to address the energy consumption question through actionable interactions with each system in the overall ICT ecosystem**. Individual per-domain approaches are still valuable, but arrive at the end of their capabilities.

Rather, each (physical) system operator should be able to query the system about the energy consumption status of the supervised system, in particular, regarding the relative efficiency of similar or same service provisioning in different parts of the supervised system. Each service user (not limited to end-users) should be able to query the respectively serving system about the previous, current and expected energy consumption of a (remote) service (instance) that is provisioned for her (e.g., energy expense per hour/day/year, but also per any suitable service unit). Similarly, a service user should be able to provide upper limits (in kgs of CO_2e, in Joules) for the energy use for a service or indications about how much QoS degradation she is prepared to accept for a given upper bound of energy consumption. Finally, the service customer/user should be able to act the service execution, e.g., by choosing among different service alternatives generally available to her. **All of the above are feasible technological approaches, which require *concrete standardization* in the 6G era**.

Research and exploration actions are required *today* to establish valid energy consumption baselines for known services as a benchmark for their potential future equivalents. In addition, **future standardization should quantify the impact of standards on energy efficiency and energy consumption**, as well as **create standards to uniformly quantify the footprint of deployed systems abiding to such standards**. **Each published standard should consider energy efficiency measures and make statements about CO_2e and GHG impacts in a separate "Sustainability Considerations" section**.

Policy and standardisation actions are required to support the awareness and application of such measures. Policy is already in place that requires products to specify energy consumption, e.g., in litres of fossil fuel or kWh per passenger-distance travelled (cars, trains, airplanes) or energy and water consumption for white goods (dishwasher, washing machine...). Upcoming policy and regulation endeavours also suggest addressing network services: for instance, the Sustainable Product Initiative (SPI) introduces the Digital Product Passport (DPP) for connected devices, different from the current static eco-label in the sense that it includes a dynamic calculation, **explicitly accounting for the use phase of all services that a connected device depends on**. SPI, a crucial part of the European Green Deal's Circular Economy, has passed the consultation phase, and the European Commission has presented its intentions on a draft standardization request for a DPP system as part of a new Eco-design for Sustainable Products Regulation (ESPR). In order to achieve this, it is necessary to define and **agree on a concept on how to sustainably measure the energy consumption for a remote ICT service**.

Note that most envisaged actions require a closed-loop control in terms of holistic energy consumption, at the service level. For this purpose, critical measures at every level of the infrastructure are needed (e.g., enabled by advanced telemetry functions in virtual RAN (vRAN)/O-RAN combined with the CPU Power Management features like Running Average Power Limit in Intel and AMD CPUs) [51]). **Furthermore, the collection of ecodata across multiple domains in an interoperable fashion is required and should be enabled by international standards.** In this perspective, **defining proper metrics for network energy consumption, and the related standardized ways to measure, gather, and report, is critical to assess the actual sustainability and energy consumption of communication networks and their services.**

Overall, to create and obtain a more sustainable 6G, it is necessary to:

- Specify ICT-suitable energy consumption and carbon emission metrics to capture energy consumption of current and future ICT services in typical distributed, partly virtualised, and cooperative environments.

- Start actually and actively measuring in the individual deployed systems, establishing benchmarks on the deployed 5G systems. In particular, all systems should be prepared to make service-level measurements, as opposed to domain-level measurements only.
- Derive models, mechanisms, algorithms and potential best practices and typical interventions to increase both system energy efficiency (green system orchestration) and service energy efficiency (green service orchestration, i.e., how to provide the same type of service in the most energy-conscious manner). Beyond the resource, deployment and system configuration questions, the latter should include the relatively novel considerations on green service configuration.
- Define how the aforementioned models can be instrumented with standard interfaces that allow:
    a. query and collection of energy consumption metrics for different services (both planned and currently consumed);
    b. introduction of target costs/thresholds in terms of energy requirements per task.
- Create an agreed industry methodology to attribute measured ecodata to the service instances (and the stakeholders of these) responsible for them. This methodology should cleanly separate idle consumption from the service specific consumption.
- Specify trustworthy, per service session eco-data collection, aggregation and exchange among the (sub)service providers and users involved into a (sub)service function chain.
- Specify the relationship of energy consumption with service key performance indicators and related societal key value indicators.

Here are the main standardization initiatives relevant in this regard:

- ITU-T: To meet the targets of the Paris Agreement, telecom operators, like other industries, need to set targets for emission reduction to arrive at a net zero situation as reported in Recommendation ITU-T L.1470; for a situation in which network traffic will increase, a common indicator is needed to measure the carbon intensities in network infrastructure. Recommendation ITU-T L.1331 [52], published in January 2022, defines several metrics for network energy efficiency, allowing it to be characterized in relation to e.g., traffic and coverage.
- ETSI: the Technical Committee on Environmental Engineering (ETSI TC EE) has introduced a set of specifications on energy efficiency. In this context it is worth mentioning the specification ES 203 228, which provides a methodology for network energy efficiency, allowing for a complete assessment of different clusters of sites (in different environments, e.g. urban, suburban, rural), to provide country-wide EE evaluations through metrics for RAN energy efficiency and methods for assessing (measuring) energy efficiency in live networks. The covered technologies are GSM (Global System for Mobile communication), UMTS (Universal Mobile Telecommunications System), LTE, but the methodology can be applied to new radio interfaces as well. More recently, ETSI has put focus on trustworthy ecodata exchange between telecommunications domains. While this

is currently considered in a novel Work Item of ETSI PDL ISG, this work might be pursued in the future in the novel TC DATA, which is about to be created.

- 3GPP: Network Energy Saving features at the base station side are of great importance to reduce environmental impact and operational expenses in 5G systems. In Dec 2022, 3GPP completed a Rel.18 study (TR 38.864) focusing on these key objectives: 1) Development of base station power consumption model; 2) Development of evaluation methodology & KPI, and 3) Identification of potential techniques to conserve power consumption. In addition to that, measures from network counters in TS 28.310, TS 28.554, Minimization of Drive Tests [53] can be effective in offering a standardized framework to gather many KPIs from the network and the terminal and correlate them with energy consumption, to build more comprehensive view and derive actions for achieving targeted environmental and/or operational expenditure metrics. It should be noted here that, inevitably, the energy consumption reduction actions might have an impact on the provided service quality, which in turn can be also monitored by e.g. QoS-related counters as specified in TS 28.552, 28.554, and TS 38.314. As mentioned above, as part of a novel study item for Rel. 19, 3GPP has also started working on “Energy Efficiency as a Service Criteria”, the considerations for which are captured in TR 22.882. Most recently, relevant technical requirements have been derived from this work and captured in TS 22.261, with which 3GPP shows a novel fresh view on the energy considerations. Similarly, the architectural impact of service (or session) level energy considerations, notably the discussed separation of views in management and control planes, is captured in TR 23.700-66, and first solutions are being discussed to overcome these limitations, with the solutions in the control plane currently getting the upper hand. This document aligns with and extends the current 3GPP roadmap. In general, to assure a good ecological posture of 6G, it is high time for each ongoing and new research efforts to start contributing concrete technical insights and ideas to these initiatives, most notably in form of novel use cases with novel requirements through SA1, novel mechanisms in RAN3 and SA2, etc. A possible, 3GPP-aligned roadmap for greener 6G standardization is laid out in [72].

The above initiatives offer a comprehensive framework for standardized measurement systems, that is essential to assess operational sustainability of telecommunication systems. Examples of energy management assessments using this framework can be found in the literature [54], where operator choices include also end-to-end considerations, i.e. including the strategic management of multiple radio access technologies (RAT) and the possible strategy to progressively switch off entirely old generations of previous networks, e.g., 2G or 3G. Looking ahead to some further benefits that 6G can provide in the field of sustainability, the industry may look at some promising techniques to sense/monitor climate change, e.g. by leveraging the inherent radio propagation characteristics of the wireless channel at terahertz frequencies [55].

Moving forward to the specific actions that can further enable the above-mentioned required technical provisions, it is worth mentioning that next-generation operational systems will be massively dominated by open interfaces (e.g., driven by functions in software) and seamless local/remote interworking. Hence, the above mechanisms need to be exposed at every level of the overall service stack and every component interaction of the communication-computation infrastructure. With distributed software and service stacks spread over different subsystems, this translates to a generalized requirement for explicit service-level energy considerations. In that perspective, exposure of proper APIs is key to enabling the aimed close-loop control of 6G sustainability, whether the exchange between the served and the serving entity is local, remote, vertical or horizontal: exposure and consumption of APIs should be allowed within the system, between systems, and between domains, to enable application portability and seamless energy posture assessments regardless of the given service implementation. In that perspective, also other standard bodies (e.g., ETSI) and open-source communities (e.g., Linux Foundation) can be impacted, as further work is required to abstract the current information at the application level, via proper service APIs to end-users, developers, app/service providers and vendors.

Finally, assessing the sustainability of 6G is an extremely complex task, for it involves a myriad of interactions and uncertainties, spanning across different domains and locations, while involving a plethora of stakeholders. Therefore, assessing the sustainability of 6G requires a holistic approach and a deeper understanding of the interaction of different entities, and what unintended consequences may arise from them.

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5 ABBREVIATIONS AND ACRONYMS

3GPP	3rd Generation Partnership Project
5GC	5G Core (network)
5GS	5G Systems
6G IA	6G Infrastructure Association
AI	Artificial Intelligence
AIaaS	AI as a Service
AMF	Access and Mobility Management Function
AMI	Advanced Metering Infrastructure
API	Application Programming Interface
BS	Base Station
BVME SG	Business Validation, Models, and Ecosystem sub-group
CAPIF	Common API Framework
cApp	Centralised Application
CPU	Central Processing Unit
C-SON	Centralised Self-Organising Network
DC	Data Centre
DC	Direct Current
DLT	Distributed Ledger Technology
DOI	Digital Object Identifier
DPD	Digital Pre-Distortion
DPP	Digital Product Passport
DQN	Deep Q-learning Network
DU	Distributed Unit
E2E	End-to-End
EC	European Commission
EE	Environmental Engineering (ETSI TC)
eMBB	Enhanced Mobile Broadband
eNB	Evolved Node B

ES	ETSI Standard
ESPR	Eco-design for Sustainable Products Regulation
ETS	Emissions Trading System
ETSI	European Telecommunications Standards Institute
EU	European Union
FPGA	Field Programmable Gate Array
GHG	Greenhouse Gas
gNB	Next Generation Node B
GPU	Graphics Processing Unit
GSM	Global System for Mobile communication
ICT	Information and Communication Technology
IEA	International Energy Agency
IMS	IP Multimedia Subsystem
INC	Integrated Network Computing
ISAC	Integrated Sensing and Communication
ITU-T	International Telecommunication Union – Telecoms. Standardisation Sector
KPI	Key Performance Indicator
KWh	Kilowatt-Hour
LCA	Lifecycle Assessment
LTE	Long Term Evolution
MANO	Management and Orchestration
ML	Machine Learning
mMIMO	Massive Multiple-Input Multiple-Output
mMTC	Massive Machine-Type Communication
MNO	Mobile Network Operator
NB-IoT	Narrowband Internet of Things
NEF	Network Exposure Function
NES	Network Energy Saving
NF	Network Function
NFV	Network Function Virtualisation

NGMN	Next Generation Mobile Networks (alliance)
NOMA	Non-Orthogonal Multiple Access
NR	New Radio
NRM	Network Resource Model
NTN	Non-Terrestrial Network
NWDAF	Network Data Analytics Function
O-RAN	Open RAN (alliance)
PHY	Physical Layer
PSF	Power Saving Feature
QoS	Quality of Service
RAN	Radio Access Network
RAT	Radio Access Technologies
RF	Radio Frequency
RIC	Radio Intelligence Controller
RIS	Reconfigurable Intelligent Surfaces
RU	Radio Unit
SDG	Sustainable Development Goals
SDN	Software-Defined Networking
SFC	Service Function Chain
SMF	Session Management Function
SNR	Signal-to-Noise Ratio
SNS JU	Smart Network and Services Joint Undertaking
SNSV SG	Smart networks and services vision sub-group
SNVC SG	Societal Needs and Value Creation sub-group
SoC	System on a Chip
SPI	Sustainable Product Initiative
TC	Technical Committee (ETSI)
THz	Terahertz
TN	Terrestrial Network
TR	Technical Report (ETSI)

TS	Technical Specification (ETSI)
UDM	Unified Data Management
UE	User Equipment
UMTS	Universal Mobile Telecommunications System
UN	United Nations
UPF	User Plane Function
URL	Uniform Resource Locator
URLLC	Ultra-Reliable Low Latency Communication
VM	Virtual Machine
VoLTE	Voice over LTE
vRAN	Virtual RAN
VSC WG	Vision and Societal Challenges Working Group

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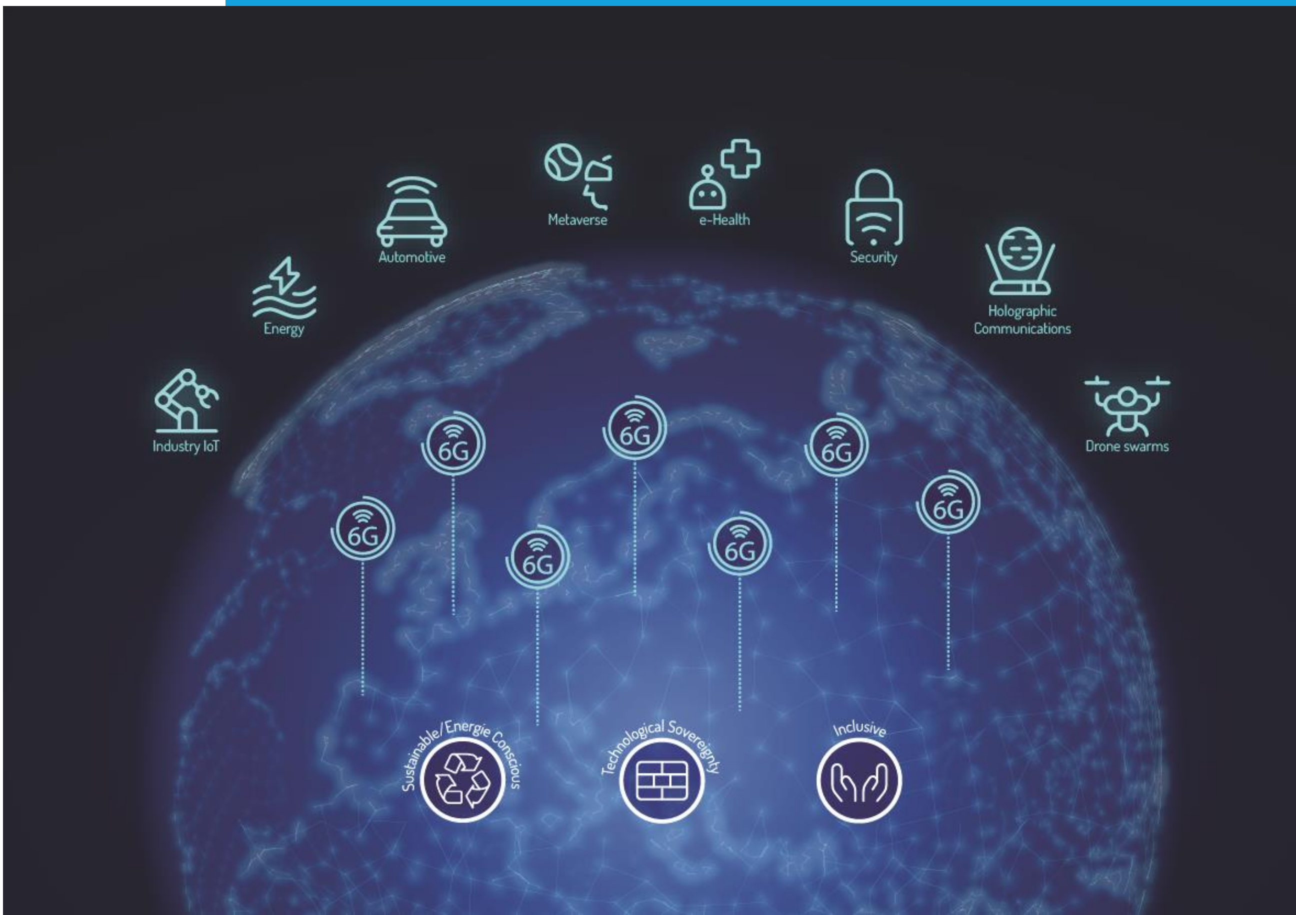

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