THE SHIFT PROJECT

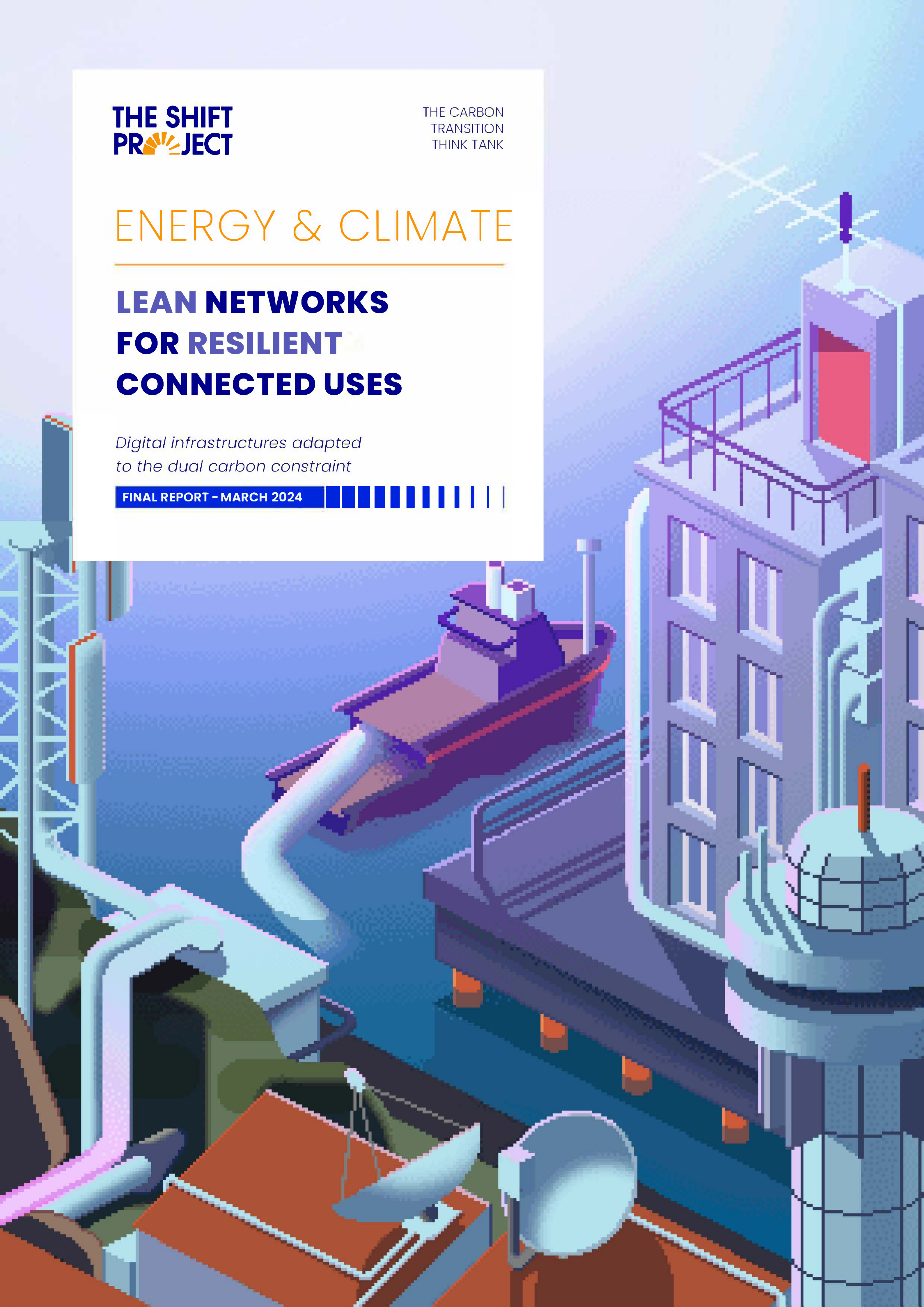
THE CARBON TRANSITION THINK TANK

ENERGY & CLIMATE

LEAN NETWORKS FOR RESILIENT CONNECTED USES

Digital infrastructures adapted to the dual carbon constraint

FINAL REPORT - MARCH 2024



Foreword

As part of its work programme devoted to the **challenges of digital technologies in relation to the dual carbon constraint (reducing our carbon emissions and freeing ourselves from our dependence on fossil fuels)**, The Shift Project has published five studies in recent years on the environmental impact of digital technology:

- **Lean ICT – Towards digital sobriety (2018)**
  Report assessing the environmental impact (particularly carbon and energy) of digital technology worldwide, both now and in 2025.

- **The unsustainable use of online video (2019)**
  Report tracing the links between the sociological construction of digital uses and the dynamics of our infrastructures, based on the example of online video.

- **Deploying digital sobriety (2020)**
  Methodological frameworks that public and private stakeholders should embrace to initiate operational transformations leading to a digital landscape compatible with decarbonisation goals

- **Environmental impact of digital technology - 5-year trends and 5G governance (2021)**
  An update on the trajectories to 2025 of the energy-carbon impact of digital technology. It also looks at the way in which the debate on 5G has crystallised, and the elements that make it a case study of the dynamics described in previous Shift reports: the evolution of uses and its interaction with the development of infrastructures.

- **Planning the decarbonisation of the digital system in France: specifications (2023)**
  A document providing an overview of the dynamics observed in the digital realm in France (electricity consumption, carbon), the risks and challenges faced by players involved in the country's energy-carbon planning (RTE (France's electricity transmission system operator), SGPE (French General Secretariat for Ecological Planning), etc.), and describing the categories of levers that need to be mobilised in order to make the digital sector resilient, based on its systemic description.

A host of initiatives have sprung up among digital players, who have rapidly and dramatically increased their expertise on the carbon and energy impact of connected goods and services. The aim of the work carried out in our programme is to **build a global vision of what is involved in a low-carbon and resilient digital economy, at least at European level, and to shed light on the central question of this challenge: "How can we turn digital technology into a genuine tool for rethinking production and consumption methods, rather than just a lever for optimising current methods?"**

The current phase of this work has two parallel axes:

- Our work on the relevance of virtual worlds in the light of energy-climate constraints, the aim of which is to document the way in which the promises and projections of new uses can trigger the deployment of certain trajectories in digital infrastructure development choices;

- Our work on network infrastructures, the impact of the deployment choices made, and the strategies that need to be implemented in order to make them resilient to the dual carbon constraint, of which this document is the final report.

About The Shift Project think tank

The Shift Project is a think tank working towards a carbon-free economy. As a recognised non-profit organisation operating under the 1901 French law and guided by the demand for scientific rigor, its mission is to enlighten and influence the debate on energy and climate transition in Europe.

The Shift Project establishes working groups around the most decisive issues of the transition, produces robust and quantitative analyses on these issues, and develops rigorous and innovative proposals. It runs lobbying campaigns to promote the recommendations of its working groups to political and economic decision-makers. Additionally, it organises events that facilitate discussions among stakeholders and builds partnerships with professional and academic organisations, both in France and abroad.

The Shift Project was founded in 2010 by several leading figures from the corporate world with experience in both the not-for-profit and public sectors. It is supported by a number of major French and European companies, as well as public bodies, business associations and, since 2020, SMEs and individuals. It is backed by a network of tens of thousands of volunteers throughout France: The Shifters.

Since its creation, the Shift Project has initiated more than 50 research projects, participated in the emergence of two international events (Business and Climate Summit, World Efficiency) and organised several hundred symposia, forums, workshops, and conferences. It has been able to significantly influence a number of public debates and important political decisions on the energy transition in France and the European Union.

The Shift Project's ambition is to mobilise companies, public authorities and intermediary bodies on the risks, but also and above all on the opportunities generated by the "double carbon constraint", represented jointly by the pressures on energy supply and climate change. Its approach is marked by a specific analytical perspective, based on the conviction that energy is a primary factor in development: therefore, the risks induced by climate change, closely linked to the use of energy, involve a particular systemic and transdisciplinary complexity. Climate-energy issues will determine the future of humanity, so we need to integrate this dimension into our social model as quickly as possible.

It is supported by a network of tens of thousands of volunteers gathered within a non-profit association: The Shifters, established in 2014 to provide voluntary support to The Shift Project. Initially designed as a structure to welcome anyone wishing to assist The Shift through research, relay, or support work, The Shifters are carrying out more and more independent work, but always with one objective: to effectively contribute to the transition away from fossil fuels at French and European levels.

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Introduction

Digital technology, both a tool and a challenge for the economy's decarbonisation

Information technologies are now central and essential to our societies, and play a crucial role in the transformation of our economy. While this digital equipment and the uses they enable and promise seem designed to meet ever greater challenges, this does not mean that they are exempt from consideration of their environmental relevance. In a world of finite resources, it's important to remember that every physical transformation, and therefore every action, requires energy. And that includes sending information. So digital technologies are not virtual tools, but physical media, even if we don't directly perceive their materiality through the actions they enable.

Digital technologies form a global system: devices (smartphones, computers, tablets, etc.) connect to each other via network infrastructures (terrestrial and submarine cables, mobile network antennas, fibre optics, etc.) to exchange information stored and processed in data centres, the beating heart of this system. But each of these elements requires energy not only to function (usage phase) but also, before that, to be produced: mining of raw materials, industrial manufacturing processes, and then delivery to consumers require substantial biotic and abiotic resources.

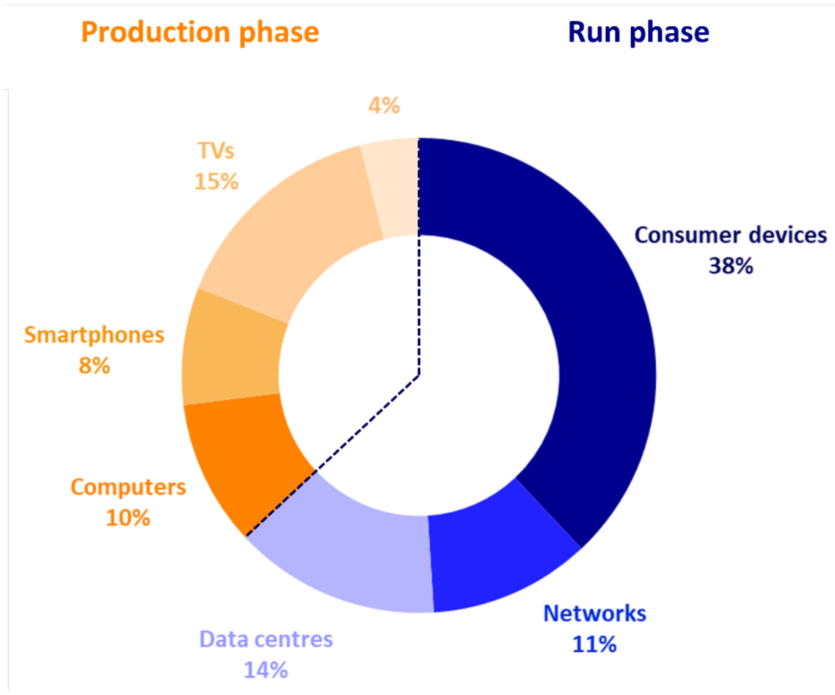


Figure 1 - Distribution of the global digital carbon footprint in 2019, by item for the production (40%) and usage (60%) phases
Source : (The Shift Project, 2021)

Each digital service relies on physical infrastructures whose resilience and relevance to the **dual carbon constraint (reducing the carbon emissions of our activities and freeing ourselves from our dependence on fossil fuels)** must be questioned. Digital technology is a catalyst: where it is deployed, it enables us to optimise, accelerate, streamline, and parallelise. Deploying it without a strategy (or rather, without a strategy designed considering this dual constraint) therefore leads to the acceleration of all dynamics, including those furthest removed from our resilience objectives. Making it a real tool for rethinking our activities, in order to make them compatible with planetary constraints, requires a systemic understanding of the impact of digital technology and an appropriate strategy.

An unsustainable trajectory that needs to be reversed

The digital sector already accounts for almost 4% of global emissions (The Shift Project, 2021), on a par with all the heavy goods vehicles in the world (IEA, 2021). In France, the digital sector accounts for 2.5% of the country's carbon footprint (ADEME (French agency for ecological transition) & Arcep (French authority in charge of regulating telecommunications, postal services, and print media distribution, 2023)).

Its particularity stems from the trends in its emissions, which are growing at a particularly rapid rate that is incompatible with its decarbonisation: +6%/year on average worldwide (The Shift Project, 2021) and +2 to 4%/year in France (ADEME & Arcep, 2023; HCC, 2020; French Senate, 2020). **Technical and operational optimisations are unable to offset the sustained growth in infrastructures, parks, and utility supplies** (ADEME & Arcep, 2023; Bol et al., 2020; European Commission, 2020; GreenIT.fr, 2019; IEA, 2022; The Shift Project, 2023b). This observation continues to hold true and has been illustrated over the last five years, although according to some studies these impacts should have levelled off thanks to technological progress (IEA, 2019; ITU-T, 2020; Masanet et al., 2020).

In France and worldwide, digital technology accounted for approximately 10% of total electricity consumption in 2022 (The Shift Project, 2021, 2023b). Against a backdrop of intense electrification of uses (mobility, buildings, industry, etc.), it is easy to see that digital energy is also at the heart of the issues involved in planning the transformation of our systems and prioritising access to resources that are now under pressure, including electricity (The Shift Project, 2023b).

Making the digital sector compatible with the dual carbon constraint therefore involves not accelerating the optimisation levers already deployed, but putting it on a fundamentally different trajectory to the one it is currently following. **In the same way as other sectors of the economy, it must achieve its decarbonisation target**, which industry players (GSMA, GeSI[1]) have set themselves through the SBTi initiative and on the basis of an ITU recommendation (SBTi et al., 2020, p. 9) of **-45% by 2030 compared with 2020 at global level**[2].

The Shift Project suggests using this target as the basis for building a national trajectory, adapting it to the specific features of the already significant decarbonisation of the country's electricity mix. **The Shift Project recommends constructing the French trajectory around this recalculated**

[1] GSMA: GSM Association, an association of international players in mobile connectivity (manufacturers, operators, etc.) | GeSI: Global enabling Sustainability Initiative, a group of international players in the digital and telecommunications sectors, whose mission is to work towards sustainable digital development.

[2] Or as part of national commitments similar to those made by French manufacturers as part of the decarbonisation roadmaps for the digital sector.

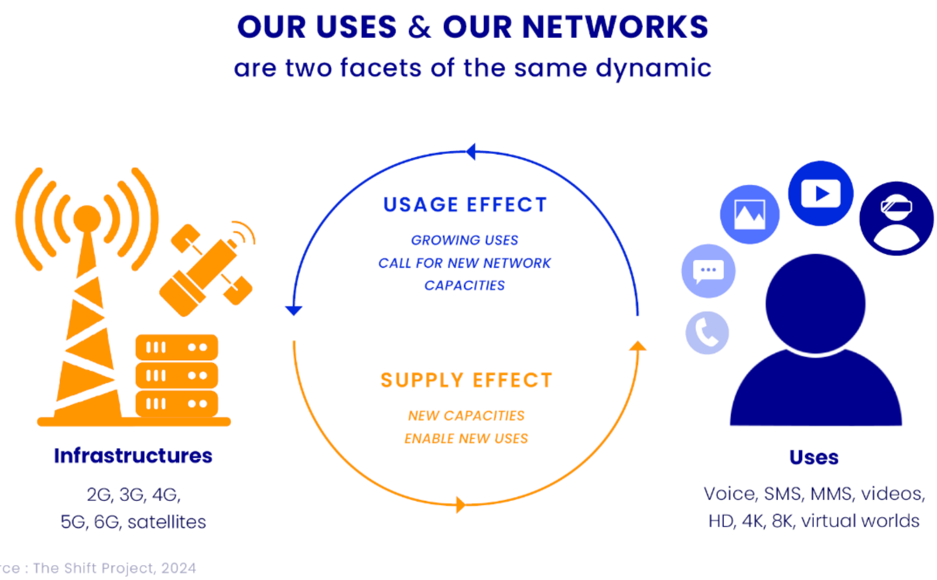
SBTi objective, aiming for a -30% reduction in sector emissions by 2030 compared to 2020, adapted to the French context.

Our digital system is built through multiple interactions between the technical system and the uses it supports. Analysing energy and the climate using a systemic approach helps us to understand that **managing the impact of our technologies will not happen without thinking about the deployment of offerings and the adoption of uses that we may or may not encourage.** A shift in device and data volumes is even **a sine qua non for keeping energy consumption under control through gains in energy efficiency (The Shift Project, 2023b).**

Why work on networks' energy-climate footprint?

Networks are a central building block of our digital system.

In quantitative terms, they represent between **12% (The Shift Project, 2021) and 25 to 35% of the carbon footprint of the digital sector worldwide** (Freitag C. et al., 2021; Malmodin J. et al., 2023) and **5.5% in France** according to current estimates by ADEME and Arcep (ADEME & Arcep, 2023). In France, the ADEME-Arcep study estimated that the electricity consumption of the 4 main operators would show an average growth rate of +6%/year between 2017 and 2021 (ADEME & Arcep, 2023), reaching almost 4 TWh in 2021[3], with 60% attributed to the mobile access network alone. (ADEME & Arcep, 2023). This growth is the result of a fall in consumption by fixed networks, due to the replacement of the copper network by the fibre network, and a sharp increase in consumption by mobile networks due to the massive and regular roll out of new sites and equipment. These dynamics are in no way unique to France, in that they can be found at European level (Lunden D. et al., 2022), as well as at global level, where the electricity consumption of mobile networks is growing by 12%/year and was already 1.5 times that of fixed networks in 2019 (The Shift Project, 2021).



[3] This figure does not include the consumption of internet routers or other network equipment installed by operators on customer premises (e.g. the UN). This figure also excludes corporate networks and networks not owned by the 4 main operators (for example, the RENATER network) (ADEME & Arcep, 2023).

Figure 2 – Our usages and our networks are two facets of the same dynamic
Source : (The Shift Project, 2021)

These network-specific dynamics are part of a **systemic rationale**: the digital world operates as a system and its three components (devices, network infrastructures, data centres) evolve together, made interdependent by data exchanges. The deployment choices made at network level have an impact on the digital system as a whole, while at the same time being the result of the general trajectory given to the system:

- The willingness to develop new uses justifies the deployment of new technical capacities (the growth in video content leads to a need for greater mobile network capacities, etc.): this is the **usage effect**;
- The roll out of new technical capacity leads to the development of new uses (the option of watching UHD videos while roaming, the need to upgrade one's smartphone to take full advantage of this new service, etc.): this is the **supply effect**;

This evolutionary mechanism, once translated into public policies and economic strategies, is self-sustaining and self-justifying: once network equipment has been rolled out, it is essential to make it profitable in the ways made possible by the projections that initially prompted it. Over the last few decades, and right up to today, **the trajectory chosen has been one involving a simultaneous increase in the three components of mobile network capacity:**

- **Increased speeds and higher frequencies**, leading to a reduction in signal range and therefore an increase in the number of sites (with constant geographical coverage);
- **Reduction in latency**,
- **Increased coverage of populations and territories**, again automatically leading to an increase in the number of sites.

As part of the systemic approach developed by The Shift Project since 2018, the aim of this study is therefore to document in greater detail the challenges facing the "network infrastructure" component of the transformation needed to make the French and European digital system lean and resilient. **The choice was made to focus on two major components:**

- **Mobile networks,** which are now the part of the infrastructure driving network power consumption and growth[4];
- **Satellite infrastructures**, which offer an additional and new infrastructure, both from the networks' point of view (with coverage, roll out, and operating methods that are completely different from terrestrial solutions) and from the aerospace ecosystem's point of view (the dynamics created by these digital infrastructures are generating major changes in the scale of the number of satellites launched into orbit and launches carried out).

The quantitative simulations on mobile networks are carried out on French mainland territory but are based on a **configurable model**. Its added value is to quantitatively highlight the environmental consequences of industrial, societal, and political choices. We hope that it can be **used to guide the thinking of public and private players in this area, in France and in Europe, to help draw up specifications for a lean and resilient digital economy at European level.**

[4] Fixed networks will obviously be included in the final systemic considerations, as explained at the beginning of this report.

This report is being conducted alongside the “Energy and climate: What virtual worlds for a sustainable real world?” report (The Shift Project, 2023a), which aims to identify the relevance of virtual worlds in light of energy-climate constraints and the technological dynamics they generate or amplify. These dynamics could lead to structural increases in network capacities.

Mobile networks: possible dimensioning and greenhouse gas emission trajectories

Network specification and deployment scenarios: key choices that determine the dimensioning of future networks

Driven by both political decisions and stakeholders' business strategies, the choices made regarding technological solutions and network deployment methods over the coming decades will determine the possible energy consumption and carbon emission trajectories for these infrastructures.

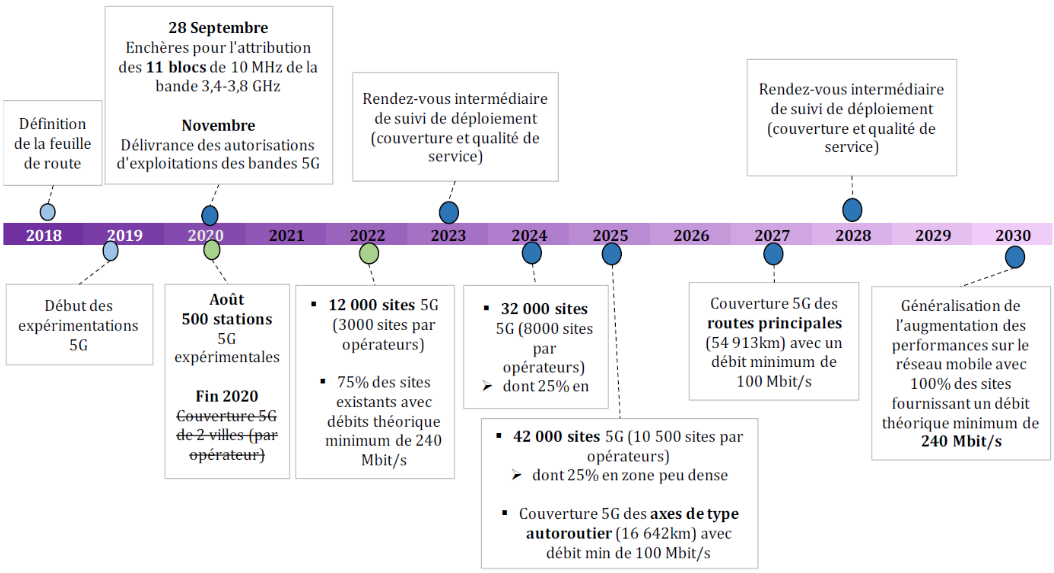


Figure 3 – Timeline of the main operator obligations of Arcep's specifications for 5G
Source: image taken from (Citizing, 2020), based on (Arcep, 2019)

Some of these choices are enshrined in the regulatory specifications drawn up by Arcep, for example as part of the process of allocating frequency ranges for the roll out of 5G (Arcep, 2019), including the deployment schedules and priorities for this mobile generation (Figure 3). The scenarios presented here are built on this basis in order to characterise the effects on network infrastructure dimensioning of past decisions (4G, 5G, etc.), future decisions (6G, etc.) and their possible alternatives.

Mobile networks scenario						
	Maximalist	Current specifications	Zero white zones	Urban	Shared	Lean example
Deployment strategies and societal issues ("as usual": Arcep 5G specifications)						
Deployment schedule, technological adequacy	as usual	as usual	as usual	as usual	as usual	reviewed and managed
Coverage - Number of sites, population, surface area	total	as usual	total	urban and suburban	as usual	as usual
Coverage - Roads, motorways, rail routes	as usual	as usual	suspended	as usual	as usual	suspended
Differentiated industrial and professional services	as usual	as usual	as usual	as usual	as usual	suspended
Agriculture connected to mobile networks	yes	no	no	no	no	no
Supply, including sharing capacity ("as usual": current trends)						
Passive (tower sharing)	as usual	as usual	as usual	as usual	strong	strong
Active (frequency sharing)	as usual	as usual	as usual	as usual	strong	strong
Demand and service mix ("as usual": current trends and strategies)						
Traffic - performances	maximal	as usual	as usual	maximal	as usual	sensible
Traffic - quantity	maximal	as usual	as usual	maximal	as usual	sensible
Traffic - IoT, IIoT	video stream	as usual	as usual	as usual	as usual	reduced
Temporal variability management	oversize	as usual	as usual	oversize	as usual	peak limitation

Table 1 - Characterisation of network specification and deployment scenarios
Source: The Shift Project, for the purpose of this report

There are several possible scenarios based on a combination of technical specifications and deployment options for mobile access networks (Table 1):

- The specific features of network deployment strategies (economic and political) in the light of coverage issues (general or differentiated):
  - **Deployment schedule** (launch, objectives, trajectory) for the different generations of network equipment between now and 2030 (5G depending on the different bands currently being deployed: 700 & 800 MHz, 1800 & 2100 MHz, 3500 MHz; 5G depending on the bands being tested: 3.8-4 GHz and 26 GHz; 6G depending on the possible development options and the frequency bands that will be chosen in the near future, favouring only energy efficiency or a paradigm shift);
  - **Territory and population coverage**, which represents the possible variations in the spatial distribution of mobile sites between the different scenarios. It is described by the number of sites and their distribution across the territory;
  - Road, motorway, and rail coverage;

- **Differentiated industrial and professional services**, covering the deployment of mobile networks in industrial and business areas which have been earmarked as having connected uses of particular interest within Arcep's specifications (automotive industry, high-precision industry, healthcare) based on slicing[5] technology (Arcep, 2019).
- **Agriculture connected to mobile networks**, which covers agricultural applications requiring access to the network (real-time monitoring of environmental variables on farms, deployment of connected sensors, etc.);

- The specific features are the result of the choices made by players on the supply side (operators), reflected in the level of mobile site sharing:
  - **Passive sharing**, which involves the sharing of towers or masts used to deploy antennas and network equipment from the various operators.
  - **Active sharing** refers to the sharing of antennas and network equipment deployed on the same tower or mast, with arrangements for sharing the usage of frequencies among different operators;
- Specific features relating to the level and type of demand (possible uses and services):
  - **Traffic-performance**: refers to the levels of technical specifications for average data transfer on the mobile network as a whole (throughput, latency, and reliability)[6];
  - **Traffic-quantity**: reflects changes in the average volume of data flowing through the network. It is linked to changes in three parameters: usage intensity (number of hours of usage per person), the number of people using the mobile network (i.e. subscribing to a mobile service) and the data intensity of mobile usage (for example, video usage is more intense than usage based on text content without images);
  - **Traffic due to the Internet of Things (IoT[7] and IIoT[8])**: reflects changes in the average volume of data flowing through the network as part of applications based on a large number of objects equipped with sensors, actuators, and connected to the network to provide automated and optimised services (home automation, logistics chains, industrial assembly lines, etc.). These applications generate significant machine-to-machine (M2M) communication requirements, the evolution of which is linked to that of three parameters: the level of deployment of these solutions in the various sectors of activity, which can be massive (number of objects deployed), the data intensity of the services rendered (volumes of data acquisition required) and the methods of processing this data (Level of data archiving for acquired data and whether computing capabilities are decentralised or not).
  - **Management of temporal variability**, which covers all dimensioning strategies in light of temporal variability in site load rates: dimensioning at peak or off-peak, off-peak/peak modulation strategy.

[5] A technology for virtually slicing the network in order to adapt its characteristics and quality of service to the differing user needs (high speed or low latency and high reliability or a greater number of connected objects).

[6] It should be noted that it would be technically possible to define and divide traffic into different categories, with these traffic categories being able to be transferred to different network slices (slicing functionality deployed for all users).

[7] IoT: Internet of Things

[8] IIoT: Industrial Internet of Things

It is the possible combinations of these variables that lead to the scenarios identified, and not the other way round: the approach chosen in this study aims to **shed light on the consequences of the technical and strategic choices made on infrastructures**. Each of these scenarios serves to highlight the macroscopic effects of these decisions on the overall dimensioning of the mobile network, by describing the resulting archetypal dynamics (Table 2).

Mobile networks scenario						
	Maximalist	**Current specifications**	**Zero white zones**	**Urban**	**Shared**	**Lean example**
Deployment strategies and societal issues Deployment objectives:	Cover the entire country (roads, rural areas, etc.) and deploy all the promised uses	Cover the territory according to the priorities set out in Arcep's 5G specifications.	Priority given to covering the entire population, ahead of other uses (roads, agriculture).	Priority given to coverage of urban areas, with the highest intensity of use.	Cover the territory according to the priorities set out in Arcep's specifications for 5G.	Revised 5G and 6G roll out specifications: refocusing on areas and services already identified as priorities.
Offering Sharing dynamics :	Sharing trend dynamics.	Sharing trend dynamics.	Sharing trend dynamics.	Sharing trend dynamics.	Strategy for increasing the degree of sharing.	Strategy for increasing the degree of sharing.
Demand and service mix Network dimensioning objectives :	Providing the optimum level of service, at all times, at all points, for all new uses.	Absorb trends in usage developments	Absorb trends in usage developments	Provide the optimum level of service at all times in urban areas, for most new uses.	Absorb trends in usage developments	Based on physical constraints, to ensure the resilience of essential uses.

Table 2 - Description of the dynamics of network specification and deployment scenarios
Source: The Shift Project, for the purpose of this report

The "Lean example" scenario is presented here as **an example of the type of dynamics that one of the trajectories compatible with digital sobriety and physical constraints** might entail. The challenges of an "Eco-design and sobriety" scenario along with recommendations for implementing it are among the outcomes of the work carried out as part of this report (see the “Systemic eco-design” and “Eco-design and sobriety” scenarios and “What levers can we use to lead our networks towards a lean and resilient future?” section).

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Description of the modelling tool: scope, methodology, structure, and possible applications

General structure and methods

The modelling tool on which the quantitative results of this work are based is designed to answer the following research question:

"What are the consequences of deployment choices and technical specifications on mobile networks' carbon and energy impacts, as well as on their ability to adopt a trajectory compatible with the sector's 2030 emissions reduction target?"

This model, which focuses on updating and consolidating the "mobile" component of our network infrastructure[9] models, aims to describe the interactions between (Figure 5):

- Deployment choices and technical specifications ("Upstream section");
- Changes in usage, in terms of quantity and technical requirements ("Upstream section");
- The resulting infrastructure requirements ("Upstream section");
- The carbon/energy footprint resulting from the infrastructure actually deployed in the studied scenario ("Downstream section").

The trajectories of possible developments in usage and the resulting demand are built alongside the work carried out on virtual worlds (The Shift Project, 2024c) in order to combine the two approaches developed by The Shift Project on the digital system: the one whose starting point is the configuration of technical infrastructures (in this case, networks) and the one whose starting point is the understanding of usage and its development dynamics (in this case, virtual worlds). It is this dual approach that enables us to document the interactions between societal dynamics and physical dynamics.

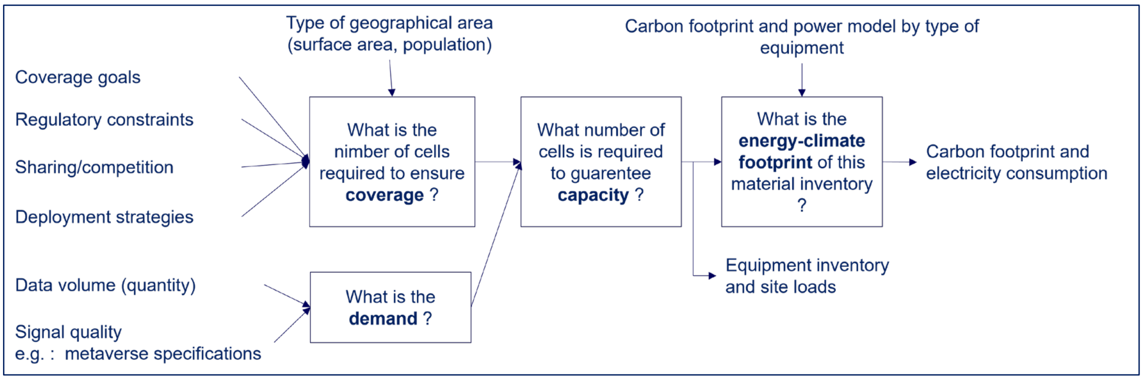

Figure 4 - Functional diagram of The Shift Project's "Mobile Networks" model and links to the report on virtual worlds (The Shift Project, 2024c)
Source: The Shift Project, for the purpose of this report

[9] Details of the technological scope chosen can be found in the section "Why work on networks' energy-climate footprint?", page 6 of this report.

The model is structured in a way that allows it to be applied to different geographical contexts: while the quantitative analysis developed in this report is based on metropolitan France, **the objective of this work is to produce tools that can be used to guide the key choices of the digital system at a European country level and, ultimately, for Europe as a whole.**

The consequential modelling method: informing choices rather than describing trends

The prospective analysis of network infrastructure impact dynamics can be based on two different modelling methods: "trend-based" or "consequential"[10]. Each of these is tailored to shed light on different issues.

Trend-based method

This method aims to build a **trend-based vision of infrastructure dynamics** (data flows, electrical consumption, energy consumption, etc.) **in view of the uses that drive them over the long term.**

To achieve this, it relies on an attributional methodology (Schaubroeck et al., 2021) to construct indicators, along with a linearised vision of the future:

- Starting with the macroscopic data that characterises the infrastructure;

For a very simplified example: total data traffic on an infrastructure in GB, and the total electricity consumption of this infrastructure in kWh.

- On this basis, ratios are constructed according to an attribution logic. What they describe is essentially the share of "responsibility" a given usage has on the carbon-energy impact of the infrastructure, in that it justifies the existence of the network in proportion to the level of demand it generates.

  In our very simplified example: electricity consumption per unit volume of data transferred, in kWh/GB. So, since the infrastructure is deployed to enable data transmission, we assume that each GB transferred is responsible for a share of the infrastructure's total consumption.

- Changes in carbon-energy impact trends are extrapolated from these ratios, according to the chosen scenarios for changes in use and changes in the variables impacting the ratios themselves.

  In our very simplified example, we may, for instance, modify the value of the ratio in kWh/GB according to the scenario for changes in energy efficiency over time. We will then obtain a projection of the infrastructure's total consumption by multiplying this new ratio by the forecast data traffic.

The modelling therefore does not seek to describe the interactions that technically link uses to their carbon and energy impacts, but to describe how changes in volumes over several years lead, on average, to an evolution of impacts. **This is the approach used in the modelling of The Shift Project's reports to date, including the latest update of our prospective scenarios (The Shift Project, 2021)**. Behind this linearisation lies the reality of infrastructure deployment, which is taken into account to a greater extent by the consequential modelling method.

[10] This approach is based on the rationale developed in the work on attributional and consequential life cycle analyses (Schaubroeck et al., 2021), but generalises some of the concepts.

Consequential modelling method

In Life Cycle Assessment (LCA), consequential LCA aims to characterise the environmental impacts of the consumption or production of one or more additional units (Schaubroeck et al., 2021). Here we generalise this concept into a method aimed at describing the effects of strategic choices (coverage, technical specifications, etc.) on infrastructures (number of base stations, number and type of network equipment deployed, etc.) and their impacts (carbon and energy, in our approach).

The carbon-energy impacts of network infrastructure have two components, each of a different nature (Guennebaud et al., 2023; Malmodin J. et al., 2023):

- **The fixed component,** which is linked only to the deployment pace and methods (coverage, number and type of equipment deployed);
- **The variable component,** which is linked to the infrastructure's level of use (site load factor, volume of data traffic).

The fixed component includes the carbon-energy impacts of network infrastructure production and deployment, as well as a portion of 90% of their total global carbon impact due to their operation phase and electricity consumption (The Shift Project, 2021).

This fixed component of network electricity consumption, and therefore of the resulting carbon emissions, accounts for the bulk of total infrastructure consumption (Bou Rouphael, R. et al., 2023): once the equipment has been deployed (fibre, antennae, core network, and access network equipment, etc.), a continuous power supply is required to keep it running. The variable consumption resulting from data transmission is added to this base. For fixed network infrastructure, this variable component represents only a few percent, compared with around 20-30% for a 4G station[11]. In both cases, this component is set to become more significant in the future, particularly with the introduction of more effective standby solutions.

In the trend-based method, which is based on an attribution logic, the fixed component is calculated proportionally to the demand on the infrastructure, to reflect the usage's "share of responsibility" in justifying the size of the infrastructure.

In the consequential modelling method, the objective is to translate the consequences of deployment decisions, which have a significant impact on electricity consumption and the network's carbon footprint. It involves **modelling the conditions that prompt new deployments:**

- Risks of saturation and loss in quality of service (in terms of speed, capacity for simultaneous connections, etc.);
- The intention to enable new uses and services requiring new technical specifications (lower latencies, higher upload and download speeds, etc.);
- Decision to cover defined areas of the country or a defined proportion of the population with a certain level of service.

In this method, therefore, modelling consists of projecting changes in the variables that drive the deployment of new network infrastructures and the ways in which they are deployed. **These are**

[11] (Malmodin J. et al., 2023) found that a 4G station with an average load of 30% would account for around 20%. A study conducted by Orange Innovation reports a 30% variable share for a typical 4G station. The same study estimates this share at 10-20% for all its mobile sites in France in 2021 (Bou Rouphael, R. et al., 2023).

the input variables for the "upstream" section of our current model (Figure 6), which adopts a consequential approach.

Description of the model

The detailed description of the model and the values assigned to various parameters are available in the appendix, "Appendix 1 – Detailed description of the model"

The French case study and the structure of the model

The tool is built based on the French case study but designed **to be adaptable and parameterised so that it can be applied to different areas and contexts.** With this in mind, the full description of the model is available in the appendix to this report ("Appendix 1 - Detailed description of the model") and the model itself is fully accessible online (The Shift Project, 2024b).

In order to simulate the development of mobile networks in metropolitan France between now and 2035, we consider a market divided between four identical generic operators offering mobile network services throughout the country. We consider one of these generic operators, an average operator which is not meant to be compared with an existing operator, but which allows the obtention of realistic orders of magnitude for the results obtained, taking account of the market segmentation.

The generic operator must meet a number of criteria in order to deploy its sites and adopt a certain deployment strategy over time. The main ones are:

- Territory characteristics,
- Demand for data traffic,
- Coverage constraints,
- Network characteristics.

In the model, these are translated into three types of requirements used as inputs for the calculation:

- **Population**, which reflects population coverage requirements;
- **Regulation**, which reflects the territorial roll outs required by the regulator;
- **Capacity**, which reflects the need for capacity deployments in order to absorb traffic growth.

These, combined with the time period under consideration, are the inputs to our model. The outputs of the model are the carbon and energy environmental impact indicators, calculated in the model's "downstream section" (Figure 5).

The model studied can be broken down into four main parts:

- Demand specification,
- The coverage model,
- The capacity model,
- The environmental model

Model inputs

The time period studied

We are studying mobile network developments in metropolitan France between 2024 and 2035. The modelling algorithm starts in 2012, in order to reconstruct historical deployment trajectories since the beginning of the 4G generation, and thus initialise the model with a plausible infrastructure made up of equipment of varying technological maturity and energy efficiency.

In the model, the introduction of **6G is expected to begin in 2030**[12] and the introduction of 5G millimetre-wave **small cells as from 2026**[13].

Area characteristics

Metropolitan France is divided into **8 geographical zones of increasing density**, representing three types of territory: **rural, peri-urban, and urban**[14].

Each geographical zone is characterised by a surface area, and a population growth rate calculated from INSEE population density data for 2024, and extrapolated in a linear manner each year until 2035 by applying the annual national population growth rate (INSEE, 2023).

Each geographical area is considered as a homogeneous zone in terms of traffic, radio propagation, and population density.

The technologies considered

Our model aims to document deployment choices over the next 10 years. **It therefore only takes into account** the three generations of mobile technologies that are likely to be deployed in the coming years: **4G (LTE), 5G (NR) and 6G**. 2G and 3G technologies, which are doomed to extinction in the near future, are not considered in the model.

Deployments of 4G and 5G may take place throughout the period studied (2024-2035). Deployments of 6G can only begin from 2030 onwards.

Demand for data traffic

The input data is the average **volume of data consumed per inhabitant**[15] **per month**. This volume is **15 GB/month in 2022**[16] **according to Arcep data, and has been increasing in a perfectly linear fashion for several years.** The growth will be considered as trends corresponding to different scenarios from 2023[17].

From the average monthly volume, proportionally calculated into a daily volume, **a "peak" volume is calculated, which is used to determine the size of the infrastructure**: it is this volume that will determine capacity deployments. It is calculated using the proportion of daily traffic consumed during the busiest hour of the day, the "busy hour". **It is assumed that 9.4% of the day's total volume is consumed during the busy hour** (Arcep, 2023b), which is equivalent to a 2.25 factor between average traffic and "peak" traffic.

[12] Arcep plans to standardise 6G by 2028-2029 (Arcep 2022, p. 8).
[13] This date is consistent with the deployment timetable for the frequency bands already allocated (Arcep, 2019).
[14] A detailed statistical description and characterisation can be found in "Appendix 2 - Description of geographical areas".
[15] As our model is based on population and zone surface area, we have used an average traffic volume per inhabitant, rather than an average volume per subscription or SIM card. As a follow-up to this work, "machine-2-machine" traffic could be taken into account by adding a specific traffic volume.
[16] Based on the total volume of mobile data consumed (Arcep, 2023g) and distributed over the number of inhabitants modelled.
[17] See "Supply effect, usage effect: what are the links between traffic, impact, and network infrastructure deployment?"

This annual traffic is broken down between geographical areas in proportion to population, then between the three technologies under consideration (4G, 5G, and 6G) according to the proportion of devices supporting each technology (penetration rate) and a bias reflecting the fact that an average 5G user, and *a fortiori* a hypothetical future 6G user, consumes significantly more data than a 4G user.

Coverage constraints

Here we take into account **coverage constraints in terms of area covered, population covered, the number of 3.5GHz 5G sites to be deployed, coverage of main roads, and the percentage of sites that must offer broadband (theoretical peak speed of 240 Mb/s).** These constraints may be the result of a generic[18] operator's strategy to offer a certain quality of service to its subscribers. They may also result from the allocation of frequencies by the regulator and thus constitute legal obligations.

For each year and each territory, objectives for each technology (4G, 5G, 6G) are laid out: coverage of a proportion of the territory and a proportion of the population by the generic operator with the technology.

The 5G coverage targets formulated by Arcep (Arcep, 2023a) are also reflected in the model:

- 8,000 5G sites in the 3.5 GHz band to be deployed in 2024;
- 10,500 5G sites in the 3.5 GHz band to be deployed in 2025;
- 25% of these sites should be in rural areas.

Network features: frequency bands

In our model, we simplify the numerous frequency bands available into 4 frequency bands accessible to our generic operator:

- **The "LOW" band** combines the 700, 800, and 900 MHz bands currently used by French operators;
- **The "LOWER_MID" band** combines the 1800, 2100, 2600 MHz bands;
- **The “UPPER_MID” band** combines the 3.5 GHz band currently available for 5G and the 6 GHz band that could be made available for 6G;
- **The "HIGH" band** represents the millimetre (e.g. 26 GHz) or sub-THz bands that could be made available in the future for 5G or 6G. In our model, only 5G "small cells" are considered for this band.

Bands can be shared between several technologies:

- It is assumed that the **"LOW", "LOWER_MID" and "UPPER_MID"** bands can be shared **between all technologies** (using "refarming" and "dynamic-spectrum-sharing");
- It is assumed that the **“UPPER_MID”** band can be shared between **5G and 6G** technologies (using the same rationale);
- It is assumed that 5G and 6G have their own “HIGH” band that cannot be shared.

[18] Remember that in our model, mobile data traffic is served by 4 identical operators, whose dynamics are modelled using a generic operator.

Each band is associated with a bandwidth:

- **For existing bands,** it is equal to the average of the widths allocated to French operators in 2023, excluding the 900 MHz band that is not yet available for 4G or above;
- **For the 6 GHz band**, in the reference scenario, the generic operator is allocated 100 MHz; in a more maximalist scenario, the operator is allocated 200 MHz[19] ;
- **When a band is shared between several technologies**, each technology is allocated a share of the spectrum band in proportion to its share of total traffic in the geographical area in question.

Network characteristics: site, base station, cell, and sector

A site is the geographical location where a base station is deployed.

A site is made up of several sectors (three in Figure 7 as an example), each sector having the shape of a regular hexagon. To calculate the average number of sectors per site, we assume that **80% of sites are tri-sector and 20% of sites are bi-sector** (i.e. an average of 2.8 sectors per site in the model).

A cell is defined as a technology/band pair on a site sector. Within the site sector, several cells may therefore overlap geographically.

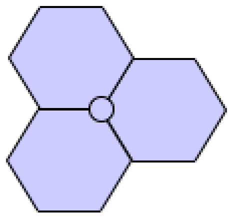

Figure 5 – Graphical representation of a tri-sector site Source
Source: The Shift Project, for the purpose of this report

The model takes into account the possibility of several operators sharing the same site (known as site sharing or passive sharing) but does not consider the sharing of their frequency bands (and therefore their cells; this is known as active sharing). **The average number of operators per site is defined for each of the eight geographical zones, and may change over time.** The value in 2023 is indexed on the basis of an ANFR (France's National Agency of Frequencies) database analysis at the end of 2023[20]..

The cells' range radius is determined for each geographical area using the zone's surface area and the number of sites with at least one 4G or 5G system from French operator Orange (considered to be representative). We have selected a recent reference year for rural areas, and an older one for urban areas, so as to limit the bias of white areas on the one hand, and capacity over-densification on the other. This radius should be understood as an average radius in the absence of densification with a 3 dB interference margin.

We also define a cellular capacity, in Mbits/s/MHz *(spectral efficiency*), for each technology and each band, based on an analysis presented as part of Arcep's "*Grand dossier 5G*" ("Comprehensive 5G Study") (Arcep, 2022b; Coupechoux, M., 2020). The values given rely on

[19] These figures are based on discussions at WRC23. The reference scenario refers to the case where the 6 GHz band is shared with Wi-Fi. The high scenario corresponds to the case where IMT technologies are allocated the entire bandwidth.
[20] Accessible open data: https://www.data.gouv.fr/en/datasets/donnees-sur-les-installations-radioelectriques-de-plus-de-5-watts-1

assumptions about MIMO configurations (i.e. the number of transmitting and receiving antennas) per band, and changes in their proportions within the technological mix.

General algorithm

The model's general principle is illustrated in Figure 5.

The core of the model involves calculating, for each year and each geographical area, the number and type (technology/band) of generic operator cells needed to satisfy the input constraints. This calculation is carried out sequentially, starting in 2012 with an empty list. For each year and each area, the list of cells from the previous year is updated by adding new cells, if necessary, to account for new coverage and regulation constraints (see coverage model) and changes in traffic (see capacity model).

This algorithm enforces a minimum number of cells that cannot decrease over time, reflecting the assumption made in this study that no dismantling of 4G, 5G, or 6G equipment will occur during the period considered.

From this list of cells, we can deduce the total number of base stations and sites, as well as the electrical energy and new equipment requirements (see environmental model).

The coverage model

The coverage model consists of implementing a cell deployment strategy to meet coverage constraints in terms of the national territory's area, population covered, and regulatory constraints. The model is based on the following strategy for the generic operator:

- Coverage is provided only by the "LOW" band, and the parts of the territory not covered are in the least densely populated geographical areas;
- The model takes as input the coverage constraints (population and surface area), the cell radii in the "LOW" band and the geographical area characteristics (population and surface area);
- For the UPPER_MID band, the algorithm considers regulatory constraints in terms of the number of 5G sites to be deployed;
- The algorithm considers regulatory constraints in terms of the percentage of sites that must offer a theoretical peak data rate of at least 240 Mb/s. This requirement is translated into the percentage of sites that must offer the "LOWER_MID" band or higher;
- The algorithm takes as input the mileage of motorways and main roads that must be covered with a theoretical peak data rate of at least 100 Mb/s, and a latency of less than 10 ms for motorways. These requirements are met by deploying additional dual-sector sites in 5G "UPPER_MID" or higher for motorways, and 4G "LOWER_MID" or higher for other routes.
- The model provides as output the required number of cells in the "LOW", "LOWER_MID" and "UPPER_MID" bands for each of the technologies and each of the zones, ensuring compliance with the population and surface area coverage constraints, as well as regulatory constraints.

A specific treatment is applied to the "HIGH" band. We assume that these frequencies will only be deployed in small cells located in very dense urban areas (for example in stations, airports, tourist sites, or shopping centres). The purpose of these small cells is not to ensure service coverage, nor to relieve the network of macro-cells. Rather, they are intended to provide a very high-speed connection for the user, in a very localised way in an outdoor space (“outdoor”) or inside a building (“indoor”). The number of these small cells is calculated using an average ratio relative to the number of macro-cells in the dense urban area of the model.

Depending on the scenario, a ratio varying from 0 (no deployment) to 1 (not all macro-cells will be enhanced with micro-cells) is assumed for 2035, with linear growth from the introduction of millimetre waves.

The capacity model

The capacity model involves adding cells in order to satisfy demand for mobile data traffic. The deployment strategy consists of placing as many new cells as possible on existing sites and densifying only if necessary. It is illustrated in the figure below and can be broken down as follows (Figure 8).

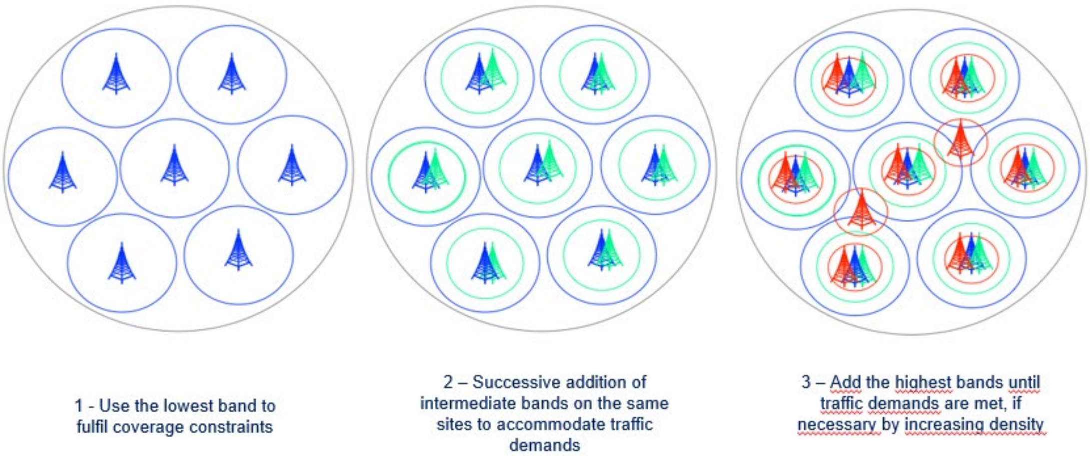

Figure 6 - Capacity deployment strategy
Source: The Shift Project, for the purpose of this report

The model measures, for each year, each geographical area, and each type of device (4G, 5G or 6G), the gap between the capacity already available and actual demand (traffic at peak times). If the existing capacity is too low to meet demand, the algorithm deploys additional cells in the geographical area, starting with the lowest technologies and bands. In the event of densification, the new sites are deployed in batches (so as to boost capacity evenly over the geographical area in question) and directly in "capacity" configuration, i.e. with all the bands available.

Once the number of cells in each zone has been calculated for each technology and each band, the model determines the number of sites and their configuration (i.e. all cells present on a site) for each geographical zone by hosting the maximum number of cells to be deployed on shared sites.

The environmental model

Each site hosts equipment that enables it to operate its various cells and transmit or receive data from the core network. The number of devices is counted according to the configuration of its cells as follows (the values are cumulative according to the configuration of the site):

- Antennas:
    - Sites with cells in the "LOW" and "LOWER_MID" bands have 1 passive antenna per sector (2T2R for the "LOW" band, 2T2R or 4T4R for the "LOWER_MID" band). These passive antennas are capable of transmitting and receiving in all the bands considered, whatever the technology;
    - Sites with cells in the UPPER_MID bands have 1 AAU MIMO 64T64R active antenna per sector. These active antennas incorporate the power amplifiers and therefore do not need an associated RRU. They are shared by 5G and 6G;
    - Sites with cells in the "HIGH" band have 1 AAU MIMO 64T64R active antenna;
- RRU (Remote radio unit):
    - Sites with cells in the "LOW" band have 1 dual-band 2T2R RRU per sector;
    - Sites with cells in the "LOWER_MID" band have 1 tri-band 4T4R RRU per sector;
- BBU (Baseband unit):
    - Sites with cells in the "LOW" and "LOWER_MID" bands have 1 BBU;
    - Sites with cells in the UPPER_MID band have 1 BBU;
    - Sites with cells in the "HIGH" band have 1 BBU;
- **Transmission system to the core network (backhaul)**: Each site is equipped with a router. Additionally, it is connected to the transport network either through optical access or via a microwave link. In the first case, the site has 1 Optical Network Unit (ONU). In the second case, the site is equipped with 1 microwave transmission management card and 1 microwave antenna. For the sake of simplicity and due to a lack of data, in our simulations, 100% of the sites are connected using the first option.
- **Power supply**: each site has 1 power supply unit and 1 AC/DC converter;
- **Each site has 1 GPS antenna** for synchronisation, but this is not modelled in our work here.
- **Each site has 1 supporting infrastructure**, potentially shared among several operators, the nature and size of which depend on the area (supporting infrastructure on buildings, towers, etc.).

Based on these rules, the lifespan of each piece of equipment[21], and the number of cells and sites output by the capacity model, the environmental model maintains an up-to-date inventory of equipment by year and by zone, with their respective ages. This inventory is then used to calculate:

The embedded carbon footprint of equipment due to its production phase, based on their respective life cycle analyses;

- The electricity consumption of the infrastructure during the operational phase, based on the modelling of equipment consumption profiles;

[21] Details of each equipment's lifespan can be found in the environmental model built for the purpose of this report (The Shift Project, 2024b, Environmental Model).

- The total carbon footprint of the operation phase, calculated by applying emission factors for electricity production in France, projected between 2024 and 2035 in a scenario in which the national electricity mix is transformed towards decarbonisation[22].

The equipment's electricity consumption is modelled as a fixed component, depending solely on the equipment's characteristics, and a variable component, also proportional to the traffic passing through the cell. This calculation takes into account the equipment's age. Indeed, the **energy efficiency of equipment** from a given technology improves with equipment renewals, towards the end of their lifespan.

Carbon footprint calculations (embedded, total, and emissions factors for electricity generation) are performed using a footprint approach. They are calculated using two complementary approaches:

- **The "stock" approach,** in which the equipment's embedded emissions are amortised over its lifetime;
- **The "flow" approach**, in which the impacts of new equipment (replacement of old equipment and new deployments) are fully attributed to the year of deployment.

Possible limitations and applications of the model

The modelling tool developed as part of this work enables us to understand the consequences of deployment choices and their drivers (population coverage, surface area, regulatory constraints, capacity requirements) on the carbon-energy footprint of the mobile network infrastructure, **using a consequential modelling approach.**

The scope and relevance of this model must be well understood to effectively inform strategic considerations and decisions

- The scope of the model is limited to the mobile access network. Using it to build a panoramic vision of the digital world means integrating it into a broader systemic vision incorporating the other network building blocks (core network, fixed network, satellite network) and the other two components of the digital system (devices, servers/data centres);
- A number of items have been ignored due to a lack of sufficiently reliable assumptions, in particular emissions linked to installation and maintenance;
- The geographical scope chosen for its construction and the results presented in this report is French, but its design has been conceived in such a way that it can be used and adapted to another geographical context;
- The timeframe considered extends to 2035. This time horizon allows for the projection of various deployment scenarios for new technologies, while remaining close enough to already have a relevant vision of the generations likely to be deployed by then (incorporating, of course, a high degree of uncertainty about the specifications that 6G will actually support);
- Only generations likely to be deployed between now and 2035 are considered. The 2G and 3G generations, which are due to be decommissioned in the coming years, are therefore not included in the model;

[22] The emission factors used are taken from models produced by Arcep for 4G and 5G mobile networks. (Arcep, 2022a).

- The model does not allow for a reduction in the number of cells, reflecting the assumption that there will be no dismantling of 4G, 5G, or 6G equipment between 2024 and 2035. Thus, any equipment deployed in the model will continue to be powered and replaced when it reaches its maximum lifespan, even if the traffic it handles were to become zero (in which case its variable consumption would also become zero, but its embedded impact and fixed consumption would continue to be counted in the total footprint). The modelling is set up to start with a level that aligns with the current deployment status across the various technologies at the time of modelling, which corresponds to the year 2024.
- Replacing equipment at the end of its life is only accounted for through its impact on the environmental model. The number of installations calculated by the coverage and capacity models only take into account new installations;
- Passive sharing (sharing of sites between operators) is taken into account in the model, unlike active sharing (sharing of frequencies between operators), whose analysis of the effect on the impact of the infrastructure cannot be carried out using the model in its current version;
- Certain effects and dynamics (such as those of passive sharing) may not appear in the model, mainly because it is based on the generalisation of choices made by a single operator. This operator optimises its roll out strategy and network dimensioning in relation to forecasts of constraint changes (coverage, capacity) whose visibility is greater than reality and whose degree of complexity is lower;
- The traffic change scenarios (in GB/month/person) are constructed on average for the French population, in order to reconstruct a trend-based variable that is adapted to our model. The underlying assumption is that growth in the number of SIM cards is indexed to population growth.

This model can be used to produce “stock” and “flow” analyses, each providing different insights and strategic choices:

- **The "stock" perspective enables us to understand the trajectory on which deployment choices will take us**. As the impacts of production are annualised, this approach can be used to make the link with a trend-based approach[23], which reflects the carbon amortisation to be assumed once the deployments have been made. This vision allows us to understand the dependencies of the infrastructure’s carbon-energy trajectory on the directions taken at key moments in the deployment choices;
- **The "flow" perspective makes it possible to characterise deployment dynamics in their physical reality:** emissions recorded for a given year are those actually emitted during the deployments that took place over this time frame. This approach enables a more direct visualisation of the challenges associated with the transformation of the network along the chosen trajectory. A significant embedded carbon impact during a period of intense deployment of new equipment, for example, indicates a key phase, which will fuel both the carbon amortisation to be addressed in the coming years, but also a period of intense equipment importation and associated emissions. Furthermore, this flow-based approach is the one adopted by operators who have begun to estimate their annual carbon footprint.

[23] Although its rationale remains consistent in translating the links between traffic growth and deployment.

From deployment choices to the impacts of the next decade

The "Specifications" scenario: regulatory constraints and usage trends

The "Specifications" scenario relates to the deployment dynamics resulting from the combination of current regulatory constraints (4G, 5G) and the trend in volumes of data consumed. It includes:

- Low-band coverage targets
- Regulatory constraints[24] :
    - Deployment of 5G coverage in the "UPPER_MID" band;
    - Coverage of main roads and motorways, with a certain level of performance;
    - Performance across the country, with a theoretical maximum download capacity target of 240 Mbit/s for 100% of sites in the country in 2030;
- Deployment of 6G technology from 2030;
- A sharing rate that remains equivalent to that of 2024;
- An increase in usage that is in line with the ADL forecast (Arthur D Little, 2023), i.e. 98 GB/month/person in 2030[25], and extended linearly from 2030 to 2035 ("Usage: reference" scenario, see "Supply effect, usage effect: what are the links between traffic, impact, and network infrastructure deployment?", p. 34).

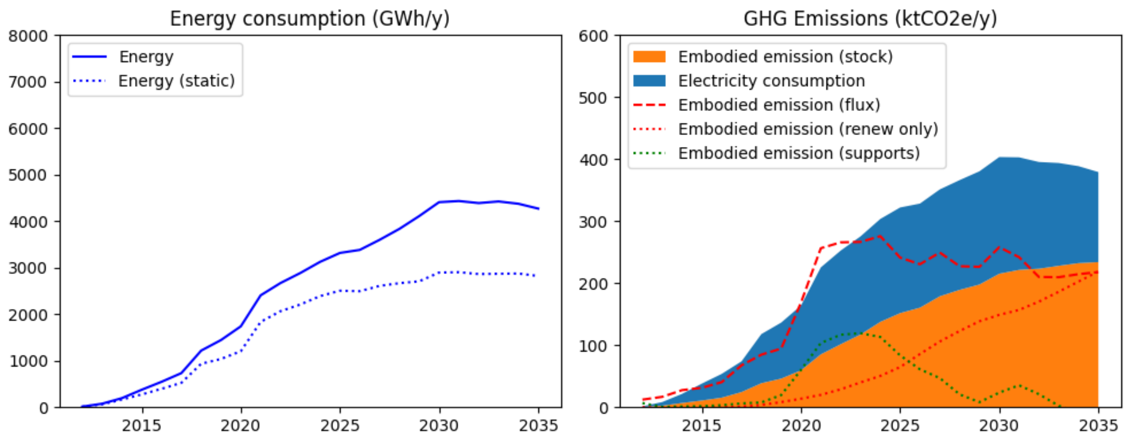

Figure 7 – Annual electricity consumption in the operation phase (left) and annualised carbon emissions associated with the production and operation phases under the "stock" and "flow" approaches (right), in the "Specifications" scenario
Source: The Shift Project, for the purpose of this report

[24] Details in the "Description of the model" section.
[25] This projection was reconstructed from ADL data, averaged over the entire population, in order to reconstruct a trend variable suitable for our model. The underlying assumption is that changes in the number of SIM cards are indexed to changes in the population.

Between 2020 and 2025, the carbon impact of a massive deployment of network equipment (4G and 5G) and specifically of new sites (depicted by the "supports" curve in the graph) appears in the "flow" view (Figure 9), which accounts for the carbon actually emitted year by year (unlike the "stock" method, which spreads production emissions over the lifetime of the equipment). Continuous emissions (depicted by the “flow” curve in the graph) up to 2030 reflect post-2025 regulatory constraints (roads, motorways, 240 Mb/s), while the peak in 2030 reflects the introduction of 6G. **This increase in infrastructure capacity is the result of regulatory constraints. Capacity requirements will then amplify the momentum created.**

A cyclical dynamic is highlighted here: deployments are justified by constraints and choices aimed at **adapting infrastructures to the expected evolution of digital uses** (increasingly essential coverage requirements due to the need for access to digitised services, the need for new technologies in view of the planned roll out of new services and content for businesses and the general public, etc.). The objective is to constantly have a network capable of supporting the usage it is intended for. Once the deployment phase has been completed, **the network's new capacities will enable new uses to be deployed: the very uses that were foreseen in the forecasts** that motivated the deployment in the first place. These new, more data-intensive uses then call for capacity deployments that complement the base stations already deployed.

In a scenario where data consumption is continually increasing, capacity deployments will always occur at the end of a given period, again adding to the total embedded carbon footprint of networks, which is impossible to reduce as such. In the absence of any dismantling of 4G, 5G, or 6G base stations between now and 2035, the replacement of this equipment, as it reaches the end of its lifespan, has the effect of maintaining the weight of annualised production impacts ("stock" view) in the network's embedded footprint, which can only continue to increase[26].

These dynamics place the network infrastructure on a trajectory that is totally incompatible with the construction of a digital system adapted to the energy-carbon constraint. While our digital system will need to reduce its impact in order to achieve a target of -30% by 2030, **the impact indicators for mobile networks, one of its structural components, are showing an uncontrolled rise between 2020 and 2030:**

- **A 2.5-fold increase in their annual carbon footprint;**
- **A 150% increase in their annual electricity consumption, i.e. an additional 2.5 TWh in 2030.**

The levelling off of impacts that seems to appear between 2030 and 2035[27] (Figure 9) is therefore in no way compatible with the objectives of reducing the digital system's carbon impact. Although it may result from a period during which energy efficiency gains are made without being offset by inflation in volumes and deployment, it can only be a temporary phenomenon if inflation in traffic volumes is maintained at too high a rate. This will fuel capacity deployments and is linked to new uses that will require new network capacities (latency, reliability, etc.), which will have the effect of guiding the design of new generations of mobile technologies in line with this acceleration.

The arrival of new technology such as 6G is linked to an acceleration in the growth of data volumes consumed, and will fuel capacity deployments from 2030 onwards (Figure 9, "flow" vision). This is because, in our model, **6G represents a generation built like its predecessors,**

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[26] The carbon footprint of site dismantlement was not examined in our work, and so we are unable to draw any conclusions as to the usefulness of reducing on-board emissions even in the event of dismantlement. For example, if the payback period for dismantling were longer than 5 years,

[27] Despite the introduction of a 6G without regulatory constraints, as opposed to the deployment of 5G initially initiated by these regulatory constraints.

i.e. with the specification of increasing mobile network capacity and performance (in terms of throughput, latency, and reliability)**. Designing 6G technology to support decarbonisation, by making the reduction of the absolute environmental impact of networks and of the digital system as a whole a cornerstone of its specifications, could potentially change this dynamic, which is observed and recurs with each new mobile generation.**

Supply effect, usage effect: what are the links between traffic, impact, and network infrastructure deployment?

Dimensioning choices endorse usage trajectories...

The deployment choices endorsed in 2020 by regulatory constraints generate an infrastructure deployment (and its associated carbon cost) **sized to support a data consumption trajectory of 150 GB/month/person in 2035.**

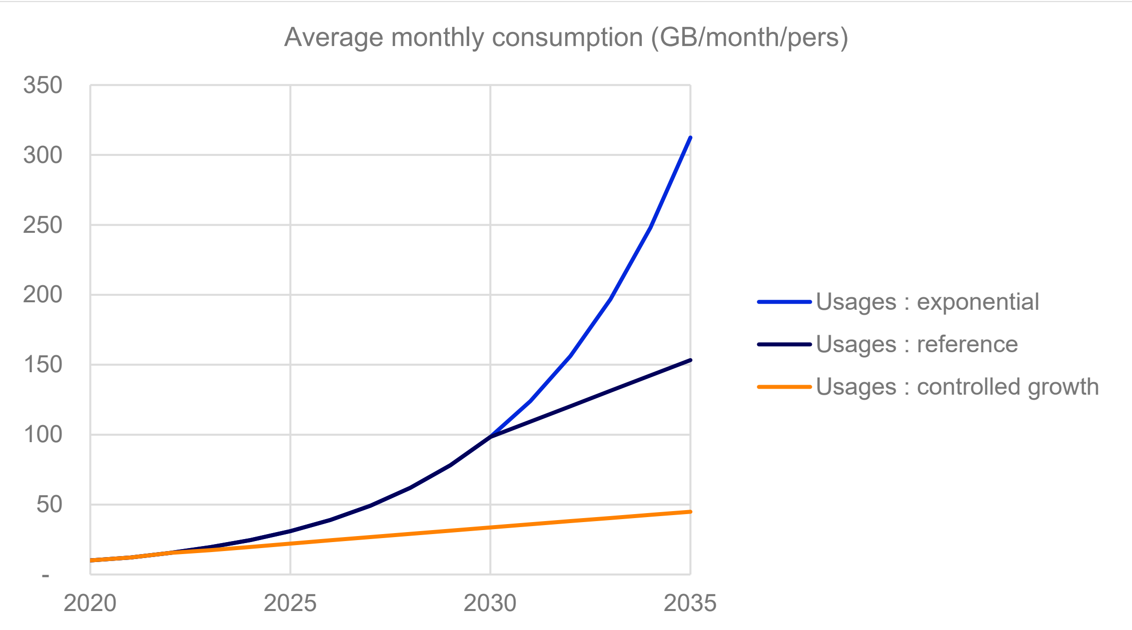


Figure 8 - Usage scenarios: changes in data consumption in mainland France by scenario
Source: The Shift Project, for the purpose of this report

This is the conclusion that emerges from a comparison of different scenarios for changes in usage:

- **The "Usages: controlled growth" scenario**, which extends the linear trend historically observed in Arcep data from 2017 to 2023 (Arcep, 2023g), leads to a data consumption of **45 GB/month/person in 2030**, remaining linear thereafter;

  → *This scenario, which leads to data consumption of 45 GB/month/person in 2035, represents a trajectory of constancy in the dynamics of changes in usage intensity*[28] *;*

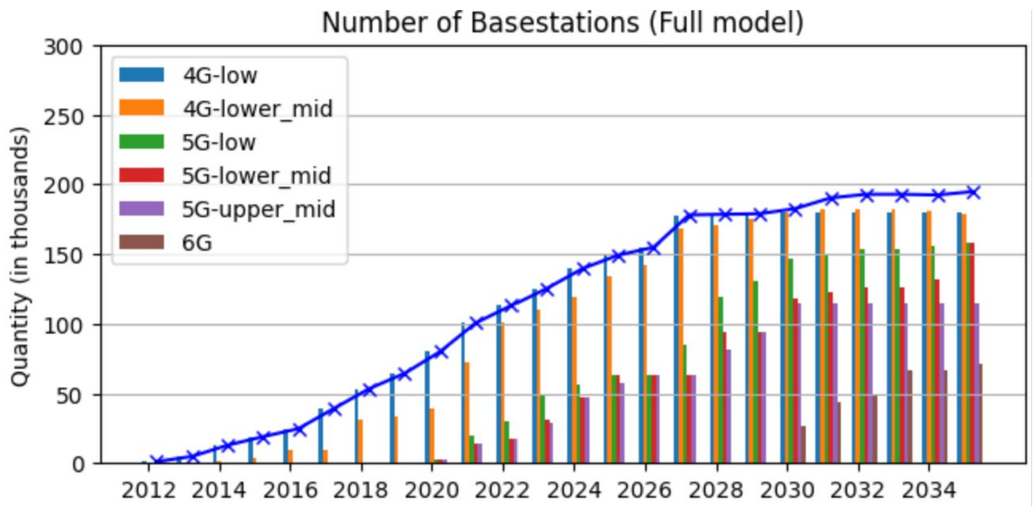
[28] It therefore implies that there are no breakthrough dynamics in the deployment and adoption of services compared with the 2017-2023 period.

- **The "Usages: reference" scenario** (the one used in the "Specifications" scenario), which forecasts data consumption that corresponds to ADL's forecast increase of **98 GB/month/person in 2030**[29] (Arthur D Little, 2023), extended with a linear trend to 2035;

  → This scenario, which leads to data consumption of around 150 GB/month/person in 2035, represents a trajectory that takes into account a change in slope when the adoption of new 5G technology becomes widespread (around the year 2025). However, there is no change in slope in 2030, considering that 6G technology and its associated new uses begin their deployment at a limited level of adoption before 2035;

- **The "Usages: exponential" scenario,** which predicts data consumption reaching 98 GB/month/person in 2030 (Arthur D Little, 2023), extended to 2035 with an exponential trend (at the same rate of +26%/year);

  → This scenario, which leads to data consumption of around 300 GB/month/person in 2035, represents a trajectory that factors in an exponential change in volumes, due to a break in momentum (upwards) at the time of widespread adoption of the new 5G technology (around the year 2025), which is sustained in 2030 with the arrival of 6G. This continuing acceleration in consumption volumes is the result of joint development of very intense professional and consumer uses, such as immersive uses, as well as IoT, IIoT and M2M communication flows, with widespread use of AI. The average value given here "per person" therefore implicitly includes a significant proportion of traffic that is different in nature from the traffic generated by the users themselves.



[29] This projection was reconstructed from the ADL data, averaged over the entire population, in order to reconstruct a trending variable suitable for our model. The underlying assumption is that changes in the number of SIM cards are indexed to changes in the population.

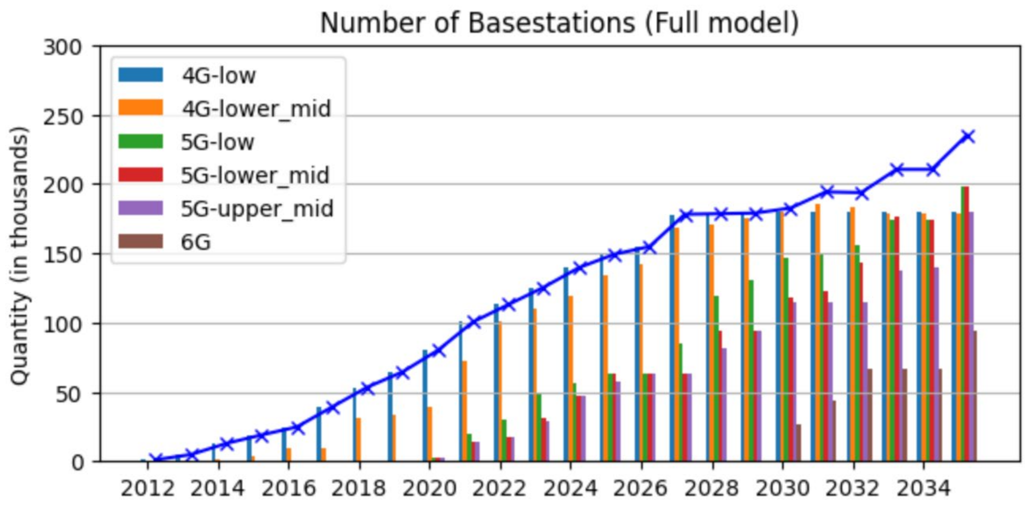


Figure 9 - Total number of base stations nationwide (blue curve) and by "technology - frequency band" pair (bar charts), in the "Specifications" scenario (top), and for the alternative "Usages: exponential" scenario (bottom). Source: The Shift Project, for the purpose of this report

A comparison of the base station deployment dynamics for the "Specifications" scenario (Figure 11, top) and for an alternative "Usages: controlled growth" usage scenario (Figure 24[30]) highlights the ratchet effect that deployment choices have on network dimensioning: **the difference between the two traffic trajectories, while significant, is not reflected in the number of base stations deployed in 2035.**

The number of base stations in the "Usages: controlled growth" scenario is equivalent in 2035 to that in the "Specifications" scenario, even though traffic is 3 times lower. As a result, the only way to make the cost of deployment profitable is to increase traffic by introducing new monetisable uses.

It is clear, therefore, that **the (implicit or explicit) initial dimensioning choices have a very strong influence on the actual dynamics of growth in usage.**

This remains true until actual demand exceeds a high plateau: for a development of the "Usages: exponential" type, the massive and widespread deployment of very intense uses (immersive worlds, IoT, IIoT, AI, etc.) generates traffic that exceeds that which the infrastructure resulting from the initial choices is capable of absorbing. **The capacity deployments required after 2030 lead to a number of base stations that is 20% higher** than in the "Specifications" scenario in just 3 years (Figure 11).

The resumption of base station deployments in the "Usages: exponential" scenario from 2032 onwards indicates the transition to a new traffic threshold. **The momentum generated by the initial choices (regulatory constraints up to 2030) has confirmed the design of a network** tailored for a world where data consumption reaches 150 [31] GB/month/person[32].

[30] Available in "Appendix 6 - Mobile network modelling: additional figures".
[31] This refers to the level of data consumption projected for the period 2032-2033 in the "Usages: Exponential" scenario.
[32] This is confirmed by the analysis of the "capacity/traffic" ratio by technology and geographical area (available in the appendix, "Appendix 6 - Mobile networks modelling: additional figures and data"), which in the "Uses: reference" scenario shows a significant "supply-demand" match between deployments and traffic levels.

.... but usage trajectories drive deployment choices.

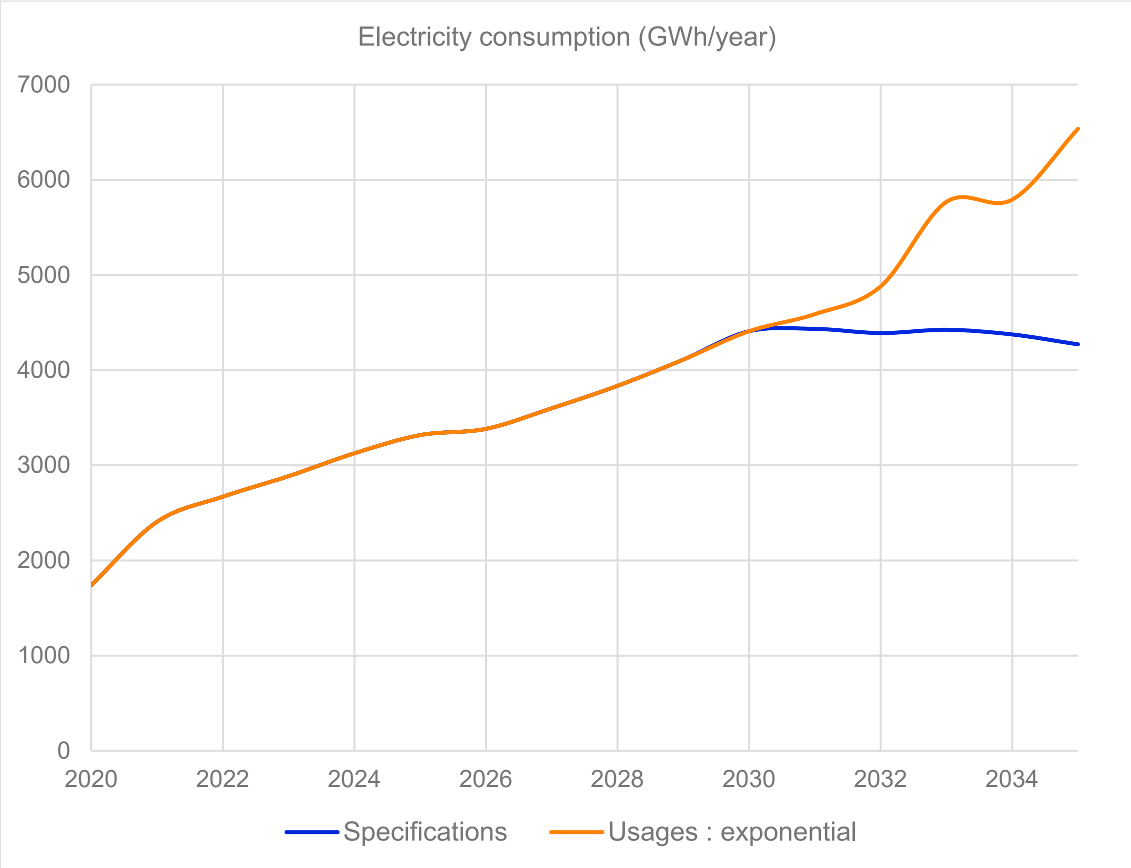


Figure 10 - Annual electricity consumption of mobile infrastructures (4G, 5G, 6G) under the "Specifications" scenario and the "Usage: exponential" scenario
Source: The Shift Project, for the purpose of this report

New uses trigger new needs and new impacts. In the "Uses: exponential" scenario, the widespread adoption of new uses leads to **a 20% increase in the mobile network's total carbon footprint, and an increase in its electricity consumption of more than 2 TWh by 2035,** versus the reference scenario (and 4 TWh versus 2020).

Operators build their deployment strategies to meet the projections (in terms of traffic and performance levels) that are taken as a benchmark by the sector's stakeholders. **However, a technological usage projection is not a description of reality:** extending a digital usage adoption trend is not a factual characterisation, but a hypothesis and a **choice for the future of technology.** Behind the projections upon which we currently choose to base deployment decisions and strategies, which we perceive as addressing a "demand" that players can only attempt to anticipate, lie **choices of directions and technological paradigms.**

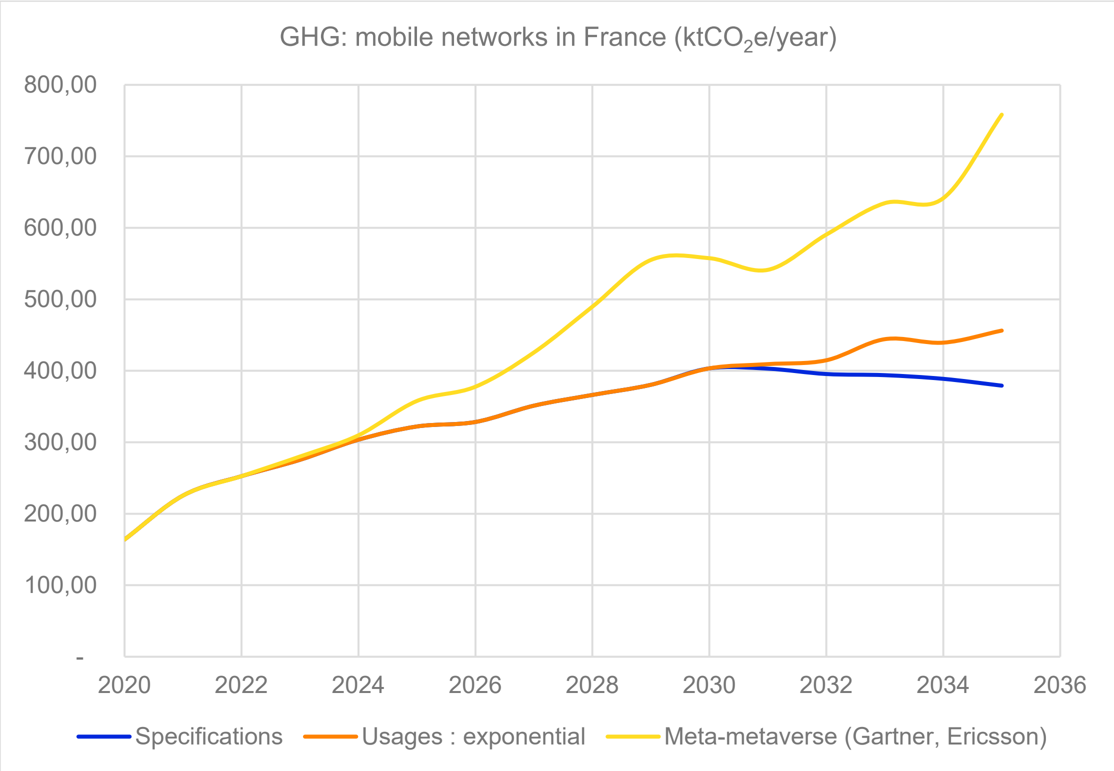


Figure 11 - Total annual carbon footprint of mobile networks in mainland France, between 2020 and 2035, for the "Specifications", "Usage: exponential" and "Meta-metaverse" scenarios Source: The Shift Project, for the purpose of this report

This is detailed in our "Energy and climate: What virtual worlds for a sustainable real world?" report (The Shift Project, 2024c), based on the case of virtual worlds and their applications. The "Meta-metaverse"[33] scenario represents a future in which the usage construction dynamics described in our report on virtual worlds come to fruition[34] : the projection of new uses and services by players in the sector is based on **very broad-spectrum promises** (from *metaconferencing* to *industrial metaverse* digital twins) **which should no doubt be interpreted more as a signal sent to the digital ecosystem to structure the technological directions and regulations taken, in a direction enabling the advent of widespread metaverse over time. The signal was taken seriously in France and Europe** (Basdevant A., François C., Ronfard R., 2022; *Direction Générale des Entreprises*, 2022; European Commission, 2023) **with a surge of announcements, investments, business start-ups and structuring around immersive technologies and on a European Union scale with the expectation that 6G will enable the advent of this type of virtual world** (European Commission, 2023; European Parliament, Committee on the Internal Market and Consumer Protection, 2023; *L'usine digitale,* 2023a). **With the usage of virtual worlds**, we see a forthcoming "stairstep" in the dynamics that The Shift Project described in terms of video use in 2019 (The Shift Project, 2019), and which would **place the digital system on a trajectory of exploding impact** (Figure 13).

This upcoming "stairstep" is not, however, the inevitable outcome of an unstoppable dynamic. **It is our responsibility to build the trajectory that we want our networks to follow**. For The Shift Project, this course should be guided by the dual carbon constraint compass in order to ensure the resilience of our digital uses over the next three decades.

[33] Detailed description in (Figure 26): "Appendix 6 - Mobile networks modelling: additional figures and data".
[34] With traffic of around 190 GB/month/person in 2030 and almost 500 GB/month/person on average in 2035.

The inevitable triptych of a decarbonised digital world: eco-design, sobriety, and a systemic vision

The "Systemic eco-design" and "Eco-design and sobriety" scenarios

The "Systemic eco-design" and "Eco-design & sobriety" scenarios characterise the effects of **harnessing the technological and reorganisation levers** available to us to **curb the inflation in the network infrastructure's energy-carbon impact:**

- The "Systemic eco-design" scenario includes:
    - Low-band coverage targets;
    - The "Specifications" scenario's regulatory constraints, but only until 2024 (see "The "Specifications" scenario: regulatory constraints and usage trends"); Suspending the roll out of 6G technology as envisaged today;
    - Extending the lifespan of network equipment;
    - Improving the energy efficiency of network equipment (a 10% reduction in the fixed component from 2026, which could reflect the introduction of a "standby" mode);
    - A level of passive sharing that remains broadly equivalent to that of 2024[35] ;
    - A change in usage that involves harnessing the most efficient codecs for video content and an eco-design benchmark for digital services, which would reduce traffic by 20% compared with the "Usages: reference" scenario.
- The "Eco-design & sobriety" scenario includes:
    - The same specifications as the "Systemic eco-design" scenario for the network's technical characteristics;
    - An evolution in usage that corresponds to a trajectory of constancy in the evolution of usage intensity: average data consumption per person continues to increase between 2024 and 2035, but according to a linear dynamic, enabling it to reach a level of 45 GB/month/person in 2035 (compared with 20 GB/month/person in 2024). This trajectory leaves room for the deployment of new uses, while keeping infrastructure[36] impacts under control.

[35] With the exception of a dismantling strategy, the carbon impact of which is not assessed in our work, no gains from passive sharing appear in the model. Some of these effects remain potentially invisible in our model, notably because it is based on the generalisation of the choices of a single operator (thus greatly simplifying the dynamics of market distribution), which optimises its deployment strategy and network dimensioning in relation to forecasts of changes in constraints (coverage, capacity) whose visibility is greater than it is in reality.

[36] Modelling of a complementary "Stable traffic" scenario, with data consumption levelling off at 2024 until 2035, shows very limited effects on traffic reduction below this threshold (see Figure 27, in "Appendix 6 - Mobile networks modelling: additional figures and data").

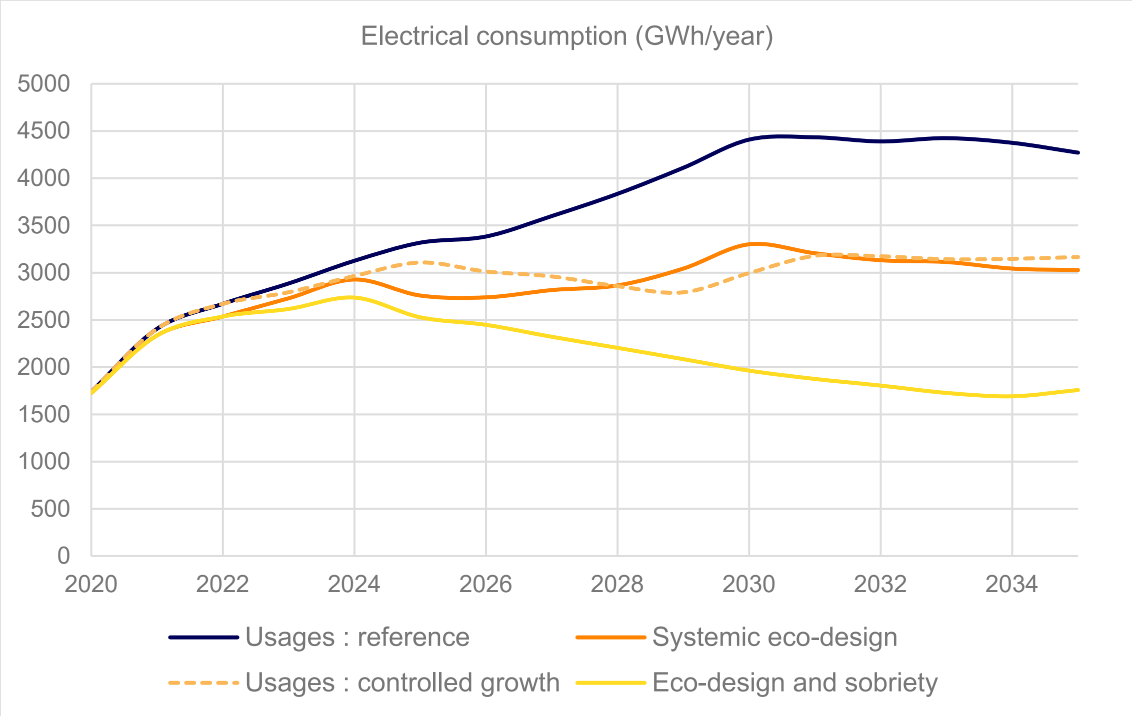


Figure 12 - Comparison of the mobile network's annual electricity consumption for the "Specifications", "Usages: controlled growth"[37], "Systemic eco-design" and "Eco-design and sobriety" scenarios Source: The Shift Project, for the purpose of this report.

Activating eco-design levers makes it possible to leverage all the available margins for reducing unit impacts. As can be seen from the dynamics observed in the "Specifications" scenarios, the continuing increase in data volumes will inevitably lead to additional deployments and associated jumps in impact, as well as pushing the variable part of network electricity consumption to its limit. **Eco-design levers, which are based on optimising network services, equipment, and operating strategies, cannot on their own mitigate the effects of usage growth on mobile networks' carbon-energy impact.**

[37] This scenario corresponds to the "Specifications" scenario, but incorporates the traffic trajectory of the "Usages: controlled growth" scenario.

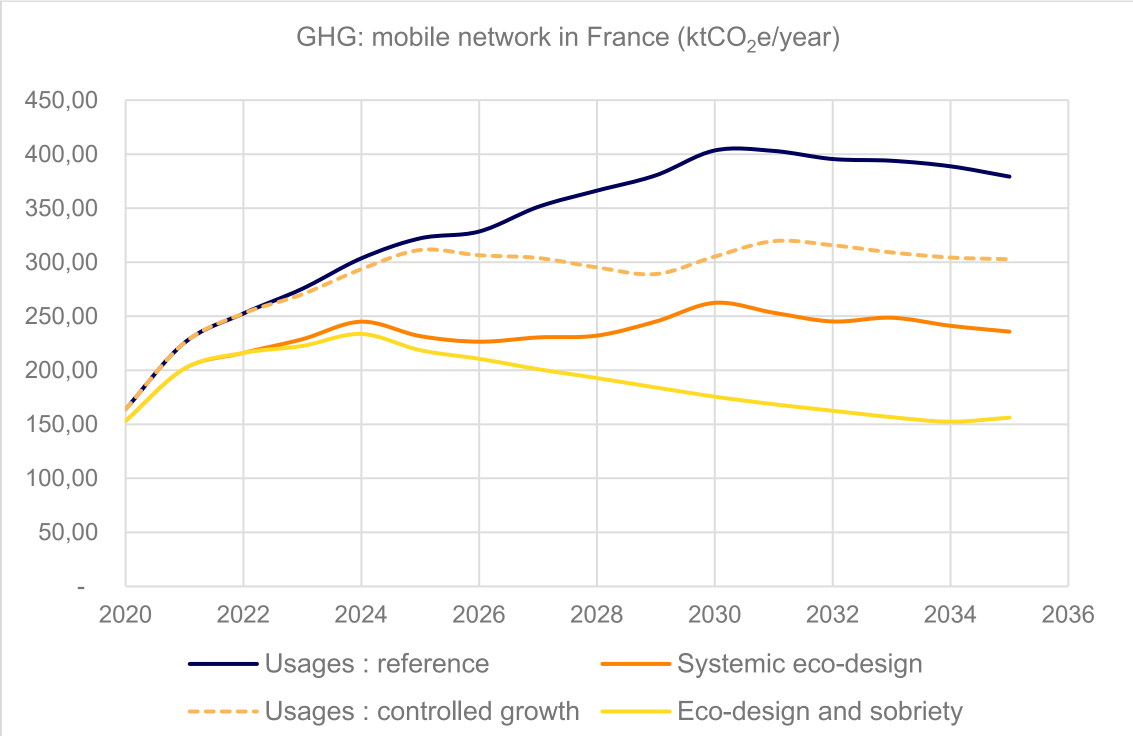


Figure 13 - Total annual carbon footprint of mobile networks in mainland France, between 2020 and 2035, for the "Specifications", "Usages: controlled growth"[38], "Systemic eco-design", and "Eco-design and sobriety" scenarios
Source: The Shift Project, for the purpose of this report

It is only by jointly activating the "eco-design" and "sobriety" levers that their mutually reinforcing effects can **put networks on a viable trajectory.**

Without a strategy to contain data traffic, efforts to extend the lifespan of network equipment in order to reduce its embedded footprint will be offset by the impact of unavoidable capacity deployment.

Similarly, continued growth in usage will systematically prevent the efforts made in terms of energy efficiency from paying off. **Curbing the inflation of data-intensive uses makes it possible both to drastically and directly reduce the variable part of network equipment electricity consumption** (around 30% of total consumption in our models) **and also optimises the efforts made in terms of energy efficiency** on the fixed portion of this consumption (Figure 28, in "Appendix 6 – Mobile networks modelling: additional figures and data").

Leveraging eco-design and sobriety in the construction of our future networks will help to contain the inflation in the mobile networks' impact, but will not put them on a trajectory that enables reduction. Since the challenge is to enable the digital system as a whole to achieve a 30% reduction in emissions by 2030 compared with 2020, **this strategy for mobile networks must be integrated into a systemic vision, at three levels: that of network infrastructures as a whole** (satellites, fixed, core, mobile), **of the digital system as a whole** (devices, networks, servers, and data centres) **and within the usage systems on which it is entirely interdependent.**

[38] This scenario corresponds to the "Specifications" scenario, but incorporates the traffic trajectory of the "Usages: controlled growth" scenario.

The “backcasting” approach, a tool for building a lean digital future

The “forecasting” approach: projecting trends

The “forecasting” approach here involves projecting, over a defined time horizon, the dynamics of key variables in the digital system (data flows, electrical consumption, energy consumption, etc.), based on trends that characterise the studied scenarios (business as usual, varying pace of energy efficiency improvement, varying pace of data flow increase, etc.).

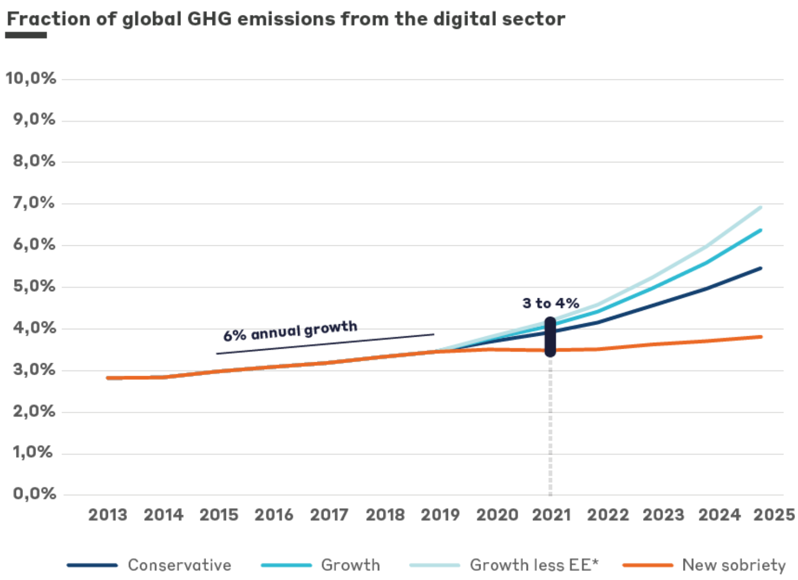


Figure 14 - Projection to 2025 of the digital sector's share of global GHG emissions, forecasting approach
Source : (The Shift Project, 2021)

This is the approach adopted for The Shift Project's 2018 and 2021 projections for network infrastructures, devices, and data centres (The Shift Project, 2018, 2021). It allows us to **describe the current situation, which is used as a reference and starting point, and to highlight two elements:**

- **Possible landing points:** in our 2021 projections, the four constructed scenarios (Conservative, Growth, Growth less EE, New sobriety) describe dynamics leading to a digital share of global emissions in 2025 ranging from 4% to 7% (Figure 5);
- **The dynamics that have the greatest influence on the actual trajectory** taken by the digital system (Table 3).

Scenarios	Energy efficiency	Data traffic	Equipment production
Conservative	Historical pace	Moderate pace	Moderate pace
Growth	Historical pace	Rapid pace	Rapid pace

Figure 15 - Description of The Shift Project scenarios, 2021 projections, forecasting approach
Source : (The Shift Project, 2021)

This approach aims to **describe the landing point to which the current trend leads, its main determining components, and the trajectories on which their possible variations place us.** The question addressed by the forecasting approach can be summarised as follows:

"Do the digital sector's current dynamics indicate that it is on a sustainable trajectory?

What determining factors could influence these trajectories, either upwards or downwards?"

The "backcasting" approach: dimensioning in view of constraints

The "backcasting" approach consists of mapping out the forms that the digital system could take in the decades to come, once the physical constraints of reducing emissions and energy consumption have been **taken into account.**

With the construction and analysis of the "Eco-design & sobriety" scenario, the work carried out as part of this report leads to an initial essential conclusion: **the objective for mobile networks must be to deploy the levers needed to stabilise and control their carbon-energy impacts, in order to enable the decarbonisation of the digital system on the scale of a 2°C objective, -30% by 2030 compared with 2020 (The Shift Project, 2023b), by facilitating and contributing to efforts aimed at optimising and reorganising the sector.**

Since the objective of reducing digital emissions cannot be applied in a consistent way to its various sub-units, formulating it at the level of the system as a whole will shed light on the trade-offs that will need to be documented and made within and between the three components (devices, networks, data centres). With modelling showing that the impact of mobile networks can be stabilised by 2030-2035, it is clear that the reduction of impacts can only come from systemic thinking:

- **By reintegrating the "mobile network" vision into a complete "network" vision**, the other three building blocks being fixed networks, satellite networks, and the core network;
- By reintegrating the complete "networks" vision into a complete "digital system" vision, the other two components being devices and data centres.

It is this systemic and quantitative approach that will enable us to develop the "backcasting" approach to the digital system as a whole, and ultimately to outline the possible paths for digital technology and its uses, in a future aligned with the dual carbon constraint.

Satellite networks: global trends and the environmental costs of our service choices

The recent boom in low-orbit satellite constellations is shaping a new network infrastructure in space. While the technologies and operational realities are obviously different, the deployment challenges are of the same nature as those for terrestrial networks: speed, level of service, latency, and choice of coverage (white zones, peri-urban areas, dense areas). The specific applications of space technologies lead to certain specificities in service and access objectives (geographical areas with varying purchasing power and different development challenges, internet access for private, professional, grouped, civil, defence, redundancy, other types of communication, etc.).

Global trends and unsustainable dynamics

Low Earth orbit constellations: an unprecedented dynamic for the space sector, built around connectivity services

The recent boom in low Earth orbit constellations, combined with the historical share of telecommunications in space activities, has led us to study satellite networks' carbon footprints. Between 2010 and 2015, telecommunications missions, particularly those placed in geostationary[39] orbit (GEO), accounted for an average of 20% of the total payload mass placed in orbit (UCS, 2023) (Figure 16).

Over the same period, the payload mass placed in low Earth orbits[40] (LEO) for telecommunications missions represented only a few percent of the total mass placed in orbit, averaging less than 10 tonnes per year. However, it increased very rapidly in subsequent years. **The payload mass in low Earth orbits became greater than the payload mass of all other space activities in 2022 (480 tonnes per year), and more than doubled between 2022 and**

[39] An orbit at an altitude of around 36,000 km, enabling the satellite to remain above the same terrestrial position. At this altitude, a satellite covers a large area. Three to four geostationary satellites are enough to cover the Earth's surface. Historically, this has been the altitude of telecommunications and meteorological satellites.

[40] Low Earth orbits are situated at an altitude of between 500 km and 2,000 km (sometimes less for very low orbits). The lower the orbit, the faster the satellites orbit Earth. Coverage is also poorer, but latency can be better (as can resolution for Earth observation satellites). Historically, this has been the altitude of Earth observation satellites.

2023 (almost 1,100 tonnes per year), i.e. two orders of magnitude in ten years. Among these missions placed in low-Earth orbit, 94% of the mass is due to large constellations such as Starlink and OneWeb, with Starlink alone accounting for 90 points.

The aim of these space missions is to set up a satellite-based internet network that will provide almost complete coverage of the globe, delivering very high-speed connectivity, guaranteeing very low latency[41] and whose capacity increases with each deployment.

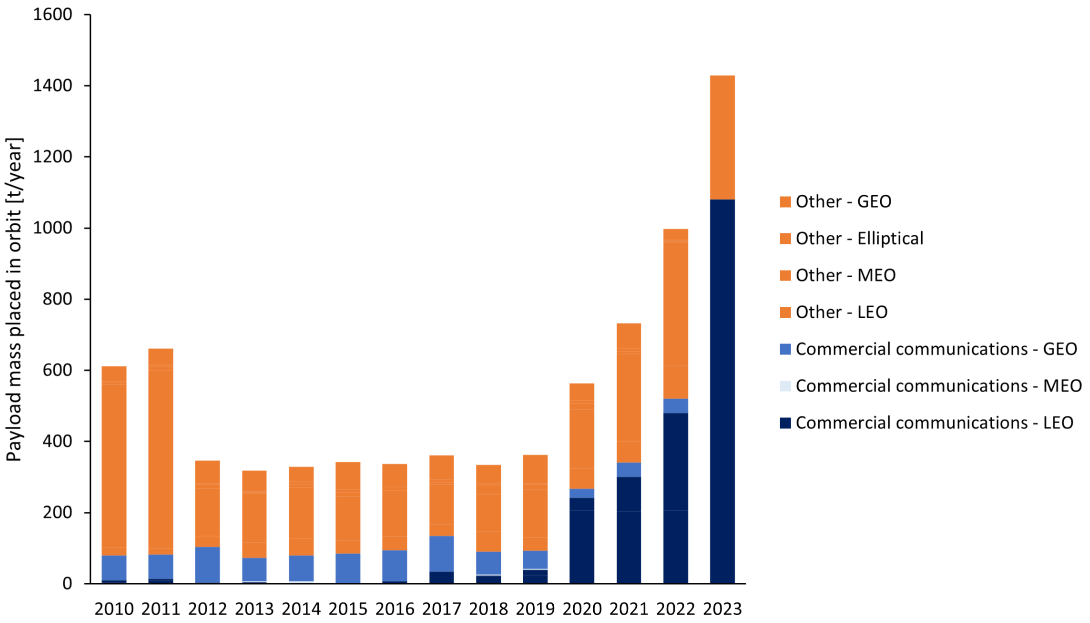


Figure 16 - 2010-2022 changes in payload mass placed in orbit each year
Sources: Aéro Décarbo - The Shift Project for the purpose of this report, based on UCS (UCS, 2023) and Discos (ESA, 2024a)

This initial approach is consolidated by defining four segments: the **satellite segment**, the **launcher segment** (rockets to put satellites into orbit), and by including ground equipment, which is essential for the operation of satellite networks and accounts for a significant proportion of the total. Ground equipment can be broken down into two segments (Figure 17):

- **The ground segment** with the mission control antennas (often shared and kept for a long time) and the teleport antennas[42] that provide access between the internet network and the satellite;
- **The user segment** with user equipment or devices, i.e. a dedicated antenna or kit for each user enabling connection to the satellite.

The ground segment and the user segment: order of magnitude examples

In the case of a constellation of satellites in low Earth orbits, Starlink currently serves 3 million users, each equipped with an antenna weighing 4.6 kg of aluminium and printed circuits, i.e.

[41] In satellite communications, latency is mainly due to the time taken for the signal to travel from Earth to the satellite and back. GEO satellites, at 36,000 km, have a higher latency (~600 ms) than LEO satellites just a few hundred km away (~50 ms).

[42] A teleport can be made up of several ground stations, themselves comprising several antennas, which can be connected to a gateway (gateway to the internet).

14,000 tonnes of antennas. The network currently has around a hundred teleports, each with 8 antennas (see "Appendix 5: Latency, coverage, capacity: environmental cost of our service choices: data and assumptions").

In the case of geostationary satellites, where a single satellite can supply several tens of millions of users, the footprint of ground equipment can become absolutely predominant compared with that of the satellite. A preliminary assessment by Eutelsat (on satellite television) (Eutelsat, 2021) concluded, for example, that there was a factor of 10 between the satellite's footprint and that of the antennas, and another factor of 10 with that of the modems, i.e. 1% of the footprint for the satellite and 99% for the ground equipment.

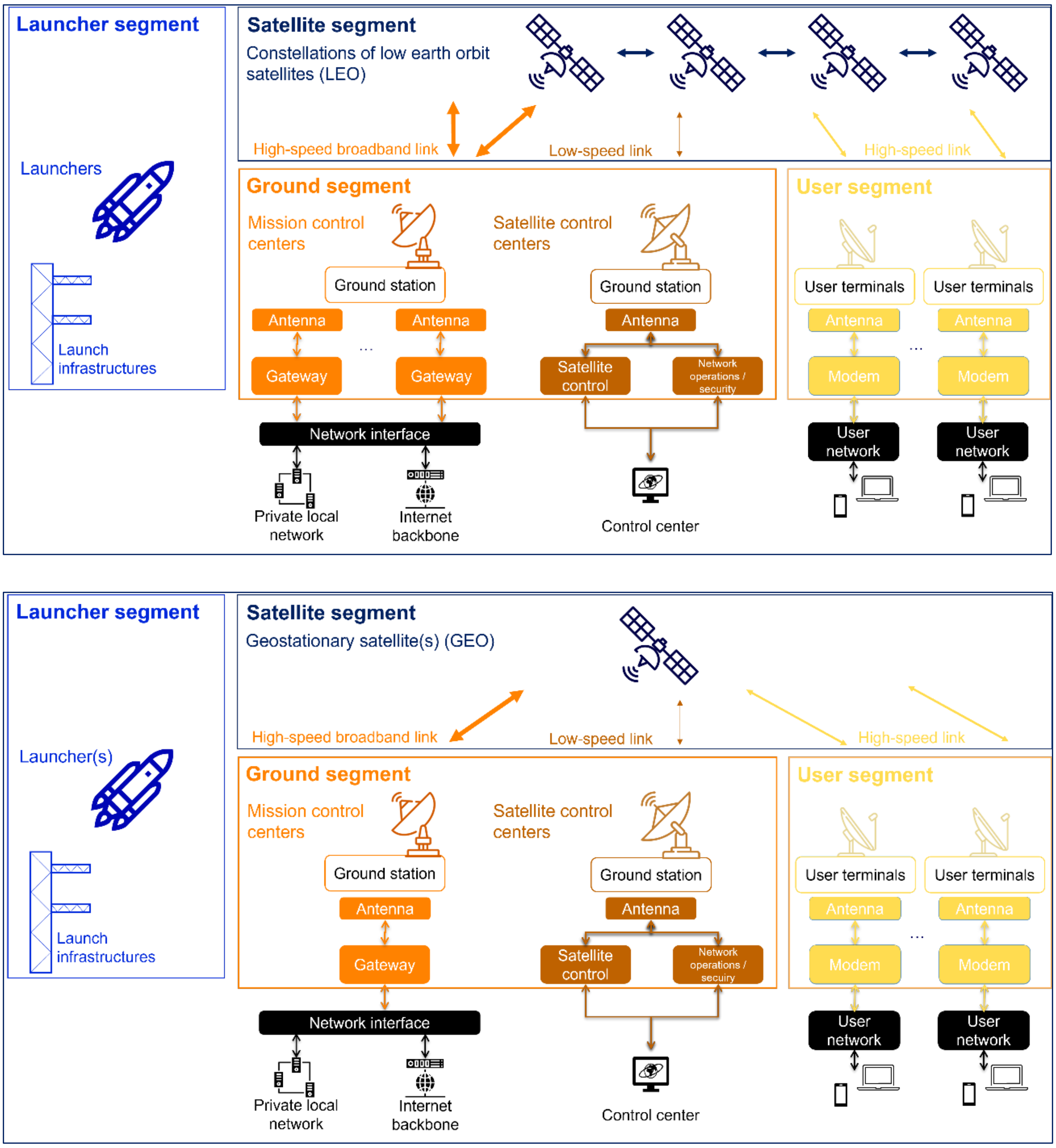


Figure 17 - Overview of the scope studied and the architecture for very high-speed internet access: low Earth orbit solution (top) and geostationary solution (bottom)
Source: Aéro Décarbo - The Shift Project for the purpose of this report

If the new deployment dynamic currently observed within the space sector (see " Low Earth orbit constellations for internet access: industry forecasts for 2020-2050 ") **generated by new connectivity services is confirmed, the change in magnitude in the mass of the payload sent into orbit will pose an additional challenge for the space ecosystem, making it even more difficult for it to align with a decarbonisation trajectory compatible with the Paris Agreement.**

The space sector, which until now has been relatively stable and still poses few quantitative questions from a macroscopic point of view in terms of its carbon impact, is now seeing this new dynamic call into question its viability in terms of its energy-climate impact and environmental impacts, first and foremost the depletion of the ozone layer (see "Non-CO_2 effects: significant uncertainty to be considered in the impact of the launcher and satellite segments"). This new dynamic also calls into question the sustainability of several space related activities: astronomy (increase in light pollution) and Earth observation (via the increase in the number of objects in orbit and the Kessler syndrome, but also via competition for access to orbital positions and frequencies between space missions) as well as terrestrial activities in the event of loss of services.

Historical context

Historically, the space sector has been linked to state issues and strategic sovereignty. The 2010s saw unprecedented reductions in the cost of access to space proposed by private players, first and foremost SpaceX. **Low Earth orbits became the new playground for companies investing massively** in standardised, smaller satellites, whereas the established players, particularly in France and Europe, traditionally produced smaller series of satellites for geostationary orbit. **It is this context, combining lower launch costs, standardised satellites and intense access to space for private players, that has opened up new satellite routes for communications networks**, relying on constellations of hundreds, thousands, even tens of thousands of satellites[43].

Non-CO_2 effects: significant uncertainty to be considered in the impact of launcher and satellite segments.

The space sector has unique characteristics that make the study of its environmental impacts a new frontier for the development of environmental and climate sciences. In particular, the **effects on the atmosphere of satellite launches and atmospheric re-entries of satellites or launchers are complex and still poorly understood.** Indeed, during their ascent from ground to orbit, launchers are the only artificial objects to emit into all layers of the atmosphere, whereas other human activities emit into its lowest layer, the troposphere[44].

These launchers emit a wide variety of compounds as a result of the different comburent/fuel combinations ("propellants") used in the industry. These include various greenhouse gases,

[43] These figures are detailed later in the report, in particular in “Appendix - Environmental cost of satellite latency: data and assumptions”

[44] The aviation industry also emits into the stratosphere, but to a lesser extent.

particles, and ozone-depleting radicals (Table 4). The quantities emitted can be very difficult to assess because of the highly complex nature of combustion in rocket engines, post-combustion, and the interactions between the plume and the surrounding atmosphere at the exit of these engines. This is particularly true of soot emissions, which are unburnt hydrocarbon aggregates.

The effect of a substance on the climate or on ozone then varies according to the altitude at which it is emitted. This is a well-known phenomenon in the case of water vapour, a powerful greenhouse gas whose contribution to climate change is negligible when emitted on the ground (Sherwood S. C. et al., 2018), but which plays a role in the aviation industry's climate impact (Lee D. S. et al., 2021) and whose impact increases considerably if it is emitted into the stratosphere (Pletzer J. et al., 2022). This is also the case for particles: their residence time is a few days after emission into the troposphere, but several years (3 to 5 years) after emission into the stratosphere, where atmospheric circulation dynamics are very different (Ross M. N. & Sheaffer P. M., 2014). They therefore have much more time to exert their power of disrupting the atmosphere's radiative balance via the absorption of light radiation, and their impact there is therefore tenfold. For example, a soot particle emitted by a rocket in the stratosphere is 500 times more effective at warming the atmosphere than the same particle emitted on the ground (Ryan R. G. et al., 2022).

Consequently, **complex models of climate and atmospheric chemistry need to be used in order to estimate the impact of launches correctly. Only a few studies have assessed their effect on the climate, with significant uncertainty surrounding many parameters.**

According to these studies, launches are currently responsible for a total radiative forcing on the stratosphere of around 4-16 mW/m2 (the conservative estimate does not take into account the alumina particles emitted by solid propulsion engines), mainly due to soot (70%), alumina (28%) and, to a lesser extent, water vapour (2%) (Ross M. N. & Sheaffer P. M., 2014; Ryan R. G. et al., 2022). This stratospheric warming could result in complex changes leading to zones of local warming and cooling on the ground (Maloney C. M. et al., 2022). The literature remains cautious on this issue, although a recent study identified a net warming (Tsigaridis K. et al., 2024).

By way of comparison, aviation's radiative forcing is around 100 mW/m2, and that of all human activities is 2.7 W/m2 (IPCC, 2023). The disruption caused by launches would therefore be around 0.1 to 0.6% of human activities, and 4 to 16% of aviation, in the context of the strong growth in the space industry described above.

The rest of the space industry's emissions take place on the ground (production of launchers, satellites and their fuels, operations, transport, etc.) and accounted for around 0.01% of global emissions in 2018, according to the only reference publication on the subject (Wilson A. R. et al., 2022). The climate impact of the space industry is therefore characterised by the overwhelming dominance of non-CO_2 effects caused by launches. Unfortunately, these effects **are not taken into account** in the available life-cycle analyses: the preliminary results described above cannot simply be expressed in conventional metrics such as the Global Warming Potential (GWP) measured in $kgCO_2e$.

Launches also affect the ozone layer by emitting ozone-depleting substances (ODS) in situ. It is estimated that their contribution to the destruction of the ozone layer is currently around 1% of that of the CFCs responsible for the hole in the ozone layer and banned by the Montreal Protocol, mainly because of emissions from solid propulsion (Ross M. N. & Jones K. L., 2022).

At the end of their mission, low Earth orbit satellites[45] and launcher stages re-enter the atmosphere at very high speed and partially or totally burn up. This results in direct emissions of metallic particles into the upper layers of the atmosphere, as well as dissociations of air molecules leading to nitrogen oxides (NOx) that can affect the ozone layer. The mass of satellite and launcher materials injected into the atmosphere each year is estimated at 350 tonnes per year (Schulz L. & Glassmeier K-H., 2021), and a recent study found that 10% of aerosols in the stratosphere contained metallic particles from satellites and launchers (Murphy D. M. et al., 2023). **The possible effects on climate, ozone and the formation of stratospheric polar clouds are still being debated.**

Much remains to be learned about the atmospheric impacts of space activities, and **there is therefore an urgent need for more research on the subject given the new and very rapid trends in the industry.** Leading institutions such as NOAA and NASA in the US, and more recently CNES, DLR and ESA in Europe, now appear to be tackling the problem, but **experts share the fear that industry growth is outpacing science and regulators** (New York Times, 2024).

[45] A geostationary satellite mission lasts 15 to 25 years. For recent constellations of low Earth orbit satellites, missions last between 5 and 7 years. The deorbiting of a launcher's upper stage takes place just after the payload has been put into position, i.e. just at the end of the launch.

	Climate impact	Impact on ozone
Emissions and post-combustion products from launch vehicles (launcher segment)		
Soots (methane, kerozene)	Warming of the stratosphere via absorption of incident solar radiation (Ross M. N. & Sheaffer P. M., 2014) (Ryan R. G. et al., 2022) Resulting effect on the complex troposphere (Maloney C. M. et al., 2022)	Acceleration of the kinetics of ozone-destroying reactions by heating the stratosphere (Ross M. N. & Sheaffer P. M., 2014) (Ryan R. G. et al., 2022)
Alumina (solid propulsion)	Reflection of incident solar radiation and absorption of upwelling terrestrial radiation, leading to a net warming of the stratosphere (Ross M. N. & Sheaffer P. M., 2014)	Acceleration of the kinetics of ozone-depleting reactions by warming the stratosphere + reaction support (Ross M. N. & Sheaffer P. M., 2014) (Ryan R. G. et al., 2022)
Chlorine (solid propulsion)	Indirect via ozone depletion	Chemical destruction of ozone (Ross M. N. et al., 2009) (Ryan R. G. et al., 2022)
Water vapor (LH2 and+)	Warming (Ross M. N. & Sheaffer P. M., 2014) (Pletzer J. et al., 2022; Ryan R. G. et al., 2022)	Negligible (Ryan R. G. et al., 2022)
All		All emit depleting ozone compounds (Ross M. N. et al., 2009)
Satellite re-entry emissions and launcher upper stages re-entry (satellite and launcher segment)		
Alumina and metal particles	To be determined (Murphy D. M. et al., 2023)	To be determined (Murphy D. M. et al., 2023)
Nitrous oxides	To be confirmed	To be confirmed (Ryan R. G. et al., 2022)

Table 3 - Summary of state-of-the-art knowledge on launcher and satellite impacts
Sources: Aéro Décarbo – The Shift Project for the purpose of this report, based on the references given in the table.

Low Earth orbit constellations for internet access: industry forecasts for 2020-2050

In order to estimate the sector's dynamics, a projection for the seven main constellations has been made using public data and a number of assumptions (all the data used is available in

"Appendix 7 - Low Earth orbit constellations: 2020-2050 industry forecasts: data, assumptions, and model"). Two periods can be distinguished in Figure 18 by:

- An initial period of constellation[46] deployment from 2022 to 2035, during which the payload mass increases as a result of this deployment;
- A second period, from 2036 to 2050, in which we see a plateau linked to a phase of renewal alone.

Changes in the various indicators (normalised from a baseline of year 2021 with no constellations) are also shown in Figure 19, highlighting dynamics with the potential for very significant increases in these impacts, ranging from a factor of 2 for the number of launches to 12.7 for water vapour.

Still based on the assumption that deployment of the Starlink and OneWeb constellations began in 2022, **the constellation projects under consideration would collectively be responsible for a 5-fold increase in pre-launch GHG emissions between 2021 and 2050.** Perhaps more worryingly**, soot and alumina emissions would be multiplied by more than 6, and water vapour by almost 13. If we put these figures into perspective with the estimates of radiative forcing mentioned in the previous section, we can fully appreciate the magnitude of the consequences that these new projects could have on the space sector's climate impact.**

It is worth noting that the upstream phases on the ground (shown in yellow in Figure 19), relating to the design, manufacture, and testing of satellite and launcher components and fuels, constitute only a small part of the complete life cycle, making it impossible to assess all the emissions generated. For the launch phases, a complex climate model would be required to assess their effects on the climate and ozone due to high-altitude emissions.

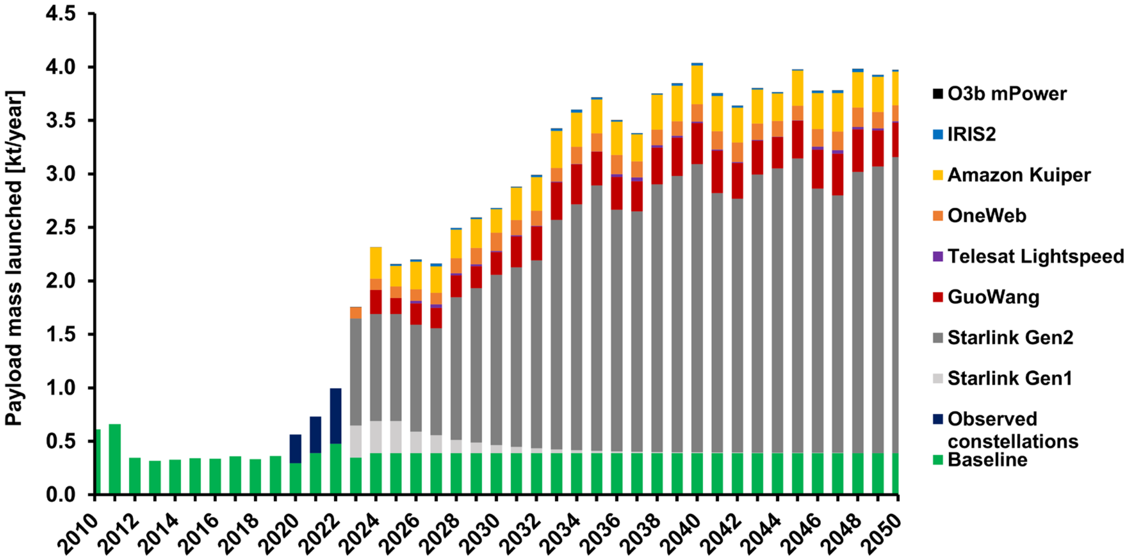


Figure 18 - Evolution of the payload mass placed in orbit: 2010-2023 period from the DISCOS database (ESA, 2024a); 2024-2050 projection from the (Miraux L. et al., 2022) model
Sources: Aéro Décarbo - The Shift Project for the purpose of this report

[46] To simplify the analysis, we have made the assumption that constellation deployment had not yet begun in 2021, which is inaccurate for OneWeb and Starlink at least. However, this approximation does not change the conclusions of the analysis.

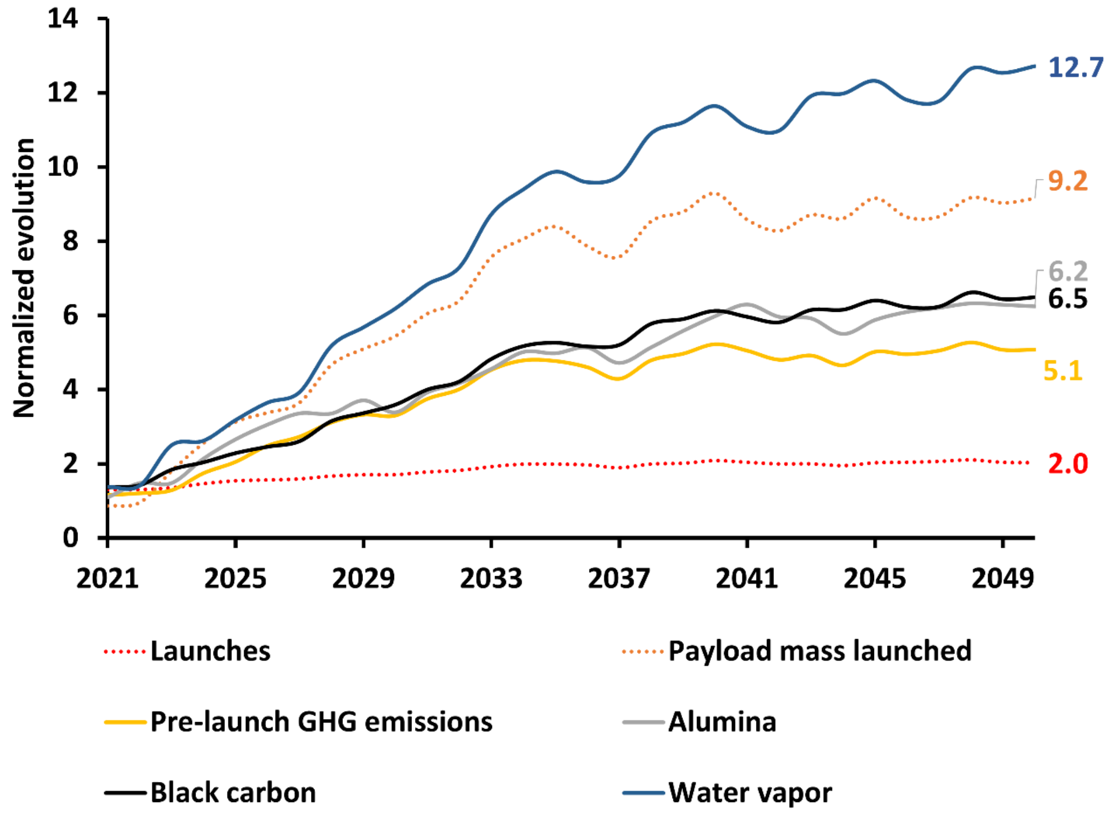


Figure 19 - Consequences of the analysed constellation projects on the evolution of launches, launched mass, and emissions from space activities derived from the (Miraux L. et al., 2022) model.
Scale normalised to 2021 without constellation
Source: Aéro Décarbo - The Shift Project for the purpose of this report

Very high-speed satellite connectivity: a new infrastructure for digital technology, but with a whole new rationale and impact

At first glance, from the digital sector's point of view, satellite internet access can be considered anecdotal[47]:

- **In terms of the number of users served, satellite internet access currently represents around 0.1% to 1%:** between 3 million very high-speed satellite subscribers to date[48] to 71 million people connected to the internet by satellite worldwide (Euroconsult, 2023) for 5.4 billion internet users worldwide (ITU, 2023)[49] ;

[47] It should be noted that only telecommunications are considered here, and that this is not the only connection between digital activities and space activities that could be of concern from an energy-climate point of view. For example, the exponential growth of Earth observation constellations and their volumes of data calculated, analysed, and stored could also be a cause for concern. (Wilkinson R. et al., 2024).
[48] Source: interview with an expert
[49] By way of comparison, fixed 4G and 5G mobile networks (FWA, Fixed Wireless Access), which offer similar types of services and uses as very high-speed satellite, have 132 million users (Ericsson, 2024).

- In terms of traffic, satellite internet access could represent 0.5%[50] - 1%[51] to 3%[52] of internet traffic.

Nevertheless, **despite data volumes that are still low, space infrastructure is taking on a growing and very specific importance within the digital ecosystem, providing a response to the political and strategic challenges of connectivity and geographical coverage (including white zones) with a service offering of comparable performance to certain terrestrial networks (high speeds, low latency, etc.)** aimed at the same types of applications and services.

Since the mechanisms behind the carbon-energy impacts of deploying space infrastructures are completely different from those operating on land (energy efficiencies, non-CO_2 effects during launch and end-of-life phases, etc.), their massive development is not simply a parallel to terrestrial infrastructures, but a genuine paradigm shift for the impacts of digital services and uses.

Satellite telecommunications services: overview and environmental costs of our service choices

Overview of satellite telecommunications networks

The spectrum of communications satellite missions (current, past, and possible[53] future ones) spans a range of applications, with characteristic orders of magnitude differing along two axes:

- The services provided axis: number and location of users served, type of use (consumer, professional), service (throughput, latency);
- The infrastructure axis: number and mass of satellites in orbit required for the constellation, number and characteristics of ground equipment (relays, antennas, modems, devices, etc.).

Overview of telecommunications satellites and satellite constellations: services provided and material footprint							
Services provided	Category	Content broadcasting	Internet access		Mobile telephony		Internet of Things
	Type of service	Linear television	Broadband	Low latency broadband	Telephony / medium-speed	Direct-to-cell (or direct-to-device)	Internet of Things

[50] Assuming that Starlink transmits 42 PB of data per day (PCMag, 2024) and that Starlink accounts for 2/3 of satellite internet traffic.
[51] On the assumption that the 71 million users have a worldwide average consumption based on (Ericsson, 2023; ITU, 2023).
[52] Or on the assumption that the 71 million users' consumption is that of fixed 4G/5G users with average fixed 4G/5G consumption (Ericsson, 2024).
[53] Not all *possible* missions are listed; those considered are the most popular in the digital and space ecosystems.

	Service features	N/A	High-speed Medium latency (600-800ms)	High-speed Low latency (<200 ms)	Telephony, data exchange	Telephony, sms, medium bandwidth	Short messages (connected objects)
	Type of satellite	GEO	GEO	LEO-MEO constellations	GEO, LEO constellations	GEO, LEO constellations	GEO, LEO constellations
	Type of users	General public	General public (mainly developed countries) Professionals: business, government, maritime, aeronautics, land mobility, cellular network backhaul, trunking, back up		Professionals worldwide	General public (mainly developed countries))	General public, Professionals
	Number of users	SES: **367 million** users Eutelsat: 274 million users	**500,000** users targeted for Konnect VHTS	**2 million** for Starlink (10,000 in France)			
Material footprint	**Existing solutions and orbital mass (kg)**[54]	Solutions GEO solutions: several tens of satellites **(~5 tonnes)**	Several tens of satellites (Eutelsat, SES, Intelsat, Viasat, Hispasat…) Ka-sat **(6 tonnes)** Konnect VHTS (6.5 tonnes)	Constellationss[55] : - Starlink **(4,425 *260kg + 7500 * [800;1250kg]** - OneWeb (> 648 sats) - Kuiper (>3236 sats) - Telesat Lightspeed (>198 sats) - China SatNet (Guo Wang) (12992 sats) - O3B - IRIS²	- Globalstar (LEO) - Iridium (LEO) - Inmarsat (GEO) - Thuraya (GEO)	- Starlink (including T-Mobile), - Globalstar (including Apple), - Iridium, - Inmarsat, - AST mobile, - Lynk Global	Historical players: Iridium, Inmarsat, Globalstar, Echostar Mobile New players: Kineis **(25 x 30kg)**, Astrocast, SWARM, Lacuna Space, Sateliot
	User devices[56]	1 satellite dish + 1 decoder / household	1 satellite dish + 1 modem + 1 router/ household	1 aerial + 1 router + 1 user connection box / household	Satellite devices	"Standard" devices (specific chip/antenna)	Low-energy devices

Tableau 1 - Overview of services provided by satellite infrastructures and associated material footprints
Source: Aéro Décarbo - The Shift Project, for the purpose of this report

Providing a linear broadcasting service, transferring data between objects, enabling telephony and access to the medium-, high- or very-high-speed internet do not have similar material footprints. **Indeed, the characteristics of the services provided are intrinsically linked to the specifications and size of the infrastructures that enable them**. For example, a higher level of service with wider coverage will call for greater satellite and ground network requirements, with a correspondingly larger carbon and energy footprint.

For several decades (from the early days of the internet to the ubiquity of mobile video content today), the multiplication and superposition of uses observed in the structuring of digital services have called for increasing specifications and material footprints for networks, as demonstrated in the rest of this report and in previous The Shift Project work (The Shift Project, 2021, 2024c). **Satellite networks are no exception: harnessing them to achieve richer service levels**

[54] The **satellite segment**'s energy-climate footprint is directly linked to the mass in orbit. At first glance, the mass in orbit is also representative of the orders of magnitude of the **launcher segment** (more mass requires more launchers) and the **ground segment** (the more satellites there are to communicate with, the more antennas are used in the ground stations to carry out the communication).
[55] See figures in "Appendix 7 - Low Earth orbit constellations: 2020-2050 industry forecasts: data, assumptions, and model"
[56] The **user segment,** on the other hand, is linked to the number of users and their devices

(high-resolution and personalised video content with video on demand), greater complexity (to the point, for example, of offering internet access services on aircraft by combining satellite connectivity with the complementary use of relay antennas on the ground[57]) and greater reliability (low latencies) requires a growing material footprint.

The most inflationary dynamics in terms of impacts are those pulling service specifications (coverage, speed, connectivity, latency) simultaneously upwards. Understanding the structuring trends of the environmental impacts evolution of the "digital-satellite telecom" system being the subject of this study, the aim here is to characterise the specificities of the most resource and energy-intensive services: very high-speed internet access services.

Very high-speed internet access from space can be based on several types of satellite network architecture, whose characteristics vary widely depending, first and foremost, on the altitude of their orbit:

- At 36,000 km, geostationary satellites (GEO) offer a stable, broad-spectrum service (reliable speed, stable latency) using a sparse network (between one and a few satellites, the great distance from the earth allowing for extensive geographical coverage). They are highly suitable for broadcast applications (e.g. satellite video) and, for the time being, for mobile internet access (e.g. on cruise ships);
- Low Earth orbit (LEO) satellite constellations, mainly located between 500 and 2000 km, enable the deployment of a level of service comparable to that of terrestrial infrastructures (4G mobile and fixed fibre), notably by greatly reducing latency compared with GEO with their much smaller distance from the surface. This characteristic makes them good candidates for applications requiring numerous exchange stages to load content, and for applications requiring low latency (video games, voice to a lesser extent), but at the price of greater variability in service quality and a very intense need for meshing (several hundred to several thousand satellites simultaneously in orbit);
- Intermediate orbits (MEO, for "Medium Earth Orbit") at 800 km provide a level of latency that is intermediate to that of GEO and LEO solutions, while at the same time reducing the required mesh size.

The speeds that can be delivered over these three types of orbit are comparable to those of certain terrestrial solutions (fixed fibre and 4G mobile, for example). The main difference is latency, which ranges from 600 ms for GEO to 60 ms for LEO.

However, **the orbit chosen for the satellite solution has a continuous influence** on two essential parameters:

- **The number of satellites required to ensure coverage of the desired areas** (which can determine the material and environmental footprint of the infrastructure, depending on its capacity). The physical counterpart of low Earth orbits is satellite motion: a satellite at 500 km remains in the line of sight of a point on Earth for approximately 12 minutes. Ensuring continuous coverage of a point on Earth by LEO requires a multiplication of the number of satellites, especially significant for lower orbits (and therefore lower latency), and requires more complex antennas to track the satellites.
- **The level of latency of the final service provided:** 600 ms for GEO to 60 ms for LEO. Now a key differentiating factor in connected applications and uses (healthcare, industry, culture and leisure, video games, etc.) (The Shift Project, 2021, 2024c), the level of latency therefore seems to be one of the key parameters in the choice of technology for very high-

[57] Inmarsat project for the European Aviation Network

speed access from space, and therefore in the carbon-energy footprint of the resulting infrastructure.

Finally, capacity deployment, whether linked to the number of users (or their use of the network and the types of service used) or to massive infrastructure investment, will also affect the size of the satellite network once coverage has been achieved.

Latency, coverage, capacity: the environmental cost of our service choices

To illustrate the underlying dynamics of satellite network design explained in the previous section, three systems were studied: a satellite placed in geostationary GEO orbit (the Konnect VHTS satellite) and two satellite constellations (OneWeb and Starlink).

The analysis is based on (Osoro B et al., 2023) but with a different perimeter: launcher segment for Osoro; launcher segment (without taking into account non-CO_2 effects) as well as satellite, ground, and user segments here. All the data and assumptions can be found in "Appendix 5: Latency, coverage, capacity: the environmental cost of our service choices: data and assumptions".

Unsurprisingly, carbon footprints are linked to material footprints[58]: the increasing number of launches, payload mass, teleports, and users generates almost an order of magnitude difference between the different systems' impacts. We can also see that the **user segment is far from insignificant,** as mentioned in the first part of this chapter.

Starlink constellation's annual footprint (Figure 20) is over 1600 ktCO_2e/year, i.e. almost twice the French fixed and mobile networks in 2020[59] for 2 million users to date. This footprint is not set to decrease, as the entire infrastructure has to be replaced every 5 years. OneWeb's business solution also implies a substantial carbon footprint (around 600 ktCO_2e), whereas the geostationary solution seems more moderate, with an annual footprint of 65 ktCO_2e/year (especially as 90% of its footprint is dedicated to the user segment, i.e. the user kit).

[58] For all three systems, the numbers of launches, payload mass in orbit, teleports, and users are ranked in ascending order.
[59] (ADEME & Arcep, 2023)

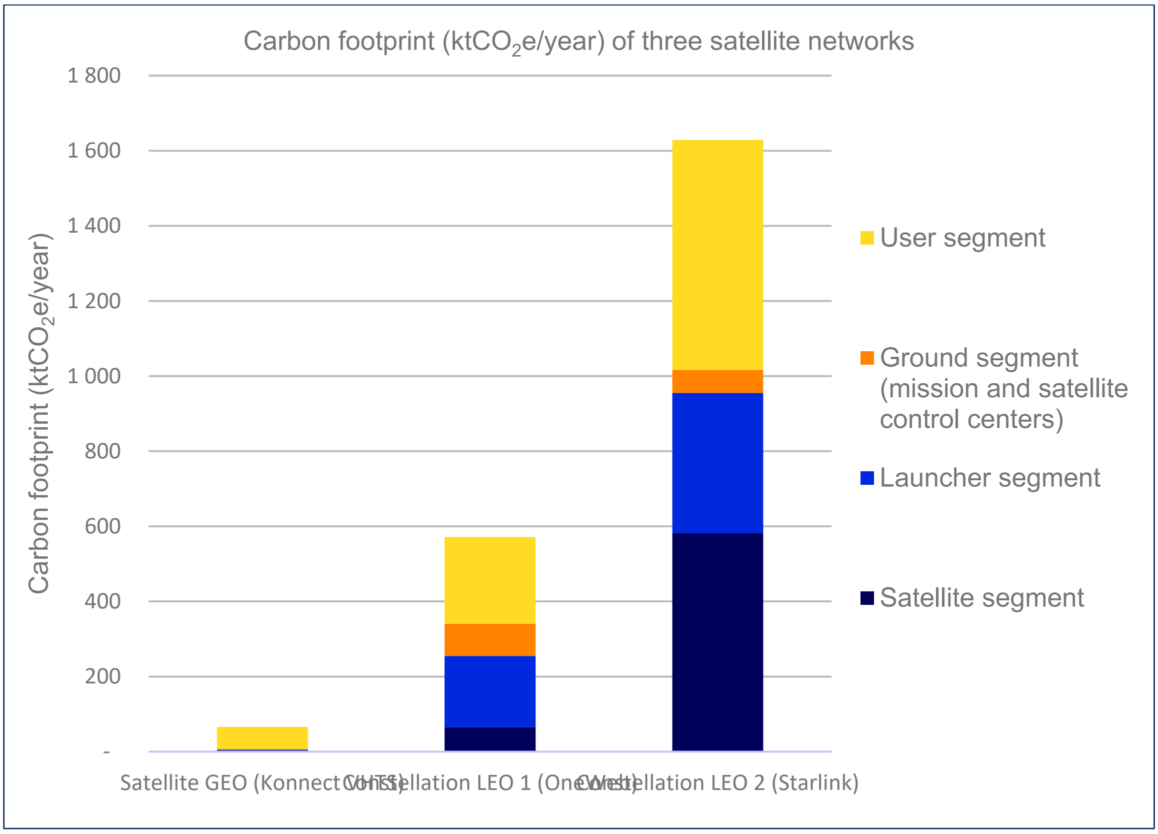


Figure 20 - Annual carbon footprint of satellite networks and breakdown by segment
Source: Aéro Décarbo – The Shift Project for the purpose of this report

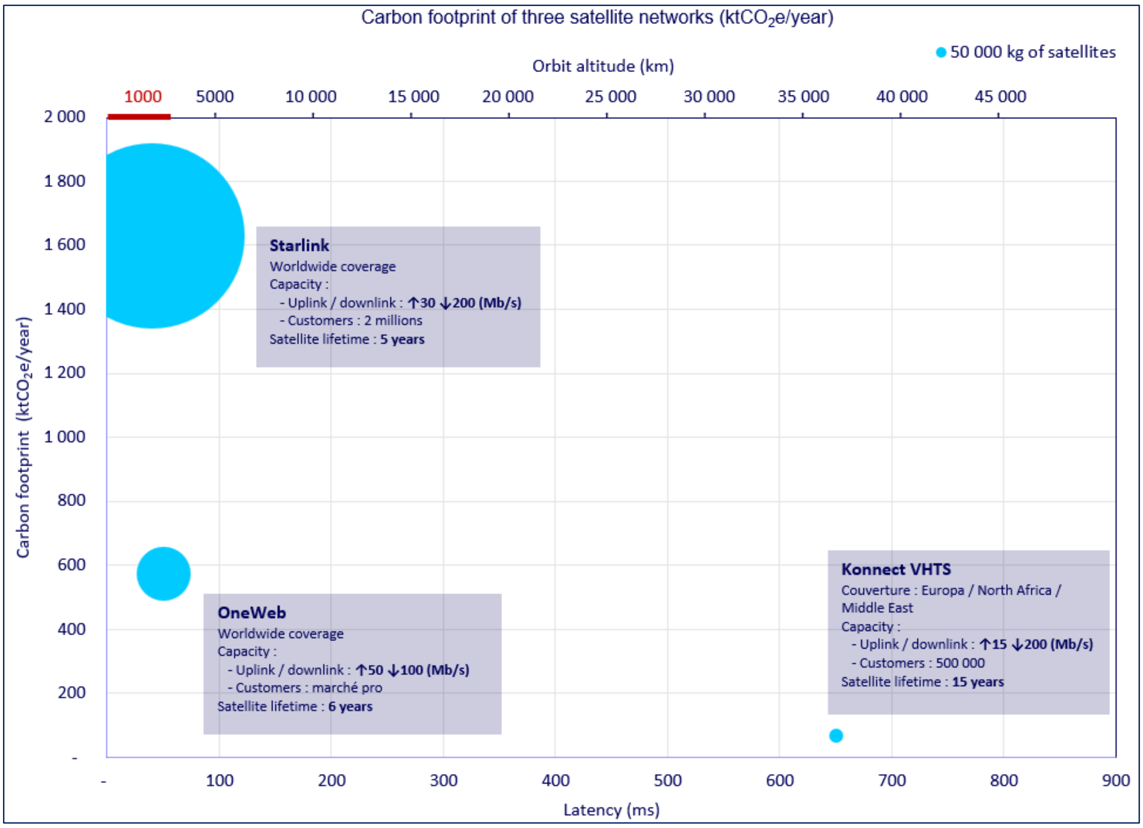


Figure 21 - Annual carbon footprint of satellite networks
Source: Aéro Décarbo – The Shift Project for the purpose of this report

Figure 21 describes the dynamics underlying constellation construction and explains the considerable environmental cost of the Starlink constellation:

- A geostationary satellite like Konnect VHTS (providing very high bandwidth with latencies of around 600ms) only covers a third of the globe; 3 of them would be needed to provide full coverage;
- A low latency objective implies low orbit solutions and therefore calls for a higher number of satellites (50 to 100) to ensure coverage;
- Beyond this number of satellites (and depending on frequency priorities), the number of satellites depends on the capacity deployment achieved. To put it another way, if we only needed to provide this service to a limited number of people, the constellation would not be so large.

In order to build an environmental model for telecommunications satellites and satellite constellations, such as the one built for mobile networks within the scope of this report, the first approach to analysis will need to be reversed in the future. This will involve being able to answer the following consequential question: depending on the coverage and service level scenarios, what network infrastructure will be deployed, and what are the energy and climate implications? This will enable us to turn to “backcasting” approaches, which will help to build a lean and resilient digital system (see "The “backcasting” approach: dimensioning in view of constraints").

Satellites' conditions of relevance for very high-speed internet access

Satellite Internet access networks are currently (Figure 22) regarded mainly as geographic coverage complements or standby solutions, just like fixed 4G/5G.

Figure 22 - Satellite internet access usage status
Source: Aéro Décarbo - The Shift Project for the purpose of this report

In particular, satellites and satellite constellations are used nowadays primarily to provide broadband or very high-speed internet access when:

- Isolation or geographical configuration make connection by wired network (ADSL, fibre, or cable) or terrestrial radio technically difficult (Arcep, 2023c),
- When ADSL speeds are low,
- Pending the roll out of fibre optics (Arcep, 2023c), and possibly for locations where copper is being phased out before fibre is deployed.

It is the combination of *very high bandwidth x very low latency* that is at stake in the environmental footprint of very high bandwidth satellite constellations in low orbit: space missions with low bandwidths (information reporting missions) are carried out with much smaller infrastructures than broadband satellite constellations. This combination of specifications is a source of growing environmental impact, and this dynamic is recurrent within the digital system: we can see it for terrestrial networks, as discussed in other parts of this report, but also for the uses that generate these needs directly. In video games (where requirements have long been focused on latency, before increasing the need for high bandwidth), common online uses (the loading time of a webpage being dependent on the multiplication of requests and latencies, and the execution of security protocols, but also content volumes with sustained growth in video content), or the new uses promised by virtual worlds, the combined race for bandwidth and latency will lead to significant increases in carbon and energy impacts (The Shift Project, 2024c).).

In white areas, geostationary satellites provide very high-speed internet access, while low orbit constellations provide access with low latency. In other words, coverage of white areas can be ensured with geostationary satellites, while low orbit constellations provide an uncompromising "premium" service, i.e. a combination of very high speed, low latency, and full coverage.

In France, fibre optic coverage currently covers 84% of the population (Arcep, 2023f) and the *France Très Haut Débit* (France Very High-Speed Broadband) plan aims to make fibre available throughout the country by 2025 (Ministry of the Economy, Finance and Industrial and Digital Sovereignty, 2023). On a European scale (European Commission, 2023), the IRIS2 constellation, which aims to provide a low latency service[60] is the first step towards a truly mass-market service. However, on a global scale, 591 million people could use a satellite solution (Euroconsult, 2023), out of the 2.6 billion people who do not have access to the internet (Euroconsult, 2023; ITU, 2022). If the chosen solution had a carbon footprint equivalent to that of Starlink, it would be like multiplying the annual footprint of this constellation by factors of 100 to 1000.

Developing a strategy for the role of telecommunications satellites in a sustainable and resilient digital system therefore requires an environmental footprint analysis for each context, considering various scenarios that vary the coverage rate by fibre and by satellite (GEO as well as LEO), and determining the conditions (types of usage to be fulfilled, population density, existing alternatives, etc.) under which the respective carbon costs become equivalent.

Satellites and satellite constellations also provide broadband internet access for mobile systems (see section "Overview of satellite telecommunications networks"): terrestrial systems in motion (aircraft, boats, connected cars[61] etc.) etc.) or more recently directly to "standard“[62] devices with

[60] European Union investment of €2.4 billion (*L'usine digitale*, 2023c).

[61] And, more recently, tractors, with the establishment of a partnership between John Deere, a manufacturer of agricultural equipment, and SpaceX. (*L'usine digitale*, 2024)

[62] As opposed to historically specific satellite devices.

"direct-to-device" and "direct-to-cell"[63] functionalities, the development of 5G NTN protocols and the ambition that 6G will enable the advent of terrestrial-satellite[64] convergence. The role of these solutions remains to be studied in terms of their environmental cost.

Making satellite infrastructures a relevant building block for a lean digital system

High-end connectivity satellite services (very high bandwidth, low latency, full coverage) and investment in constellation capacity deployment imply a major shift in dynamics (increasing size of constellations, shorter satellite lifetimes, etc.) which, coupled with uncertainties about the "non-CO_2" effects of activities in the upper atmosphere, could increase the climate impact of the space sector tenfold:

- **Global trends in the number of launches and the mass sent into orbit are incompatible with controlling the environmental footprint of the space sector.** These trends are the result of very high-speed, very low latency internet access satellite constellations, which are now synonymous with a reduction in expected satellite lifetimes, requiring more frequent renewal of the fleet and therefore more launches;
- **The persistent gaps** in scientific knowledge about the effects of particles emitted during the launch and re-entry of satellites into the atmosphere, both on the climate and on the ozone layer, mean that, **in addition to reducing uncertainties in the medium term, decisions need to be taken accordingly;**
- Because of their quantitative importance, only space-based broadband internet access missions are included in this study. **Assessing the environmental cost of our choice of satellite internet access services (latency, coverage, capacity) raises questions about the relevance and role of satellites and constellations, and about strategies for covering white zones;**
- **A consideration of possible decarbonisation trajectories for the space sector and its role in achieving France's carbon neutrality targets by 2050 must include an in-depth examination of the range of telecommunications missions it carries out.**

[63] There are two types of solution: proprietary solutions such as Apple's partnership with Globalstar for emergency messages and the Snapdragon Satellite solution for two-way text messaging via satellite (*L'usine digitale*, 2023a, 2023b); or international standards such as 5G NTN (Non Terrestrial Network).
[64] (6GSNS, 2021; ESA, 2024)

Making network infrastructures compatible with the dual carbon constraint

Network infrastructures: risks and resilience

Network infrastructures are part of our physical infrastructures. They are subject to the same constraints and resilience challenges as all our other systems, and if **we want to preserve their essential uses and contributions, we need to adopt a strategy that makes them as resilient as possible against new risks.**

The risks associated with the dual carbon constraint **are twofold:**

- Physical risks:
    - Increasing variability of weather conditions in an unstable climate, with more frequent and intense **extreme events** as a result (risk of damage to high points and fixed infrastructure in the event of storms, fire, or flooding, for example);
    - **Energy supply** (constraints on fossil fuels, competing uses for electricity, power cuts in the event of extreme weather events, etc.);
    - **Supply of technical equipment and components** (dependence on the geological, technical, geopolitical, and climatic conditions in which the value chains for metals, rare earths, copper, etc. operate);
- **Transition risks**, which result from the transformations undergone by the rest of society in which the infrastructures are situated (regulatory changes, shifts in demand and usage, disruptions or reorientations of key players in subcontracting or supply value chains, etc.).

These risks are a reflection of the growing degree of uncertainty faced by all sectors of activity, now and in the years to come. They can manifest as **abrupt phenomena** (semiconductor supply crises, floods, power grid load shedding and therefore supply disruptions for high points, etc.) or as **underlying phenomena** (increasing disruption to value chains required for equipment maintenance and renewal, growing volatility in the prices and accessibility of materials and components, etc.).

Stakeholders (operators, regulators, manufacturers) in the networks sector must therefore incorporate the conclusions drawn from the investigation of the following questions into their strategies:

- Is a maximalist strategy (Table 1, Table 2), aimed at deploying networks as widely as possible and with the best possible performance to enable the maximum number of potential applications (including those not yet identified), compatible with these resilience issues?
- What convergences and divergences are there between the choices that maximise resilience in the face of climate and supply risks and those that respond to the dual carbon constraint (for example, redundancy could conflict with energy-carbon efficiency and sobriety, but a leaner system that is less dependent on inputs could make its uses more resilient)?

Placing our digital systems - and networks in particular - on a low-carbon trajectory that is consistent with the dual carbon constraint means that we can now embark on a more resilient trajectory for our connected uses and services, which will help preserve their essential contribution to the functioning of our societies. At the same time, it **gives all digital stakeholders the time and resources to adjust their technological and economic dynamics.**

What levers can we use to lead our networks towards a lean and resilient future?

The magnitude of the changes in dynamics required means that we need to use all the levers at our disposal to transform network infrastructures. Technological levers are essential, but not enough if they are not combined with societal and organisational levers: **decarbonising digital technology involves not only technical decisions, but also societal and political ones.**

It is the systemic approach that will enable, by harnessing the **four categories of actions** in the right places and at the right level, to redirect networks towards a future compatible with the dual carbon constraint:

- Measurement and transparency;
- Systemic optimisation and eco-design;
- Collective reorganisation towards sobriety;
- Training and new skills.

To achieve this, all stakeholders will have to be actively involved, each with the capacity and responsibility to initiate some of these levers:

- The players involved in public decision-making and management:
    - Public authorities;
    - Public players in carbon-energy planning;
    - Public players in digital regulation and planning;
    - Public players in space regulation and operations;
- Players producing technical analyses of the sector and its environmental impact:
    - Players producing standards and conventions for impact methodologies;

    - Players producing impact assessments of network equipment;
    - Academic community;
- Business players in the digital sector, throughout the value chain:
    - Network equipment suppliers;
    - Network operators;
    - Telecommunications and space systems players;
    - Digital service providers (publishers, content, applications);
    - Organisations using digital technologies;
- Players involved in initial training (universities, engineering schools, courses specialising in digital technology, etc.).

The list of recommendations presented here outlines the next steps to be taken by stakeholders to initiate the transformation of network infrastructures.

To implement them effectively, it will be necessary to involve the right players and ensure that the conditions of relevance for each lever are met. **This comprehensive range of levers to be harnessed, their conditions of relevance, and, for each, the list of players in a position to initiate them are also available in detail in** (Appendix 9 - Detailed Recommendations: actions to be taken and players to mobilise).

Measurement and transparency
Objective 1: Ensure the completeness, transparency and robustness of environmental impact assessments for network equipment and services.
Ensure that the data required for impact assessments is available in a public and transparent manner.
Frame impact assessment methodologies around principles that make them transparent, comparable, recognised, and auditable.
Systematically and transparently take into account the different phases in the life cycle of network equipment (production, transport, use, end of life).
Develop a sufficiently robust method for assessing the impact of launcher and satellite infrastructures.
Objective 2: Establishing a quantitative reference framework for managing the digital sector under the dual carbon constraint.
Establish a reference carbon trajectory for the digital sector in France (-30% from 2020 to 2030) and in Europe.
Include a sufficiently consolidated assessment of electricity consumption by the digital sector in national planning exercises (RTE, DGEC, SGPE) so that it can be included in the closing exercise.
Include energy and environmental performance in the criteria used by the regulator to assess operators.
Objective 3: Produce indicators that will enable digital strategies to be realigned to ensure compatibility with the dual carbon constraint.
Suppliers of equipment and services to make environmental data and indicators available to customers (the general public and businesses or organisations) in a suitable, standardised format.
Develop feedback on equipment power consumption.
Develop and standardise carbon cost indicators by functionality, specification, or service, in order to provide guidance on the technological choices to be made for our future services.

Optimisation
Objective 1: Eco-design network equipment to reduce power consumption.
Maximise and optimise cell shutdown based on traffic (sleep mode) by frequency band and technology, and develop power transmission modulation.
Establish metrology to monitor and limit network equipment consumption.
Objective 2: Optimise deployment strategies and technological strategies to reduce electricity consumption in the operational phase.
Study the potential benefits of reducing the frequency ranges used.
Direct research and innovation aimed at optimising network resources (use of AI, optimisation tools, etc.) towards a reduction in absolute energy consumption at constant bandwidth or capacity, rather than towards an increase in performance.
Manage the deployment of satellite infrastructures according to needs and energy-carbon impact studies, avoiding redundancy and stacking.
Objective 3: Reduce the carbon impact of network equipment production, deployment, and operation.
Integrate carbon criteria into site construction specifications, to encourage the use of low-carbon methods and materials.
Set up accounting, technical and strategic frameworks to extend the lifespan and encourage the re-use of network equipment.
Structure the collection, sorting, repair, and processing of network equipment and internet routers in order to reduce the impact of the end-of-life phase.
Objective 4: Promote technological developments that facilitate network optimisation.
Implement a functionality that automatically directs devices towards Wi-Fi connection when detected.
Produce clear guidelines on the adoption of the most efficient video codecs reducing bandwidth consumption.

Collective reorganisation towards sobriety
Objective 1: Curtail the inflation of data-intensive usages.
Make any increase in traffic or network infrastructure performance conditional on compliance with the trajectory for reducing the network's carbon-energy impact.
Adopt a targeted 5G deployment strategy for priority uses and sites.
Make the reduction of the absolute environmental impact of networks a key criterion in the specifications for 6G.
Set maximum bandwidths for applications that could become critical, such as remote surveillance cameras.
Introduce an eco-design benchmark for digital services within the market: • Activation of a data-saving mode by default for content delivery and devices; • Integration of an "audio-only" function on video platforms; • Default resolution adjusted to device type; • Make the highest resolutions (4K and 8K) inaccessible over the mobile network on tablets and smartphones, limiting them to technically relevant uses; • Prohibit auto-play and continuous scrolling designs unless there is minimal interaction with the user (e.g. via a "show more" option).
Design the equipment to accommodate a wider section of traffic than the busy hour.
Objective 2: Enable the paradigm shift that will drive new choices in infrastructure, with the aim of making it leaner.
Generalise automatic bitrate adaptation to digital services other than video.
Ensure compatibility of (existing, future) mobile network specifications with energy-climate objectives by making trade-offs in coverage and capacity deployment (fixed, mobile, satellite) and service objectives.
Draw up a charter for lean digital data transfers.

Training and skills
Objective: Enable all stakeholders to fully understand the issues at stake and technical requirements necessary to implement new paradigms.
Introduce systematic and compulsory continuous training in energy and climate issues and the impact of digital technology.
Include the knowledge needed to design and deploy eco-designed, lean networks in the initial training of networking professionals.

Conclusion: networks, a pivotal point towards digital sobriety?

The digital sector is currently unsustainable in relation to the dual carbon constraint. The sector operates on a logic of abundance that extends as much to its infrastructures as to the associated usage systems. As a result, the sector's energy and environmental impact is increasing too rapidly to be contained by the dazzling advances in technology and efficiency. This exposes it to a loss of resilience in the face of a probable scarcity of the resources (energy, material) on which it depends.

Digital technologies have become a cornerstone of our societies and their ability to function. A shift to a logic of sobriety and discernment is therefore necessary, but requires us to understand that the **evolution of technical systems is inseparable from that of usage systems, and that our digital infrastructure will only become resilient and decarbonised through methodical and rigorous reflection on the uses it enables.**

Networks, the pivotal point towards sobriety and resilience

The work conducted within the scope of this report has highlighted the **significant impact of collective choices on the dimensioning of mobile networks regarding the development of new services and methods of access (geographical, temporal) to these services.** It seems that only a **combination of eco-design levers (systemic rather than functional) and sobriety is likely to make our mobile networks compatible with the dual carbon constraint:** extending the lifespan of equipment, energy efficiency gains, changing regulatory constraints, sharing, suspending the roll out of 6G as envisaged today, and controlling the growth in usage.

In a next step, it will be necessary, using a "backcasting"[65] approach, to develop a quantitative vision for the entire network infrastructure (fixed networks, mobile networks, satellite networks) in order to identify a trajectory compatible with the dual carbon constraint. While developments in fixed networks over the next decade are largely determined by strategic choices that have already been made, the satellite segment is a newcomer to the network ecosystem, with far from negligible ambitions that have yet to be determined and that could have a decisive impact on the environmental impact of the system as a whole.

If data centres are the beating heart, networks are the nervous system of the global digital world. As such, the players and stakeholders in this ecosystem who design, operate, and use them can drive essential structural transformations necessary for building a digital landscape that is commensurate with this century's challenges. Because they are familiar with the materiality and realities of the inertia and possibilities at the crossroads of the technical system and the systems of uses that connect to it, the network players have a

[65] See "The 'backcasting' approach, a tool for building a lean digital future" section, p. 44.

vision that naturally combines the two key ingredients - physical and systemic - of the challenges that will be ours for several decades to come.

Planning the decarbonisation of the digital system

Given the pivotal role played by digital technologies in our essential uses (mobility, social and cultural interaction, industrial value chains and food supply chains, governance and public services, etc.), **the recognition that a technological choice is a societal choice** has become inescapable.

In our previous reports, documenting how the 5G debate unfolded in 2020 (The Shift Project, 2021) as well as the necessary levers to be implemented now to plan the decarbonisation of the digital system in France (The Shift Project, 2023b), we recommended following the steps for building and deploying a digital decarbonisation plan:

- **Produce a reference trajectory** for the decarbonisation of the digital sector, to be incorporated into the National Low Carbon Strategy (SNBC3) and into the General Secretariat for Ecological Planning (SGPE)'s feedback work;
- Drive the production of roadmaps by the sector's economic players and the territories, by adapting the consolidated national strategy;
- **Create a space for consultation** (citizens' and companies' conventions, expert interviews, institutional assignments and/or other modalities);
- **Ensure that the roadmaps drawn up by the players are monitored and reviewed** by the public authorities, based on standardised quantitative measurements and indicators endorsed by the academic and expert communities.

This planning should make it possible to identify and organise the implementation of the **four main sets of levers to be mobilised in order to decarbonise the digital system:**

- **Measurement and transparency:** without measurement, informed prioritisation is impossible. Without transparency, there can be no reliable measurements or orders of magnitude;
- **Optimisation**: this is a complementary lever that is only truly useful if services remain constant, and must therefore be coupled with mechanisms to avoid rebound effects;
- **Collective reorganisation of uses to achieve sobriety**: this is the disruptive transformation of uses and economic models, without which decarbonisation objectives cannot be achieved;
- **Training and skills**: effectively implementing roadmaps at the appropriate level of ambition requires the players (manufacturers, operators, businesses, institutions) to acquire and harness the necessary skills and human resources.

Creating the right conditions for an informed societal debate

Designing spaces for co-constructing trajectories and strategies is essential if we want to ensure a good match between the specificities of our networks, the needs they address, and the constraints that apply to them. They must enable us to align the level of stakeholders' knowledge on the subjects of decarbonisation and digital resilience and facilitate a national (and territorial) debate on the role of digital technology in the transformed society.

These forums should involve:

- Public authorities,
- Regulatory bodies,
- Professional communities,
- The economic players concerned,
- Civil society,
- Society at large.

Technological choices, no matter how they are made, must be informed and driven by a consideration of the societal elements that have emerged during debates in recent years. **The transformation of our digital systems cannot be based solely on technological levers or exclusively on individual behavioural modifications. It will require consultation and coordination between all stakeholders.**

Documenting the benchmarks for a French, European, and international digital economy that is truly coherent with this century's challenges, will require putting the necessary energy into building a systemic vision of the digital system as a whole, that is accessible and usable by the players as benchmarks for their own transformation and that of their ecosystems, suppliers, value chains, and partners. Describing the range of possibilities for our equipment and services, once they are compatible with the dual carbon constraint. This vision will be the basis for informing the debate on the organisation of the digital system: infrastructure governance, data sovereignty, cybersecurity, underlying business models, etc... To set a course and a method for navigating a digital system designed for the 21st century.

THE SHIFT PROJECT

The Shift Project is a think tank working towards a post-carbon economy. As a non-profit organization recognized as being in the public interest and guided by the demands of scientific rigor, our mission is to enlighten and influence the debate on the energy transition in Europe. Our members are large companies that want to make the energy transition their priority.

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Graphic design

Cover illustration : Virgile Bellaiche
Layout : Karine Pellan