Sustainability & 6G

FNS contribution to sustainability of and by 6G

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Major contributions to impact pathways

Sustainable earning power	
Digital autonomy and reliability	
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Summary

One of the impact goals of the Future Network Services (FNS) programme[1] is to ensure energy efficiency in 6G solutions and to contribute to the sustainability transition. The FNS programme does this in the following ways:

1. **R-ladder-based**: Focus on needed technology based on actual demand (Programme Line 3 & 4)
2. **Greening of IT**: Focus on improving energy efficiency compared to current technology (PL1 & 2)
3. **Greening by IT**: Focus on enabling sustainability elsewhere (PL3).

On the first point: The R-ladder outlines a hierarchy of circular strategies such as Refuse and Rethink, Re-use, Re-furbish and Re-cycle (see Figure 3). By steering the technical developments with the use cases in PL3, FNS is focussing on developing 6G technology in a demand-driven way. This is a main principle for sustainability applied by FNS: focus on needed technology instead of applying a technology-push for potential use later. FNS does this by working from the start on applications and their requirements in PL3.

For the energy efficiency of the 6G infrastructure, FNS optimises power amplifiers for use in mobile base stations. In mobile network infrastructure, the base stations represent the major portion of the energy use, up to 80% of the total. The power amplifier is the component with the single most impact on the energy use of the base station and is as such the prime candidate for achieving higher efficiency in the mobile network.

For further energy efficiency, FNS is working on introducing and optimising cell-free architectures. In such architectures, data signal transport to end terminals can be optimised for energy use. This is achieved through modelling the various base stations available to a terminal and constructing the optimal combination of signals. This both requires development of cell-free architectures and the creation of optimisation modelling to achieve the energy efficiency.

Finally, FNS can contribute to various domains of application of 6G to improve efficiency and thus sustainability by IT. One example use case in FNS with a clear focus on sustainability is the use case of Energy Management Systems that focuses on achieving real-time grid flexibility. 6G creates this possibility by providing extreme high reliability and low-delay networking for real-time exchange of energy measurements and control, thereby preventing grid outages when enabling dynamic steering. The work is based on best practices in building energy management and is applied in the interaction between grid and energy consuming entities such as office buildings.

During the analysis for this paper several topics raised new follow-up questions. Based on the work so far, the whitepaper contains a number of observations to consider for the future work in the FNS programme.

[1] https://futurenetworkservices.nl/en/

1. Introduction

1.1. Sustainability & 6G

The information and communication technologies (ICT) domain has a non-negligible and growing impact in terms of environmental sustainability. For providing ICT services, electricity is used in running the data centres, network infrastructure and end user devices. Such electricity use comes with its related GreenHouse Gas (GHG) emissions, depending on the local and current energy mix. The production, shipment, installation, and maintenance of hardware such as servers, base stations and mobile terminals comes with its own impacts, again related to energy use and GHG emissions but also to the use of critical raw materials, the use of (clean) water, and various other environmental impacts. A recent study by the GreenIT Association[2] concludes that in 2023 the digital domain accounts for 3.4% of global GHG emissions and shows the broader impact by including various other indicators, see Figure 1. Further growth of the ICT domain is expected by the uptake of technologies such as artificial intelligence (AI) and Internet-of-Things (IoT)[3].

Indicator Name	Acronym and unit	Global footprint in 2023
Global warming potential	GWP (kg CO_2 eq.)	1,832 billion
Resource Use, Minerals and Metals	EPDA (kg Sb eq.)	41 million
Resource use, fossils	ADPf (MJ)	24,995 billion
Eutrophication, freshwater	Epf (kg P eq.)	673 million
Particulate matter, human health	PM (Disease Occurrence)	79 111
Acidification	AP (mol H+ eq.)	9,947 million
Ionising radiation, human health	IR (kBq U_{235} eq.)	953 billion
Total Primary Energy	TPE (GM)	28,634 billion

Figure 1. Global digital environmental impacts of ICT in 2023 for selected indicators.

Of these impacts, network infrastructure accounts for about 20% to 25% of the impact, depending on the indicator. For future network infrastructure such as developed by FNS, this means an effort is needed to lower these impacts to meet international targets such as the EU Green Deal[4] and international agreements such as the Paris Agreement[5]. It targets one part of a larger effort to reduce the environmental impact of the ICT domain, as shown in Figure 2.

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[2] https://greenit.eco/nos-etudes-et-essais/impacts-environnementaux-du-numerique-dans-le-monde-2025/

[3] https://unctad.org/publication/digital-economy-report-2024

[4] https://commission.europa.eu/strategy-and-policy/priorities-2019-2024/european-green-deal_en

[5] https://unfccc.int/process-and-meetings/the-paris-agreement

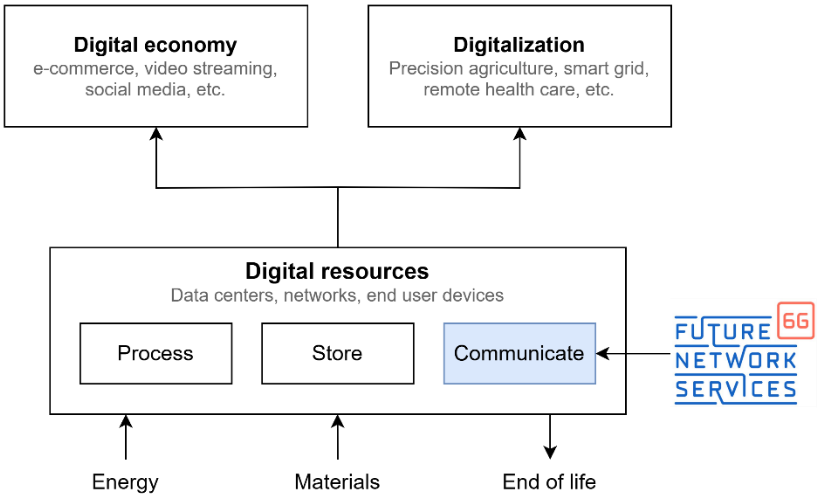

Figure 2. Overview of FNS in the broader sustainability & digitalisation context.

1.2. Contribution to FNS impact pathways: sustainability

Future Network Services (FNS) has sustainability as one of its impact pathways in its theory of change. The topic of sustainability in the ICT domain has two main angles: the sustainability of the digital infrastructure itself ("greening of ICT"), and the sustainability effects by applying ICT in other domains ("greening by ICT"). FNS has a focus on both. Various existing approaches give guidance on how to approach sustainability as a goal when designing and building systems. A main approach is the R-ladder[6], which is focused mainly on circularity. FNS has chosen a clear focus on energy efficiency for sustainability, but still the R-ladder applies.

	R-Strategies
Narrowing the loop:	R0 - Refuse
	R1 - Rethink
	R2 - Reduce
Slowing the loop:	R3 - Reuse
	R4 - Repair
	R5 - Remanufacture
	R6 - Refurbish
	R7 - Repurpose
Closing the loop:	R8 - Recycle
	R9 - Recover
	R10 - Remine

Figure 3. Main approaches and R-strategies for creating a sustainable economy.

[6] R-ladder - Strategieën van circulariteit | RVO.nl

The first strategies to consider (most desirable) in the R-ladder hierarchy are Refuse, Rethink and Reduce, followed by Reuse and only then come steps like Repair/Refurbish and Recycle. FNS is clearly use-case and demand-driven: a variety of use cases developed based on clear industry demand drives technological progress. The focus in FNS is strongly on the main 6G technology, and not on niche or corner cases. This is well aligned with the R-ladder, particularly Rethink and Reduce: focus on the need for technology first and only built and deploy technology to the extent that there is such a need. The target that FNS has set for itself is a 20% reduction in electricity use with 6G compared to the pre-6G era. Even though many operational networks are running mostly on renewable energy, reducing overall electricity use will help the overall energy transition towards a fully renewable one.

Finally, various FNS use cases are about enabling sustainability elsewhere. A focus is on the role of 6G in the twin transition: how to apply ICT to support the energy and material transition towards a more sustainable future?

This gives a three-way approach to sustainability in FNS:

1. **R-ladder-based**: Focus on needed technology based on actual demand (PL3 & PL4)
2. **Greening of IT**: Focus on improving energy efficiency compared to current technology (PL1 & 2)
3. **Greening by IT**: Focus on enabling sustainability elsewhere (PL3).

The higher tiers of the r-ladder are built into the FNS approach, which is positive, as explained above. This whitepaper focusses on points 2 and 3. The whitepaper will describe the FNS work on improving energy efficiency in the radio domain, as that is the part of the network with by far the most energy use, and it will show the work on an Energy Management System (EMS) use case, strongly related to the twin transition. It will conclude with some more general observations about the sustainability of future mobile networks, also going somewhat beyond the scope of FNS.

2. Optimising 6G radio to reduce overall energy use of mobile networks

To provide digital services, three main components of the digital infrastructure are needed: end user devices, networks, and data centres. FNS focuses on networks, which account for about 20% to 25% of the environmental impacts of the digital infrastructure. Radio is by far the most energy-consuming part of a mobile network, with estimations in the range of 70% to 80%[7]. This area is therefore the main focus for improving the energy efficiency in 6G. Focus is also on the core evolution in 6G in providing more bandwidth and coverage to a growing number of devices, and not on specific 6G features such as sensing or non-terrestrial network.

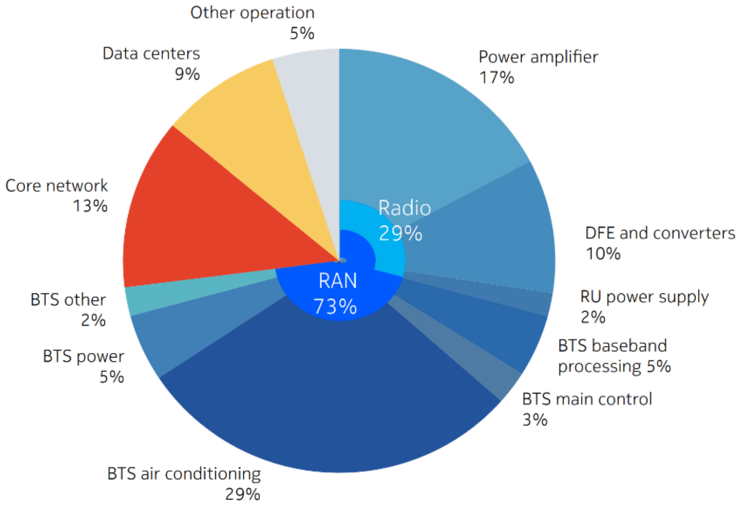

Figure 4. Distribution of energy consumption for Communication Service Provider Operations (source: Nokia).

There are two main approaches to this in FNS: hardware and systems. The hardware approach focusses on the power amplifier (PA). PAs handle a large share of power consumption in a mobile network base station, both directly (approx. 20% of mobile network's energy) and indirectly due to their need for cooling (approx. 30%). The systems approach focusses on a shift to cell-less architectures with distributed base stations, combined with the modelling needed to optimise this in terms of throughput, energy efficiency and power consumption.

2.1. Optimising PAs for higher frequencies and off-peak traffic conditions

Modern power amplifiers are mostly optimised for the current spectrum usage, i.e., sub-6 GHz. There are two main tracks working on efficiency for 6G networks. The first track is on efficiency in the use of higher frequencies. This is a hard problem to tackle. Higher frequencies mean lower efficiency and also mean that components are closer together which causes more heat issues. This potentially requires active cooling, and both heat and active cooling affect reliability and lifespan. New designs and potentially new materials are investigated to improve the power amplifier efficiency for higher frequencies.

[7] Nokia: Energy efficiency in next-generation mobile networks

Highly efficient transmitters in FNS

Decreasing the power consumption of base station transmitters has always been one of the major driving factors in the development of new transmitter architectures and technologies for wireless communication. In particular, the power amplifier in the transmitter is the most 'power hungry' part of the system and has the biggest impact on the total power efficiency of the transmitter. This has led to state-of-the-art amplifiers, in e.g. 5G, in which currently the most advanced RF power transistor technology is used, GaN-pHEMT technology, in combination with advanced Doherty PA concepts and digital pre-distortion (DPD) to achieve the best efficiency for a given linearity and bandwidth. These efficiencies are typically in the range of 50% to 60% for sub 6GHz systems meaning that the power consumption is not more than only twice the rated RF output power. It also enables small solutions since the limited heat dissipation can be handled by passive cooling.

For 6G the power efficiency is not of lesser importance. In fact, two aspects of 6G will put the currently achieved efficiencies under severe pressure. These are the increase in required bandwidths and the shift towards higher operational frequencies. Both aspects mean that new advances need to be made on transistor technology level, on PA concept level and on system level.

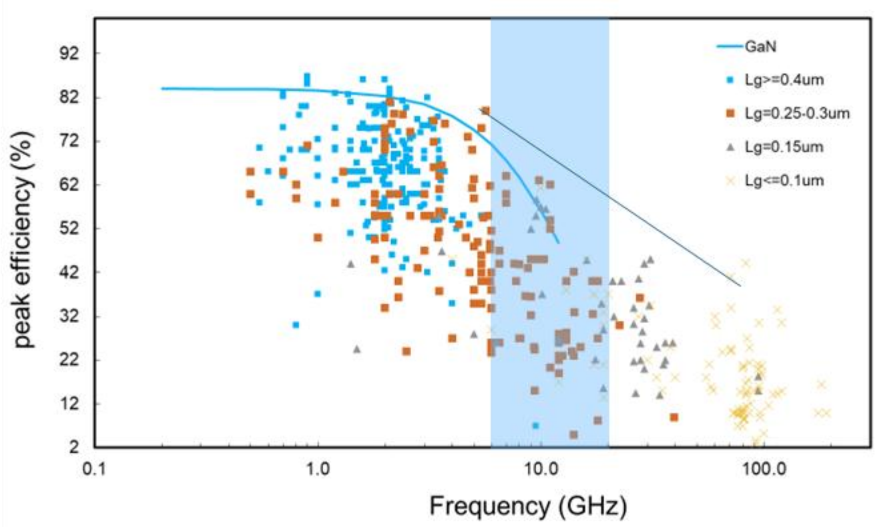

Figure 5. Frequency dependence of peak drain efficiencies of GaN technology as reported in literature.

While for sub-6GHz, efficiencies are well above 80%, this number decreases to 40% at 20 GHz. In FNS, therefore, there is a strong focus on improving power efficiency performance at distinct levels:

1. **At transistor technology level**: Investigate performance of sub-micron GaN technology and other new emerging technologies at high frequencies.
2. **At PA-concept level**: Development of new concepts like LMBA and advanced digital PA architectures that potentially can improve the linearity-bandwidth-efficiency trade-off. At the same time, these concepts can also help to increase efficiency in back-off meaning that power consumption can be reduced further when the system is in low traffic mode.
3. **At PA-system level**: In current systems isolators are used between PA and antenna to eliminate loading effects on the PA. These components are bulky and lossy. A new load-insensitive power amplifier could potentially eliminate these components and increase the system efficiency considerably.

The second track is on limiting power usage in times of lower data demand. In peak traffic conditions with many terminals using the network, base stations work at full performance. In off-peak conditions, energy can be saved in several ways. Beamforming, i.e. radio technology to propagate signals in specific directions to mobile terminals, can be used to limit energy use to where it is needed, lower voltages can be applied to limit signal strength and traffic bursts combined with short power-off periods can also save power. Still, all such options require adaptation of the power amplifier to cater for this.

2.2. Develop optimisation models for applying cell-free architectures

The concept of cell-less or cell-free architectures is a complete break with pre-6G radio network design. The main idea is that each 6G mobile terminal is served from a number of access points, where a centralised compute unit determines the optimal beamforming signal across access points to serve the terminal. This approach requires many more access points than current cellular networks and more compute overhead but will result in higher energy efficiency in data transmission.

The modelling to optimise such an architecture will be complex, involving the various 'costs' to accomplish the beamforming: gathering telemetry data on all the mobile terminals, the overhead costs of the compute power needed to calculate all signals, the available access points and their possible power states, taking into account the used channel access method used. In a first step, theoretical models are developed for this. In a later stage, the FNS testbeds will be used to validate and improve these models.

Cell-Free MIMO Networks

The foundational concept of cells in mobile networks introduces a well-known challenge: the cell-edge where interference from co-channel cells is typically highest or users may require a handover to another. As a result, users located at the cell-edge often experience lower signal quality compared to those near the centre of the cell, where the serving base station (BS) is located. Consequently, such cell-edge users experience lower throughput or a less stable connection. Achieving consistent and reliable performance across the entire network, regardless of user location, is critical for user satisfaction and reliable service delivery.

To address this issue, the cell-free architecture proposes a paradigm shift: it places the focus on the user rather than the base station. In this approach, each user is at the centre of its own cell as shown in Figure 6 and connects to multiple network nodes, known as access points (APs), to ensure stable and high-quality connectivity. Moreover, the degree of multi-connectivity can be tuned, e.g., based on throughput or reliability requirements of the user.

Cell-free networks, also known as user-centric networks, rely on each user being served by a specific group of APs, referred to as an AP cluster. These APs transmit coherently to the user in the downlink, while the user transmits to its AP cluster in the uplink. Central processing units (CPUs or CUs) play a key role in determining the precoding strategies needed for coherent downlink transmission by the APs. Beyond precoding and AP clustering, maintaining high-precision time synchronization among APs in the same cluster is essential for coherent operation, posing added technical challenges. Moreover, from a deployment perspective, network operators must ensure that the AP density is sufficient to meet service requirements, CPUs have adequate processing capacity, and high capacity (wireless) fronthaul links are available to connect APs cost-effectively. These operational and deployment considerations are critical to unlocking the full potential of user-centric architectures.

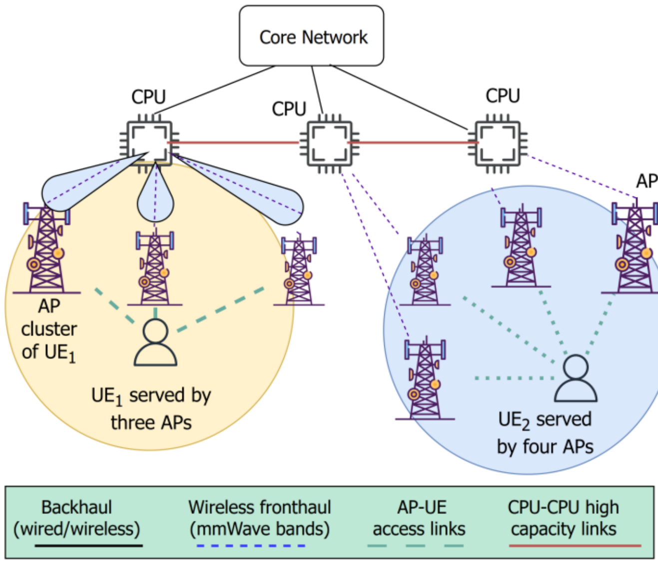

Figure 6. Cell-free networks with dense APs and users served by their AP clusters.

While tackling with these listed challenges is essential for guaranteeing a consistent and high-rate user connectivity, it is paramount to ensure that technical solutions do not come at the expense of power consumption. Hence, another important question concerns the energy and environmental impact of this new architecture. What deployment and operational strategies can ensure a low carbon and energy footprint for cell-free networks? This forms a central question related to FNS research on sustainable mobile networking, which aims to inform and guide the future deployment of these architectures.

More specifically, FNS aims at developing insights on the minimum deployment density of the APs that can ensure desired coverage and throughput capacity and whether mobile network operators (MNOs) can benefit from infrastructure sharing for cell-free operation. Various modes of infrastructure sharing from spectrum to radio access network sharing can be considered for future 6G deployments. From a sustainability perspective, such sharing modalities might offer different degrees of saving in operational energy consumption (and potentially carbon emissions) and embodied carbon, e.g., when fewer APs are deployed jointly rather than separate AP deployment by each MNO. Future mobile network architectures mitigating the shortcomings of the cell concept should only be deployed and operated at regimes where they offer benefits also from an environmental footprint perspective.

3. Using 6G for flexibility in the energy transition

The energy transition towards the use of fully renewable electricity requires a dynamic approach of matching supply and demand, using energy storage for decoupling these to some extent as well. Supply will be heavily dependent on sun and wind, but demand and storage can be steered at least to some extent.

ICT is seen as enabling technology for controlling and steering energy use and storage. Through enhanced reliability and with guaranteed network delays, 6G can play a role in the energy transition. To prevent outages of the energy grid, steering demand and storage requires high reliability and guaranteed response times. Both are provided by the 6G network and not to a sufficient degree by earlier mobile network generations.

Within FNS, the use case with the clearest sustainability impact is on energy management systems. The work is carried out on the use case of building energy management, both for demand steering and as a testbed for the technology later to be applied on a larger scale in the electricity grid. This increases sustainability in several ways. Reducing building energy use is obviously immediately beneficial but applied at scale is also a large factor in the grid congestion and can play a key role in the energy transition. On an even larger scale, in collaboration between many buildings' energy management systems and the local electricity grid, grid flexibility can be enabled based on existing facilities in use today. Grid flexibility combined with a lowering of energy demand may together even lead to a reduction in required energy network upgrades, saving further environmental impact elsewhere.

3.1. Using EMS to optimise and steer buildings' energy use

Building sustainability starts with optimising the energy used inside a building, based on the requirements of the users of the building. For office buildings this is typically 'comfort' based on temperature, humidity, CO2 levels, airflow, etc. By measuring these in high granularity with sensors and controlling the heating, cooling, and ventilation precisely, taking into account the building's occupancy level, large amounts of energy can be saved in keeping the office climate comfortable. Key in this is to measure locally but to control the building as a whole, preventing local sub-optimisations.

The next step is from a Building Management System (BMS) to an Energy Measurement System (EMS). Buildings can nowadays have solar panels, charging points for EV vehicles, electricity storage and even wind turbines. Combining the BMS with control over these electrical systems allows for controlling the energy use and energy provisioning of a building. The building can then become an element that can be used in the local electricity grid to help keep the grid balanced, provided that the EMS is opened to the electricity grid.

For this step, 6G may not be needed. 6G IoT solutions may offer a good option for large-scale roll-out of such systems, but existing IoT solutions are available for such in-building sensor infrastructure.

Integration of BMS, EMS and grid EMS

Increasing sustainability starts with optimising energy usage within buildings, based on the requirements of the users using this energy. For office buildings the main requirement is typically 'comfort,' based on numerous factors, including temperature, humidity, CO2 levels, airflow, etc. With the concept created by Comforest, these factors are measured in high granularity and frequency with the usage of sensors. By controlling the heating, cooling, and ventilation systems precisely, taking into account the building's occupancy level, a great amount of energy can be saved. The key function of the system is to measure the energy usage locally while controlling the building as a whole, preventing local sub-optimisations.

For the system to run optimally, the technical construction of the building must be checked on air density and insolation. The best performance of the air- and HVAC distribution system itself must be ensured. FNS partner Comforest created a highly functional system concept for the above-mentioned elements to function optimally and to be of high quality. By implementing these concepts, 25% of energy will be saved automatically. By combining these elements with the control system, we created a fully functional system and has with this saved 75% on energy usage in their pilot building. Furthermore, the usage of AI and prediction algorithms are expected to further optimise the system. These will be used with concepts such as anticipating the usage and occupancy of rooms and by making decisions between requirements, such as comfort levels, and energy usage.

The next step is to integrate the Building Management System (BMS) and the building EMS concept with the Energy Measurement System (EMS). Buildings nowadays tend to have solar panels, charging points for electric vehicles, storage for remaining energy, and even wind turbines. Integrating the BMS with control over these electrical systems allows for control of energy usage and energy provisioning of a building. This allows for optimalisation of the local use of available renewable energy. In this way, the building could also become a valuable element in the local electricity grid, by allowing the EMS to support and relieve pressures from the local grid. Here again, we foresee the concept of 'measure locally' (energy use at the building level) and control as a whole (energy grid level) to optimise the complete system.

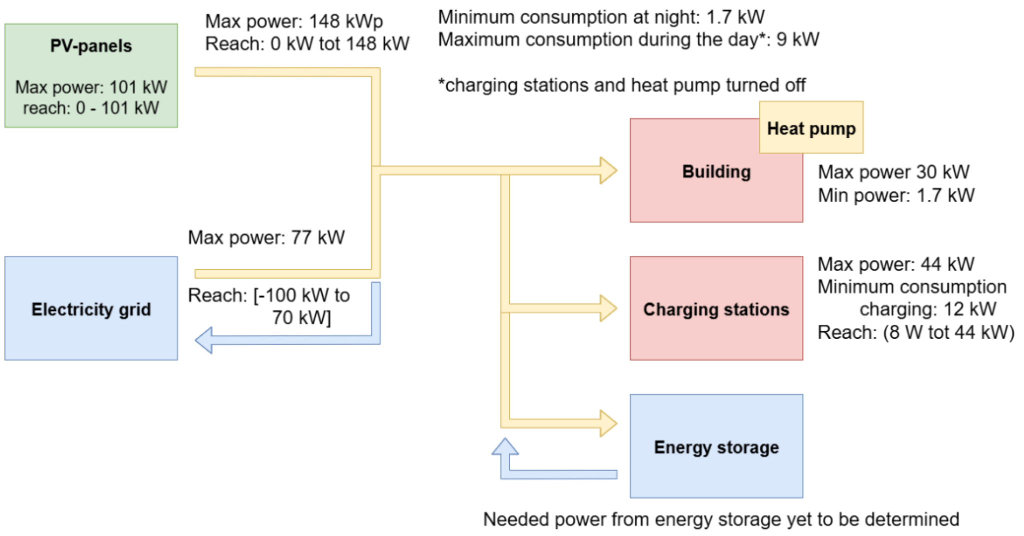

Figure 7. Overview of BMS, EMS and grid-EMS integration with power levels.

FNS is currently collaborating with Enexis to create a test setup that sets up data communication between the EMS and the local transformer station. Based on this test setup, work will be done on a proof of principle to proactively respond to grid congestion and optimise the use and storage of local and renewable energy. To further optimise this, we are working on a 48-hour prediction model of the harvest and energy consumption of the building.

With these systems FNS looks to improve and optimise energy usage in buildings, and with this, provide optimal comfort for its users.

3.2. Using EMS to enable grid flexibility and support the energy transition

This next step is where future 6G does come in: to provide the reliability, resilience, and guaranteed network delays as a pre-condition for a grid-wide EMS. To maintain grid stability, the control of decentral energy use and energy provisioning needs to be available reliably and with quick response times. On a local scale, if EMS connections used for grid flexibility would drop out, this could quickly lead to a local power outage, hence the need for high reliability.

Using 6G allows for reliable connections between the local energy transformer and the installations that can be controlled, such as smart buildings as explained above. Here the same principle applies measure locally, and control centrally. In this manner, grid flexibility can be introduced in the local energy grid.

Many factors play a role here. The grid cannot 'control' a building's energy use exactly, this will probably be a kind of collaborative approach, with specific contracts and specific terms and conditions. Measurements, predictions, modelling, and optimisation all play a role here in which presumably AI will play a significant role. This combines well with edge computing in the mobile network, allowing for highly secure and local data processing.

4. Observations

Apart from the points in the previous section, a number of additional observations have been made on sustainability and the FNS work. These are offered here as a further reflection on the work and for discussion in the FNS consortium in the planning of future work.

4.1. Environmental impacts beyond electricity use

Energy use and related greenhouse gas (GHG) emissions are important and significant but are only one environmental impact out of many and only covers the use phase of mobile networks. FNS may consider extending their scope to include (1) other environmental impacts, such as the scarcity of raw materials or water usage, and (2) the entirety of the life cycle of mobile networks, covering impacts embodied in the manufacturing, installation, maintenance or end-of-life of hardware. Failing to do so may lead to sub-optimizations resulting in potential undesirable burden shifting between environmental impacts categories or between life cycle stages. Optimization modelling may also be carried out during the network planning phase to take such factors into account, following a sustainability-by-design mindset and aiming at lowering the overall environmental impact of 6G roll-out and use.

4.2. Active infrastructure sharing can further reduce energy use

Building multiple 6G mobile networks in the same country is less efficient than deploying a single larger network and actively sharing this infrastructure between the various mobile providers, beyond current site sharing as is done today. It will also lower the deployment costs for the providers but has a downside the lack of individual control and can no longer bring a competitive edge by e.g. first mover advantage. Even though this would be a substantial change in deployment, some countries do now follow this model showing its feasibility.

4.3. Use of lower frequency will be more energy efficient

Providing higher bandwidths by using higher frequencies comes at a clear cost in terms of energy efficiency. However, the availability of spectrum in the lower bands is limited, hence a move to higher frequencies. Sustainability may be considered as a factor in spectrum allocation. Models can be developed that show the environmental impact of the various alternatives that could be envisioned.

4.4. Use and extrapolate current operational data to plan for migration

Migration to 6G should ultimately be demand-driven. Migration to 6G would ideally closely follow the demand for connectivity and applications. An early migration creates a risk of premature roll-out and an unnecessary environmental impact and unnecessary costs. An overly late migration means customer experience and application uptake will suffer. Good migration plans can be based on traffic forecasts and modelling of data growth rates, and that will help plan for any migration to come. This also has a relation with spectrum assignment or auction, as the conditions of the allocation may lead to a higher environmental impact in case of a premature roll-out without existing market demand. Additionally, care should be taken to mitigate rebound effects. The increase in bandwidth and communication efficiency as well as the new use-cases coming with 6G may create additional demand that may counterbalance sustainability gains if left uncontrolled.

4.5. Fair attribution of impact reduction to 6G

Part of the environmental impact of an innovative technology is its effect elsewhere, i.e. in this case 'greening by 6G'. The use case of grid flexibility is a key example offered here. Still, claiming such an environmental impact reduction by 6G technology is perhaps not fair: several factors play a role in reaching such a reduction, amongst which 6G as enabling technology. Modelling approaches exist to have a fair allocation of impact amongst actors, incentivising action amongst all needed actors.

5. Conclusion

This whitepaper shows how the FNS programme approaches the intersection between environmental sustainability and 6G mobile networks. Two main impact pathways are highlighted: sustainability *of* 6G with use phase energy optimisation and the sustainability *by* 6G for energy management, respectively. FNS is engaged both in top-down contributions with its demand and use-case driven approach, as well as bottom-up activities by thoroughly investigating and improving key elements of the networks value chain.

To go further with sustainability and 6G, several opportunities were identified for FNS to extend their scope and activities, which can be considered for the next phases. In particular, (1) the scope of sustainability can be broadened beyond energy consumption during the use phase, (2) infrastructure sharing and lower frequency use can both contribute to energy efficiency, (3) demand forecasts for mobile networks can be used to further root FNS into the reality of the market, and (4) sustainability gains should be allocated fairly along the value chain.

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Alle rechten voorbehouden. Niets uit deze uitgave mag worden verveelvoudigd en/of openbaar gemaakt door middel van druk, fotokopie, microfilm of op welke andere wijze dan ook zonder voorafgaande schriftelijke toestemming van Future Network Services.