Assessing the carbon footprint of shutting down 2G and 3G networks and migrating their services to 4G/5G

Detailed Report

Mobile Network Technical Experts Committee

September 2023

FOREWARD

The Technical Expert Committee on Mobile Networks was set by Arcep in 2018. Made up of technical experts working over a long-term horizon, the Committee may provide an independent technical recommendation/insight enabling to share views and to build up a sectoral consensus on any technical topic relating to mobile networks and technologies. Chaired by Catherine Mancini from NOKIA, the secretariat and management of the Committee are provided by Arcep.

Committee's published studies

Title of the study	Publication date
Committee's report on technical coexistence issues in 3,4 - 3,8 GHz band	05/2019
Energy assessment of 4G vs 5G deployment	01/2022
Assessing the carbon footprint of shutting down 2G and 3G networks and migrating their services to 4G/5G	09/2023

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Assessing the carbon footprint of shutting down 2G and 3G networks and migrating their services to 4G/5G

Mobile Network Technical Experts Committee

Detailed report of the study

1. Study objective and framework

The current level of 4G coverage – which is poised to equal that of 2G and 3G[1] – combined with the steady growth of the number of 4G-compatible devices in circulation, raises the question of how necessary it is to maintain 2G and 3G networks across the country. Moreover, the growing demand for mobile data driven chiefly by 4G and 5G may justify having frequency resources currently allocated to 2G and 3G networks being reused by more recent and more spectrum-efficient 4G/5G technologies.

For any operator, the decision to shut down 2G/3G technologies is a strategic one that involves multiple considerations such as operational constraints, technical considerations, market strategy, skills maintenance, etc. It is particularly worth noting that the technology mix makes operating a network an increasingly complex undertaking, and that maintaining the skills and knowledge needed to manage and optimise older technologies is a real challenge as 4G and 5G networks become more and more complex.

Three mobile network operators in France have already provided information about their planned 2G/3G network shutdowns. This is part of a global shift towards more modern and more spectrum and energy-efficient technologies which are better suited to mobile network customers' current and future behaviours. The Global Mobile Suppliers Association (GSA) identified 142 operators[2] that have announced the forthcoming or already completed shutdown of their 2G and/or 3G networks.

Environmental concerns also factor in to these decisions; moreover the topic has now become a matter of public debate.

The Mobile Technical Experts Committee, which Arcep created in October 2018, began conducting technical work to assess the carbon footprint impact of shutting down 2G/3G networks in France and migrating their services over to 4G/5G. The Committee members include experts representing mobile network operators and equipment suppliers, along with participants from academia and French National Frequency Agency, ANFR. It is chaired by Catherine Mancini, and Arcep assumes its secretarial duties. The Committee's composition can be found in *Annex E: Composition of the Experts Committee*

This study is the deliverable of that work. Aimed at public actors in particular, it seeks to provide qualitative and quantitative input on the environmental issues surrounding 2G/3G network shutdowns, such as climate change.

Assessing these networks' energy consumption makes it possible to measure the scale of the energy issue, and to lay out an initial analysis.

[1] https://monreseaumobile.arcep.fr/

[2] https://gsacom.com/paper/2G/3G-switch-off-october-2022-summary/

The shutdown of 2G and 3G networks and the migration of their services will have energy-related and material impacts that will be quantified: the possible obsolescence of material elements of the networks and devices that belong to the Information and Communications Technologies (ICT)[3] sector is also examined.

This study is not meant to replace a detailed report that an operator would produce about its own network, but rather to assess the carbon-related benefits of such a migration.

Attached to this memorandum is an FAQ document about the study.

All feedback on this report is welcome, and can be submitted by e-mail (before 30/12/2023) to: ComiteExpertsMobile@arcep.fr

2. Assessing the carbon footprint impact of replacing 2G/3G networks

2.1. Introduction

In one initial approach to the problem, the study examined 2G/3G networks' share of mobile operator networks' total energy consumption by conducting two complementary analyses that made it possible to obtain an estimated range, and to pinpoint trends: a "generic" analysis that considered the profile of an average generic operator with an average (for all operators combined) distribution of cell sites, and a "specific" analysis based on primary data provided an operator who is a Committee member.

To situate the assessment in a more realistic shutdown timeframe, for both analyses, 2G and 3G networks' energy consumption is evaluated both currently and up to 2025, factoring in the regulatory obligations that are due to be in place by the time[4].

The detailed description of the assumptions and computational method of each of the two approaches can be found in the memo's *Annex A: Calculating 2G/3G networks' energy consumption*.

The different results obtained through the two approaches constitute different items of evidence indicating that 2G and 3G networks account for **a not insignificant share of mobile networks' power consumption**. 2G and 3G networks currently represent between 21% and 33% of all network base stations (aka cell towers), a figure that could stand at around 17% by 2025 depending on the assumptions considered.

Far from being insignificant, this share of energy consumption raises the question of what savings could be expected from shutting down these networks.

However, because 2G/3G enables services such as voice and M2M, it is impossible to simply cut off these technologies as the future of these services needs to be guaranteed which, alternatively, could be ensured by the use of 4G/5G technologies. This switchover to 4G/5G technologies could only happen in the medium or long term given the operational and business constraints involved in such a migration.

As a result, in what follows, the study assesses the environmental effects, such as climate change, of shutting down 2G and 3G technologies, and migrating their services to 4G/5G technologies.

[3] As per Recommendation ITU-T L.1450 "Methodologies for the assessment of the environmental impact of the information and communication technology sector" (09/2018)

[4] https://www.arcep.fr/fileadmin/user_upload/grands_dossiers/5G/procedure-attribution-band-3_5GHz-obligations.pdf

The memorandum progresses through two main chapters that describe the methodology used and assumptions applied, followed by the findings and conclusions, and onto *Annex B: Carbon footprint impact of replacing 2G/3G networks* detailing different elements examined in these two Chapters.

2.2. Methodology and assumptions

2.2.1. Methodological framework

The methodology will be based on a comparison of two scenarios:

- A reference scenario with 2G and 3G
- A migration scenario for replacing 2G and 3G with 4G/5G

Different considerations help to understand how to define these scenarios:

- 2G currently uses the 900 MHz band. The different mobile operators are in the process of migrating the 2.1 GHz band to 4G or 5G, with 3G using only the 900 MHz band. The study's assumption is therefore that all 2G and 3G services only use base stations operating in the 900 MHz band.
- 2G and 3G primarily relay voice and M2M services. Another simplified assumption is that the study must focus on these two services.
- Under the migration to 4G/5G scenario, services that are still using 2G/3G on the day of the migration (M-Day) are carried on a low-band frequency. A low-band frequency is needed to achieve good coverage for voice and M2M services which were previously using the 900 MHz band with 2G/3G technologies.
- As a result, and to simply compare the two scenarios, under a first option it is supposed that all voice and M2M traffic using 2G and 3G technologies remain on the 900 MHz frequency band under the migration scenario. Another option examined is the case where these services use another target frequency such as the 700 MHz band under the migration scenario.

The methodology is based on assessing the differences between a reference scenario and a migration scenario:

- Reference scenario: voice and M2M services using a so-called reference 2G and 3G mobile network[5] in the 900 MHz band.
- Migration scenario: <u>the same voice and M2M services</u> using a 4G/5G mobile network, all of whose 2G and 3G reference network equipment has been upgraded to 4G/5G on M-Day.

It should be noted that migration day (or M-Day) corresponds to the moment when the two 2G and 3G technologies have been migrated to 4G/5G in the case of the migration scenario. This does not mean that the two technologies were migrated at the same time, keeping in mind that this study does not assess the intermediate situation before migration day, during which only one of the two technologies (2G or 3G) has been migrated.

The migration scenario is compared to the reference scenario for the reference operator's mobile network in Metropolitan France, over a one-year period.

The migration considered involves having the services using one or several old technologies – i.e. chiefly voice and M2M – use 4G/5G instead.

The following two cases were examined for the migration scenario:

[5] The reference network is defined in Chapter *2.2.3*

- Services that are still using 2G/3G on M-Day are carried on the 900 MHz band using 4G/5G.
- These same services are relayed over 4G/5G on another low-band frequency[6] such as the 700 MHz band.

The following different phases of the life cycle are included in the comparative analysis:

- Extraction of raw materials, production and distribution.
- Use: the energy consumption of different network equipment and certain data centre servers (e.g. IMS)

The end of life phase for equipment is not assessed (except for smartphones).

All of the equipment considered in the study belongs to the Information and Communications Technologies (ICT) sector, as defined by Recommendation ITU-T L.1450. Its scope details the systems under study and rules of exclusion from the study are described in Chapter *4.2 Boundaries of the systems under study and rules of exclusion*.

2.2.2. Methodology

In the case of a comparative analysis, if the goal is to assess the difference in impact between two product systems, rather than the total impact of each product system, the process and the input/output data can be excluded if they are identical for both product systems[7] (in this case, between two ICT services).

Based on the comparative functional diagram, the following table summarises the identified differences between the reference scenario and the migration scenario, which are evaluated as part of the comparative analysis.

Table 1 – Differences between the reference and the migration scenarios

Product category	Equipment	Differences identified	Observations (exclusions, allocations etc.)
Data centres	IoT/M2M service platform	Same platform: No evaluation required	
	IMS servers (for voice and SMS over LTE)	Only use phase needs to be examined	Impact disregarded[8]
Networks	Core network	Core network circuit in the case of the reference scenario with a configuration that could be kept in the reference scenario[8]	Impact disregarded[8]
	Backbone network	Same network: No evaluation required	

[6] A low-band frequency is needed to achieve good coverage for voice and M2M services which were previously using the 900 MHz band with 2G/3G technologies.

[7] As indicated in the general comments in the second part of Recommendation ITU-L 1410.

[8] See Chapter: *Summary of exclusions for* the purposes of the study *part of the study* in Annexe B for further details

	2G/3G RNC	Hardware removed in the case of a migration. Only use phase needs to be examined	Impact disregarded (in keeping with the cut-off rules[8])
	Aggregation/backhaul network	Same network and same volume of traffic: No evaluation required	
	900 MHz cell sites (excl. base stations)	Same components: No evaluation required	
	900 MHz band base stations	Production phase to be examined for the migration scenario if new hardware deployed on M-Day. Use phase to be examined	It is supposed that installed network equipment is 4G/5G-ready (no new hardware needed) Allocation rule needed to consider voice/M2M services' share of the carbon footprint during 900 MHz band base stations' 4G/5G use phase
Mobile phones	Non-VoLTE smartphones	Production phase to be examined following the premature replacement of non-VoLTE-compatible smartphones under the migration scenario.	Factoring in the remaining share of smartphone's life when amortising its embodied carbon Factoring in the case of refurbished smartphones
	Feature phones	Production phase to be examined following the premature replacement of feature phones with VoLTE-compatible phones under the migration scenario	Factoring in the remaining share of the feature phone's life, when amortising its embodied carbon
Connected objects	2G/3G cellular IoT	Production phase to be examined following the premature replacement of 2G/3G-only cellular IoT modules with 4G/5G-compatible IoT modules under the migration scenario	Factoring in the remaining share of IoT device's life, when amortising its embodied carbon Only the connected object's connectivity module (modem) is considered in the evaluation

For each set of equipment in the comparative functional diagram it is also important to examine whether voice and M2M services are the only ones to use that set of equipment, or if other services also use it.

In the latter case, all of the equipment is shared by several services, and a rule for allocation between these services needs to be defined[9].

In the case of the 2G/3G reference scenario, voice and M2M services are the only ones to use the set of equipment to be assessed.

Under the migration scenario, however, 4G/5G base stations are also used by the data service, which means an allocation rule needs to be defined.

[9] See Chapter: 6.3.3.9 of Recommendation ITU-T L.1410 for the ICT services allocation procedure

The Chapter on Assumptions as well *Annex B: Carbon footprint impact of replacing 2G/3G networks* provide a detailed description of the allocation rule for these base stations.

LCA impact data for the different equipment to be assessed for the two scenarios will be calculated based on the scope and rules of exclusion and the allocation rules, then summed up for each scenario.

2.2.3. Assumptions

The reference network needs to be defined in detail for all of the equipment included in the comparative functional diagram:

- The number of 900 MHz band base stations considered for the reference network will be the average of the number of 2G/3G networks' 900 MHz band base stations in Metropolitan France, extrapolated on M-Day (see Chapter: *Evaluation of the number of 900 MHz-band base stations on M-Day*).
- It is assumed that an operator will regularly upgrade and replace their 2G/3G 900 MHz-band base stations, such that on Migration Day all of the network equipment will be 4G/5G-ready[10], i.e. compatible with MIMO 2x2, and this for both of the scenarios[11].
- The other migration cases studied for the services being considered is the use of another target low-band frequency (such as the 700 MHz band) which is already being used by 4G/5G.

The production phase does therefore not need to be evaluated for the network portion in these two scenarios.

For the voice traffic being considered in the study as of Migration day, the study is based on the following assumption:

- The volume of voice traffic is considered constant for both scenarios. This traffic is evaluated based on known voice traffic at the end of 2021 and a percentage of this traffic remaining on 2G/3G on M-Day. (see Chapter: *Assessment of voice traffic Erlangs during the busy hour*).

M2M/IoT traffic on a mobile network will be evaluated to better understand its impact on this study.

4G/5G base stations using the 900 MHz band are shared between voice/M2M services on the one side and data services on the other.

The following approach will therefore provide the ability to define an allocation rule for 4G/5G base stations:

- The power consumption of a 4G/5G base station is the sum of a fixed portion (powering the different RRU electronic circuits, transmission of common channels in the different sectors, and BBU equipment), and a variable portion which is proportionate to the base station's load.
  - The variable portion of the power consumption that comes from migration scenario traffic needs to be kept in its entirety.
  - However, the fixed portion of power consumption must be shared between voice/M2M and data services as the corresponding resources (powering the different RRU electronic circuits, common transmit channels, BBU) are indeed shared: the allocation rule can only factor in a percentage of the fixed portion of the base station's

[10] Even if the study does not make an assumption of the exact date of Migration Day, for operational reasons this date is relatively far off, all of the reference operator's 900 MHz band base stations will have been upgraded by that date to be compatible with 4G and 5G technologies due to the obsolescence of older hardware and its replacement.

[11] In the case of 2G/3G, it should be noted that there are additional environmental effects from maintaining these technologies in working condition, such as replacing parts on obsolescent hardware for 2G/3G radio network controllers (BSCs, RNCs) and their maintenance.

power consumption for the migration scenario in the case where the 900 MHz band is used for the migrated services (see Chapter: *Results and conclusions* and *Annex B: Carbon footprint impact of replacing 2G/3G networks* for detailed explanations and illustrations).

2.3. Results and conclusions

2.3.1. Introduction

The difference between a 2G/3G and a 4G/5G base station's power consumption is determined, first, using a literal equation.

This difference depends on voice traffic during a base station's peak traffic time (i.e. busy hour) M-Day: this traffic is then measured.

After which a numeric value is calculated.

2.3.2. Determining the difference between a 2G/3G base station and a 4G/5G base station's power consumption

The following calculation determines the difference between a 2G/3G and a 4G/5G base station's power consumption over the course of one day, with both using the same frequency band and the allocation rule.

M2M/IoT traffic is evaluated at between 6 MB and 24 MB per day, per cell on the mobile network[12], which means that the 4G/5G network will need to relay very little traffic at peak load time: only voice traffic affects the load and is taken into consideration in the following assessment.

The assumption is that a 2G/3G or 4G/5G base station's instantaneous electrical consumption expressed in kilowatts can be approximated by a linear function of the kind: ***a*x + b*** (where ***x*** is the load and ***a*** and ***b*** two coefficients expressed in kW).

The following curve (*Figure 1*), which is representative of the situation in France[12], provides the standardised load (i.e. maximum load = 100%) for a base station's voice traffic over the course of a day.

Distribution of daily voice traffic

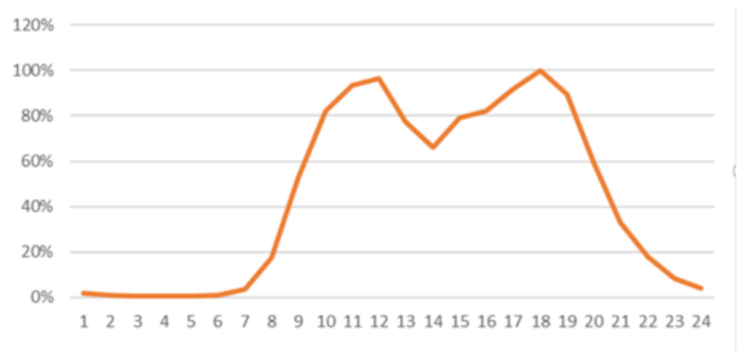

Figure 1 – Typical curve of the distribution of daily voice traffic

The average of this standardised curve is equal to 44%. The busy hour represents 9.4% of the day's total traffic.

[12] Based on information provided by an operator who is a Committee member, and a discussion with the other members.

A base station's instantaneous electrical consumption (in kW) will thus be calculated as follows:

- Consumption (t) = a*L(t) + b, where L is the period function of the 24-hour period deduced from the standardised brown curve above by multiplying it by the maximum load (BH load) during the busy hours for voice traffic.

To calculate the base station's total consumption for the entire day, expressed in kWh, its instantaneous consumption over the 24 hours of the day needs to be integrated as follows:

BS-consumption (kWh) = $\int_{t=0}^{24}(a * L(t) + b)dt = a * \int_{t=0}^{24} L(t)dt + 24b$= **24 (a * Average (L) +b)**

With Average (L) = Max-Voice Load* A, with A = Average (brown standardised curve) = 44%

BS-consumption (kWh) = 24 (a * A * Max-Voice-Load + b),

For 2G/3G, this gives:

BS_{23}-Consumption (kWh) = 24 (a_{23} * A * Max-Voice-Load$_{23}$ + b_{23})

And for 4G/5G with these same voice and M2M services, without the allocation function, this gives:

BS_{45}-Consumption (kWh) = 24 (a_{45} * A * Max-Voice-Load$_{45}$ + b_{45})

i.e. Max-Load: maximum load for a 4G/5G base station considered during the busy hour for voice, M2M and data services.

Factoring in the allocation function, we therefore get:

BS_{45}-Consumption-alloc (kWh) =

24 (a_{45} * A * Max-Voice-Load$_{45}$ + b_{45}* Max-Voice-Load$_{45}$/Max-Load)

I.e. MaxVoiceTraffic: maximum voice traffic during the 2G/3G and 4G/5G base station's busy hour, expressed in Erlangs. This traffic corresponds to the voice traffic remaining on 2G/3G on M-Day, and relayed over a base station.

Max-Voice-Load$_{23}$ = MaxVoiceTraffic/MaxVoiceCapacity$_{23}$, with MaxVoiceCapacity$_{23}$ expressed in Erlangs

Max-Voice-Load$_{45}$ = MaxVoiceTraffic/MaxVoiceCapacity$_{45}$, with MaxVoiceCapacity$_{45}$ expressed in Erlangs

For 2G/3G, this means:

BS_{23}-Consumption (kWh) = 24 (a_{23} * A * MaxVoiceTraffic/MaxVoiceCapacity$_{23}$ + b_{23})

Factoring in the allocation function, we therefore get:

BS_{45}-Consumption-alloc (kWh) = 24 (a_{45} * A * MaxVoiceTraffic/MaxVoiceCapacity$_{45}$+ K * b_{45})

With K = (MaxVoiceTraffic/MaxVoiceCapacity$_{45}$)/Max-Load

K is the coefficient of the b_{45} allocation rule.

2.3.3. Assessment of voice traffic Erlangs during the busy hour

To evaluate voice traffic Erlangs on every mobile network in France, the following needs to be determined on these mobile networks:

- Voice call traffic originating on mobiles in France
- Mobile to mobile voice call traffic in France
- Fixed to mobile voice call traffic in France
- Voice services traffic originating on mobiles in France

All of these voice calls need to be considered to determine total Erlangs of traffic.

The ARCEP document [ARCEP – 2022] on electronic communications services in France provides information on these different traffic streams. The figures used are from Q4 2021.

Trafic de la téléphonie mobile selon le mode de souscription *(en millions de minutes)*	T4 2020	T1 2021	T2 2021	T3 2021	T4 2021	Variation T421/T420
Abonnements et forfaits	*53 571*	52 881	*52 610*	*48 174*	50 624	-5,5%
Cartes prépayées	*1 855*	1 789	1 786	1 706	1 654	-10,9%
Trafic de communications vocales au départ des mobiles	***55 426***	**54 671**	***54 396***	***49 880***	**52 278**	**-5,7%**
dont communications mobiles en voix sur Wifi	1 792	1 920	1 855	*1 747*	2 153	20,2%

Figure 2 – Mobile traffic statistics by subscription type

Trafic de la téléphonie mobile par destination d'appel *(en millions de minutes)*	T4 2020	T1 2021	T2 2021	T3 2021	T4 2021	Variation T421/T420
Communications mobiles vers fixe national	7 908	7 548	*7 170*	*6 386*	6 612	-16,4%
Communications mobiles vers mobiles nationaux	45 635	45 329	*45 375*	*41 133*	43 725	-4,2%
Communications mobiles vers l'international	857	812	811	798	733	-14,4%
Roaming out *	*1 027*	981	1 040	1 562	1 209	17,7%
Trafics de communications au départ des mobiles	***55 426***	**54 671**	***54 396***	***49 880***	**52 278**	**-5,7%**

(*) Le "roaming out" correspond aux appels émis et reçus à l'étranger par les clients des opérateurs mobiles français.

Figure 3 – Mobile traffic statistics by call destination

Trafic de "Roaming in" des opérateurs mobiles	T4 2020	T1 2021	T2 2021	T3 2021	T4 2021	Variation T421/T420
Communications vocales (en millions de minutes)	1 226	*1 237*	*1 275*	*1 610*	1 333	8,8%
Trafic de SMS (en millions)	99	*94*	105	*206*	137	38,3%
Consommation de données (en teraoctets)	17 710	*18 548*	*23 064*	*52 595*	37 279	110,5%

Les chiffres en italique ont été modifiés par rapport à la publication précédente.

Figure 4 – Roaming-in mobile traffic statistics

Voice call traffic originating on mobiles on French networks is determined in the following manner, based on data on electronic communications services in France:

- Calling traffic originating on mobiles – voice over Wi-Fi – roaming out + roaming in

Communications vocales depuis les lignes fixes (en millions de minutes)	T4 2020	T1 2021	T2 2021	T3 2021	T4 2021	Variation T421/T420
Vers fixe national	8 094	7 813	7 074	5 690	6 029	-25,5%
Vers l'international	835	802	735	580	581	-30,3%
Vers les mobiles	3 714	3 655	3 511	3 006	2 983	-19,7%
Ensemble des communications depuis les lignes fixes	**12 642**	**12 269**	**11 319**	**9 277**	**9 594**	**-24,1%**

Figure 5 – Statistics on voice traffic originating on fixed lines

Trafic vers les services vocaux à valeur ajoutée (en millions de minutes)	T4 2020	T1 2021	T2 2021	T3 2021	T4 2021	Variation T421/T420
Au départ des clients des opérateurs fixes	605	617	567	552	543	-10,1%
Au départ des clients des opérateurs mobiles	692	670	664	661	704	1,8%
Trafic total	1 296	1 287	1 231	1 213	1 247	-3,8%

Figure 6 – Statistics on traffic to value-added voice services

		Comments
Selected time period	Q4 2021	
Mobile outgoing voice traffic (quarterly; millions of minutes)	50624	ARCEP value
Outgoing Voice over WIFI traffic	2153	ARCEP value
Roaming out traffic	1209	ARCEP value
Roaming in traffic	1333	ARCEP value
Mobile outgoing voice traffic (quarterly; millions of minutes)	48595	Voice over WIFI subtracted Roaming out subtracted Roaming in added
Incoming mobile calls to national mobiles	43725	ARCEP value
Incoming fixed calls to mobiles	2983	ARCEP value
Value added services	704	ARCEP value
Total voice communications traffic on mobile networks (over one quarter; in millions of minutes)	96007	Outgoing calls +Mobile2Mobile+ fixed to mobiles + voice services
Total voice communications traffic on mobile networks (over one day; in millions of minutes)	1052	Divided by the number of days in a quarter
Total voice traffic on mobile networks (at busiest time; in millions of minutes)	99.16	Multiply by the share of traffic at the busy hour
Number of parallel voice calls in the busiest hour on all networks (in millions of calls) --> number of millions of Erlang in the busiest hour	1.65	Number of minutes of communication per busy hour / 60

Figure 7 – Synthesis of mobile traffic statistics for Metropolitan France for the reference operator

For the reference scenario, it is estimated that voice traffic representing 10% of all voice traffic[13] at the end of 2021 will still be on 2G/3G on M-Day. 20% of the voice traffic remaining on 2G/3G is also examined as part of a sensitivity analysis (see Chapter on *Sensitivity analysis*).

To determine voice traffic on a base station on the day of the migration (M-Day), an assessment needs to be made of the number of base stations in existence on that date (see Next Chapter).

2.3.4. Evaluation of the number of 900 MHz-band base stations on M-Day

The goal of this Chapter is to evaluate the number of 900 MHz-band base stations on M-Day.

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[13] Based on an assessment by an operator who is a Committee member and accepted by consensus amongst Committee members.

A history of the growth in the number of 900 MHz-band base stations is provided below, to better understand the evaluation required.

Among the different observatories published by French national frequency agency, ANFR **[ANFR – 2023]**, the number of GSM900 MHz and UMTS900 MHz band base stations as of 1 January, from 2017 to 2022, is listed in the following table:

For each operator, the number of 900 MHz-band base stations is considered to be equal to:

- Max (GSM900, UMTS 900)

Table 2 – 900MHz base station statistics in Metropolitan France, by operator

	1/1/2017	1/1/2018	1/1/2019	1/1/2020	1/1/2021	1/1/2022
GSM 900 ORANGE	18181	18457	18871	18976	18961	19210
GSM 900 SFR	17232	18379	19534	19563	19696	19954
GSM 900 BYT	12560	14893	17612	18838	19350	20013
GSM 900 FREE	0	0	0	0	0	0
TOTAL GSM 900	**47973**	**51729**	**56017**	**57377**	**58007**	**59177**
UMTS 900 ORANGE	13583	16738	18976	21781	24254	26645
UMTS 900 SFR	13254	16317	18629	19510	20655	21770
UMTS 900 BYT	8921	11933	15459	18650	20422	21660
UMTS 900 FREE	8487	12082	14422	16961	19330	21572
TOTAL UMTS	**44245**	**57070**	**67486**	**76902**	**84661**	**91647**
Base stations 900 MHz ORANGE	18181	18457	18976	21781	24254	26645
Base stations 900 MHz SFR	17232	18379	19534	19563	20655	21770
Base stations 900 MHz BYT	12560	14893	17612	18838	20422	21660
Base stations 900 MHz FREE	8487	12082	14422	16961	19330	21572
TOTAL Base stations	**56460**	**63811**	**70544**	**77143**	**84661**	**91647**

Table 3 – Rate of progress of 900MHz base station deployment by operator

Increase per year	2017	2018	2019	2020	2021	Common ratio of geometric sequence-1 over 5 years	Common ratio of geometric sequence -1 over 3 years
Base stations 900 MHz ORANGE	1.5%	2.8%	14.8%	11.4%	9.9%	*7.9%*	*12.0%*
Base stations 900 MHz SFR	6.7%	6.3%	0.1%	5.6%	5.4%	*4.8%*	*3.7%*
Base stations 900 MHz BYT	18.6%	18.3%	7.0%	8.4%	6.1%	*11.5%*	*7.1%*
Base stations 900 MHz FREE	42.4%	19.4%	17.6%	14.0%	11.6%	*20.5%*	*14.4%*
TOTAL Base stations	13.0%	10.6%	9.4%	9.7%	8.3%	*10.2%*	*9.1%*
Previous year's evolution ratio		81.0%	88.7%	104.2%	84.7%		

Looking at these different figures, it is considered that in 2022 and the following years, the number of 900 MHz-band sites progresses chiefly according to the number of new physical cell sites created, with the following assumptions:

- The percentage of new cell sites in the 900 MHz band in 2022, all operators combined, was 5%.
- The year on year (YoY) percentage increase in the number of sites is equal to 80%[14] of the previous year's increase: i.e. the rate of increase.

Year	2022	2023	2024	2025	2026	2027	2028
Increase per year	5.0%	4.0%	3.2%	2.6%	2.0%	1.6%	1.3%
Cumulative increase since 2021	5.0%	9.2%	12.7%	15.6%	17.9%	19.9%	21.5%

Figure 8 – Rate of increase for 900MHz sites up to 2028

The table ends in 2028 as, with this model, the increase would stand at around 1% in 2029, and lower still the following year, which becomes insignificant.

Thus, with 91,647 900 MHz-band sites in 2021 and the model used, we obtain around 110,000 900 MHz-band sites all operators combined on M-Day[15] (or 27,500 sites for the operator of the modelled reference network).

[14] Value chosen by Committee members for future years and corresponding to the low-end range of the previous years' rate of increase.

[15] It is supposed that the closest Migration date is 2028. Keeping in mind that the number of 900 MHz-band sites is not likely to increase significantly after that date in 2028. 27,500 900 MHz-band sites for the operator of the modelled reference operator is applicable for every Migration date in this study.

2.3.5. Calculation of the numerical value of the difference in the electricity consumption of 2G/3G and 4G/5G base stations in the 900 MHz band

In its tables 24 and 26, the "JRC Science for Policy Report" (see [JRC – 2023]) provides the power consumption of a GSM/EDGE base station and an LTE base station in three states: "Busy-load-state", "Medium-Load-State" and "Low-load-state".

The ETSI ES 202 706-1 v.1.6.1 standard (see [ETSI – 2018]) found in Annexes B and D, respectively, provide the reference boundaries for a GSM/EGDE and an LTE system:

- For GSM:
  - Table B.1 indicates that "Low-load-state" traffic corresponds to only BCCH (shared GSM channels) transmissions with the other TRX in "idle" mode;
  - Table B.2 indicates that "Busy load state" traffic corresponds to 50% of the maximum traffic that the base station can process.
- For LTE:
  - The definition of "Low-load-state" traffic shows that the shared channels' signals are transmitted, but no data are relayed;
  - The definition of "Busy load state" shows that 50% of the physical resource blocks (PRB) for the data are transmitted.

In both cases, then, the "Low load" corresponds to a load of 0%, and the "Busy load" corresponds to a load of 50%.

In other words, **Low-Load** and **Busy-Load** express in Watts the base station's respective "low load" and "busy load" consumption as indicated in the document [JRC – 2023].

With the linear model used[16]:

BSConsum (x) = a *x + b expressed in W with x representing the base station load

BSConsum (0) = b = **Low-Load**

BSConsum (50%) = ½ a + b = ½ a + **Low-Load = Busy-Load**

To determine the values of a and b sought, we have:

- b= **Low-Load**
- a= 2*(**Busy-Load – Low-Load)**

The values for a "Radio Unit power of <= 200 W" are used

Table 4 – Parameters of the 2G/3G and 4G/5G base station power consumption model

2G/3G		4G/5G		2G/3G		4G/5G	
BS: Busy-load	BS: Low-load	BS: Busy-load	BS: Low-load	BS: a	BS:b	BS: a	BS:b
855.0	585.0	780.0	560.0	540.0	585.0	440.0	560.0

Note that for this study, it is value b for 2G/3G that will most heavily influence the results of the study, compared to the other "a" and "b" values.

[16] For instance, as explained in Recommendation L.1390 ([ITU – 2022]) on this topic

In the case of 2G/3G, the channels shared by 2G and 3G are transmitted, while the determined value of b only factors in 2G common channels (and the remainder of the base station's energy consumption does not depend on the load of the BBU and other constant elements in the rest of the base station).

Value "b" of a 2G/3G base station is therefore higher than the value "b" determined here: the base station's power consumption is therefore probably minimised, giving lower savings resulting from the migration to 4G/5G. This will be covered by the sensitivity analysis performed.

The base case is assessed based on voice traffic distributed evenly over all of the base stations.

VoLTE capacity is the one equivalent to the same bandwidth (8.7 MHz), without prejudging the total capacity to be used.

An initial sensitivity analysis is then performed, factoring in the following case of the busiest base stations:

- 80% of voice traffic on 20% of the base stations, corresponding to four times more voice traffic than average;
- 20% of the remaining traffic on 2G/3G on M-Day.

A second sensitivity analysis is performed, considering a maximum 4G/5G load of 25% instead of the base case's 50%, while stressing that 50% is indeed the default value considered by ETSI (as explained above), notably for 4G and 5G.

Table 5 – Results of the network savings calculated for the base case and the two sensitivity analyses

	Type of parameter	Base Case	Sensitivity study	Sensitivity study 2
N°cas étudié pour la partie réseau		1	2	3
M	Common	44%	44%	44%
%voix over 2G-3G	2G-3G	10%	20%	10%
Multiplication factor for the average number of Erlang per base station	Common	1.0	4.0	1.0
Voice Max traffic (per base station, Erlang)	Common	1.5	12.0	1.5
Number of Base Stations at date Tm	Common	110000	110000	110000
VoiceMaxCapacity2	2G	17.4	17.4	17.4
VoiceMaxCapacity3	3G	135.0	135.0	135.0
VoiceMaxCapacity23	2G,3G	152.4	152.4	152.4
a23 (W)	2G,3G	540.0	540.0	540.0
b23 (W)	2G,3G	585.0	585.0	585.0
Consumption-BS23 (kWh) over 24 hours	2G,3G	14.10	14.55	14.10
VoiceMaxCapacity45	4G,5G	600	600	600
Max-Load (including data)	4G,5G	50%	50%	25%
a45 (W)	4G,5G	440.0	440.0	440.0
b45 (W)	4G,5G	560.0	560.0	560.0
K: Coefficient allocation rule for b45	4G,5G	0.50%	4.01%	1.00%
Consumption-BS45 (kWh) per base station, over 24 hours, with allocation rule	4G,5G	0.08	0.63	0.15
Network gain 4G-5G vs 2G-3G /BS over 24 hours (kWh)		14.02	13.92	13.96
4G-5G network gain: reference 2G-3G		99.44%	95.66%	98.96%

The two sensitivity analyses on this network portion, numbered 2 and 3, are also incorporated into the general sensitivity analysis, with the first case constituting the base case.

The savings indicated as a percentage is the consumption avoided by 4G/5G base stations taking 2G+3G base stations' consumption as their point of reference:

$$Consumption\ avoided\ by\ 4G/5G\ vs.2G + 3G\ = (C - Q)/C$$
$$C\ Consumption\ of\ 2G + 3G\ base\ stations\ in\ kWh\ over\ 12\ months\ starting\ on\ M - Day$$
$$Q\ Consumption\ of\ 4G/5G\ base\ stations\ with\ an\ allocation\ rule\ in\ kWh\ during\ those\ same\ 12\ months$$

Shutting down 2G/3G radio network controllers (RNC, BSC) generates additional savings for the 4G/5G scenario, which are not evaluated in the above table (and not incorporated into the 2G/3G reference), but these relatively weak gains[17] do not alter the above conclusion. The same applies to the savings generated by shutting down the core network's mobile switching centre (MSC), which are weaker still.

2.3.6. Using another target low-band frequency for 4G/5G technologies

The methodology is based on an assessment of the difference between a reference scenario and a migration scenario:

- Reference scenario: Voice and M2M services using a "reference" 2G/3G mobile network[18] in the 900 MHz frequency band.
- Migration scenario in this case: The same voice and M2M services using a 4G/5G mobile network wherein all of the 2G and 3G reference network equipment has been upgraded to 4G/5G on M-Day using another target low-band frequency (such as the 700 MHz band) which is already being used by 4G/5G.

The assumption is that on M-Day different services, including data, are already making substantial use of the target frequency band considered for 4G/5G.

4G/5G base stations in the target frequency band (e.g. 700 MHz) are therefore shared, on the one hand, between voice, M2M services from 2G/3G technologies and, on the other, services including data services using the target band on M-Day.

We therefore find ourselves in a situation analogous to the case of porting 2G/3G services to the 900 MHz band, with the same approach to defining the allocation rule, identical calculation principles and the same conclusion.

It should be noted that a simple way to understand this case is to consider that the very minimal voice traffic will generate very little additional energy consumption for 4G/5G base stations in the target band (e.g. 700 MHz), which means that what is saved is virtually the totality of 2G/3G energy consumption in the 900 MHz band.

2.3.7. Conclusions on the network portion

In terms of the 2G/3G voice traffic capacity of a three-sector 900 MHz cell site (152.4 Erlangs), 2G/3G voice up to Migration day is very light (between 1.5 and 12 Erlangs, or 1% to 8% of total capacity) and indicates that the 900MHz band would therefore be underused, and the band's energy efficiency would be very low.

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[17] 2G/3G radio network controllers' energy consumption represents a few percent of 2G/3G 900 MHz-band base stations' energy consumption (see *Boundaries of the systems under study and rules of exclusion* in Annex B).

[18] The reference network is defined in the Chapter: *Assumptions*

Switching voice/M2M services using the 900MHz band over to 4G/5G would make the voice traffic load lighter still, by the magnitude of VoLTE capacity (600 Erlangs), as a result of which 1.5 Erlangs and 12 Erlangs of voice traffic correspond to only 0.25% and 2% of the base station's voice capacity. As the base station's remaining capacity (i.e. virtually its entirety) will thus be used for data traffic, voice traffic will account for only a tiny portion of the power consumption. This is what is modelled by the allocation rule's K coefficient. Among other things, this explains why these energy savings are a major impetus for migrating to 4G/5G.

In the case where another target low-band frequency (e.g. 700 MHz) would be used for 2G/3G services, shutting down 2G/3G would also result in very significant energy savings.

2.3.8. Factoring "ICT end-user goods" into the results

The "*Boundaries of the systems under study and rules of exclusion*" Annex describes the study's scope of reference including the network portion, and mobile phones and smartphones for ICT end-user goods. Connected objects used for machine-to-machine communications (M2M/IoT) are included as part of the extended scope of reference.

This study is constructed by assessing the difference in the carbon footprint of the reference scenario of keeping 2G and 3G, and a migration scenario where 2G/ 3G are replaced by 4G/5G, and this starting on Migration day (M-Day) – i.e. the date when both 2G and 3G technologies have been migrated to 4G/5G.

This means that for mobile phones, smartphones and M2M connected objects, a calculation needs to be made of how many of these devices will not be 4G/5G-compatible on M-Day, and which will therefore need to be replaced at that time, in addition to factoring in the remaining percentage of those devices' lifespan on M-Day when amortising their embodied carbon (see Chapter: *4.3.3* for the calculation of devices' carbon cost with amortisation).

The following table indicates the unit costs of embodied carbon for the different types of device (smartphones, feature phones, IoT objects).

Table 6 Unitary values of embodied carbon

Unit cost of a smartphone's embodied carbon (kgCO2e)	72.24	This unitary value includes refurbishment. See Chapter: *4.3.3* for the calculation of devices' carbon cost with amortisation and the inclusion of refurbishment in Chapter *4.3.3.2*. See value excluding refurbishment in Chapter *4.3.1*.
Unit cost of a feature phone's embodied carbon (kgCO2e)	14.00	See Chapter: *4.3.1*
Unit cost of an IoT module's embodied carbon (kgCO2e)	4.60	See Chapter: *4.3.2*

For each type of device (smartphones, feature phones, IoT objects), the total carbon footprint resulting from these devices' migration is calculated by means of the following equation:

Total carbon footprint (kgCO2e) for a type of device

*= number of carbon units * unit cost of embodied carbon (kgCO2e) for this type of device.*

The number of carbon units included in the calculations are determined in the next two chapters. This number of carbon units factors in the amortisation of the different devices on M-Day as explained in Chapter *4.3.3*[19] .

2.3.8.1. Mobile phones and smartphones

In the case of mobile phones, an evaluation needs to be made of the number of these devices for the reference operator which are not Voice over LTE (VoLTE) compatible on M-Day, and which therefore need to be replaced as of that date under the migration scenario.

For these mobile phones, the following needs to be factored into the analysis:

- As part of their own decision to shut down 2G/3G technologies, every mobile operator will have their own A-Day and M-Day for, respectively, announcing and migrating the two technologies to 4G/5G. Obtaining a simple current average of the four operators' active mobile phone base, to then extrapolate them for M-Day would mean positing that the four operators have the same announcement date as of this writing, then the same migration day. This does not match the reality of the situation, as each mobile operator's history and strategy is unique. The parameters for the reference operator on A-Day will be chosen in such a way as to make the performance of the migration on M-Day reasonable in terms of planning, notably the number of mobile devices and IoT/M2M objects affected by the migration.
- A distinction needs to be made between feature phones and smartphones as these two types of phone have a very different carbon footprint, in addition to differing in number and obsolescence. For the purposes of this study, the devices that need to be replaced when assessing the migration scenario on M-Day, a feature phone will be assumed to be replaced a feature phone, and a smartphone by a smartphone.[20]
- The (percentage) breakdown by age will also be required for the different devices in the reference operator's network that are not VoLTE-compatible on the day the operator announces the shutdown of 2G/3G technologies (A-Day), to be able to assess the number of devices to be replaced under the migration scenario. The different numbers on A-Day are represented by different Di values, with i being the age of the device:
    - D1: % of devices that are less than one year old (0 to 1 year old)
    - Di: % the percentage of devices that are less than **i** years old (i-1 to i years old)
    - If max is the device's maximum lifespan, then Di=0 for i>max
    - The respective maximum lifespan of smartphones and feature phones are 8 and 10 years[21].
    - It should be stressed that the sequence of Di values varies every year (2020, 2021, 2022...). An exact sequencing would have been Di,j, with **i** being the age of the devices from year **j** (j= 2020, 2021, 2022…), knowing that it is this table with j=the year before A-Day that will interest us.
    - See Annex B in the Chapter: *Determination of the distribution of telephones and IoT devices based on their life cycle* regarding the determination of the distribution of smartphones/feature phones and of these remaining phones based on their life cycle.

[19] This Chapter shows that the number of carbon units for a device that still has S years left in its normal life cycle on M-Day, and a lifespan of D years is equal to S/D based on an assumption of a linear carbon amortisation.

[20] Only the external restrictions that the migration scenario would impose on a user are taken into account, which is not the case, for instance, when a user decides to replace their feature phone with a smartphone, a trend that exists independently of the possible scenario of 2G/3G technologies being replaced by 4G/5G.

[21] These maximum lifespans are observed on the network of a mobile operator who is a Committee member.

- To extrapolate the number of devices right before M-Day, we need to know the percentage of devices remaining in the network after **i** years. These different numbers are represented by different Ri values, with **i** being the age of the device. These Ri values depend only on the device's life cycle:
  - Ri: % the percentage of devices remaining after i years
  - If max is the device's maximum lifespan, then Ri=0 for i>max.
  - The assumption is that the different Ri values, which are tied to the device's life cycle are independent of the year being considered. In other words, the series of Ri values (R1, R2 … Rmax) are applicable regardless of the year.
  - No sub-segmentation other than smartphone/feature phone was introduced (brand of phone, screen size, price, etc.).
  - See Annex B of the Chapter: *Determination of the distribution of telephones and IoT devices based on their life cycle* regarding the method used to calculate the breakdown smartphones/feature phones and these remaining phones based on their life cycle.
- Under the migration scenario, new Voice-over-LTE (VoLTE) compatible devices come to replace older non-VoLTE-compatible devices that could have continued to function using 2G/3G. When calculating the comparative carbon footprint of these two scenarios, the age differential needs to be taken into account: see Annex B, Chapter *Calculating devices' carbon cost with amortisation* for more on this topic.

In addition to tables Di and Ri for smartphones and feature phones and their embodied carbon values, the main parameters for evaluating the reference operator's mobile devices for this study are:

- M-Day – A-Day duration = 6 years
- Two million feature phones on Announcement Day: none of these feature phones are VoLTE-compatible[22]
- 18 million smartphones[23] on Announcement Day:
  - 98%[24] of smartphones that are less than a year old on Announcement Day are VoLTE-compatible.
  - 80%[24] smartphones that are between one and 2 years' old on Announcement Day are VoLTE-compatible.
- Every new mobile phone from Announcement Day onwards is VoLTE-compatible.

For this section on devices, the study is based on the following supplementary elements:

[22] VoLTE-compatible feature phones are already sold, but the choice of a conservative assumption was made.

[23] There were around 80 million active SIM cards in France at the end of 2022, including around 4 million internal data cards, see **[ARCEP – 2023]**. This gives an average (80-4)/4= 19 million SIM cards for telephones. Based on a ratio of 90%:10% (based on information provided by a mobile operator who is a Committee member), this would mean around 17 million SIM cards on average per operator for smartphones and 1.9 million for feature phones. The figure of 1.9 million SIM cards corresponds to 1.9 million mobile phones (equipment), i.e. around 2 million. The number of smartphones (equipment) would be around 17/1.1 or 17/1.15 (ratio assumed by the Committee), since a smartphone can have two SIM cards. This would mean roughly between 15 and 15.5 million smartphones (equipment) on average. The reference operator was chosen with an overestimation of smartphones (18 million) and a sensitivity analysis is performed to calculate the number of feature phones.

[24] The percentage was shared by a mobile operator who is a Committee member, with a smaller percentage chosen for the reference operator in the study to provide some leeway for the assessment of the carbon footprint of the migration to 4G/5G.

- Roaming is understood to have no impact on the results of this study:
    - Roaming-in: the trend of voice devices' penetration in 4G/5G, combined with 2G/3G technologies being replaced by 4G/5G is a global one, and so including Europe: there is no reason to think that the 4G/5G migration in France will have a major specific impact on user devices with a SIM card belonging to a foreign operator, including those who plan to travel to France.
    - Roaming-out: by the same token, there is also no reason to think that the migration of networks in foreign countries will significantly accelerate the penetration of devices that are compatible with 4G/5G voice services in France.
    - Even supposing there may be a certain impact, and knowing that the volumes of roaming-in/out traffic are similar, the resulting carbon footprint impact on the reference network in France and on foreign networks will be nil.

The case of smartphones

Table 7 – Calculation of the number of carbon units for smartphones

Year i	REMAINING Ri (table)	Distribution Di (table)	Number terminals year Ta (kU)	Ratio voice/LTE terminals at year i	Terminal years of service just after Tm	Table REMAINING Shifted	Number terminals at Tm (kU) non Voice/LTE	Number years S of life cycle remaining at Tm	Number carbon units for migration scenario (kU)
1	100.00%	32.02%	5763	98%	7.0	3.27%	3.8	2.0	0.9
2	99.42%	32.11%	5780	80%	8.0	0.52%	6.1	1.0	0.8
3	65.98%	19.55%	3518	0%	9.0	0.00%	0.0	0	0.0
4	29.10%	8.95%	1611	0%	10.0	0.00%	0.0	0	0.0
5	13.45%	4.09%	737	0%	11.0	0.00%	0.0	0	0.0
6	7.49%	2.21%	399	0%	12.0	0.00%	0.0	0	0.0
7	3.27%	0.93%	167	0%	13.0	0.00%	0.0	0	0.0
8	0.52%	0.14%	25	0%	14.0	0.00%	0.0	0	0.0
TOTAL		100.00%	18000				9.9		1.7

To determine the values in tables Ri and Di, See Chapter: *Determination of the distribution of smartphones and these remaining phones based on their life cycle* in Annex B.

To calculate the number of carbon units for the migration scenario, See Chapter: *Calculating devices' carbon cost with amortisation* in Annex B. The following table provides an example that illustrates the reason why, if A-Day was in late 2022, devices that are seven and eight years old just after M-Day need to be taken into account (i.e. up to early 2029 in this instance), and the values in yellow in the preceding table taken as the percentage of devices in late 2022 that are still operational (remaining percentage) in early 2029.

Table 8 – Sample illustration of the life cycle of a device

Dates	Ta: end of that year						Tm: end of that year		
Year	2022	2023	2024	2025	2026	2027	2028	2029	2030
Terminal years of service introduced in 2022	0	1	2	3	4	5	6	7	8
Number S of remaining years in the terminal's normal life cycle		8	7	6	5	4	3	2	1

The case of feature phones

Table 9 – Calculation of the number of carbon units for the feature phones

Year i	REMAINING Ri (table)	Distribution Di (table)	Number terminals year Ta (kU)	Ratio voice/LTE terminals at year i	Terminal years of service just after Tm	Table REMAINING Shifted	Number terminals at Tm (kU) non Voice/LTE	Number years S of life cycle remaining at Tm	Number carbon units for migration scenario (kU)	% carbon impact over total
1	100.00%	17.55%	351	0%	7	20.27%	71	4	28.47	54.82%
2	99.42%	18.18%	364	0%	8	13.52%	49	3	14.83	28.57%
3	76.98%	14.64%	293	0%	9	9.00%	34	2	6.84	13.18%
4	49.10%	10.95%	219	0%	10	4.00%	18	1	1.78	3.44%
5	38.45%	9.00%	180	0%	11	0.00%	0	0	0.00	0.00%
6	28.49%	7.71%	154	0%	12	0.00%	0	0	0.00	0.00%
7	20.27%	6.75%	135	0%	13	0.00%	0	0	0.00	0.00%
8	13.52%	5.79%	116	0%	14	0.00%	0	0	0.00	0.00%
9	9.00%	5.79%	116	0%	15	0.00%	0	0	0.00	0.00%
10	4.00%	3.66%	73	0%	16	0.00%	0	0	0.00	0.00%
TOTAL		100.00%	2000				173		51.93	100.00%

For the determination of tables Ri and Di, See Chapter: *Determination of the distribution of remaining feature phones and mobile phones based on their life* cycle (Annex B). For the calculation of the number of carbon units for the migration scenario, see Chapter: *Calculating devices' carbon cost with amortisation* (Annex B).

Only devices that are less than 10 years old just before M-Day are taken into consideration, as devices that are older (10, 11, 12 etc.) will have already disappeared by the time of migration.

2.3.8.2. The case of M2M connected objects

The objects used for cellular machine-to-machine (M2M) communications and equipped with modems that are not 4G/5G-compatible will need to be replaced prematurely when migration happens. This premature replacement needs to be taken into account when assessing the impact of the migration scenario.

Factoring in the impact of replacing these objects, for the purposes of this study, is shaped by three considerations: the scope of the objects considered, an inventory of the objects targeted on Migration day, and data on these objects' embodied carbon.

The main choices made to address these considerations are summarised below (and detailed in Annex B):

- **Scope of the objects considered:** Although a sizeable number of connected objects will be affected by the migration to 4G/5G technologies, only a selection of connected objects should be included in the assessment, in keeping with the study's methodological framework set out above, and constituting the study's extended scope of reference. The selection of objects affected, including intercoms, PoS devices, IoT equipment for meter reading, etc. is detailed in the Chapter: *Boundaries of IoT objects* (in Annex B).
- **Inventory of objects on Migration Day:** The Chapter on the *The case of IoT* in Annex B explains the methodology used, which is analogous to the one used for mobile phones, to determine the number of carbon units to consider for IoT. This number of carbon units is multiplied by the object's embodied carbon (see following paragraph) to determine the total embodied carbon of these objects.
- **Data on these objects' embodied carbon:** Impact data are estimated by reusing the bottom-up modelling developed by Pirson and Bol[25]. It should be noted that the material scope used for the assessment concerns only the object's communications module (modem, antenna, etc.) (cf. more details in the Chapter: *Carbon footprint* in Annex B).

A sensitivity analysis (see Chapter: *Sensitivity analysis* in Annex B) including different IoT-specific cases assesses the impact on the study of examining variations in different parameters, such as the value of the object's communication module's embodied carbon, or influencing the number of carbon units, such as the sale of smart objects before and after Announcement day, and the number of objects that exist on Announcement Day.

2.3.9. Results of the assessment on the entire scope of reference and extended scope of reference (base case)

The results must create the ability to assess the carbon footprint-related benefit of migrating 2G/3G technologies to 4G/5G technologies for the scope of reference and the extended scope of reference.

As shown in the network analysis, migrating 2G/3G technologies to 4G/5G technologies enables continuous and steady energy savings compared to the option of keeping 2G/3G technologies in the reference mobile operator's network from M-Day onwards. These energy savings between the analysed scenarios also results in a continuous and steady reduction in the network's carbon footprint from M-Day onwards

But this migration has a carbon footprint impact on M-Day for the mobile (scope of reference) and IoT (extended scope of ICT) devices that are not compatible with 4G/5G technologies.

The following table summarises the main results for the different types of device[26]:

[25] "Assessing the embodied carbon of IoT edge devices with a bottom-up life-cycle approach", 2021, Thibault Pirson and David Bol: https://www.sciencedirect.com/science/article/abs/pii/S0959652621031577

[26] See Annex B. The number of smartphones that are not VoLTE-compatible on Announcement Day is calculated by factoring in percentages D1 and D2 on Announcement Day and the percentages of devices that are VoLTE-compatible.

Table 10 – Synthesis of the main findings of the inventory of devices on A-Day and M-Day

	Smartphones	Feature Phones	Total Telephones	IoT 10 years	IoT 15 years	IoT 20 years	Total IoT
Total number of terminals at Ta date (kU)	18000	2000	20000	2000	1000	1000	4000
Maximum lifetime (years)	8	10		10	15	20	
Total number of terminals at date Ta (kU) unable to support 4G-5G migration	7729	2000	9729	2000	1000	1000	4000
% terminals unable to support 4G-5G migration at date Ta	42.94%	100.00%	48.64%	100.00%	100.00%	100.00%	100.00%
Number of terminals at Tm (kU) unable to support 4G-5G migration	9.86	172.68	182.53	213.08	269.26	390.91	873.25
% of terminals unable to support migration at date Tm compared with total number at date Ta	0.05%	8.63%	0.91%	10.65%	26.93%	39.09%	21.83%
Number of carbon units (kU)	1.70	51.93	53.63	65.42	117.56	197.27	380.25
Carbon unit % of total number of terminals at date Ta	0.01%	2.60%	0.27%	3.27%	11.76%	19.73%	9.51%

The study will evaluate the amount of time from M-Day, in number of months, required to reach the breakeven point for the two scopes of reference being considered, between the networks' steady and ongoing energy savings and the carbon cost of devices that are non 4G/5G-compatible on M-Day.

Based on the memorandum's different assumptions, these durations in number of months for the two scopes (reference/extended) will create the ability to assess the benefit in terms of carbon footprint of migrating 2G/3G to 4G/5G technologies in each of the two cases.

The study does not seek to obtain an exact assessment of the amount of CO2e savings generated by the shutdown of 2G/3G and the migration to 4G/5G ever year from M-Day.

It should also be noted that the calculation is performed only for one year from M-Day, to be able to assess the time required to reach the two breakeven points for the two scopes of reference under study.

This study does not seek to replace a detailed report that an operator would produce about its own network, but rather to assess the carbon-related benefit of such a migration.

The study is completed by a sensitivity analysis which could, among other things, lead to a better understanding of the key parameters of the migration, and those areas requiring special attention.

The following table includes the different results for the base case.

Different parameters and results will vary depending on the sensitivity analysis performed (cf. *Annex B*).

The different values in the table's green boxes are calculated for devices (smartphone, feature phone, IoT) by dividing these devices' carbon footprint by the networks' monthly savings, then added together to determine the breakeven points in number of months for the two scopes of reference being considered.

Table 11 – Results of the assessment of the scope of reference and extended scope of reference

4G-5G vs 2G-3G /BS gain over 24 hours (kWh)	14.02
Electricity intensity (gCO2e/kWh)	44.40
Total number of base stations	110000
Number of reference operator base stations	27500
Annual 4G-5G vs 2G-3G network gain (in Tonnes of CO2e) for reference operator	6250
Monthly 4G-5G vs 2G-3G network gain (in Tonnes of CO2e) for Reference operator	521
Smart Phone	
Number of Carbon Units (in KU) Reference operator (after depreciation for migration scenario)	1.70
Embodied carbon footprint 1 smartphone (kg)	72.24
Embodied carbon footprint Telephones (in tonnes of CO2e)	123
Embodied carbon footprint Telephones (in Months saving 2G-3G shutdown)	0.2
Feature Phone	
Number of Carbon Units (in KU) Reference operator (after depreciation for migration scenario)	51.93
Embodied carbon footprint of 1 feature phone (kg)	14.00
Embodied carbon footprint Telephones (in Tonnes of CO2e)	727
Embodied carbon footprint Telephones (in in Months saving 2G-3G shutdown)	1.4
Feature Phone	
Number of Carbon Units (in KU) Reference operator (after depreciation for migration scenario)	51.93
Embodied carbon footprint of 1 feature phone (kg)	14.00
Embodied carbon footprint Telephones (in Tonnes of CO2e)	727
Embodied carbon footprint Telephones (in in Months saving 2G-3G shutdown)	1.4
IoT	
Number of IoT carbon units (in KU) Reference operator (after depreciation for migration scenario)	380.25
Embodied carbon footprint 1 object (kg)	4.6
Embodied carbon footprint IoT (in tonnes of CO2e)	1749
Embodied carbon footprint IoT (in Months saving 2G-3G shutdown)	3.4
Feature Phones + Smart Phones	
Embodied carbon footprint all Telephones (in Months saving 2G-3G shutdown)	**1.6**
0	
IoT+ Feature Phones + Smart Phones	
Embodied carbon footprint all Terminals (in Months saving 2G-3G shutdown)	**5.0**

The embodied carbon of all mobile phones (expressed in months of savings from the time of the 2G/3G shutdown) also makes it possible to determine the amount of time (in months) needed to reach the breakeven point in the migration to 4G/5G for the scope reference (i.e. network + all mobile phones).

The embodied carbon of all devices (expressed in months of savings from the time of the 2G/3G shutdown) also makes it possible to determine the amount of time (in months) needed to reach the breakeven point in the migration to 4G/5G for the extended scope reference (i.e. network + all mobile phones + IoT).

2.3.10. Conclusions on the results of the assessments of the two scopes of reference

In the case of the scope of reference (network + all mobile phones), the breakeven point is reached in under two months.

In the case of the scope of reference extended to include IoT, the breakeven point is reached in under six months.

The analysed base case thus reveals a real benefit in terms of carbon footprint from migrating 2G/3G to 4G/5G as much for the scope of reference, as the extended scope of reference.

3. Annex A: Calculating 2G/3G networks' energy consumption

This Annex details the computational reasoning (presentation of the two approaches – generic and specific, and the associated assumptions) that makes it possible to obtain an estimate of 2G/3G networks' energy consumption for an operator's entire network (all technologies combined).

3.1. Methodology and assumptions

3.1.1. Methodology

The study calculates the percentage of mobile networks' energy consumption that can be attributed to 2G/3G by considering multiple parameters (radio network architecture: distributed vs. centralised, MIMO configuration, network sharing, etc.). This involves calculating 2G/3G base stations' share of the energy consumed by all of the base stations all technologies combined that make up the mobile network.

Two approaches are taken to this exercise:

- The first, referred to as the "**generic approach**", considers an average generic operator that has a mobile network composed of 2G, 3G, 4G and 5G technologies with an average distribution of mobile cell sites, compared to all operators.
- The generic approach is completed by a so-called "**specific approach**" where the calculation is based on the network of an operator who is a Committee member.

Combining two approaches makes it possible to obtain a range of outcomes and to pinpoint trends.

The study performs an inventory of transmitting sites using the frequency/frequencies that carry 2G and 3G networks, and the transmitting sites using the frequency/frequencies that carry 4G and 5G. This inventory is weighted to factor in the generation of hardware that can be deployed on cell sites, as well as the different radio network configurations that can exist depending on the technologies deployed and bands being considered (MIMO, transmit power, spectral width, etc.).

The study provides an estimate of these networks' consumption in relative values, i.e. 2G/3G networks' energy consumption compared to the network's total consumption, all technologies combined. Note that only base stations' (i.e. cell towers) energy consumption is calculated.

In addition, to situate the assessment in a more realistic shutdown timeframe, 2G and 3G networks' energy consumption of is evaluated up to 2025. The forecast up to that date factors in the regulatory obligations that are due to be in place by the time[27], notably the increase in the number of sites using the 3.5 GHz band, and the New Deal for Mobile[28] obligations resulting in an increased network density.

3.1.2. Assumptions

The study is based on several assumptions which are detailed below and summarised in the following table:

Table 12 – Main assumptions of each approach

Approach	Generic	Specific
Frequency holdings and number of sites	The study considers the following generic distribution: 8.6MHz for 2G/3G services carried by the 900 MHz band and 155MHz for services 4G/5G carried by other FDD and TDD. frequency bands. Number of sites: average of the four network operators' cell sites according to ANFR statistics [ANFR - 2023] Details of site distribution by technology and frequency (see below)	The study considers the cell site inventory of a network operator who is a Committee member as well this operator's distribution of frequency use by technology.
Equipment's energy consumption	Measured consumption data taken from the equipment of a supplier who is a Committee member. The study assumes a 30% load per technology.	Typical transmit power values by technology in the operator's network. Network load by technology is not considered; equal load on all of the network's frequency bands.
Base station configuration[29]	Three possible configurations: centralised base station/non rehabilitated hardware, 2T2R distributed/single band base station and 4T4R/multi-band distributed base stations with rehabilitated hardware. The choice between these configurations is detailed below.	The configuration of base stations powering the operator's network including a percentage of MIMO 4T4R-configured sites and a percentage with a 2T2R configuration.

[27] https://www.arcep.fr/fileadmin/user_upload/grands_dossiers/5G/procedure-attribution-band-3_5GHz-obligations.pdf

[28] https://www.arcep.fr/la-regulation/grands-dossiers-reseaux-mobiles/la-couverture-mobile-en-metropole/le-new-deal-mobile.html

[29] The network's different cell sites do not have the same radio configuration (hardware generation, type of MIMO antennas, etc.) considering that: the percentage of MIMO sites is not the same for all of the bands; spectral widths are not the same on the different bands; radio parameters are not the same for the different bands; the rate of transmitting site sharing is not the same for the different technologies and the different bands.

Forecast up to 2025	Addition of 10,500 sites in the 3.5 GHz band according to operator's rollout obligations written into their licences to use frequencies in the 3.5GHz band, as well as the New Deal for Mobile obligations set for that deadline. The power assigned to the different bands is considered to be constant up to 2025.

- As it stands, because there are still very few 3.5 GHz band cell sites, they were not taken into account when assessing 2G/3G's share of the network's energy consumption.
- The study does not take cell site sharing between operators into account.

3.1.3. Distribution of transmitting sites by technology/band

The distribution of spectrum inventory by technology and by frequency band is detailed in the following table:

Table 13 – Distribution of spectrum inventory by technology

Bandwidth/band		2G	3G	4G	5G	Total
FDD	**700 MHz**	X	X	5	5	10
	800 MHz	X	X	10	X	10
	900 MHz	3,6	5	X	X	8,6
	1800 MHz	X	X	20	X	20
	2100 MHz	X	X	10	5	15
	2600 MHz	X	X	20	X	20
TDD	**3.5 GHz**	X	X	X	80	80

The number of multi-2G/3G/4G technology base stations by frequency band (700 /800/900/1800/ 2100/2600 MHz) in service is assessed based on the results provided by French national frequency agency, ANFR, as of 1 January 2022 in its observatory of mobile network deployments in Metropolitan France [ANFR-2023].

This creates the ability to determine the percentage breakdown of transmitters by frequency band, and to determine the order of magnitude of the corresponding percentage of power consumption.

900 MHz band transmitters represent around **a quarter** of all transmitters. **This gives an order of magnitude for 2G/3G technologies' percentage of energy consumption** (when the 2100 MHz band will be more widely migrated over to 4G/5G, knowing that the observatory shows that are there are still around 54,000 UMTS sites using the 2100 MHz band).

As a result, 2G/3G networks' power consumption represents a not insignificant share of mobile network's energy consumption in France, making this study a worthwhile endeavour, without drawing any a priori conclusions.

Table 14 – Current percentage of transmitters by technology/frequency band

Frequency bands	Technologies	Number	%	Source	Comment
700	4G	33,863	9.1%	Observatory: 4G summary table. LTE700 in service.	700 MHz only for 4G (excluding 5G)
800	4G	69,927	18.8%	Observatory: 4G summary table. LTE800 in service.	800 MHz only for 4G
900	2G, 3G	91,647	24.6%	Observatory: 3G summary table. UMTS900 in service.	the number UMTS900 includes this number of sites
1800	2G+4G	65,839	17.7%	Observatory: 4G summary table. LTE1800 in service.	the number LTE1800 includes this number of sites
2100	3G+4G	65,839	17.7%	Number LTE 1800 MHz	UMTS 2100: 53946 sites But there is UMTS/LTE sharing. Assumption of a similar number of 1800 MHz and 2100 MHz sites.
2600	4G	45,100	12.1%	Observatory: 4G summary table. LTE2600 in service.	2600 MHz only for 4G
Total		372,215	100.0%		

It should be noted that 5G using the 3.5 GHz band has not been factored into the assessment, keeping in mind that 3.5 GHz band rollouts are still in the early phases (10,500 cell sites in the observatory [ANFR-2023]). In addition, 5G in other frequency bands (700 MHz, 2100 MHz) is taken into consideration automatically in the table due to sharing with 4G.

Beyond this first approximation, the following reasoning estimates 2G/3G networks' share of energy consumption according to the two above-mentioned approaches.

3.1.4. Base stations' configuration and radio equipment's energy consumption

Generic approach:

The figure below provides an estimate of the 900MHz band's share of the base station's energy consumption for different hardware configurations, based on each frequency's share.

The different levels of energy consumed by the radio equipment (RRU, RFU) in the different frequency bands listed below are obtained from direct measurements of this radio equipment taken by the supplier in their lab at a 30% load.

Figure 9 – 900MHz band's estimated share of a base station's energy consumption

	Scenario 1	Scenario 2	Scenario 3
	BS centralised RFU	BS distributed RRU 2T2R	BS distributed RRU 4T and/or 4R
	RRU-700M-2x60W	RRU-700M-2x40W	RRU-700M/800M/900M-2x160W
	RFU-800M-2x60W	RRU-800M-2x40W	
	RFU-900M-2x80W	RRU-900M-2x60W	
	RFU-1800M-2x80W	RRU-1800M-2x60W	RRU-1800M/2100M-4x80W
	RFU-2100M-2x80W	RRU-2100M-2x60W	
	RRU-2600M-2x60W	RRU-2600M-2x40W	RRU-2600M-4x40W
Part of 900MHz in the BTS power consumtion	33%	29%	24%

Specific approach:

To measure the carbon footprint impact of a 2G/3G shutdown, we assessed 2G/3G's share of the energy consumed by cell sites only (i.e. without factoring in the possible shutdown of service platforms or other parts of the core or transport networks).

Conducting this exercise on the network of an operator who is a Committee member resulted in **a value of 21%** (= 2G/3G's share of energy consumption, all technologies combined)

3.1.5. Calculating energy consumption up to 2025

Looking ahead to the end of 2025, when each operator will have deployed 10,500 sites in the 3500 MHz band (regulatory obligation written into licences to uses frequencies in this band[30]) as well as the obligations resulting from the New Deal for Mobile for this deadline[31], **this percentage is expected to fall to 17%.**

3.2. Results

Under the generic approach, all of the cell sites are considered to belong to the same generation. Even though this is a strong assumption, it makes it possible to confine the impact that any generation of hardware can have on 2G and 3G's share of power consumption. For **older generation hardware** (centralised base station configuration) the new weighted calculation gives a **33%** share of the network's base stations' (aka cell towers) total consumption, whereas this percentage is estimated at **29% for 2T2R single-band distributed base stations** and at **24% for new-generation hardware** with 4T4R multi-band distributed base stations.

Under the specific approach, the study reveals a percentage **for 2G/3G technologies' share of consumption of around 21%**.

Looking ahead to 2025, and by incorporating 10,500 5G sites operating in the 3.5 GHz band into the network, with an updated configuration and all of the deployments planned to take place under the New Deal for Mobile by that deadline, 2G and 3G's share of energy consumption would drop to **17%.**

These results up to 2025 are to be considered in light of the above-mentioned assumptions, to wit:

- If the percentage of power assigned to bands other than the 900 MHz band were to increase in the coming years, 2G/3G's share of energy consumption would thus be smaller than what has been calculated in this study;
- By the same token, any network density increase operation (to increase capacity or coverage) or deployment of new frequency bands would also increase 2G/3G's share of networks' overall consumption, all technologies combined.

[30] https://www.arcep.fr/fileadmin/user_upload/grands_dossiers/5G/procedure-attribution-band-3_5GHz-obligations.pdf

[31] https://www.arcep.fr/la-regulation/grands-dossiers-reseaux-mobiles/la-couverture-mobile-en-metropole/le-new-deal-mobile.html

4. Annex B: Carbon footprint impact of replacing 2G/3G networks

4.1. Carbon intensity/energy mix

To assess the "CO2e generated per kWh" consumed in France, the distribution network for electricity produced in France needs to be taken into account, as does imported electricity (a very small percentage, as France is an exporter of electricity).

The ADEME technical data sheet[32] also reveals the relevance of considering the CO2e per kWh consumed by type of use, as each use can have a significantly different impact on the production means employed, hence on CO2e emissions. This data sheet describes the main methods of calculation by use (seasonality method, average per time step, or forecasting by incorporating the analysis of the consequences of setting CO2e at a certain value).

Annex 3 of the data sheet lists CO2e per kWh consumed for different uses at the time of its writing:

Table 15 – CO2e emissions factor for different uses (excerpted from the ADEME Technical data sheet)

Résidentiel					Tertiaire				
Chauffage	Climatisation	ECS	Eclairage	Autres	Chauffage	Climatisation	ECS	Eclairage	Autres
210	65	83	121	65	210	66	66	66	66

This document now lists the value of 79 gCO2e/kWh for the emissions factor for use of heating.

To our knowledge, no emissions factor has been defined for mobile networks.

The technical data sheet also provides other information:

- Average values since 2015 are 55 and 60 gCO2e/kWh at the point of consumption, i.e. including system losses. The trend for this average figure has been one of decrease since 2010, with the gradual shutdown of coal and oil-fired power plants.
- It is also indicates that based on a business-as-usual forecast of the multiannual energy plan (MAEP), the average content in 2035 will be around 17 gCO2e/kWh in direct emissions and 34 gCO2e/kWh with an LCA calculation.

For the purposes of this memo, the assessment has chosen the value of **60 gCO2e/kWh** in **2020**[33] and **34 gCO2e /kWh in 2035** with a linear extrapolation between these dates (start of 2020 to the end 2035).

The study also factors in the value **of 56.9 gCO2e/kWh** in **2021** [BASE CARBONE database – 2022] for the purposes of a sensitivity analysis, keeping the value **34 gCO2e/kWh in 2035** with a linear extrapolation between 2021 and 2035 (start of 2021 to the end of 2035).

The linear extrapolations were made to determine the emissions factor on M-Day[34].

4.2. Boundaries of the systems under study and rules of exclusion

The boundaries of the systems under study are set according to the goal of the study, pursuant to the provisions of Recommendation ITU L.1410.

[32] Technical data sheet – ADEME's positioning on calculating the carbon content of electricity, in the case of electrical heating/*Positionnement de l'ADEME sur le calcul du contenu C02 de l'électricité, cas du chauffage électrique* – July 2020

[33] 2020 is the publication date of the ADEME Technical data sheet that was used.

[34] 2029 was the date chosen for Migration Day for the calculations used to determine the breakeven points, keeping in mind that these points are reached in under a year.

4.2.1. Boundaries of the systems under study

For goods and services based on life cycle, Appendix I of Recommendation UIT-T L.1450 employs the OECD definition of the ICT sector[35] to derive the following main categories:

- ICT end-user goods
- ICT network equipment
- Data centres
- ICT service development and operational support

In particular, Appendix I indicates that intermediate goods such as parts are not considered to be ICT end-user goods as such, but rather as parts used for ICT goods, and will be taken into account when calculating GHG emissions for the complete lifecycle of ICT end-user goods.

For the purposes of this study, only the first two categories are taken into account.

Annex A of the above-mentioned Recommendation provides a more detailed definition of the different categories.

For the network portion, we find the different parts of a mobile network as described in the table in this memo showing the comparative functional diagrams of the reference and migration scenarios.

For ICT end-user goods, and as expected, Annex A includes computers and their peripherals, consumer devices such as desktop and laptop computers, mobile phones, smartphones and tablets.

However, it excludes different items such as televisions, printers and game consoles which are considered to belong to the entertainment and media sector.

It also indicates that IoT is made optional.

Note too that the EDNA[36] defines the following categories and groups in a report[37]:

[35] Note, for instance, that INSEE (national statistics institute) in France uses the same OECD definition of ICT as its point of departure, and that it seems important for the different statistics and study results published to also be based on the same premises.

[36] Electronic Devices and Networks Annex (EDNA): https://www.iea-4e.org/edna/

[37] https://www.iea-4e.org/wp-content/uploads/publications/2021/02/EDNA-TEM2.0-Report-V1.0-Final.pdf

Electronic Devices & Networks Annex
EDNA

Table 4. Selected devices updated with regional shipment data in the TEM2.0

Category	Group	Device
Automation	– Appliances	• Fridges • Freezers • Washing Machines • Tumble Dryers
	– Space Conditioning	• Air Conditioners • Smart thermostats
	– Lighting	• Home lighting
	– Street lights	• Street lights
	– IoT	• Sensor/SIM (LTE-M, NB-IoT & LPWA)
	– Audio	• Digital Voice Assistants
ICT	– Mobile	• Smart Phones
	– Tablet	• Tablet
	– PC	• Desktop • Laptop
Entertainment	– Display	• Smart TV • Digital Signage
	– Media Device	• Casting Sticks • Games Consoles
Security	– Control	• Smart locks
	– Video	• IP cameras

Figure 10 – Excerpt from the EDNA report on device classification

Unsurprisingly, we find desktop and laptop computers, mobile phones, smartphones and tablets belonging to the Information and Communication Technologies (ICT) sector.

On the other hand, according to EDNA, the Internet of Things (IoT) is excluded from the ICT sector, and included instead in other categories, notably "automation".

When defining the boundaries of ICT end-user goods, as much as defined by Recommendation ITU-T L.1450 as under the approach taken by EDNA, it is entirely reasonable to confine the scope of reference to desktop and laptop computers, mobile phones, smartphones and tablets. The case of connected objects (IoT) must also be addressed by examining an extended scope of reference, in line with the margin of inclusion found in the Recommendation (cf. sub-section below).

For the purposes of this study for replacing 2G/3G technologies with 4G/5G technologies, the scope of reference for ICT goods is confined to mobile phones and smartphones: this constitutes the scope of reference for the study. The scope of reference is then extended to include a specific selection of connected objects (IoT). The rules governing this extension are detailed in the following sub-section.

4.2.2. Rules of exclusion and extending the scope of reference

4.2.2.1. Boundaries of IoT objects

Although IoT was made optional in the Recommendation ITU-T L.1450 definition of the ICT sector boundaries, it does specify that, "*as a first step to categorizing IoT device data based on data availability, the following categories may be included: public displays, surveillance cameras, payment devices, smart meter communication modules and wearables*". In the absence of more specific information for the purposes of our study, the Experts Committee took a three-step approach to selecting the objects concerned:

- First, a list was drawn up of connected objects likely to use 2G/3G technologies;
- Second, this list was submitted for examination to the Technical Experts Committee on measurement[38] which gave its opinion on whether to include each category of object in the ICT sector, according to its interpretation of Recommendation ITU-T L.1450;
- Third, the extended scope of reference was defined based on this opinion.

The following table lists the connected objects that were chosen to be included or excluded for the purposes of the study:

Table 16 – Assessment of the inclusion/exclusion of IoT objects for the purposes of this study

2G/3G connected object	Measurement Committee opinion	Mobile Committee choice
Home/industrial remote alarms	Excluded	Excluded
Intercoms	Included, optional	Included
Mobile PoS devices	Included, optional	Included
eCALL in-car systems	Excluded	Excluded
IoT device on beverage vending machines	Excluded	Excluded
Remote meter reading and meters (water, electricity, etc.)	Included, optional	Included
IoT devices for rolling stock (trains)	Excluded	Excluded
IoT devices for lifts	Excluded	Excluded
Wearables	Included, optional	Included
IoT devices for parking meters	Included, optional	Included
Weather stations	Currently excluded, to be reviewed(*)	Excluded
IoT devices for object tracking/geolocation	Included, optional	Included
LWSS devices[39]	Currently excluded, to be reviewed(*)	Excluded
Remote assistance for elderly/disabled persons	Currently excluded, to be reviewed(*)	Excluded
Smart street lamps	Excluded	Excluded

(*) as part of a future review of Recommendation ITU-T L.1450.

The figure below illustrates the scope of reference and extended scope of reference chosen for the purposes of this study.

[38] The Technical Experts Committee on Measurement was created by Arcep and ADEME in 2020. Chaired by Catherine Mancini, Committee members include industry players, academics and digital and environmental think tanks. The Committee issues fully independent opinions on technical issues surrounding the digital environmental footprint.

[39] Alarms for lone workers/Lone worker safety solutions.

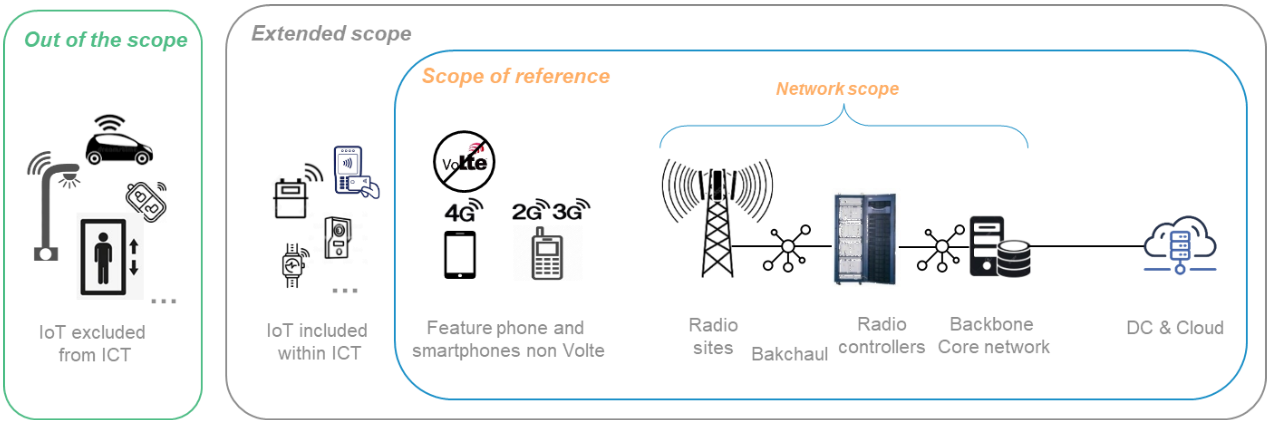

Figure 11 – Illustration of the scope of reference chosen for the study[40]

4.2.2.2. Additional considerations regarding the boundaries of the systems under study

INSEE indicates that a sector of activity includes manufacturing, sales and service firms that have the same main activity as defined by the Nomenclature of French activities and products (NAF)

The NAF is a nomenclature of productive economic activities, devised chiefly to facilitate the organisation of economic and social information. To facilitate international comparisons, it has the same structure as the European nomenclature of economic activities (NACE), which is itself derived from the International Standard Industrial Classification of all economic activities (ISIC)[41].

The current version of the nomenclature (NAF rév.2[42]) includes the following 21 sections which are common to the NACE and ISIC:

- Agriculture, forestry and fishing
- Mining and quarrying
- Manufacturing
- Electricity, gas, steam and air conditioning supply
- Water supply, sewerage, waste management and remediation activities
- Construction
- Wholesale and retail trade; repair of motor vehicles and motorcycles
- Transportation and storage
- Accommodation and food service activities
- Information and communication
- Financial and insurance activities
- Real estate activities
- Professional, scientific and technical activities

[40] Although elements of the core and backhaul networks are Included in the scope of the study, they are overlooked in the assessment (their impact remains marginal) (see Chapter: *Rules of exclusion and extending the scope of reference* in Annex B)

[41] https://www.insee.fr/fr/information/2406147

[42] Nomenclature of French activities and products (NAF) rév2-CPF rév.2.1 2020 reissue, INSEE

- Public administration and support service activities
- Education
- Human health and social work activities
- Arts, entertainment and recreation
- Other service activities
- Activities of households as employers; undifferentiated goods-and-services-producing activities of households for own use
- Activities of extra-territorial organisations

As this nomenclature makes clear, the digital sector does not exist as such.

What we would call and understand as “digital” or “digital equipment or devices” are found in all of these sections, testifying the tremendous degree of digitisation in our society.

But this concept has no statistical reality, which would provide a clear set of boundaries for a study such as this one, exploring technologies standardised at the global level by the 3GPP, for mobile networks using frequencies that have been harmonised at the European level, and all that within the framework of European single market for which study findings should be comparable. That being said, although questions about boundaries are legitimate given the increasing digitalisation of society through technologies such as IoT, this is a topic that is already being explored by other bodies, including the work that is currently being done by the Arcep/ADEME Experts Committee on measuring the digital environmental footprint.

4.2.3. Summary of exclusions for the purposes of the study

As describe in the previous sections, the boundaries of the systems under study were set in accordance with the provisions of Recommendations ITU L.1410 and ITU L.1450. Once the boundaries (*i.e.* the scope and extended scope of reference) of the examined systems were defined, some mandatory processes/activities were excluded from the assessment, in accordance with the rules of exclusion set forth in Recommendation L.1410[43].

For ICT goods, networks and services:

- All of the elements identified as relevant to the study within the boundaries of the systems under study, and whose associated data were available or reasonably able to be estimated through assumptions, have been incorporated into the analysis.
- General speaking, environmental modelling needs to cover a set percentage of the equipment and systems. The criteria used for exclusion include the mass, energy or weight of the environmental impact (in this case, carbon footprint), the latter of which can be addressed using a qualitative approach, in keeping with Recommendation L.1410. The cut-off threshold used for each criterion for the purposes of the study is set at 5%, in other words the excluded processes/activities/flows must not cumulatively contribute to an increase of more than 5% of the criterion of the entire product system under study.
- Given that the total environmental impact (in this case, carbon) of the entire system is hard to estimate, an alternative cut-off method would consist of considering a reference value based on the most important activities in the product system, and using this reference value to justify the exclusion of certain processes or traffic whose contribution is insignificant compared to

[43] See Clause 6.2.4 of Part I of Recommendation ITU L.1410 for further details on the provisions pertaining to the cut-off rules for ICT goods, networks and services systems. These provisions also draw on the clauses of the ISO 14044 standard on cut-off rules.

this value. This approach is appropriate as soon as a limited number of phases/processes are pre-identified as making a strong contribution (i.e. environmental footprint assessment hotspots). The Recommendation indicates that the use of secondary data is sufficient for establishing this reference/reference value[44].

For the purposes of our study, this cut-off rules method is also used; the reference value considered is the carbon footprint during the use phase of 2G/3G base stations using the 900MHz band in the reference scenario, considering that base stations using the 900MHz band constitute a hotspot in the environmental footprint assessment of product systems (reference scenario and migration scenario) and will be used to justify the exclusion of processes / activities in both the reference scenario and migration scenario.

For some of the excluded equipment (circuit switched core and packet-switched network, 2G/3G radio network controllers) the equipment's carbon footprint includes both operational emissions (use phase) and the equipment's embodied emissions, which are calculated using the ratio profiling method. This method, which is described in the ICT supplement of the GHG Protocol[45] and detailed in the Report from the Experts Committee on measurement[46], consists of estimating the equipment's embodied carbon by applying a percentage to their operational emissions (a ratio of 10% is considered for the purposes of our study, based on the GHG Protocol's ICT sector guidance supplement).

The excluded processes and activities have individually and cumulatively made a less than 5% contribution to the reference value (cf. see table below).

In the case of a comparative analysis as in our study, additional provisions apply[47]:

- In addition to the provisions on taking into account first-order effects (i.e. the direct footprint of ICT goods/networks/services) explained above, second-order effects should be considered. For our study, this is the same voice/M2M services carried by 2G/3G in the reference scenario that are migrated to 4G/5G in the migration scenario. In the case mobile phones, the switch to VoLTE should not alter users' behaviour (no increment of use). In the case of IoT/M2M objects, these are mainly coverage services that already existed with the other low-band frequencies (700 and 800MHz) and for which the migration to 4G/5G using the 900MHz band should not bring any change. The few cases of capacitive services such as IoT/M2M resulting from the migration, would potentially be due to the increment in data traffic generated by the increased functions of new, replacement IoT objects. For more details on this subject, refer to the development in Chapter *4.2.4*.
- The study aims to assess the difference in impact between two ICT services, rather than the total impact of each ICT service. Processes or input/output data can be excluded if they are identical in both ICT services. These processes/activities include transmission and backbone networks, backhaul and aggregation networks, and cell sites excluding 900MHz base stations.

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[44] "*As the total values of environmental impacts can be difficult to calculate, another alternative cut-off method would be to create a reference value based on important activities and to use this reference value to cut-off processes having a negligible contribution compared to that value. Such an approach is especially appropriate when a limited number of processes or phases of a single aspect of the life cycle, contribute by a disproportionate amount to the overall impact. To establish the reference value, secondary data is considered sufficient*." (Clause 6.2.4, p.33 of the Recommendation ITU L.1410)

[45] GHG Protocol – ICT Sector Guidance (see Chapter: 5 of the Guidance)

[46] See Appendix II of the Experts Committee on Measurement report on "Assessment of the environmental impact of the ICT sector: methodological gap analysis": https://www.arcep.fr/uploads/tx_gspublication/impact-environnement-analyse-ecarts-methodologiques-secteurICT_avril2023.pdf

[47] See Clause 12.2.3 of Part II of Recommendation ITU L.1410

Details of the activities excluded/included in each phase of the life cycle according to their requirement in the assessment (mandatory vs. recommended vs. optional) are explained in the Chapter: *Taking Recommendation ITU-T L.1410* in Annex B.

The excluded activities and processes have been incorporated into the sensitivity analysis as recommended in Recommendations ITU L.1410 and ISO 14040. These 3% variations indicated below would reduce the time needed to reach the breakeven points for the same value, while not calling into question the conclusions of the study.

The following table summarises the list of exclusions assumed in the study:

Table 17 – List of the exclusions assumed in the study

Product	Excluded Processes/Activities	Comments and rationale
Core network	• Share of voice/M2M services in packet switched core consumption in the migration scenario • Circuit switched core consumption in the reference scenario • Replacement of circuit switched core equipment in the reference scenario • Early scrapping of circuit switched core equipment in the migration scenario	• Regarding the circuit switched core: Based on the GSMA scenario [GSMA - 2021], a circuit switched core configuration could be maintained in the case of the migration scenario. Operators are also continuing to study engineering solutions to optimise situations where the circuit switched core network can be dispensed with and thus capitalise on additional gains. • Regarding IMS: the migration of the voice service from MSCs to an IMS core will be done on a reduced number of machines, which should reduce power consumption. This will shorten the time needed to reach the breakeven points without changing the conclusion of the study. The exact quantification will depend on the specific implementations of each operator.
IMS (Data Centre)	• Share of voice/M2M services in the consumption of IMS platform servers	
2G/3G radio controller	• RNC/BSC equipment consumption in the reference scenario • Replacement of RNC/BSC equipment in the reference scenario • Early scrapping of RNC/BSC equipment in the migration scenario	• The power consumption of RNC/BSC controllers represents less than approximately 3% of the total power consumption of the network's 900MHz 2G/3G base stations in the reference scenario. • The contribution of RNC/BSC controllers is less than 3.3% of the reference value of the reference scenario.
Feature phone and IoT module	• Recycling and end-of-life	• End-of-life impacts (including recycling) are not taken into account due to lack of data and the marginal share[48] of the end-of-life phase in general in the carbon footprint of ICT equipment.

[48] For example, the end-of-life phase represents less than 0.2% for devices according to the ADEME/Arcep study on the environmental impact of digital technology in France (03/2023): https://www.arcep.fr/uploads/tx_gspublication/note-synthese-au-gouvernement-prospective-2030-2050_mars2023.pdf

4.2.4. Considerations regarding the assessment of potential rebound effects of shutting down 2G/3G networks

The migration to 4G/5G could provide an impetus for those who are using only 2G/3G services (voice, SMS, MMS and narrowband data) to consume additional traffic (direct and rebound effect). It is possible that some of these users could, for instance, upgrade from a feature phone to a smartphone to be able to access services like video streaming, thereby significantly increasing data traffic on mobile networks. On the flipside, other users could choose to stay with a 4G/5G feature phone. Some smartphone owners may generate very little data traffic (notably by not watching videos on their phone). This is therefore a complex question as it is very much bound up with changes in consumers' behaviour.

In any event, it seems possible to consider that the rebound effect linked to the shutdown of 2G/3G networks should be very limited. This is the result of the analysis of the following two main possible effects:

- The one related to the migration of 2G/3G and 4G non-VoLTE mobiles to 4G VoLTE/5G mobiles;
- The one related to the refarming of the 900 MHz band to 4G/5G.

4.2.4.1. Rebound effect of upgrading 2G/3G devices to 4G/5G devices

Regarding devices, this concerns very small volumes of traffic:

    - On M-Day, fewer than 1% of phones are not LTE-compatible, compared to the total number on Announcement Day – cf. Chapter: *Determination of the distribution of remaining feature phones and mobile phones based on their life* cycle
    - More recent mobiles for customers who give up their smartphone (for the moment a niche group according to the experience of operators who are Committee members)

- All these users will have the ability to switch their 2G/3G feature phone to a VoLTE-compatible feature phone if they do not want to buy a smartphone, in which case they will have the same services before and after, i.e. voice calls, SMS, MMS.
- There could be a rebound effect for some users who choose to switch to a smartphone, but this does not concern customers with non-VoLTE 4G smartphones who will have to upgrade to a VoLTE-compatible smartphone, and who therefore already had access to 4G. For the percentage of users equipped with feature phones and who would choose to switch to VoLTE-compatible smartphones when the shutdown happens, the study evaluated the worst case of rebound effect associated with the transition from voice call to video calls thanks to migration by concluding that it is almost non-existent, due mainly to the very low proportion of phones affected on M-Day (less than 1% of the active base of phones on A-Day).[49] Voice migration should therefore not generate significant additional traffic.

Regarding ICT connected objects:

[49] Considering the following most conservative assumptions: Volume of video traffic associated with a video call (10MB/min); Duration of a video call (10min); Number of video calls/week (7 sessions); Photo size (10MB/photo); Number of photos exchanged per week (10 photos); Number of phones affected (200,000 phones); we obtain an additional volume of traffic (photos and video calls) on the entire network equal to 200,000 * 52 * (10 * 10 * 7 + 10 * 10) = 8320TB per year, or 2.4Gbps per busy hour on the entire network; this represents less than 0.4 Mbps per busy hour per site (reminder: 27,500 sites); i.e. an increment on the load of the base station of less than 1%.

The Committee identified few ICT IoT use cases in the study that will change radically when moving to 4G. For the purposes of the study, this could apply to the case of new 4G/5G compatible intercoms generating more data than older 2G/3G intercoms because they are equipped with cameras, for example. In this case and considering a maximalist calculation, where all new intercoms would be equipped with this type of feature, this would represent a very low traffic increment per cell site: around 0.24Mbps at most during the busy hour[50] or, in the worst case, a load increment per cell site of less than 1%[51], which translates into an increase in the power consumption of a 4G/5G cell site of less than 1% (considering the conservative assumption that 900MHz 4G/5G sites would have a maximum load of 25% for all services combined[52]). The technology change for the connected objects examined for the purposes of the study should therefore not increase base stations' load (hence carbon footprint) significantly enough to call into question the benefits of the migration.

4.2.4.2. Analysis of switching 2G/3G services using the 900 MHz band to 4G/5G in terms of data consumption

The 900 MHz band is not a high-capacity band: despite its good propagation qualities (providing good network coverage), it provides only limited bandwidth due to its size (2x35 MHz divided between the four mobile operators), even with more efficient 4G/5G technologies. As result, refarming these frequencies after the shutdown of 2G/3G networks is not likely to provide enough additional capacity to generate different uses from the services already being delivered in 4G/5G using the operators' other frequency bands.

At a constant level of quality of service before and after refarming (e.g. the network ensures a speed of 8 Mbps), there is no reason why refarming should push users to consume more data (same uses, same QoS*)*.

If the network is congested and 4G/5G 900MHz improves QoS at the target level, **there could be an expectation of heavier consumption since users had previously been constrained by insufficient quality of service**: the network was not able to meet customer demand. **But this therefore means that demand was already greater than network capacity**, so the operator is responding to customer demand and is able to ensure adequate QoS. A key factor in ARCEP's measurement campaigns is to encourage operators to ensure this QoS.

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[50] Considering the following assumptions: Throughput required per video call Intercom (2 to 5 Mbps according to figures from a provider of videotelephony intercom solutions (see https://www.2n.com)); average session duration (1 to 5 min); number of sessions/week (1 to 3 sessions) which gives a volume of data traffic of 30 to 375MB/session. Considering: 9.4% of traffic during busy days and 391,000 new intercoms to M-Day equipped with video calling features, we get an increment of traffic per busy hour on the entire network between 0.2Gbps (i.e.: 391,000*1*30*52*9%*8*50%/(365*3600)) at 6.5Gbps, or 0.01Mbps to 0.24Mbps.

[51] Considering the following assumptions: Capacity of an LTE FDD cell (without DSS) of 20MHz bandwidth in 2T2R equal to 35 Mbps (see Appendix A of the Experts Committee study [Committee – 2022]); Capacity for an LTE FDD cell with a low-band bandwidth of 8.7MHz (reduced throughput of 20%) estimated at 12.2 Mbps (i.e.: 35*8.7*20%/20); Assuming that the entire increment of data traffic associated with videophone video is carried exclusively by the 900MHz band, we obtain a site load increment on this band between 0.02% and 0.65% (i.e.: 0.24/(12.2*3)).

[52] Worst-case reasoning: Considering a data profile of 76% (see [Committee – 2022]); the new load of the 900MHz base station hosting, in addition to its 4G traffic (25%), the load increment due to videophone traffic (0.65%) and that of video traffic during video calls calculated previously (1%) is equal to 26.65% (or 25%+1%+0.65%); with the parameters of the consumption model of the 4G/5G base station (*a, b*) explained in the previous chapters, we obtain a daily electricity consumption equal to 15.57KWh (i.e. 24* (76% * 0.44 * 26.65% + 0.56)). Knowing that the daily power consumption of a 4G/5G base station without this traffic increment would be equal to 15.45KWh (i.e. 24*(76%*0.44*25%+0.56)), we therefore obtain a daily consumption increment of 0.13KWh per 4G/5G site, i.e. a consumption increment of 0.83%.

- In this scenario, if 900MHz refarming is not available, the alternative would be to increase the network's density with additional sites, which is a far more negative option in terms of carbon footprint.
  The number of customers concerned on M-Day, hence additional traffic generated, seems to us too low to be able speak of a rebound effect.

In conclusion, the rebound effect remains hard to qualify and quantify, but assessing the different pieces of evidence detailed below indicates that it should remain quite minor.

4.3. Embodied carbon of ICT end-user goods

4.3.1. Carbon footprint data considered for telephonic devices

The Mobile Experts Committee's use of public data from French administrations (Arcep, ANFR, ADEME, CREDOC) for its various studies makes it possible, a priori, to guarantee that these are good quality data.

For the carbon footprint values of mobile devices (smartphones, feature phones), ADEME's Base Carbone and IMPACTS databases (v 2.02) are used. The Base Carbon database is a public database of emissions factors needed to carry out the organisations' carbon accounting exercises (for example, as part of regulatory or voluntary GHG assessments). It is administered by ADEME, but its governance is ensured by multiple stakeholders, and it remains open to expansion. The IMPACTS database is designed to support environmental labelling exercises and product assessments. It should be noted that Ademe is currently working to consolidate the impact data from these two databases as part of the creation of the Footprint database (*Base Empreinte*).

- In the case of smartphones, the study is based on impact data gathered by the NegaOctet consortium as part of the PERFECTO 2018 project and contributing to the IMPACTS database[53]. Note that there can be some variability in the data between the retained value and other data on the embodied carbon of a smartphone in France from databases such as Boavizta[54], or device manufacturers' (PCF) carbon assessment data (see Chapter: "*Data quality analysis*"). Despite this variability, the study retained data from the IMPACTS database that aligns with other recent studies by ADEME and Arcep on the digital environmental footprint[55].
- For feature phones, the IMPACTS database does not provide impact data for this type of device; these data are nevertheless input into Base Carbone database under "classic phone".[56]

In conclusion: in this study, the embodied carbon of a feature phone and a smartphone (excluding the use phase) has the **respective values of 84 and 14 kg of CO2e/unit.**

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[53] https://base-impacts.ademe.fr/gestdoclist

[54] https://datavizta.boavizta.org/manufacturerdata

[55] Examples: the ADEME study on the impact of refurbishment (09/2022): https://librairie.ademe.fr/dechets-economie-circulaire/5241-evaluation-de-l-impact-environnemental-d-un-ensemble-de-produits-reconditionnes.html; the ADEME/ARCEP study on the environmental impact of digital technology in France (03/2023): https://www.arcep.fr/uploads/tx_gspublication/note-synthese-au-gouvernement-prospective-2030-2050_mars2023.pdf , the ADEME study on the environmental impact of the digitalisation of cultural services (11/2022): https://librairie.ademe.fr/dechets-economie-circulaire/5942-evaluation-de-l-impact-environnemental-de-la-digitalisation-des-services-culturels.html

[56] https://data.ademe.fr/datasets/base-carbon(r)

4.3.2. Carbon footprint data considered for IoT connected objects

IoT connected objects are characterised by their diverse designs, which makes the LCA performance for a specific connected object far from representative of the variety of designs and applications in the area of IoT. To determine IoT impact data, the study reuses the work and results of the bottom-Up modelling approach in the Pirson and Bol's publication[57]. In this approach, a connected object is broken down into functional modules (actuators, calculation, power supply, connectivity, etc.); each functional module is characterised by a hardware specification level on a scale of 0 to 3 to reflect the complexity of that module's hardware profile. The hardware specification level of each module is linked to a technical modelling by the authors to determine the object's carbon footprint data.

Recommendation ITU-T L. 1450 is not explicit and prescriptive on the scope of impact accounting (i.e. the allocation rules to be used) of IoT, due to the diversity of object composition profiles, and the difficulty of defining a clear boundary between connectivity and other functionalities/modules embedded in the object[58]. To assess the objects' embodied carbon, the study therefore proposes to confine itself to only the embodied carbon of the object's connectivity component: this share includes the modem and all other elements supporting the object's connectivity function (antennas, any other discrete elements etc.). Such a choice is consistent with the characterisation of ICT (whose main purpose is connectivity) and makes it possible to limit uncertainties in the face of the lack of data to characterise the object as a whole.

With reference to Table 4 of Recommendation L.1410, all of the processes covered and the types of "cradle to gate" data used to quantify their impact are detailed:

Table 18 – Types of data used in the study vs. type de data required by Recommendation ITU L.1410

Phase	Process	Type of data required by the Recommendation	Type of data used in the study
Raw materials acquisition	Extraction of raw materials	Secondary	Secondary
	Raw materials processing	Secondary	Secondary
Production	Components manufacturing (Cf. Table 19)	ICT-specific primary and secondary data	ICT-specific secondary data (Cf. Table 19)
	Assembly (Cf. Table 19)	ICT-specific primary and secondary data	ICT-specific secondary data (Cf. Table 19)
	Manufacturer support activities	ICT-specific primary and secondary data; secondary data	Not applicable
	Production pf support goods	ICT-specific primary and secondary data; secondary data	Not applicable
	Construction of ICT-specific sites	ICT-specific primary and secondary data; secondary data	Not applicable

- **Modelling the parts manufacturing and assembly processes**

With reference to Table E.1 (Annex E) of Recommendation ITU L.1410, the constituent parts of the connectivity module are modelled in accordance with the Recommendation. The other parts/processes attributable to the Connectivity module are also explained and their contribution is

[57] "Assessing the embodied carbon of IoT edge devices with a bottom-up life-cycle approach", 2021, Thibault Pirson and David Bol.

[58] For example, for less sophisticated objects, some modules include more than one feature.

estimated via mark-up factors applied to the Connectivity module impact data in the Pirson and Bol publication.

These mark-up factors are the result of discussions (expert estimates) with Thibault Pirson, author of the aforementioned study. Some uncertainty nevertheless remains over these mark-up factors:

Table 19 – Mark-up factors applied to impact data

Components	Unitary processes	Comment
B1.1.4 Integrated Circuits (ICs)	**IC:** Modelling per part based on the surface of the chip ("Silicon die surface") with details on the type of packaging and the technological node. Taking into account the impact of all relevant unit processes in the production of the CI including "Frontends" processes (wafer production, chip production) and "Backend" processes (acquisition of raw materials, encapsulation/packaging of the CI).	No mark-up
B1.1.5 Mechanical and material parts	**Antennas:** Modelling by part and mass via a custom model (parametric LCA) integrating the generally constitutive elements of an antenna, the model integrates the impact of the acquisition of raw materials; does not include assembly.	No mark-up No consideration of a patch antenna
Other elements attributable to the Connectivity module increasing the impact data considered (these elements are originally counted in other modules)		
B1.1.3 Electromechanical elements	Connectors and electromagnetic shield	Increase of 10-30%
B1.1.8 Other PCBA components	Interfacing elements with other modules of the IoT object (e.g. with the power module, the computing unit of the object etc.), passive components (e.g. for impedance matching)	
B1.1.10 Black box modules	"Cradle-to-Gate" LCA of the SIM card (includes the SIM card (IC) + associated components allowing its operation: SIM trolley/connectors, additional PCB surface, SIM power supply.	Increase of 175 gCO2e[59]
B1.1.7 PCB	PCB when mounting the modem on a dedicated board and assembly process	50% mark-up
B1.2 Assembly	*Not included in the connectivity module but in the IoT PCB module*	

In conclusion, the sum of the carbon footprint of the connectivity module components and all the elements attributable to this module gives a "Cradle to Gate" estimate equal to **4.6 Kg CO2e/connectivity module.**

4.3.3. Calculating devices' carbon cost with amortisation

This section explains the amortisation-based approach used to calculate devices' embodied carbon in the reference and migration scenarios. The development of the approach distinguishes the specific case of not taking refurbishment into account (e.g. case of feature phones) then a generalisation by taking refurbishment into account (e.g. case of smartphones)

[59] https://www.izm.fraunhofer.de/en/news_events/tech_news/independent-study-confirms-esim-as-an-environmentally-friendly-sim-solution.html

4.3.3.1. Excluding refurbishment from the calculations

Calculation principle:

- A device whose embodied carbon is C with a lifespan of D years has an embodied carbon amortised by C/D every year of its normal lifespan of D years (linear amortisation)
- A device whose embodied carbon is C and which is no longer used at all during the course of its life cycle despite S years remaining in its normal lifespan of D years has an immediate and one-time carbon footprint of C* S/D, as a still undepreciated tangible (material) asset that is destroyed and which would thus represent a loss to be booked.
- No refurbishment taken into account.

Example:

- An old mobile phone with a lifespan of 5 years, with an embodied carbon of A has already been in use for 3 years on M-Day, so it has 2 years left in its normal life cycle.
- A new mobile phone with a lifespan of 5 years, with an embodied carbon of N is introduced as new at different moments depending on the scenario:
    - In the reference scenario when the old device completes its life cycle
    - In the Migration scenario, this new device is introduced from M-Day, replacing the old device.

Table 20 – Illustration of the amortisation of a device's embodied carbon by scenario

Scenario	Year	1	2	3	4	5	Comments
Reference	Carbon footprint: normal life cycle	A/5	A/5	N/5	N/5	N/5	Normal life cycles for all devices
Migration	Carbon footprint: normal life cycle	N/5	N/5	N/5	N/5	N/5	
Migration	Carbon footprint: end of device	2/5 A					Old device binned on M-Day has a one-time carbon footprint on this day of 2/5 A
Calculation (Migration – reference)	Calculation by year	N/5+A/5	N/5-A/5	0	0	0	

- Reference scenario: total impact of 2/5 A + 3/5 N
- Migration scenario: total impact of 2/5 A + 5/5 N

Difference (migration – reference) = 2/5 N

The same result is found using the year-by-year differences between the two scenarios.

Difference (migration – reference) = N/5+A/5 +N/5-A/5 = **2/5 N**

This second calculation shows that the result is not related to the number of years covered by the calculation as soon as we take a number of years greater than or equal to the lifetime of the old device (2 years in the example).

The result can simply be interpreted with an additional cost for the N/5 migration scenario per year during the remaining 2 years of the normal life cycle of the old device.

Another example: case of a non-VoLTE-compatible phone with a lifespan of 8 years replaced by a VoLTE-compatible smartphone on M-Day in the migration scenario while it had 1 year left in its normal life cycle.

Difference (migration – reference) = 1/8 N

More generally, D being the lifespan of the new device, S being the number of years remaining in the life cycle of the old device, and N being the embodied carbon of the new device, we have:

Difference (migration – reference) = N/A * N = S * (N/A)

The result can simply be interpreted with an additional cost for the N/D migration scenario per year during the remaining S years of the normal life cycle of the old device.

It can also be noted that the S/D ratio is the number of carbon units to be taken into account for this device

4.3.3.2. Generalisation taking refurbishment into account

The following reasoning applies only to the case of smartphones.

In case of refurbishment, the new device is a refurbished device in both the reference and migration scenarios.
Taking the example illustration above and considering: “N’” the embodied carbon of the refurbished device, “D'” the theoretical lifetime of the refurbished device, “S” the number of remaining years of the lifespan of the old device, we obtain a difference between the reference and migration scenario equal to:

Difference (migration – reference) = S * (N'/D')

The calculation logic remains the same as for the case of not taking refurbishment into account except to consider the following parameters:

- "N'": Embodied carbon of refurbishment. This impact includes emissions from remanufacturing processes including sorting and control, consumption of the refurbishment site, replacing defective parts, testing and all logistics associated with remanufacturing (collection of devices and supply of parts). This impact is much lower than the embodied carbon of a new device: N'= α.N
- "D'": Lifespan of a refurbished device. Although refurbished devices have smaller upstream carbon footprint than their new counterparts, they also have a shorter lifespan. D'= β.D

Considering an "r" ratio of refurbished phones among device sales, the previous equation is rewritten as:

Difference (migration – reference) = r *S*(N'/D') + (1-r)*S*(N/A)

With the parameters introduced above, we obtain the following general form:

Difference (migration – reference) = S*(N/A) * (1 + r*(α/β – 1))

In order to apply the formula, the following values were considered:

- "α": The study published by ADEME[60] on the impact of refurbished products considers the embodied carbon of a refurbished device estimated at 8% of that of a new device. This data

[60] https://librairie.ademe.fr/dechets-economie-circulaire/5241-evaluation-de-l-impact-environnemental-d-un-ensemble-de-produits-reconditionnes.html

corresponds to an average profile of a refurbished[61] phone in France; it is established on the basis of primary data (collected from representative samples of mobile phone refurbishment actors in France (2020)) and validated by a critical review.

- "β": According to the same ADEME study, a ratio of 2:3 is assumed between the two durations.
- "A": refurbished devices represent 13% of devices sold according to Arcep's annual Achieving digital sustainability survey (April 2022)[62].

Assuming these values remain valid at the time of the migration date, we get:

Difference (migration – reference) = 0.84* S*(N/A) = S * ((0.84 * N)/D)

The value of N being 86 kgCO2e (see Chapter: *4.3.1*), in this study the value of 0.84 * 86 = 72.24 kgCO2e represents the unit cost of a smartphone's embodied carbon.

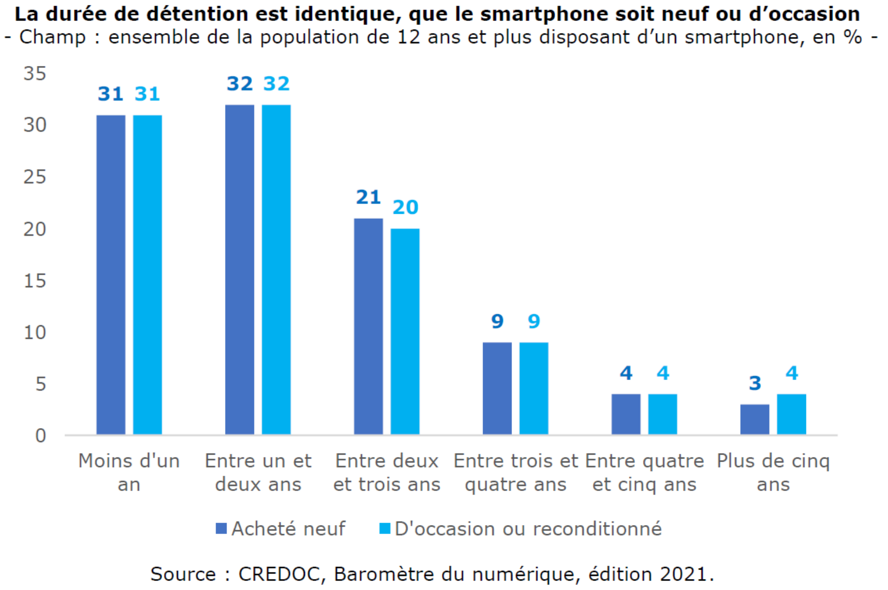
Note too that the S:D ratio also represents the number of carbon units to be taken into account for smartphones.

4.4. Determination of the distribution of telephones and IoT devices based on their life cycle

4.4.1. Determination of the distribution of smartphones and these remaining phones based on their life cycle

The following graph is used to determine the two tables being sought: distribution of smartphones and remaining smartphones:

Figure 12 – Distribution of smartphone ownership periods in France according to CREDOC



[61] Including average refurbishment method and configuration profile

[62] https://www.arcep.fr/uploads/tx_gspublication/enquete-PNS-edition2022-infographie_avril2022.pdf

Only the graph on new smartphones is used directly in the study: further details are found in this chapter.

$D_i: Percentage\ of\ phones\ owned\ between\ i-1\ and\ i\ years$

Based on the 2021 edition of the Digital market barometer, **and therefore the distribution values for 2020 examined here**, for new smartphones we have:

D1=31%; D2=32%; D3=21%; D4=9%; D5=4%

Considering that a smartphone has a maximum lifespan of 8 years, we have: D6 + D7 + D8 = 3%. The three values D6, D7 and D8 have been distributed using an additional assumption detailed later in this chapter.

$R_i: Percentage\ of\ phones\ remaining\ in\ the\ network\ after\ i\ years$

$V_i: Number\ of\ telephones\ sold\ with\ V_1\ representing\ sales\ for\ the\ year\ being\ examined$ (2020)

and V_{i+1} *sales for the preceding year's sales. Here, sales in 2019, sales in 2018 etc.*
$V_i V_2 V_3 V_i: can\ also\ be\ defined\ as\ the\ number\ of\ phones\ sold\ in\ the\ xst\ year\ before$ 2021.

$T_i: Number\ of\ phones\ between\ i-1\ and\ i\ years\ old\ still\ in\ the\ network$

$These\ T_i\ devices\ reaching\ the\ end\ of\ year\ i; to\ simplify: these\ T_i\ devices\ are\ i\ years\ old$

$T_i = V_i * R_i$

$\frac{T_i}{\sum_{i=1}^{max} T_i} = D_i$; $\sum_{i=1}^{max} T_i$: *this sum representing the total number of devices of different ages still in the network.*

From the two above equations, we deduce that:

$$\frac{V_i * R_i}{\sum_{i=1}^{max} T_i} = D_i$$

$$\frac{V_{i+1} * R_{i+1}}{D_{i+1}} = \frac{V_i * R_i}{D_i} = \sum_{i=1}^{max} T_i$$

We can therefore easily successively determine the different Ri with:

$$R_{i+1} = \frac{D_{i+1}}{D_i} * \frac{V_i}{V_{i+1}} * R_i\ et\ R_1 = 100\%$$

$$By\ posing\ k_{i=} \frac{V_1}{V_i}, on\ a\ V_{i=} \frac{V_1}{k_i}$$

$$\boxed{\boldsymbol{Equation\ 1: R_{i+1} = \frac{D_{i+1}}{D_i} * \frac{k_{i+1}}{k_i} * R_i\ and\ R_1 = 100\%}}$$

To calculate the different Ri, the different ki values tied to smartphone sales in France need to be determined.

The light blue graph produced by Credoc also includes the case of refurbished and used smartphones that have not been repaired before being sold. Because these two different types of device behave differently, it is difficult from a mathematical standpoint to utilise this graph directly. It is however possible to incorporate these two types of smartphone into the study as explained in the following two sections.

Case of refurbished smartphones

The ARCEP document on the replacement of devices (see [ARCEP – 2021]) indicates that refurbished phones represent 13% of all smartphones sold in 2020.

Happydemics found a very close number in an online survey conducted for YesYes (see [YESYES-2021]) indicating that refurbished phones represented 14% of smartphone sales in 2020.

The ARCEP document (see [ARCEP – 2021]) also states that:

- With regard to refurbished devices sold, the stakeholders interviewed by Arcep stressed that the market was concentrated around a small number of devices, mainly high-end devices and mainly produced by the brands Apple and Samsung. These devices would retain a high value longer. By way of illustration, and according to the discussions held and data collected, the refurbished iPhone 8 was the best-selling refurbished device in 2020.

It should be noted that the iPhone 8 is VoLTE-compatible, and that visiting platforms selling refurbished smartphones reveals the trend described by ARCEP – i.e. that it is mainly Apple[63] and Samsung[64] VoLTE-compatible smartphones being sold.

We should thus find the same trend with refurbished smartphones as with new smartphone sales: the vast majority of the smartphones sold during the two years before A-Day are VoLTE-compatible, and refurbished smartphones should not alter the conclusions regarding the assessment of smartphones' footprint in this study in terms of VoLTE compatibility.

We will consider a refurbished smartphone, in the same way as a new smartphone, including in its maximum lifespan of 8 years, which is a worst case for the assessment of phones' carbon footprint, but keeping in mind that the Credoc light blue graph that pertains especially to refurbished phones appears to show a life cycle for refurbished phones that is relatively close to that of new smartphones.

Case of used smartphones (excl. refurbishment)

Graph 194 of the CREDOC[65] document (see [CREDOC-2021]) indicates a percentage for second hand and refurbished phones in 2020 of 17%.

This therefore represents around 4%[66] of phones acquired in 2020, i.e. a fairly small number.

It should be noted that buyers of new smartphones keep them for the full first two years, which means that used smartphones are more than two years old at the time of second-hand purchase, and their maximum total life span of eight years remains unchanged (since no repair work was done before they were resold).

The device's change of ownership after more than two years with no repair or alteration has no reason to alter the Ri table, **i** years' old values apply only to the device. General calculations for new smartphones therefore incorporate the case of used smartphones (excl. refurbishment).

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[63] The GSA (Global Mobile Suppliers Association) Gambod database shows that iPhones have been VoLTE-compatible since the iPhone 6.

[64] The GSA's Gambod database shows 280 Samsung smartphone models being VoLTE-compatible, with Galaxy S4 and many Galaxy S5 models already available.

[65] Credoc is a research centre devoted to the study and observation of living conditions in France

[66] 24% of 17% based on ARCEP ([ARCEP – 2021]) and CREDOC ([CREDOC – 2021]) figures

Determination of the different ki (smartphone sales)

Based on the above considerations, an assessment needs to be made of smartphones sold in France, whether new or refurbished.

The combined data on sales of new smartphones in France, and data on smartphone sales worldwide[67] provide a good estimate of new smartphone sales since 2007.

Moreover, the Happydemics survey (see [YESYES-2021]) indicates that 2.6 million refurbished smartphones were sold in 2020, representing an annual increase of 20%.

In addition, an article published by "Les numériques"[68] states that: "*According to the firm Gfk, no fewer than 3.1 million refurbished smartphones were sold in 2021. A 20% increase compared to the previous year, a sign that buying a used smartphone is becoming increasingly common*."

It should be noted that the two studies provide consistent findings since 3.1/1.2 = 2.6

Determination of the different Ri

The different Ri are determined with Equation 1 above.

Total lengths of ownership of more than five years (3%) were interpreted by the values in green such that the absolute value of smartphones' CAGR increases.

Table 21 – Determination of the remaining tables for Smartphones

Number years (REF 2020) i	% holding period Smart Phone: Di	Ki= V1/Vi	%Remaining Smart phone Ri	Smart phone = %disappeared per year	CGAR Smartphone per year
1	31.00%	100.00%	100.00%	0.00%	0.00%
2	32.00%	96.31%	99.42%	0.58%	-0.29%
3	21.00%	97.40%	65.98%	33.44%	-12.94%
4	9.00%	100.24%	29.10%	36.88%	-26.55%
5	4.00%	104.26%	13.45%	15.65%	-33.05%
6	2.10%	110.58%	7.49%	5.96%	-35.07%
7	0.80%	126.89%	3.27%	4.22%	-38.64%
8	0.10%	162.16%	0.52%	2.75%	-48.14%
9	0.00%	228.29%	0.00%	0.52%	-100.00%
TOTAL	100.00%			100.00%	

Determination of the different Di the year before A-Day

[67] Source: "The number of smartphones sold to end users worldwide between 2007 and 2021 (in million units)" by Gartner published in February 2021; GFK for the France report, covering the period from December 2021 to July 2022. Percentages were determined for France, except for 2020 where the number was adjusted upwards to take into account the proportionally smaller impact of Covid. The number chosen for 2022 was 95% of 2021, keeping in mind that various press articles indicated a decrease in smartphone sales (global decrease of around 11%, reduced to 5%, using a similar approach).

[68] "Refurbishment: a fast-growing market in France": article published on 13/09/2022 in "*Les numériques*": https://www.lesnumeriques.com/telephone-portable/le-reconditionne-un-marche-en-pleine-progression-aupres-des-francais-n191579.html

The Credoc graph made it possible to determine the different Di for 2020.

We need the different Di for the year prior to the day the 2G/3G shutdown was announced (A-Day), keeping in mind that we have the Ri table, using the assumption that this table is true regardless of the year.

The following equation is reused (see previous Chapter):

$$Equation\ 1: R_{i+1} = \frac{D_{i+1}}{D_i} * \frac{V_i}{V_{i+1}} * R_i\ and\ R_1\ = 100\%$$

We deduce the following equation which will make it possible to determine telephones' length of ownership by year:

$$Equation\ 2: D_{i+1} = \frac{R_{i+1}}{R_i} * \frac{V_{i+1}}{V_i} * D_i\ and\ R_1\ = 100\%$$

We also know that:

$$Equation\ 3: \sum_{i=1}^{max} D_i = 100\%\ with\ max\ being\ the\ lifespan\ of\ the\ phone\ in\ question$$

We begin by determining D1. From Equation 2, we deduce that:

$$D_2 = \frac{R_2}{R_1} * \frac{V_2}{V_1} * D_1 = R_2 * \frac{V_2}{V_1} * D_1\ since\ R_1 = 100\%$$

$$D_3 = \frac{R_3}{R_2} * \frac{V_3}{V_2} * D_2 = \frac{R_3}{R_2} * \frac{V_3}{V_2} * R_2 * \frac{V_2}{V_1} * D_1 = R_3 * \frac{V_3}{V_1} * D_1$$

By the same token, we have:

$D_8 = R_8 * \frac{V_8}{V_1} * D_1$ (demonstrable by recurrence: see end of this Chapter)

$D_1 + D_2 + .. + D_8 = 1$

From the previous equations we deduce that:

$$D_1 + R_2 * \frac{V_2}{V_1} * D_1 + \cdots + R_8 * \frac{V_8}{V_1} * D_1 = 1$$

$$D_1 = 1 \Big/ \left(1 + R_2 * \frac{V_2}{V_1} + \cdots + R_8 * \frac{V_8}{V_1}\right)$$

$$By\ establishing\ that\ k_i = \frac{V_1}{V_i},\ on\ a\ V_i = \frac{V_1}{k_i}$$

$$Equation\ 4: D_1 = 1 / (1 + R_2/k_2 + \cdots + R_8/k_8)$$

D1 can be calculated since the different Ri are already known, and the different ki are known for phone sales up to the year preceding A-Day. A-Day=2022 served as the basis to determine the ki.

We then determine the other Di in succession for i=2, 3 … 8

$$D_i = R_i * \frac{V_i}{V_1} * D_1$$

$$Equation\ 5: D_i = R_i/k_i * D_1$$

Table 22 – Determination of the Di of smartphones before A-Day, then verification of the Ri

i (year beforeTa)	Ki=V1/Vi	Ri (table)	Ri /Ki	Di	Ri Check
1.00	100.00%	100.00%	100.00%	32.02%	100%
2.00	99.13%	99.42%	100.29%	32.11%	99.42%
3.00	108.07%	65.98%	61.05%	19.55%	65.98%
4.00	104.08%	29.10%	27.96%	8.95%	29.10%
5.00	105.26%	13.45%	12.78%	4.09%	13.45%
6.00	108.32%	7.49%	6.92%	2.21%	7.49%
7.00	112.68%	3.27%	2.91%	0.93%	3.27%
8.00	119.50%	0.52%	0.44%	0.14%	0.52%
TOTAL			312.35%	100.00%	

$$The\ amount\ 312.35\%\ is\ equal\ to\ \left(1+\frac{R_2}{k_2}+\cdots+\frac{R_8}{k_8}\right)\ and\ D_1\ is\ equal\ to\ its\ own\ inverse$$

$$Then\ we\ find\ the\ other\ different\ D_i\ knowing\ that\ D_i = R_i/k_i * D_1\ with\ D_1 = 32.02\%$$

To check the consistency, the different Ri are recalculated according to the Di and Ki we found using Equation 1.

To check the consistency, we recalculate the different Ri based on Equation 1.

As per the study's assumption, we indeed have constant Ri regardless of the year, but the different ki and Di change from year to year, since smartphone sales (new + refurbished) are not consistent from year to year.

<u>Mathematical induction:</u>

We induce mathematically that: $D_I = R_i * \frac{V_i}{V_1} * D_1$

$D_1 = R_1 * \frac{V_1}{V_1} * D_1$; so the equation is true in row 1

If true in row n (mathematical induction): $D_n = R_n * \frac{V_n}{V_1} * D_1$

then:

$$D_{n+1} = \frac{R_{n+1}}{R_n} * \frac{V_{n+1}}{V_n} * D_n\ according\ to\ Equation\ 2$$

$$D_{n+1} = \frac{R_{n+1}}{R_n} * \frac{V_{n+1}}{V_n} * R_n * \frac{V_n}{V_1} * D_1\ according\ to\ the\ assumption\ of\ mathematical\ induction$$

$$D_{n+1} = \frac{R_{n+1}}{\cancel{R_n}} * \frac{V_{n+1}}{\cancel{V_n}} * \cancel{R_n} * \frac{\cancel{V_n}}{V_1} * D_1 = R_{n+1} * \frac{V_{n+1}}{V_1} * D_1$$

And the equation is still true at row n+1.

4.4.2. Determination of the distribution of remaining feature phones and mobile phones based on their life cycle

We will begin by determining the different Ri for a feature phone. Then the ki, and the Di the year preceding A-Day are calculated.

Determination of the different Ri

We have a table that lists the length of smartphone ownership thanks to the CREDOC study [CREDOC-2021], and the percentages of smartphones remaining by year have thereby been deduced (see previous Chapter). But we do not have this same information directly about feature phones.

The CREDOC study [CREDOC-2021] also provides users' reasons for replacing a smartphone, showing that 25% of purchase were "for pleasure".

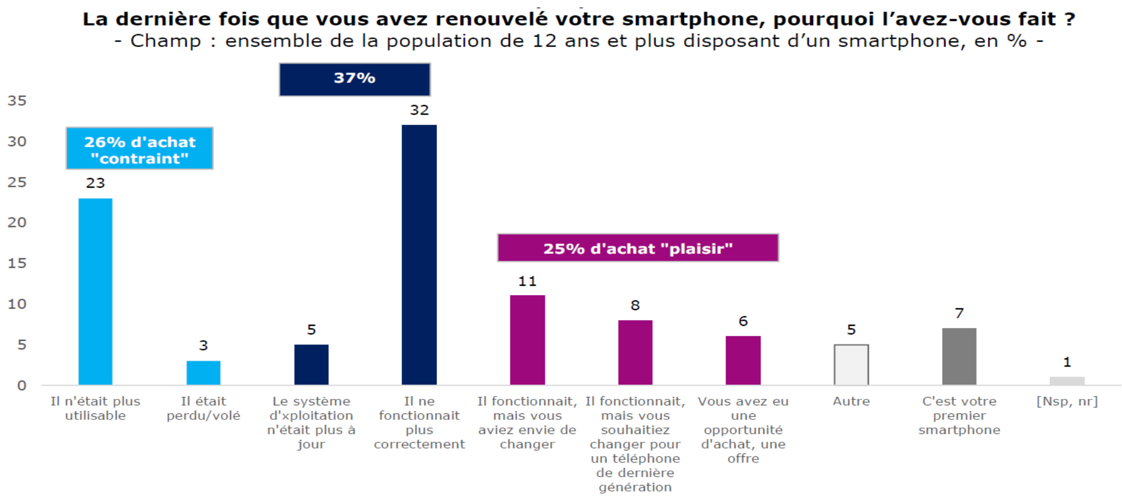


Figure 13 – Statistics on the reasons for buying a new smartphone in France, according to CREDOC

The assumption is that these "for pleasure" buys do not exist for feature phones: these 25% of devices have been distributed fairly evenly over the last years of the feature phone cycle on an assumption of a maximum lifespan of 10 years and so that the absolute value of the equivalent AAGR increases per year, as for smartphones.

We thereby deduce the feature phones disappearing per year (at the start of each year) and the percentage remaining each year (after the disappearances at the start of the year).

Table 23 – Determination of the table of remaining Ri for feature Phones

Number years (REF 2020) i	% holding period Smart Phone: Di	Ki= V1/Vi	%Remaining Smart phone Ri	Smart phone = %disappeared per year	CGAR Smartphone per year	Feature phone = %Delta smartphones disappeared per year	Feature phone = %disappeared per year	%Remaining Feature phone Ri	CGAR feature phone per year
1	31.00%	100.00%	100.00%	0.00%	0.00%	0.0%	0.00%	100.00%	0.00%
2	32.00%	96.31%	99.42%	0.58%	-0.29%	0.0%	0.58%	99.42%	-0.29%
3	21.00%	97.40%	65.98%	33.44%	-12.94%	-11.0%	22.44%	76.98%	-8.35%
4	9.00%	100.24%	29.10%	36.88%	-26.55%	-9.0%	27.88%	49.10%	-16.29%
5	4.00%	104.26%	13.45%	15.65%	-33.05%	-5.0%	10.65%	38.45%	-17.40%
6	2.10%	110.58%	7.49%	5.96%	-35.07%	4.0%	9.96%	28.49%	-18.88%
7	0.80%	126.89%	3.27%	4.22%	-38.64%	4.0%	8.22%	20.27%	-20.39%
8	0.10%	162.16%	0.52%	2.75%	-48.14%	4.0%	6.75%	13.52%	-22.13%
9	0.00%	228.29%	0.00%	0.52%	-100.00%	4.0%	4.52%	9.00%	-23.47%
10	0.00%	323.77%		0.00%	-100.00%	5.0%	5.00%	4.00%	-27.52%
11	0.00%			0.00%	-100.00%	4.0%	4.00%	0.00%	-100.00%
TOTAL	100.00%			100.00%		0.00%	100.00%	439.24%	

Determination of the different ki and Di

The following curve will be used to determine the different ki[69]:

Table 24 – Statistics on feature phone sales in Southern Europe (Statista excerpt)

It then remains to determine the percentages of the length of ownership of feature phones the year preceding A-Day, chosen as 2022 for the calculations.

Equation 4 is used to determine D1, then Equation 5 is used to determine the other Di (D2, D3 ... D10) as in the previous Chapter. To verify consistency, we recalculate the different Ri based on Equation 1.

69 https://www.statista.com/outlook/cmo/consumer-electronics/telephony/feature-phones/southern-europe#volume

The different Vi from the Southern Europe curve is shown above, and are expressed in millions of devices.

The different Ki are then calculated using the assumption that the Ki curve is also applicable to the reference network for this study.

Table 25 – Determination of the different Ki and Di (feature phone), then verification of the Ri

i	Vi	Ki= V1/Vi	Ri (table)	Ri /Ki	Di	Ri Check
1.00	4.80	100.00%	100.00%	100.00%	17.55%	100%
2.00	5.00	96.00%	99.42%	103.56%	18.18%	99.42%
3.00	5.20	92.31%	76.98%	83.40%	14.64%	76.98%
4.00	6.10	78.69%	49.10%	62.40%	10.95%	49.10%
5.00	6.40	75.00%	38.45%	51.27%	9.00%	38.45%
6.00	7.40	64.86%	28.49%	43.92%	7.71%	28.49%
7.00	9.10	52.75%	20.27%	38.44%	6.75%	20.27%
8.00	11.70	41.03%	13.52%	32.96%	5.79%	13.52%
9.00	17.60	27.27%	9.00%	33.00%	5.79%	9.00%
10.00	25.00	19.20%	4.00%	20.83%	3.66%	4.00%
TOTAL				569.78%	100.00%	

$The\ amount\ 569.78\%\ is\ equal\ to\ \left(1+\frac{R_2}{k_2}+\cdots+\frac{R_8}{k_{10}}\right)\ and\ D_1\ is\ equal\ to\ its\ inverse$

$Then\ we\ find\ the\ other\ different\ D_i\ knowing\ that\ D_i = R_i/k_i * D_1\ with\ D_1 = 32.02\%$

To check the consistency, the different Ri are recalculated according to the Di and Ki we found using Equation 1.

4.4.3. The case of IoT

The approach consists of using a method analogous to the one used for mobile phones (smartphone, feature phone) for IoT, i.e. based on the following key elements:

- The (percentage) breakdown by age of the different IoT devices in the reference operator's network whose communication module is not 4G or 5G-compatible, and the objects using voice services are not VoLTE-compatible on the day the operator announced the shutdown of 2G/3G technologies (A-Day), to be able to assess the number of communication modules to be replaced under the migration scenario. These different numbers on A-Day are represented by different Di values (percentages), with i being the age of the device/module;
- To extrapolate the number of these IoT objects just before M-Day, we need to know the percentage of IoT objects remaining in the network after i years;
- We calculate amortisation in a manner analogous to the one used for mobile devices.

Among the different IoT objects in the ICT sector, by far the most numerous are:

- Mobile PoS devices: these devices are considered to have a maximum lifespan of 10 years.
- Remote meter readers: these devices are considered to have a maximum lifespan of 15 years.
- Intercoms: these devices are considered to have a maximum lifespan of 20 years.

The Ri table for feature phones is used for objects with a maximum lifespan of 10 years.

The Ri table for objects with a lifespan of 15 and 20 years are extrapolated from the Ri for objects with a maximum lifespan of 10 years as follows:

- Different points are extrapolated by horizontal expansion[70] when feasible with integer values: these points are highlighted in colour in the following table
    - For instance, for IoT with a max. lifespan of 15 years (10 = 15 * 1/1.5), on a $R_{15years}(3)=R_{10years}(3/1.5)=R_{10years}(2)=99.42$ (value highlighted in brown)
    - For IoT with a max. lifespan of 20 years (10=20 * 1/2), $R_{20\ years}(12)=R_{10\ years}(20*1/2)=R_{10years}(6)$ (value highlighted in light brown)
- The other Ri are deduced by linear extrapolation between the Ri previously deduced by horizontal expansion.

Table 26 – Determination of the table of remaining Ri for IoT objects

Number years i	%Remaining Feature phone= IoT max lifespan 10 years Ri	CGAR feature phone per year= IoT max lifespan 10 years	%Remaining IoT max lifespan 15 years Ri	%Disappeared IoT max lifespan 15 years	CGAR IoT max lifespan 15 years	%Remaining IoT max lifespan 20 years Ri	%Disappeared IoT max lifespan 20 years	CGAR IoT max lifespan 20 years
1	100.00%	0.00%	100.00%	0.00%	0.00%	100.00%	0.00%	0.00%
2	99.42%	-0.29%	100.00%	0.00%	0.00%	100.00%	0.00%	0.00%
3	76.98%	-8.35%	99.42%	0.58%	-0.19%	99.71%	0.29%	-0.10%
4	49.10%	-16.29%	82.65%	16.77%	-4.65%	99.42%	0.29%	-0.15%
5	38.45%	-17.40%	65.87%	16.77%	-8.01%	88.20%	11.22%	-2.48%
6	28.49%	-18.88%	49.10%	16.77%	-11.18%	76.98%	11.22%	-4.27%
7	20.27%	-20.39%	42.23%	6.87%	-11.59%	63.04%	13.94%	-6.38%
8	13.52%	-22.13%	35.36%	6.87%	-12.19%	49.10%	13.94%	-8.51%
9	9.00%	-23.47%	28.49%	6.87%	-13.02%	43.78%	5.32%	-8.77%
10	4.00%	-27.52%	23.50%	4.99%	-13.48%	38.45%	5.32%	-9.11%
11	0.00%	-100.00%	18.51%	4.99%	-14.22%	33.47%	4.98%	-9.47%
12	0.00%	-100.00%	13.52%	4.99%	-15.36%	28.49%	4.98%	-9.93%
13	0.00%	-100.00%	10.35%	3.17%	-16.01%	24.38%	4.11%	-10.29%
14	0.00%	-100.00%	7.17%	3.17%	-17.15%	20.27%	4.11%	-10.77%
15	0.00%	-100.00%	4.00%	3.17%	-19.31%	16.90%	3.38%	-11.18%
16	0.00%	-100.00%	0.00%	4.00%	-100.00%	13.52%	3.38%	-11.75%
17	0.00%	-100.00%	0.00%	0.00%	-100.00%	11.26%	2.26%	-12.05%
18	0.00%	-100.00%	0.00%	0.00%	-100.00%	9.00%	2.26%	-12.52%
19	0.00%	-100.00%	0.00%	0.00%	-100.00%	6.50%	2.50%	-13.40%
20	0.00%	-100.00%	0.00%	0.00%	-100.00%	4.00%	2.50%	-14.87%
21	0.00%	-100.00%	0.00%	0.00%	-100.00%	0.00%	4.00%	
TOTAL				100.00%			100.00%	

To determine the Di distribution tables of the three sub-sets of ICT objects with different maximum lifespans, we employ the same method as the one used for feature phones.

To this end, an additional assumption needs to be made on the sale of objects that are only 2G/3G-compatible before A-Day, which will be accomplished with the help of a sensitivity analysis (see Next Chapter).

[70] Mathematical transformation which consists in determining a function F from the horizontal deformation of f by postulating: y=F(x)=f(a*x). We speak of horizontal deformation when |a|< 1. With the maximum durations of 15 and 20 years, the coefficient A is respectively equal to 1/1.5 and 1/2; in the case with a duration of 15 years on a for instance: F(3)= f(3/1.5)= f(2); F(6)= f(6/1.5)= f(4)

4.5. Sensitivity analysis

The first case corresponds to the base case under study; the other case corresponds to the other case examined for the sensitivity analysis. The parameters having been altered compared to the base case are indicated in yellow. The approach consists of introducing only a single variant compared to the base case (case No. 1).

The following table summarises the different case examined, with their parameters and results.

Table 27 – Table of the parameters and different results of the cases examined for the sensitivity analysis

Type of case	Base case	Number Telephones	Number Telephones	Values Dx Smarphone	Values disappeared Feature Phones	Number IoT	Number IoT	Sales IoT before Ta	Sales IoT before Ta	Sales IoT after Ta	Sales Smartphone before Ta	a & b	a & b	a & b	a & b	Network	Network	Carbon feature phone	Carbon IoT	elect carbon intensity
Case number	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Carbon intensity value (gCO2e/KWh)	44.40	44.40	44.40	44.40	44.40	44.40	44.40	44.40	44.40	44.40	44.40	44.40	44.40	44.40	44.40	44.40	44.40	44.40	44.40	43.81
D6 smartphones	2.10%	2.10%	2.10%	1.66%	2.10%	2.10%	2.10%	2.10%	2.10%	2.10%	2.10%	2.10%	2.10%	2.10%	2.10%	2.10%	2.10%	2.10%	2.10%	2.10%
D7 smartphones	0.80%	0.80%	0.80%	0.90%	0.80%	0.80%	0.80%	0.80%	0.80%	0.80%	0.80%	0.80%	0.80%	0.80%	0.80%	0.80%	0.80%	0.80%	0.80%	0.80%
D8 smartphones	0.10%	0.10%	0.10%	0.44%	0.10%	0.10%	0.10%	0.10%	0.10%	0.10%	0.10%	0.10%	0.10%	0.10%	0.10%	0.10%	0.10%	0.10%	0.10%	0.10%
D1 smartphones	31.00%	31.00%	31.00%	31.00%	31.00%	31.00%	31.00%	31.00%	31.00%	31.00%	31.50%	31.00%	31.00%	31.00%	31.00%	31.00%	31.00%	31.00%	31.00%	31.00%
D2 smartphones	32.00%	32.00%	32.00%	32.00%	32.00%	32.00%	32.00%	32.00%	32.00%	32.00%	31.50%	32.00%	32.00%	32.00%	32.00%	32.00%	32.00%	32.00%	32.00%	32.00%
Constant smartphone sales	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	YES	NO	NO	NO	NO	NO	NO	NO	NO	NO
Feature Phone disappeared (6)	4.0%	4.0%	4.0%	4.0%	7.00%	4.0%	4.0%	4.0%	4.0%	4.0%	4.0%	4.0%	4.0%	4.0%	4.0%	4.0%	4.0%	4.0%	4.0%	4.0%
Feature Phone disappeared (7)	4.0%	4.0%	4.0%	4.0%	5.50%	4.0%	4.0%	4.0%	4.0%	4.0%	4.0%	4.0%	4.0%	4.0%	4.0%	4.0%	4.0%	4.0%	4.0%	4.0%
Feature Phone disappeared (8)	4.0%	4.0%	4.0%	4.0%	4.50%	4.0%	4.0%	4.0%	4.0%	4.0%	4.0%	4.0%	4.0%	4.0%	4.0%	4.0%	4.0%	4.0%	4.0%	4.0%
Feature Phone disappeared (9)	4.0%	4.0%	4.0%	4.0%	4.00%	4.0%	4.0%	4.0%	4.0%	4.0%	4.0%	4.0%	4.0%	4.0%	4.0%	4.0%	4.0%	4.0%	4.0%	4.0%
Feature Phone disappeared (10)	5.0%	5.0%	5.0%	5.0%	3.00%	5.0%	5.0%	5.0%	5.0%	5.0%	5.0%	5.0%	5.0%	5.0%	5.0%	5.0%	5.0%	5.0%	5.0%	5.0%
Feature Phone disappeared (11)	4.0%	4.0%	4.0%	4.0%	1.00%	4.0%	4.0%	4.0%	4.0%	4.0%	4.0%	4.0%	4.0%	4.0%	4.0%	4.0%	4.0%	4.0%	4.0%	4.0%
Check sum	*25.0%*	*25.0%*	*25.0%*	*25.0%*	*25.00%*	*25.0%*	*25.0%*	*25.0%*	*25.0%*	*25.0%*	*25.0%*	*25.0%*	*25.0%*	*25.0%*	*25.0%*	*25.0%*	*25.0%*	*25.0%*	*25.0%*	*25.0%*
Number of Smartphones (kU) year Ta	18000	16000	16000	18000	18000	18000	18000	18000	18000	18000	18000	18000	18000	18000	18000	18000	18000	18000	18000	18000
Number of Feature phones (kU) year Ta	2000	4000	4000	2000	2000	2000	2000	2000	2000	2000	2000	2000	2000	2000	2000	2000	2000	2000	2000	2000
Feature phone voice/LTE ratio year before Ta	0%	80%	100%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Feature phone voice/LTE ratio year before Ta-1	0%	0%	80%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Number of IoT (kU) year Ta	4000	4000	4000	4000	4000	1000	5500	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000
Sales of IoT objects 20-year lifespan between Ta and Tm	NON	NON	NON	NON	NON	NON	NON	NON	NON	OUI	NON	NON	NON	NON	NON	NON	NON	NON	NON	NON
TACM Sale of IoT objects lifespan 20 years between Ta and Tm	0%	0%	0%	0%	0%	0%	0%	-5%	5%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Case study no. for values a and b	1	1	1	1	1	1	1	1	1	1	1	2	3	4	5	1	1	1	1	1
Case study no. for the network part	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	2	3	1	1	1
Feature phone: %sup embodied carbon	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	25%	0%	0%
IoT: %sup embodied carbon	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	25%	0%

Number of Smartphone carbon units (kU)	1.7	1.5	1.5	4.4	1.7	1.7	1.7	1.7	1.7	1.7	1.2	1.7	1.7	1.7	1.7	1.7	1.7	1.7	1.7	1.7
Number of Feature phones carbon units (kU)	51.9	58.3	23.2	54.2	39.0	51.9	51.9	51.9	51.9	51.9	51.0	51.9	51.9	51.9	51.9	51.9	51.9	51.9	51.9	51.9
Number of IoT carbon units (kU)	380.2	380.2	380.2	381.6	350.6	95.1	522.8	334.0	420.2	565.0	375.0	380.2	380.2	380.2	380.2	380.2	380.2	380.2	380.2	380.2

4G-5G network gain: 2G-3G reference	99.4%	99.4%	99.4%	99.4%	99.4%	99.4%	99.4%	99.4%	99.4%	99.4%	99.4%	99.2%	99.3%	99.6%	99.6%	95.7%	99.0%	99.4%	99.4%	99.4%
Number of months Smartphones impact	0.2	0.2	0.2	0.6	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.3	0.2	0.2	0.2	0.2	0.2	0.2	0.2
Number of months Feature Phones impact	1.4	1.6	0.6	1.5	1.0	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.9	1.4	1.1	1.4	1.4	1.7	1.4	1.4
Number of months impact TOTAL TELEPHONES	**1.6**	**1.8**	**0.8**	**2.1**	**1.3**	**1.6**	**1.6**	**1.6**	**1.6**	**1.6**	**1.5**	**1.6**	**2.2**	**1.6**	**1.3**	**1.6**	**1.6**	**2.0**	**1.6**	**1.7**
Number of months IoT	3.4	3.4	3.4	3.4	3.1	0.8	4.6	2.9	3.7	5.0	3.3	3.4	4.5	3.4	2.7	3.4	3.4	3.4	4.2	3.4
Number of months TOTAL Telephones + IoT	**5.0**	**5.1**	**4.2**	**5.4**	**4.4**	**2.5**	**6.2**	**4.6**	**5.3**	**6.6**	**4.8**	**5.0**	**6.7**	**5.0**	**4.0**	**5.0**	**5.0**	**5.3**	**5.8**	**5.1**
%Delta base case: Total Telephones	0.0%	8.9%	-48.9%	26.7%	-21.2%	0.0%	0.0%	0.0%	0.0%	0.0%	-6.1%	0.2%	33.6%	-0.1%	-20.1%	0.8%	0.5%	21.4%	0.0%	1.3%
%Delta base case: Total IoT	0.0%	0.0%	0.0%	0.3%	-7.8%	-75.0%	37.5%	-12.2%	10.5%	48.6%	-1.4%	0.2%	33.6%	-0.1%	-20.1%	0.8%	0.5%	0.0%	25.0%	1.3%
%Delta base case: Total Telephones + IoT	0.0%	2.9%	-16.0%	9.0%	-12.2%	-50.5%	25.2%	-8.2%	7.1%	32.7%	-2.9%	0.2%	33.6%	-0.1%	-20.1%	0.8%	0.5%	7.0%	16.8%	1.3%
Absolute value of maximum deviation	0.0%	8.9%	48.9%	26.7%	21.2%	75.0%	37.5%	12.2%	10.5%	48.6%	6.1%	0.2%	33.6%	0.1%	20.1%	0.8%	0.5%	21.4%	25.0%	1.3%

4.5.1. Description of the sensitivity analysis case

Case No. 2

The number of feature phones was doubled (4,000 kU instead of 2,000 kU), and the percentage of these feature phones that are VoLTE-compatible the year before A-Day (year 1) is 80% (instead of 0%).

Table 28 – Number of carbon units for feature phones in the sensitivity analysis (Case No. 2)

Year i	REMAINING Ri (table)	Distribution Di (table)	Number terminals year Ta (kU)	Ratio voice/LTE terminals at year i	Terminal years of service just after Tm	Table REMAINING Shifted	Number terminals at Tm (kU) non Voice/LTE	Number years S of life cycle remaining at Tm	Number carbon units for migration scenario (kU)	% carbon impact over total
1	100.00%	17.55%	702	80%	7	20.27%	28	4	11.39	19.53%
2	99.42%	18.18%	727	0%	8	13.52%	99	3	29.67	50.88%
3	76.98%	14.64%	585	0%	9	9.00%	68	2	13.69	23.48%
4	49.10%	10.95%	438	0%	10	4.00%	36	1	3.57	6.12%
5	38.45%	9.00%	360	0%	11	0.00%	0	0	0.00	0.00%
6	28.49%	7.71%	308	0%	12	0.00%	0	0	0.00	0.00%
7	20.27%	6.75%	270	0%	13	0.00%	0	0	0.00	0.00%
8	13.52%	5.79%	231	0%	14	0.00%	0	0	0.00	0.00%
9	9.00%	5.79%	232	0%	15	0.00%	0	0	0.00	0.00%
10	4.00%	3.66%	146	0%	16	0.00%	0	0	0.00	0.00%
TOTAL		100.00%	4000				231		58.31	100.00%

For reference purposes, the carbon footprint of feature phones in the base case (case No. 1) is provided again here:

Table 29 – Number of carbon units for feature phones in the base case (Case No. 1)

Year i	REMAINING Ri (table)	Distribution Di (table)	Number terminals year Ta (kU)	Ratio voice/LTE terminals at year i	Terminal years of service just after Tm	Table REMAINING Shifted	Number terminals at Tm (kU) non Voice/LTE	Number years S of life cycle remaining at Tm	Number carbon units for migration scenario (kU)	% carbon impact over total
1	100.00%	17.55%	351	0%	7	20.27%	71	4	28.47	54.82%
2	99.42%	18.18%	364	0%	8	13.52%	49	3	14.83	28.57%
3	76.98%	14.64%	293	0%	9	9.00%	34	2	6.84	13.18%
4	49.10%	10.95%	219	0%	10	4.00%	18	1	1.78	3.44%
5	38.45%	9.00%	180	0%	11	0.00%	0	0	0.00	0.00%
6	28.49%	7.71%	154	0%	12	0.00%	0	0	0.00	0.00%
7	20.27%	6.75%	135	0%	13	0.00%	0	0	0.00	0.00%
8	13.52%	5.79%	116	0%	14	0.00%	0	0	0.00	0.00%
9	9.00%	5.79%	116	0%	15	0.00%	0	0	0.00	0.00%
10	4.00%	3.66%	73	0%	16	0.00%	0	0	0.00	0.00%
TOTAL		100.00%	2000				173		51.93	100.00%

In case No. 2, the carbon footprint logically doubles every year, except for the first line of the table where we find a footprint of: 28.47*2*(1-0,8)= 28.47*0.4= 11.39 as indicated.

The carbon footprint of case No. 2 is larger than in case No. 1, but the increase is only around 12% compared to case No. 1 as the carbon footprint in the first line of the table in case No. 1 is proportionately very high (close to 55%; or 45% for the other lines).

Case No. 3

The number of feature phones is 4,000 kU (instead of 2,000 kU in case No. 1, i.e. the base case), and the percentage of these feature phones that are VoLTE-compatible the 2 years before A-Day (years 1 and 2) are 100% and 80%, respectively (instead of 0%).

Table 30 – Distribution table for feature phones for the sensitivity analysis (case No. 3)

Year i	REMAINING Ri (table)	Distribution Di (table)	Number terminals year Ta (kU)	Ratio voice/LTE terminals at year i	Terminal years of service just after Tm	Table REMAINING Shifted	Number terminals at Tm (kU) non Voice/LTE	Number years S of life cycle remaining at Tm	Number carbon units for migration scenario (kU)	% carbon impact over total
1	100.00%	17.55%	702	100%	7	20.27%	0	4	0.00	0.00%
2	99.42%	18.18%	727	80%	8	13.52%	20	3	5.93	25.58%
3	76.98%	14.64%	585	0%	9	9.00%	68	2	13.69	59.03%
4	49.10%	10.95%	438	0%	10	4.00%	36	1	3.57	15.39%
5	38.45%	9.00%	360	0%	11	0.00%	0	0	0.00	0.00%
6	28.49%	7.71%	308	0%	12	0.00%	0	0	0.00	0.00%
7	20.27%	6.75%	270	0%	13	0.00%	0	0	0.00	0.00%
8	13.52%	5.79%	231	0%	14	0.00%	0	0	0.00	0.00%
9	9.00%	5.79%	232	0%	15	0.00%	0	0	0.00	0.00%
10	4.00%	3.66%	146	0%	16	0.00%	0	0	0.00	0.00%
TOTAL		100.00%	4000				124		23.19	100.00%

The carbon footprint is thus much smaller than in case No. 2, and even in case No. 1.

This is due in particular to the fact that the carbon footprint of the first two lines of the table for case No. 1 represent more than 80% of the total.

Case No. 4

The CREDOC table [CREDOC -2021] for new smartphones indicates that for years of ownership beyond five years, the percentage of new smartphones that have been owned for more than five years is estimated at 3%. This gives rise to the question of how to distribute these 3% for 6, 7 and 8 years, knowing that we want absolute values for growing CAGR, and that smartphones' carbon footprint will be increased if the Remaining (7) and Remaining (8) values are increased.

This borderline case is reached in the following instance with the three final CAGR[71] being equal.

[71] It is in fact necessary to solve a cubic equation to determine the value of 1+ CAGR, the details of which are not given. We see that by lowering the value of R(6) of case No. 1 (5.92% instead of 7.49%), we manage to increase the two values R(7) and R(8) which are respectively 3.69% and 2.30% instead of 3.27% and 0.52%.

Table 31 – Distribution table for smartphones for the sensitivity analysis (case No. 4)

Number years (REF 2020) i	% holding period Smart Phone: Di	Ki= V1/Vi	%Remaining Smart phone Ri	Smart phone = %disappeared per year	CGAR Smartphone per year
1	31.00%	100.00%	100.00%	0.00%	0.00%
2	32.00%	96.31%	99.42%	0.58%	-0.29%
3	21.00%	97.40%	65.98%	33.44%	-12.94%
4	9.00%	100.24%	29.10%	36.88%	-26.55%
5	4.00%	104.26%	13.45%	15.65%	-33.05%
6	1.66%	110.58%	5.92%	7.54%	-37.58%
7	0.90%	126.89%	3.69%	2.23%	-37.59%
8	0.44%	162.16%	2.30%	1.39%	-37.59%
9	0.00%	228.29%	0.00%	2.30%	-100.00%
TOTAL	100.00%			100.00%	

The table for case No. 1 is provided for reference purposes.

Table 32 – Distribution table for smartphones in the base case (Case No. 1)

Number years (REF 2020) i	% holding period Smart Phone: Di	Ki= V1/Vi	%Remaining Smart phone Ri	Smart phone = %disappeared per year	CGAR Smartphone per year
1	31.00%	100.00%	100.00%	0.00%	0.00%
2	32.00%	96.31%	99.42%	0.58%	-0.29%
3	21.00%	97.40%	65.98%	33.44%	-12.94%
4	9.00%	100.24%	29.10%	36.88%	-26.55%
5	4.00%	104.26%	13.45%	15.65%	-33.05%
6	2.10%	110.58%	7.49%	5.96%	-35.07%
7	0.80%	126.89%	3.27%	4.22%	-38.64%
8	0.10%	162.16%	0.52%	2.75%	-48.14%
9	0.00%	228.29%	0.00%	0.52%	-100.00%
TOTAL	100.00%			100.00%	

Case No. 5

The different blue values of case No. 1, whose sum must be 25% ("for pleasure" smartphone purchases according to the Credoc survey [CREDOC -2021]) have been distributed, and in fact creating a worst case scenario for feature phones in terms of carbon footprint, generating significant R(9) and R(10) values (respectively 9% and 4%) and distributed almost evenly over these blue values. In the case of the sensitivity study, the blue values are chosen as decreasing, while ensuring lower and probably more realistic R(9) and R(10) values (respectively 4% and 1%).

Table 33 – Distribution table for feature phones for the sensitivity analysis (case No. 5)

Number years (REF 2020) i	% holding period Smart Phone: Di	Ki= V1/Vi	%Remaining Smart phone Ri	Smart phone = %disappeared per year	CGAR Smartphone per year	Feature phone = %Delta smartphones disappeared per year	Feature phone = %disappeared per year	%Remaining Feature phone Ri	CGAR feature phone per year
1	31.00%	100.00%	100.00%	0.00%	0.00%	0.0%	0.00%	100.00%	0.00%
2	32.00%	96.31%	99.42%	0.58%	-0.29%	0.0%	0.58%	99.42%	-0.29%
3	21.00%	97.40%	65.98%	33.44%	-12.94%	-11.0%	22.44%	76.98%	-8.35%
4	9.00%	100.24%	29.10%	36.88%	-26.55%	-9.0%	27.88%	49.10%	-16.29%
5	4.00%	104.26%	13.45%	15.65%	-33.05%	-5.0%	10.65%	38.45%	-17.40%
6	2.10%	110.58%	7.49%	5.96%	-35.07%	7.0%	12.96%	25.49%	-20.37%
7	0.80%	126.89%	3.27%	4.22%	-38.64%	5.5%	9.72%	15.77%	-23.19%
8	0.10%	162.16%	0.52%	2.75%	-48.14%	4.5%	7.25%	8.52%	-26.49%
9	0.00%	228.29%	0.00%	0.52%	-100.00%	4.0%	4.52%	4.00%	-30.07%
10	0.00%	323.77%		0.00%	-100.00%	3.0%	3.00%	1.00%	-36.90%
11	0.00%			0.00%	-100.00%	1.0%	1.00%	0.00%	-97.03%
TOTAL	100.00%			100.00%		0.00%	100.00%	418.74%	

For reference purposes, below is case No. 1:

Table 34 – Distribution table for feature phones in the base case (case No. 1)

Number years (REF 2020) i	% holding period Smart Phone: Di	Ki= V1/Vi	%Remaining Smart phone Ri	Smart phone = %disappeared per year	CGAR Smartphone per year	Feature phone = %Delta smartphones disappeared per year	Feature phone = %disappeared per year	%Remaining Feature phone Ri	CGAR feature phone per year
1	31.00%	100.00%	100.00%	0.00%	0.00%	0.0%	0.00%	100.00%	0.00%
2	32.00%	96.31%	99.42%	0.58%	-0.29%	0.0%	0.58%	99.42%	-0.29%
3	21.00%	97.40%	65.98%	33.44%	-12.94%	-11.0%	22.44%	76.98%	-8.35%
4	9.00%	100.24%	29.10%	36.88%	-26.55%	-9.0%	27.88%	49.10%	-16.29%
5	4.00%	104.26%	13.45%	15.65%	-33.05%	-5.0%	10.65%	38.45%	-17.40%
6	2.10%	110.58%	7.49%	5.96%	-35.07%	4.0%	9.96%	28.49%	-18.88%
7	0.80%	126.89%	3.27%	4.22%	-38.64%	4.0%	8.22%	20.27%	-20.39%
8	0.10%	162.16%	0.52%	2.75%	-48.14%	4.0%	6.75%	13.52%	-22.13%
9	0.00%	228.29%	0.00%	0.52%	-100.00%	4.0%	4.52%	9.00%	-23.47%
10	0.00%	323.77%		0.00%	-100.00%	5.0%	5.00%	4.00%	-27.52%
11	0.00%			0.00%	-100.00%	4.0%	4.00%	0.00%	-100.00%
TOTAL	100.00%			100.00%		0.00%	100.00%	439.24%	

This significantly reduces feature phones' carbon footrpint, and also reduces IoT's footprint.

Cases No. 6 and No. 7

The total number of ICT objects varies from the minimum number as assessed in the study (case No. 6) to its maximum number (case No. 7).

Cases No. 8 and No. 9

In cases No. 8 and No. 9, CAGR for 2G/3G IoT sales are adjusted, respectively to -5% and +5%, before A-Day, knowing that case No. 1 uses an assumption of 0%.

An increase in the CAGR (-%5< 0% <+5%) results in an increase in IoT's carbon footprint, knowing that the number of objects on Announcement Day is constant; we thereby "bring down" the age of the objects distribution on Announcement Day.

Case No. 8 (CAGR=-5%)

Table 35 – Sensitivity analysis of IoT (case No. 8)

	IoT max lifespan 10 years	IoT max lifespan 15 years	IoT max lifespan 20 years
i	Di	Di	Di
1.00	20.08%	11.90%	7.99%
2.00	21.01%	12.52%	8.41%
3.00	17.12%	13.11%	8.83%
4.00	11.50%	11.47%	9.27%
5.00	9.48%	9.62%	8.66%
6.00	7.39%	7.55%	7.95%
7.00	5.54%	6.84%	6.85%
8.00	3.89%	6.02%	5.62%
9.00	2.72%	5.11%	5.27%
10.00	1.27%	4.44%	4.88%
11.00		3.68%	4.47%
12.00		2.83%	4.00%
13.00		2.28%	3.61%
14.00		1.66%	3.16%
15.00		0.98%	2.77%
16.00			2.33%
17.00			2.05%
18.00			1.72%
19.00			1.31%
20.00			0.85%
TOTAL	100.00%	100.00%	100.00%

Case 1 (CAGR= 0%)

Table 36 – Sensitivity analysis of IoT (case No. 1)

	IoT max lifespan 10 years	IoT max lifespan 15 years	IoT max lifespan 20 years
i	Di	Di	Di
1.00	22.77%	14.70%	10.79%
2.00	22.63%	14.70%	10.79%
3.00	17.53%	14.62%	10.76%
4.00	11.18%	12.15%	10.73%
5.00	8.75%	9.68%	9.52%
6.00	6.49%	7.22%	8.31%
7.00	4.62%	6.21%	6.80%
8.00	3.08%	5.20%	5.30%
9.00	2.05%	4.19%	4.73%
10.00	0.91%	3.46%	4.15%
11.00		2.72%	3.61%
12.00		1.99%	3.08%
13.00		1.52%	2.63%
14.00		1.05%	2.19%
15.00		0.59%	1.82%
16.00			1.46%
17.00			1.22%
18.00			0.97%
19.00			0.70%
20.00			0.43%
TOTAL	100.00%	100.00%	100.00%

Case 9 (CAGR=+5%)

Table 37 – Sensitivity analysis of IoT (case No. 9)

	IoT max lifespan 10 years	IoT max lifespan 15 years	IoT max lifespan 20 years
i	Di	Di	Di
1.00	25.36%	17.50%	13.68%
2.00	24.01%	16.67%	13.03%
3.00	17.71%	15.78%	12.38%
4.00	10.76%	12.49%	11.75%
5.00	8.02%	9.48%	9.93%
6.00	5.66%	6.73%	8.25%
7.00	3.84%	5.52%	6.44%
8.00	2.44%	4.40%	4.78%
9.00	1.54%	3.37%	4.05%
10.00	0.65%	2.65%	3.39%
11.00		1.99%	2.81%
12.00		1.38%	2.28%
13.00		1.01%	1.86%
14.00		0.67%	1.47%
15.00		0.35%	1.17%
16.00			0.89%
17.00			0.71%
18.00			0.54%
19.00			0.37%
20.00			0.22%
TOTAL	100.00%	100.00%	100.00%

Case No. 10

In the case of objects with a lifespan of 20 years, we consider that the sale of these 2G/3G objects continues between Announcement day and Migration day at a decreasing pace[72] over time, at a rate defined by the percentages in the third column.

The value of 108 kU corresponds to the D(1) value already determined on Announcement Day (2022 in the example given.

Table 38 – Sensitivity analysis on IoT (case No. 10)

Year i (year 0 = year Ta)	*Year as an example*	% compared to Year Ta	IoT Sales(kU)	REMAINING Ri (table)	Ti table year 2029	Number of years S of life cycle remaining at Tm	Number Carbon units for migration scenario (kU)
6	*2028*	10%	11	100.00%	11	20	11
5	*2027*	15%	16	100.00%	16	19	15
4	*2026*	25%	27	99.71%	27	18	24
3	*2025*	35%	38	99.42%	38	17	32
2	*2024*	65%	70	88.20%	62	16	50
1	*2023*	85%	92	76.98%	71	15	53
0	*2022*	100%	108				
TOTAL					224		185

[72] These are intercoms purchased by various types of user which could create more problems in terms of the end of 2G/3G/non VoLTE-compatible device sales.

Table 39: Number of total carbon units for IoT (case No. 10)

	Standard case	Additional number worst case taken into account	TOTAL
Carbon Impact (kU)	380	185	565

Case No. 11

This case corresponds to steady smartphone sales up to Announcement Day.

This would reduce smartphones' carbon footprint from 1.7 kU of carbon in the base case to 1.2 kU, since the number of smartphones is set on Announcement Day, we would bring up the age of smartphones on Announcement Day.

This case is provided for informational purposes to show the impact of reducing the slope of smartphone sales.

This demonstrates the benefit of having sought a reaslistic smarphone sales curve, even if this is not the study's most sensitive endpoint, as the results show.

Cases No. 12, 13, 14 and 15

These different cases concern a sensitivity analysis performed on the different a and b values of the refined model for a 2G/3G and 4G/5G base station's power consumption.

The different sub-case studies of these values a and b are indicated by their values (2, 3, 4 and 5) which correspond respectively to cases No. 12, 13, 14 and 15 in the main sensitivity analysis, and are described in the table below: the basic values a e b (case No. 1) have been multiplied by a coefficient so as to vary the 2G-3G and 4G-5G values.

Table 40 – Sensitivity analysis on the network parameters (Case No. 12, 13, 14, 15)

Table of a and b values according to Sub-cases a&b analyzed		2G/3G		4G/5G		2G/3G		4G/5G		Comments
	Values of Sub-cases a&b in main sensitivity study	BS: a	BS:b	BS: a	BS:b	Multiplier factor:a	Multiplier factor:b	Multiplier factor:a	Multiplier factor:b	
Base values	1	540.0	585.0	440.0	560.0	1.00	1.00	1.00	1.00	
increased 4G-5G values	2	540.0	585.0	880.0	700.0	1.00	1.00	2.00	1.25	Will reduce the environmental benefits of 4G-5G migration compared with the base case
lower 2G -3G values	3	405.0	438.8	440.0	560.0	0.75	0.75	1.00	1.00	Will reduce the environmental benefits of 4G-5G migration compared with the base case
lower 4G -5G values	4	540.0	585.0	330.0	420.0	1.00	1.00	0.75	0.75	Will increase the environmental benefits of 4G-5G migration compared with the base case
increased 2G-3G values	5	675.0	731.3	440.0	560.0	1.25	1.25	1.00	1.00	Will increase the environmental benefits of 4G-5G migration compared with the base case

Cases No. 16 and 17

These are the two cases already mentioned in the network portion.

Cases No. 18 and 19

Feature phones and IoT's embodied carbon values are increased by the percentage (25%) indicated in the table for the different cases.

Case No. 20

See in Annex B, the Chapter on carbon intensity/energy mix which explains how the emissions factor is calculated on M-Day. This gives the following values:

- Base case (No. 1): **44.40 gCO2e/kWh**
- This case (No. 20): **43,81 gCO2e/kWh**

4.5.2. Some interesting conclusions from the sensitivity analysis

Smartphones:

- The absolute impact of smartphones is negligible on this study; the relative tripling of case No. 4 does not change this conclusion. The results for the reference scope (network + phones) are related mainly to feature phones.

Feature phones/total impact of telephones/scope of reference:

- The breakeven point for the scope of reference is achieved with only about two months of network energy savings, fully testifying to the benefit of migrating to 4G/5G.
- Cases Nos. 2 and 3 are interesting because they show that an operator that currently has a much larger number of feature phones could wait between one and two years to find a similar or even smaller impact.

IoT/extended scope of reference

- Cases 6 and 7 show that the number of IoT objects considered logically influences the result. The number of IoT objects in case 7 is considered an overestimate of this number of objects, and the breakeven point is about six months.
- Case No. 7 describes the situation where sales of IoT objects would continue after the date of announcement of the 2G/3G shutdown with a breakeven point at seven months. This is undoubtedly an important point that shows how vital it is to have clear communications with the entire ecosystem to limit these sales.

Other cases examined that affect the two breakeven points

- The variations in values a and b in cases No. 12 and No. 14 have very little impact: this corresponds to the variations in 4G and 5G values, because the traffic that is carried by 2G/3G services and transferred to 4G/5G, is very light.
- The variations in values a and b in cases No. 13 and No. 15 correspond to the variations in the 2G/3G values, which have more of an impact. It is by considering lower values (case No. 13) that we delay the breakeven point to a value of about seven months: as explained earlier in the memorandum, the power consumption values do not take into account the common 3G channels, and therefore this case No. 13 is probably extreme.
- The two cases of network parameter variations (cases No. 16 and No. 17) have a negligible impact on the breakeven points, confirming the network-specific sensitivity analysis made in a previous chapter.
- By increasing the embodied carbon values of feature phones and IoT respectively in cases No. 18 and No. 19, we logically delay the breakeven points compared to the base case, but we remain with a value of less than two months for the scope of reference, and less than six months for the extended scope of reference.
- Emission factor (case No. 20): this case has almost no impact on breakeven points (+0.1 months approximately).

4.6. Taking Recommendation ITU-T L.1410 into account

4.6.1. Compliance check for the comparative analysis of ICT services

The second part of ITU-T Recommendation L 1410[73] served as a guideline for comparing the scenarios under study in this memo.

in its Appendix XII, Recommendation ITU L.1410 offers a table summarising the requirements contained in the body of the Recommendation. The study is aligned with the requirements of the Recommendation **with the exception of some non-mandatory specifications** relating to clause 6.3 of the Recommendation (inclusion and exclusion of certain activities/processes by life cycle phase).

Recommendation ITU L.1410 lists (in its Table 2) for each phase of the life cycle all the mandatory and optional processes and activities to be considered when carrying out an LCA of an ICT good, network or service (clause 6.3 of the Recommendation); this list also applies in the context of a comparative analysis of two ICT services.

[73] Part II – Comparative analysis/LCA between ICT and reference product system (baseline scenario): framework and guidance.

The table in Appendix Y of the Recommendation is repeated below to explain the extent to which the study did or did not comply with the required processes/activities:

Table 41 – Reporting of an ICT service’s process and activities by life cycle according to Recommendation ITU L.1410

Activity by life cycle phase			Process	Recommendation requirement for an “ICT Service”	Taken into account in the study and comments
A	Raw materials acquisition				
A1		Raw materials extraction		Mandatory	Taken into account in the embodied carbon of ICT goods included in the study’s scope and extended scope of reference
A2		Raw materials processing		Mandatory	Taken into account in the embodied carbon of ICT goods included in the study’s scope and extended scope of reference
B	Production[74]				
B1		ICT goods production			
B1.1			Parts production	Mandatory	Taken into account in the embodied carbon of ICT goods included in the study’s scope and extended scope of reference
B1.2			Assembly	Mandatory	Taken into account in the embodied carbon of ICT goods included in the study’s scope and extended scope of reference
B1.3			ICT manufacturer support activities	Recommended	**Not taken into account** These are the manufacturer’s support activities for maintaining and updating 2G/3G (reference scenario) and 4G/5G (in the migration scenario) network equipment. These recurring activities (therefore may take place even if no network equipment is deployed) are not taken into account. Migration to 4G/5G networks saves the impact of 2G/3G support activities (4G/5G support activities already exist before the migration date and there is no reason for them to increase especially during migration)
B2	Production of support goods				
B2.1			support goods manufacturing	Mandatory	Taken into account In the two scenarios, no production of support goods is involved
B3	Construction of ICT-specific sites				
B3.1			Construction of ICT-specific sites	Recommended	Taken into account

[74] This phase includes the manufacturer’s transport/logistics activities up to the ICT good’s installation location: the distribution of new VoLTE-compatible devices and new IoT devices is therefore included in this phase (embodied carbon of the ICT good).

					In the two scenarios, no ICT-specific site construction activity (whether to house ICT end-user goods or support goods)
C	Use				
C1		Use of ICT goods		Mandatory	Taken into account
C2		Use of support goods		Mandatory	Taken into account Use of support goods is identical in the two scenarios
C3		Support operator activities		Recommended	**Non taken into account** The migration to 4G/5G networks saves the impact of 2G/3G support activities, which include software update of 2G/3G network equipment, service calls to the site, 2G/3G network configuration tasks, maintenance of 2G/3G expertise. This category does not include activities related to the delivery of SIM cards or those associated with changing devices (phones, IoT), these activities are included in phase D.
C4		Service provider support activities		Recommended	**Non taken into account** The study did not take into account the incremental impact due to migration. Indeed, the current operational activities of the service provider on all of the equipment (compared to those specific to the connectivity module) is a question that remains open from a methodological point of view (an allocation rule may be required).
D	Goods end of life treatment[75]				
D1		Preparing ICT good for reuse		Mandatory	Taken into account Taken into account (notably in the case of refurbished smartphones) No distinguishing elements for this activity between the two scenarios
D2		End of life specific ICT-specific			
D2.1			Stockage, disassembly, dismantling, shredding	Mandatory	Taken into account but excluded from the assessment for non-smartphone products No difference between the two scenarios

[75] Transport and logistics for devices (telephones and IoT) that will enter their end of life phase due to their premature replacement on Migration day is included here (generic process included in D2). The impact of these activities are already factored into the new device's embodied carbon.

D.2.2			Recycling	Mandatory	Taken into account but excluded from the assessment for non-smartphone products No difference between the two scenarios
D3		Other end of life activities		Mandatory	Taken into account but excluded from the assessment for non-smartphone products No difference between the two scenarios

4.6.3. Analysis of data transparency and qualification

The data employed in the study – from the expertise of the Committee members or from relevant references cited in the memo – play a structuring role in ensuring the robustness of the conclusions. In order to assess the transparency and quality of the activity and impact data used, this Annex refers to the definition of this transparency and to a matrix of quality indicators as recommended in ITU-T Recommendation L.1410.[76]

The quality indicator matrix focuses on an assessment of methodological consistency, completeness of modelling, uncertainty, data acquisition and collection, independence of the data provider, representativeness of the data, age of the data used, geographical correlation, technological correlation and the criteria considered for exclusion or inclusion.

The quality indicator matrix is detailed in Table 42.

Assessing the quality of the data is a both qualitative exercise and one of quantification providing scores as a form of guideline.

Moreover, Appendix IX[77] of Recommendation ITU-T L.1410 clarifies that:

- An LCA does not predict absolute or precise environmental impact due to the relative expression of potential impacts to a reference unit, the integration of environmental data over space and time, the inherent uncertainty in modelling environmental impact, and the fact that some possible environmental impacts are clearly future impacts.
- In practice, it is virtually impossible to collect enough data for an assessment to give the absolute performance of a product system. Even then, the results would still have model and scenario uncertainty.
- Consequently, any LCA result is only valid under the assumptions of the study and is still associated with substantial uncertainty, which needs to be considered so the outcome of the assessment is interpreted correctly.

In its Chapter 8.2 on the uncertainty analysis, this Recommendation states that "*The uncertainty of the results of an LCA study shall be assessed in accordance with [ISO 14044] to the extent needed to understand the study results*".

In its Chapter 8.3 on the sensitivity analysis it indicates that, "*The results of the LCI[78] or LCIA[79] phases shall be interpreted according to the goal and scope of the study.* ***The interpretation shall include a sensitivity check of the significant inputs, outputs and methodological choices, and defined use scenarios, in order to understand the uncertainty of the results*****". As a result, uncertainty over a certain parameter is assessed in relation to the study's results, notably thanks to the sensitivity analysis, rather than analysing the uncertainty of the parameter as such.**

This study does not escape these various important details, and the quality of the data and uncertainties of the results must be interpreted in the context of the objectives of this study: to assess

[76] Although the study is not intended to perform a life cycle assessment per se, ITU-T Recommendation L.1410 is used to make the analysis as comprehensive and objective as possible. For the sake of transparency, the Recommendation states in Chapter 9 that: *"For LCA results to be credible, a level of transparency in the reporting of how the data has been collected, to an extent that does not conflict with confidentiality considerations, is recommended."*

See table "Table I.2" in Appendix I and table "Table VII.1" in Appendix VII of ITU-T Recommendation L.1410 for more details on the indicator grid.

[77] Appendix IX "Opportunities and limitations in the use of LCAs for ICT end-user goods, networks and services.

[78] LCI: Life cycle inventory

[79] LCIA: Life cycle impact assessment

the benefits from a carbon footprint standpoint of migrating 2G/3G technologies to 4G/5G technologies for the scope of reference and the extended scope of reference, within the framework of a comparison of two scenarios and different assumptions and models used.

This study thus evaluates the time required in number of months from Migration Day in order to reach the breakeven points for the two scopes of reference considered, between the continuous and regular network energy savings and the carbon cost of non-4G/5-compatible devices terminals on Migration Day.

Based on the memorandum's different assumptions, these durations in number of months for the two scopes (reference/extended) will create the ability to assess the benefit in terms of carbon footprint of migrating 2G/3G to 4G/5G technologies in each of the two cases.

In the case of the scope of reference (network + mobile devices), the study shows the breakeven point is reached in less than <u>two months</u>.

In the case of the scope of reference extended to include IoT, the breakeven point is reached in under <u>six months</u> (or around four additional months with IoT).

These time periods are relatively short, which would seem to testify to the benefits of the migration from a carbon standpoint: the important question for this chapter is to determine what could radically increase these durations with respect to the quality of these data and the uncertainty of the results, but on the basis of the methodology used and the different associated models, and taking into account the entire sensitivity analysis (19 cases analysed).

The following table, based on two examples[80] provided in ITU-T Recommendation L.1410, describes the different data quality indicators used in this study.

[80] Appendix VII of the Recommendation, which is not an integral part of the Recommendation, provides a first example of quality indicators. Another example is shown in Appendix I, which applies the Recommendation to the case of a mobile phone.

Table 42 – Quality indicators for the data used in the study

Indicator	Possible qualification score				
Score (colour code)	**1**	**2**	**3**	**4**	**5**
Methodological consistency[81]	Very good	Good	Decent	Mediocre	Very mediocre
Completeness	Very good	Good	Decent	Mediocre	Very mediocre
Uncertainty	Very good	Good	Decent	Mediocre	Very mediocre
Acquisition method	Data directly measured or taken from reliable databases, surveys or reports[82]	Data calculated based on measurements or databases from reliable databases, surveys or reports	Data calculated based on assumptions	Expert estimates	Unqualified estimates
Supplier independence	Data verified by an independent source	Data verified by a firm that is a stakeholder in the study	Independent source but based on unverified data	Data unverified by the industry	Data not verified by a firm that is a stakeholder in the study
Data representativeness	Data representative of a sufficiently large sample of sites over an adequate period of time, including abnormal fluctuations	Data representative of a small sample of sites but over a decent period of time	Data representative of a decent sample of sites but over a short period of time	Data of a small sample of sites and over a short period of time, or incomplete data on a decent sample and time period	Unknown representativeness or incomplete data on a tiny sample of sites and/or over short periods of time
Data age	<3 years	<6 years	<10 years	<15 years	Age unknown
Geographical correlation	Data from the exact region	Average data for a larger region	Data for a region with similar production conditions	Data for a region with slightly similar production conditions	Unknown region
Technological correlation	Data for the studied process supplied exactly by the firm	Data for the studied process from a firm with a similar technology	Data for the studied process from a firm with a different technology	Data for a process from a firm with a similar technology	Data for a process from a firm with a different technology

[81] According to the JRC ILCD Handbook (2010) (see [ILCD - 2012]) this criterion aims to assess the extent to which life cycle inventory methods and modelling methodological choices (e.g. consequential or attributive modelling approach, allocation and substitution rules, etc.) are adapted to the objective of the study and their application is consistent throughout the study. This criterion therefore applies when looking at the level of the product system as a whole over its entire life cycle (i.e. at the scale of the entire study). This is why this criterion is not assessed for each product category taken separately (network, smartphone, feature phone, IoT).

[82] E.g. data in the ANFR and ARCEP observatories, taken from reports published by reputed institutions such as CREDOC, JRC or statistical data from firms such as GfK.

Rules of inclusion/exclusion	Transparent, justified and homogeneous application	Transparent, justified and non-homogeneous application	Transparent, not justified and non-homogeneous application	Not transparent about the exclusions but specific about the Inclusions	Unknown
Total score by indicator	*Sum of the scores by indicator + (lowest score x 4)/(10+4)*[83]				

The analysis is performed by data sub-system (network, mobile phones, IoT) for the different indicators.

Then the minimums, maximums and averages for each indicator are calculated by sub-system.

For each scope (reference, extended), and for each indicator, the minimum, maximum, and the maximum value of the average of sub-systems indicators included in the scope are taken into account.

[83] In accordance with the quality indicators de defined by the ILCD handbook: see [ILCD – 2012] Chapter 12.3 Data quality indicators. This is used in the devices example of Recommendation ITU-T L.1410 in its Appendix I

Table 43 – Analysis of the study's Network data

Parameter	Type	Methodological consistency (study wide)	Completeness (by subsystem)	Uncertainty	Data acquisition method	Data supplier independance	Data representativeness	Data age	Geographical correlation	Technological correlation	Exclusion/ inclusion criteria (study wide)	Comments/justification
2G/3G and 4G/5G Base Station Energy Consumption	Network	1	1	1	2	1	1	1	2	2	1	JRC data. Sensitivity study carried out on these values showing that they are not very sensitive. A supplier member of the Committee reproduced the base case with its base stations and found similar results, very largely within the range of the sensitivity analysis Technological correlation is rated "2" because the values refer to 2G or 3G base stations and not 2G+3G which may have greater power consumption.
Erlang Trafic calculation (2022)	Network	1	1	1	1	1	1	1	1	1	1	ARCEP data
Voice trafic (normalized) profile	Network	1	1	1	1	2	1	1	1	1	1	Supplied by an mobile operator member of the Committee
%voice trafic 2G/3G at Tm and multipler factor for Erlang trafic	Network	1	1	1	3	2	1	1	1	1	1	Committee's hypothesis based on feedback from operators. Insensitive value
Base station number at Tm	Network	1	1	2	2	2	1	1	1	1	1	The number of base stations to date comes from ANFR observatories. The extrapolation to year Tm has been validated by all the operators who are members of the Committee
Maximum BS load at busy hour	Network	1	1	1	1	1	1	1	2	1	1	Default value from ETSI (50%). The sensitivity study shows that the parameter is not very sensitive
Electricity grid intensity	Network	1	1	2	2	1	1	1	1	1	1	Extrapolated from ADEME data (see Annexe B).

Table 44 – Analysis of the study's Telephone data

Parameter	Type	Methodological consistency (study wide)	Completeness (by subsystem)	Uncertainty	Data acquisition method	Data supplier independance	Data representativeness	Data age	Geographical correlation	Technological correlation	Exclusion/ inclusion criteria (study wide)	Comments/justification
Sale of smartphones	Smartphone	1	1	1	2	1	1	1	2	1	1	Source Gartner (global numbers) for new smartphones Source Gfk: France sales of new smartphones Refurbished: Source lesnumériques (recovered from GFK) and Yes Yes Some additional assumptions (CAGR repackaged; 2020 value was adjusted to take into account the impact of Covid)
Smartphone lifetime	Smartphone	1	1	1	1	2	1	1	1	1	1	An operator member of the Committee observes this value in its
Remaining smartphones	Smartphone	1	1	1	2	1	1	1	1	1	1	Calculated directly from smartphone ownership value Di (primary data from CREDOC except for certain Di which are deduced) and smartphone sales
Smartphone ownership distribution (2022)	Smartphone	1	1	1	2	1	1	1	1	1	1	Direct computed values from Remaining smartphones
Number of smartphones at Ta and proportion of Volte per year	Smartphone	1	1	1	2	2	2	1	1	1	1	Number of smartphones: for the Reference operator: increase by 1/4 of the number of smartphones in France (checking was made on the basis of the number of SIM cards in France, sales figures and Ri values) %VoLTE smartphones at years Ta and Ta-1: increases chosen in relation to the values of an operator member of the Committee.
Smartphone embodied carbon footprint	Smartphone	1	1	1	2	1	1	1	1	1	1	Calculated value from NégaOctet which is included in ADEME database.
Remaining featurephones	FeaturePhone	1	1	2	2	1	1	1	1	1	1	Extrapolated from the Remaining Smartphones using primary data from Credoc (pleasure purchases of smartphones) Sensitivity study on extrapolation showing that the base case is in fact a worst case
Featurephone lifetime	FeaturePhone	1	1	1	2	2	1	1	1	1	1	An operator member of the Committee observes this value in its network.
Featurephone ownership distribution (2022)	FeaturePhone	1	1	1	2	1	1	1	2	1	1	Calculated directly from Sales and Remaining. The sales curve comes from Statista data for Southern Europe.
Number of featurephone at Ta and proportion of Volte per year	FeaturePhone	1	1	2	2	2	1	1	1	1	1	Number of feature phones: The number taken for the reference operator and the number taken in the sensitivity study cover the cases
Sale of feature phones	FeaturePhone	1	1	2	2	1	1	1	2	1	1	The sales curve comes from Statista data for Southern Europe.
Feature phone embodied carbon footprint	FeaturePhone	1	1	3	2	1	1	1	1	1	1	Value taken from the ADEME database, but without a critical review carried out. Sensitivity analysis carried out on this value.

Table 45 – Analysis of the study's IoT data

Parameter	Type	Methodological consistency (study wide)	Completeness (by subsystem)	Uncertainty	Data acquisition method	Data supplier independance	Data representativeness	Data age	Geographical correlation	Technological correlation	Exclusion/ inclusion criteria (study wide)	Comments/justification
2G-3G IoT sales before Ta	IoT	1	3	1	5	5	1	1	1	1	1	Assumption of the Committee, the sensitivity analysis shows that this parameter is not very sensitive
Remaining IoT	IoT	1	3	2	3	3	1	1	1	1	1	Extrapolated from the Remaining number of Feature Phones by taking into account featurephone lifetime and considering a linear extrapolation. Pure mathematical modelling approach without particular refinement
Number of IoT ICT modules	IoT	1	3	2	3	2	1	1	1	1	1	Reflects the understanding of the Committee on the basis of data collected from operators by ARCEP which made it possible to define a lower and upper bound for the number of IoT modules. The value of the base case was chosen within this range, but closer to the upper bound.
lifetime values (10/15/20 years) and their distribution	IoT	1	3	2	3	2	1	1	1	1	1	The Committee's understanding based on public information collected and the observation that the vast majority of IoT ICT modules come from payment terminals, smart meters and intercoms. No sensitivity study directly carried out on these two parameters, but the extrapolation (within the sensitivity analysis) on the number of IoT modules should also cover this case.
Additional sales of IoT between Ta and Tm	IoT	1	3	3	3	5	1	1	1	1	1	Assumption of the Committee, the sensitivity analysis shows that this parameter is not very sensitive
IoT module Embodied carbon footprint	IoT	1	3	2	3	3	3	1	2	1	1	These data come from a Bottom-Up modeling based on assumptions and challenged by exchanges with the author of the study (T. Pirson).

Table 46 – MIN, MAX, AVERAGE by sub-system studied

Parameter	Type	Methodological consistency (study wide)	Completeness (by subsystem)	Uncertainty	Data acquisition method	Data supplier independance	Data representativeness	Data age	Geographical correlation	Technological correlation	Exclusion/ inclusion criteria (study wide)	Comments/justification
RESEAUX: MIN		1	1	1	1	1	1	1	1	1	1	
RESEAUX:MAX		1	1	2	3	2	1	1	2	2	1	
RESEAUX:Average		1,0	1,0	1,3	1,7	1,4	1,0	1,0	1,3	1,1	1,0	
PHONES : MIN		1	1	1	1	1	1	1	1	1	1	
PHONES : MAX		1	1	3	2	2	2	1	2	1	1	
PHONES: Average		1,0	1,0	1,4	1,9	1,3	1,1	1,0	1,3	1,0	1,0	
IoT: MIN		1	3	1	3	2	1	1	1	1	1	
IoT: MAX		1	3	3	5	5	3	1	2	1	1	
IoT: Average		1,0	3,0	2,0	3,3	3,3	1,3	1,0	1,2	1,0	1,0	

Table 47 – Values indicators for the two scopes: MIN, MAX, MAX of sub-system averages

Parameter	Methodological consistency (study wide)	Completeness (by subsystem)	Uncertainty	Data acquisition method	Data supplier independance	Data representativeness	Data age	Geographical correlation	Technological correlation	Exclusion/ inclusion criteria (study wide)	MAX
SCOPE OF REFERENCE : MIN	1	1	1	1	1	1	1	1	1	1	
SCOPE OF REFERENCE : MAX	1	1	3	3	2	2	1	2	2	1	
SCOPE OF REFERENCE: MAX of the averages by sub-system	1,0	1,0	1,4	1,9	1,4	1,1	1,0	1,3	1,1	1,0	1,9
Weight of each dimension	1	1	1	1	1	1	1	1	1	1	4
EXTENDED SCOPE OF REFERENCE : MIN	1	1	1	1	1	1	1	1	1	1	
EXTENDED SCOPE OF REFERENCE : MAX	1	3	3	5	5	3	1	2	2	1	
EXTENDED SCOPE OF REFERENCE : MAX of the averages by sub-system	1,0	3,0	2,0	3,3	3,3	1,3	1,0	1,3	1,1	1,0	3,3
Weight of each dimension	1	1	1	1	1	1	1	1	1	1	4

Table 46 lists the MIN, MAX and average of the different indicators by sub-system (Networks, Telephones, IoT).

Then, with Table 47, we deduce the MIN, MAX, and overall score for each indicator in the two scopes (reference, extended) in the following manner:

- The MIN, and MAX are respectively the MIN and MAX of the sub-systems that are included in each scope

- We define an overall score for each indicator in the scope by selecting the highest average of the sub-systems Included. In other words, the worst average is chosen systematically.

Table 48 – Weighted average of all indicators

	Weighted average of all indicators	Quality level (cf. ILCD Handbook of JRC)
SCOPE OF REFERENCE	1,4	High Quality (=< 1,6)
EXTENDED SCOPE OF REFERENCE	2,3	Basic Quality (> 1,6 et <3)

Then the weighted average of all of the indicators is determined in accordance with the ILCD Handbook (see [ILCD – 2012]).

Still based on the same document that defines the different quality levels, we deduce in Table 48 a high level of quality for the data used for the scope of reference and an average quality for the extended scope.

4.7. Explanations on the allocation rules for 4G/5G's power consumption

The goal of this Chapter is to provide a better understanding of the allocation rule used for 4G/5G, through additional explanations and a simple example.

The assumption is that a 2G/3G or 4G/5G base station's instantaneous power consumption expressed in Watts can be approximated by a linear function of the kind: *a*x + b (*where *x* is the base station's load).

In the case that interests us, it is the voice service that was assessed, as the assumption is that 2G/3G will not be used for data services on M-Day and that M2M/IoT traffic will be insignificant.

To obtain the total consumption of the base station over the entire day expressed in kWh (excluding allocation method), it will therefore be necessary to integrate its instantaneous consumption over the 24 hours of the day, and we then obtain[84]:

Consumption-BS (kWh) = 24 (a * A * Max-Voice-Load + b)

For 4G/5G there is the question of defining an allocation rule because the same 4G/5G base station is used for voice (and M2M/IoT traffic considered insignificant), but also for data:

- The term "**24 (a * A * Max-Voice-Load)" representing consumption due to voice traffic,** has a value proportional to the voice traffic relayed in 2G/3G before migration and must be retained in full.
- On the other hand, the term "**24 b**", **representing no-load consumption,** is the fixed part related to the common channels and BBU and must be divided between voice and data services. This distribution is made proportionate to load as follows:

Consumption-BS (kWh) for 4G/5G= 24 (a * A * Max-Voice-Load + K * b)

With K = Max-Voice-Load/Max-Load, where Max-Load is base station's load during the busy hour, all services combined.

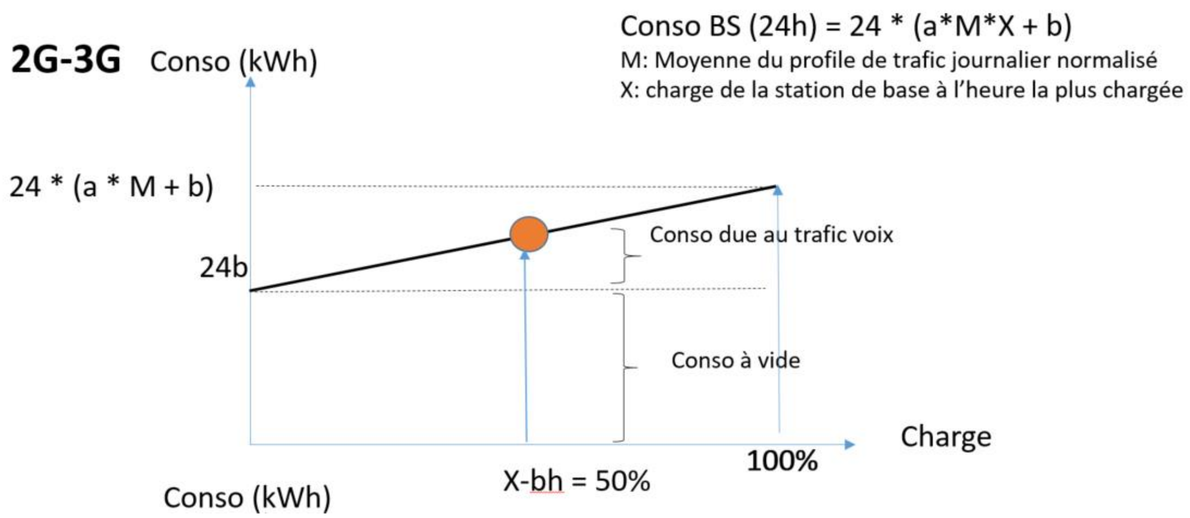
All of this is shown below with example numerical values provided: <u>these values are different from the study's, and were chosen to enable a simple illustration.</u>

The following values are used as an **<u>example</u>** for the entirety of 2G/3G base stations:

- Busy hour traffic = 75 Erlangs
- 2G3G-Voice-Capacity = 150 Erlangs

In this example, the 2G/3G base station's "X-bh" busy hour load is therefore equal to 75/150 = 50%

[84] See Chapter: : Determining the difference between a 2G/3G base station and a 4G/5G base station



The following values are used as an example for the entirety of 4G/5G base stations:

- Busy hour traffic = 75 Erlangs (same value as for 2G/3G)
- 4G/5G-Voice-Capacity = 600 Erlangs
- Max-Load all services combined at busy hour: 50%

The 2G/3G 4G/5G base station's "X-bh" load during the busy hour is therefore equal to 75/600 = 12.5%

K est le coefficient for the allocation rule, and is therefore equal to X-bh/Max-Load= 12.5/50 = ¼

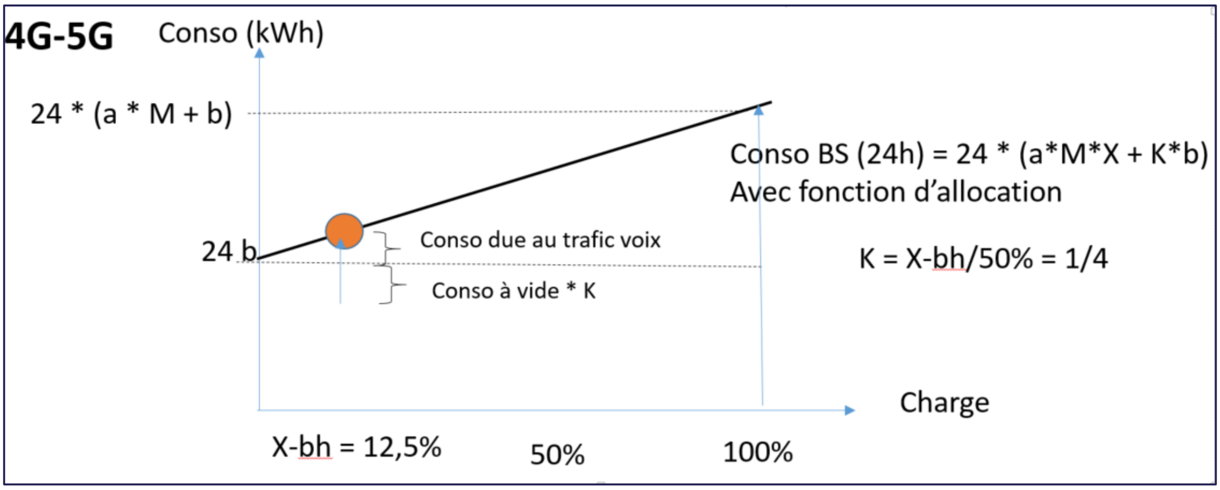


Figure 14 – Illustration of the base station consumption model with allocation function

For the purposes of the study, the following points need to be underscored:

- 2G/3G voice traffic on M-Day being very low, it is virtually the entirety of 2G/3G's energy consumption that will be saved;
- This translates, for instance, into the following numbers that come from the sensitivity analysis performed on the network portion (Case No. 2 in *Table 5*; see Chapter: *Calculation of the*

numerical value of the difference in the electricity consumption of 2G/3G and 4G/5G base stations in the 900 MHz band)
  - Busy hour traffic by base station= 12 Erlangs
  - X-bh= 12/600 = 2%
  - M*X-bh = 44% * 2% = 0.88%
  - K=2/50= 4%
- In the base case (Case No. 1 in *Table 5*; see Chapter: *Calculation of the numerical value of the difference in the electricity consumption of 2G/3G and 4G/5G base stations in the 900 MHz band*)
  - Busy hour traffic by base station = 1.5 Erlangs
  - X-bh= 1.5/600 = 0.25%
  - M*X-bh = 44% * 0.25% = 0.11%
  - K=0.25/50= 0.5%

5. Annex C: Glossary

- **BBU:** Baseband Unit. This is the base station's module responsible for processing the base band's traffic and implementing wireless access communication protocols.
- **Embodied carbon:** All of the carbon emissions other than those generated during the equipment's use phase[85].
- **Feature phone:** A basic mobile phone that keeps the shape factor of previous generations of mobile phones, typically with a keypad, a small non-touch LCD screen, a microphone, a camera in the back and GPS services. They are called feature phones to distinguish them from smartphones. Feature phones provide the ability to make phone calls, exchange text messages and use certain basic mobile applications: calendar, calculator, multimedia apps and a basic mobile web browser[88].
- **GHG:** Greenhouse gases. GHG are natural gases in the earth's atmosphere that trap the sun's heat, keeping the temperature on the planet's surface at a reasonable level.
- **Information and Communications Technologies (ICT)**: The sectors of economic activity that contribute to the viewing, processing, storage and transmission of information by electronic means[86].
- **Internet of Things (IoT):** Objects that become internet compatible (IoT devices) typically interact via integrated systems, a form of communication network, and a combination of leading edge computing and Cloud Computing. The data produced by the devices connected to the IoT are often (but not solely) used to create new applications for end users[88].
- **Life Cycle Assessment (LCA):** Compilation and assessment of inputs and outputs and potential environmental impacts of a product system during its life cycle[87].

[85] GHG Protocol ICT Guidance: https://www.gesi.org/research/ict-sector-guidance-built-on-the-ghg-protocol-product-life-cycle-accounting-and-reporting-standard

[86] OECD definition: https://www.oecd.org/digital/ieconomy/2771153.pdf

[87] ISO 14040:2006: Environmental Management — Life cycle assessment — Principles and framework: https://www.iso.org/obp/ui/#iso:std:iso:14040:ed-2:v1:en

- **Machine to Machine (M2M):** The technologies used by machines to be able to "talk" to each other, with no direct human involvement. In the study, IoT and M2M are treated indistinctively.
- **MIMO:** Multiple Input Multiple Output. A wireless transmission technology that consists of using multiple antennas at both the source (transmission) and destination (receiver) to boost capacity and improve users' speed by generating multiple versions of the same signal.
- **Smartphone:** A mobile phone that performs many of the functions of a computer, and which typically has a touchscreen interface, can access the internet over Wi-Fi and mobile networks, a GPS connection and an operating system (OS) capable of running downloaded applications[88].
- **VoLTE:** Voice over the LTE (4G network): A voice calling service relayed over IP via the LTE (4G) mobile access network[89].

6. Annex D: References and bibliography

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7. Annex E: Composition of the Experts Committee

- **Committee Chair:** Catherine Mancini
- **Secretary and management:** Arcep (Ahmed Haddad)
- **ANFR:** Didier Chauveau
- **Bouygues Telecom:** Vincent Lemoine, Vincent Merat, Franck Bliah
- **Ericsson:** Zied Malouche, Arnauld Taffin
- **Free Mobile:** Bertand Fiévet, Damien Genouville, Abdenour Medjkane

[93] Joint Research Centre. The JRC “provides independent, evidence-based knowledge and science, supporting EU policies to positively impact society. for more information, see: https://commission.europa.eu/about-european-commission/departments-and-executive-agencies/joint-research-centre_en

[94] See in particular Chapter 6.2 “Reference and variable power consumption” which describes the refined model used in this memorandum.

- **Huawei:** Michael Jolly, Jérôme Danneel
- **Orange:** Sabrina Saudai, Franck Payoux, Catherine Cano-Menda, Sara Bertoglio
- **Nokia:** Edouard Pereira, Mirela Andouard
- **SFR:** Benoit Thuillier, Pierre Lescuyer
- **Telecom ParisTech:** Marceau Coupechoux