Final report for Huawei

Impact of additional mid-band spectrum on the carbon footprint of 5G mobile networks: the case of the upper 6GHz band

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Contents

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1 Executive summary

To better understand the environmental impacts of meeting future wireless connectivity targets in Europe, and how these environmental impacts might be affected by spectrum availability, Huawei commissioned Analysys Mason to conduct this study to compare scenarios for future public mobile network deployments. Specifically, this study focuses on the carbon emissions of a Fifth Generation (5G) mobile network in addressing future connectivity targets through the availability of additional spectrum, compared to the network meeting the same future connectivity targets without additional spectrum. Both with and without additional spectrum, we assume that the existing network grid will be densified (in terms of the numbers of macro sites and/or outdoor small cells), but in the absence of additional spectrum, the required densification is greater due to less spectrum being available. The impact on carbon emissions over the 2022–2032 time period is considered, with modelling directed at achieving specific targets for future connectivity in Europe in 2030.

Context for the study

The spectrum we focus on in our study is mid-band spectrum, which refers to a type of spectrum that is widely used for 5G today, due to its ability to deliver both capacity and coverage. The GSMA assessed the future mid-band spectrum needs for 5G and beyond in a previous report, and in that context, it forecast a demand for further mid-band spectrum in the second half of the 2020s to meet connectivity needs [1]. The intention of this report is to provide input to policy discussions on future 5G spectrum requirements and, in Europe specifically, on the future use of mid-band spectrum, with particular reference to the upper 6GHz band (6425–7125MHz).

While other studies have considered the impact of mid-band spectrum availability on 5G mobile networks in terms of delivering new services, meeting future traffic demands, infrastructure requirements, or the cost of deployment, this study aims to consider the addition of mid-band spectrum from an environmental impact perspective. This consideration of impact on carbon emissions in relation to spectrum policy decisions aligns with the opinion published by the Radio Spectrum Policy Group (RSPG) on the role of spectrum policy to combat climate change, which examines the aspects of spectrum management that relate to climate change, including considerations relating to future spectrum for 5G mobile networks [2].

The methodology we developed for this study, which we describe in Section 3, is applicable to network modelling for 5G mid-band spectrum in general and is not band-specific. Results in Section 4 are also relevant to mid-band spectrum in general, although modelling assumptions regarding spectral efficiencies and coverage for the additional mid-band spectrum refer to the upper 6GHz band specifically. This is because the upper 6GHz band has attracted significant interest as a candidate band for 5G evolution. Hence this report provides some specific analysis for this band. The analysis of the upper 6GHz band provides an assessment of the impact on carbon emissions for a scenario in which the band would be used for 5G, and for a scenario in which the upper 6GHz band would be used for wireless local area networks (WLANs). We also consider whether there would be an impact on the carbon footprint of Wi-Fi if the upper 6GHz band were used in addition to the existing frequency bands available for Wi-Fi in Europe.

This study has considered the density of macro sites and outdoor small cells needed to meet future connectivity targets within a representative model of site deployment in a market where three mobile operators run 5G networks (with spectrum deployments and spectral efficiencies in line with the frequency bands used for 5G in Europe today), based on two typical scenarios:

- 5G mobile broadband (MBB) in a highly populated European city with a population density of 15 000/km² (i.e. dense urban)
- 5G MBB as well as fixed broadband through 5G-based fixed-wireless access (FWA) in a rural town or village. The rural town or village is modelled assuming a population density of 300/km² and assuming the population lives outside of the reach of fibre.

Modelled connectivity targets in Europe

In Europe, the European Commission's Digital Decade policy programme has established objectives and targets for digital transformation, and lays out a vision to be achieved by 2030. Of most relevance to this study are targets for all end users at fixed locations to have gigabit connectivity at least equivalent in speed to that of 5G, and for all populous areas to be covered by high-capacity 5G mobile networks [3]. For 5G MBB, the radiocommunications sector of the International Telecommunications Union (ITU-R, which is responsible for defining global telecommunications standards and for international frequency allocations) has defined minimum performance requirements for IMT-2020 (being ITU-R terminology for 5G) as including a downlink speed of 100Mbit/s and an uplink speed of 50Mbit/s [4].

In accordance with the targets described above, our study considers the infrastructure required to meet the following targets:

- In the dense urban area we model a 5G mobile network designed to target[1] delivery of MBB services with a downlink speed of 100Mbit/s and an uplink speed of 50Mbit/s to users in the busy hour (with assumptions on the number of active users likely to be accessing the service)

- In the rural town or village we model a 5G mobile network designed to target delivery of MBB and FWA services, with the MBB targets as above, and FWA supporting 1Gbit/s downlink and 200Mbit/s uplink to users in the busy hour (with the same assumptions on the number of active users as above).

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1 In a wireless network, the data rate experienced by a user can vary depending on the user's location in a cell, the loading of the cell and propagation effects. Hence when we model a *target* delivery, we are modelling a network designed to achieve the stated downlink and uplink speeds to users in a busy hour, in a typical urban (or rural) cell.

Summary of our analysis

We have built a 5G mobile network model in Microsoft Excel to simulate the size of deployment needed (in terms of the densities of macro sites and outdoor small cells) in the dense urban area and in the rural town or village, with and without the additional mid-band spectrum. The model has several key assumptions and inputs defined by Analysys Mason, validated by Huawei and, where possible, aligned with published studies. For example, we have taken note of a previous study conducted on behalf of the GSMA, entitled "Estimating the mid-band spectrum needs in the 2025–2030 timeframe" [5]. Whilst that study had a different objective (to estimate the amount of additional mid-band spectrum needed), there are some similarities with the approach and assumptions we have used in our modelling. In our modelling, the key output is in terms of the number of sites per km^2, and then we use environmental inputs per site multiplied by the number of sites to arrive at the carbon footprint. When calculating the number of sites required, the following should be noted:

- We calculate the capacity of macro cells and outdoor small cells assuming a portfolio of spectrum similar to that of European mobile network operators today, i.e. using low-band spectrum (sub-1GHz), lower mid-band spectrum (1500MHz, 1800MHz, 2100MHz and 2600MHz), upper mid-band spectrum (3500MHz plus, in our study, the upper 6GHz band), and high-band spectrum (e.g. typical millimetre-wave spectrum, such as 26GHz).
- We estimate a per-user growth in targeted Mbit/s in the busy hour in both the downlink and the uplink direction, reaching the target speeds for MBB (in the dense urban area) and MBB and FWA (in the rural town or village) by 2030.

We then estimate the 5G mobile network carbon emissions based on the output of network modelling (in terms of sites per square kilometre) – we consider for each site both the embodied footprint (which relates to the fabrication, construction and installation stages of the base stations and sites) and the recurring footprint (which relates to the operation of the base stations in terms of powering and maintaining the sites).

The study is focused on the infrastructure-related carbon emissions, i.e. carbon emissions associated with the production and operation of base stations. In this study, we were not asked to consider the impact on the carbon footprint of mobile devices (our model assumes a 'natural' renewal of devices in line with their expected lifetime, rather than forcing user migration), nor do we consider the enablement impact of mobile networks on other sectors (e.g. by enabling other sectors to improve the efficiency of their real-time or remote operations).[2] We note that other third-party reports do address these considerations.[3] Overall, the aim of our study is to consider whether the saving in carbon emissions associated with having fewer macro sites and outdoor small cells in a mobile

2 Information on the enablement effect is available in the 2023 GSMA Report: "Spectrum: the Climate Connection Spectrum policy and carbon emissions". [20]

3 For example, the GSMA's report "The enablement effect" [18] discusses mobile network enablement technologies and assesses six different sectors in which these mobile network enablement technologies can reduce carbon emissions for that sector.

network due to having more spectrum outweighs the incremental carbon emission cost of implementing and deploying the additional spectrum in 5G mobile networks.

In Section 5, considering ongoing discussions on future use of the upper 6GHz band in Europe and in some other markets, we consider simulations made available to us in order to estimate the impact of increasing mid-band spectrum availability on Wi-Fi throughput. In particular, we consider whether there is an impact in terms of the number of access points needed for Wi-Fi to meet a gigabit connectivity target in typical dense urban, and rural town and village, indoor settings, if the upper 6GHz band is used alongside existing spectrum bands already available for Wi-Fi in the 2.4GHz, 5GHz and lower 6GHz bands.

Key findings

Overall, our analysis demonstrates that the carbon footprint of future 5G mobile networks is expected to be lower if additional mid-band spectrum is made available to meet future capacity targets, by avoiding a significant densification of macro sites and outdoor small cells. This applies both in the dense urban area and in the rural town or village we have modelled in our study.

More specifically, our main conclusions are as follows:

- Our modelling results show that lower network carbon emissions arise in 5G mobile networks with additional mid-band spectrum available to meet the future connectivity targets we have considered in this report, compared to a situation where networks are densified through additional macro and outdoor small cells without the availability of additional mid-band spectrum.
- We calculate that the carbon emission savings from having less densification in 5G mobile networks outweigh the incremental carbon emission costs of deploying and operating new radios (to support the additional mid-band spectrum we have modelled) on macro sites and outdoor small cells for the dense urban area and for macro sites in the rural town or village.
- It should be noted that in the dense urban area we consider two deployment variants for densification (in the absence of additional mid-band spectrum):
  - firstly, densification primarily via macro sites (with some supporting outdoor small cells)
  - secondly, densification primarily via additional outdoor small cells (and thus lower macro-site densification).

  In each case, the incremental carbon emission cost of deploying and operating new upper mid-band radios at the dense urban macro sites and outdoor small cells is lower than the incremental carbon footprint associated with the higher level of densification needed without the additional mid-band spectrum.
- In addition to the increased carbon footprint associated with greater densification, the levels of densification that would be required in 5G mobile networks to meet the connectivity targets in

the absence of additional mid-band spectrum would be practically challenging and also potentially technically unfeasible (due to interference between sites that are too close to each other).

- For Wi-Fi, based on simulations made available to us and considering the future connectivity targets for fixed broadband (i.e. an aggregated throughput of more than 1Gbit/s per premises), the availability of the upper 6GHz band would not translate into any reduction in carbon emissions, given such targets can be met via the latest Wi-Fi technology using spectrum bands already available for Wi-Fi use in Europe (2.4GHz, 5GHz and lower 6GHz).

While these results have been modelled assuming upper 6GHz deployment (e.g. in terms of the bandwidth available), these conclusions may apply to other upper mid-band spectrum, provided that the alternative upper mid-band spectrum exhibits similar characteristics to those modelled here.

2 Introduction

This report contains the results of a study conducted by Analysys Mason to investigate the environmental impacts of meeting future wireless connectivity targets in Europe with and without additional mid-band spectrum.

2.1 Background and context

Growth in wireless traffic in outdoor and indoor environments is well documented and has been explored in several published reports. However, most published studies tend to consider the benefits of further spectrum for one use only (e.g. Wi-Fi or mobile). Various studies specifically on the role of Wi-Fi for future connectivity refer to the energy efficiency of Wi-Fi due to its low-power transmission, but without addressing how future connectivity targets over the wider area (e.g. to all populated areas, in line with the European Commission's (EC's) Digital Decade objectives) will be met.[4]

In the outdoor environment, much of the mobile broadband (MBB) connectivity to smartphones and other connected devices in Europe is via mobile networks, now in their Fifth Generation (5G) of deployment. These 5G mobile networks use a combination of newly assigned frequency bands harmonised in Europe for 5G deployment (e.g. the 700MHz and 3.5GHz bands) together with frequency bands used for previous generations of mobile network that are now progressively being used for 5G, such as the 1800MHz or 2100MHz bands. In the indoor environment, smartphones and other connected devices either use a mobile network (outside-in coverage), or, where available, wireless local area network (WLAN) connectivity, predominantly delivered today via short-range wireless technologies such as Wi-Fi. The growth in Wi-Fi traffic has been well documented, and the question of future Wi-Fi capacity needs is being addressed through technology evolutions and, in some markets, through the addition of further frequencies in the 6GHz band.

Mid-band spectrum has been a particular focus of 5G deployment, and it will remain so as 5G networks evolve and MBB traffic increases. Mid-band spectrum can be considered as intermediate spectrum – between the low-band spectrum used for 4G and prior generations, and high-band spectrum in the millimetre-wave range such as the 26GHz band – that provides both capacity and coverage to a mobile network.

Despite the global movement to reduce carbon emissions, and sustainability goals being a core part of the vision for 6G, the impact of future mobile spectrum assignments on the wireless industry's carbon footprint has not been widely addressed.

This study has sought to provide a different perspective on future mobile spectrum needs, focused on the environmental implications of mid-band spectrum assignment, in contrast to other previous

4 We elaborate on various reports we have reviewed as part of this study in Annex B.

studies, which have considered factors such as infrastructure deployment, financial viability, coverage and quality of service. The study has focused on the addition of mid-band spectrum to 5G mobile networks, and the implications for the carbon footprint of 5G mobile networks of using this spectrum compared to the densification needed to meet future connectivity targets without additional mid-band spectrum.

Our study has considered 5G mobile networks in two typical locations:

- a highly populated European city
- a rural town or village outside the reach of fibre networks.

In Europe, the EC's Digital Decade policy programme has established objectives and targets for digital transformation in Europe, and lays out a vision to be achieved by 2030. Of most relevance to this study are targets for all end users at fixed locations to have gigabit connectivity at least equivalent in speed to that of 5G, and for all populous areas to be covered by high-capacity 5G mobile networks [6]. For 5G MBB, the radiocommunications sector of the International Telecommunications Union (ITU-R, who are responsible for defining global telecommunications standards and for international frequency allocations) has defined minimum performance requirements for IMT-2020 (being ITU-R terminology for 5G) as including a downlink speed of 100Mbit/s and an uplink speed of 50Mbit/s [4].

In accordance with the European targets described above, our study considers the infrastructure required to meet the following targets:

- In the dense urban area we model a 5G mobile network designed to target[5] delivery of MBB services with a downlink speed of 100Mbit/s and an uplink speed of 50Mbit/s to users in the busy hour

- In the rural town or village we model a 5G mobile network designed to target delivery of MBB and FWA services, with the MBB targets as above, and FWA supporting 1Gbit/s downlink and 200Mbit/s uplink to users in the busy hour.

2.2 Objectives of the study

The main objectives of the study have been to:

- explore the future infrastructure needed to meet the minimum performance requirements defined by the International Telecommunication Union (ITU) for IMT-2020/5G in populated areas together with EC gigabit connectivity targets for end users at fixed locations

5 In a wireless network, the data rate experienced by a user can vary depending on the user's location in a cell, the loading of the cell and propagation effects. Hence when we model a *target* delivery, we are modelling a network designed to achieve the stated downlink and uplink speeds to users in a busy hour, in a typical urban (or rural) cell.

- consider the need for additional mid-band spectrum for both 5G and Wi-Fi, in the context of how additional mid-band spectrum can mitigate the need for infrastructure densification
- compare the impacts of addressing future connectivity targets on a 5G mobile network's carbon footprint (embodied and recurring), with and without additional mid-band spectrum
- conduct sensitivity analysis to demonstrate how the results vary based on key assumptions.

2.3 Structure of this document

The remainder of this document is laid out as follows:

- Sections 3 and 4 cover the modelling of the 5G mobile network's carbon footprint
  - Section 3 details the inputs and assumptions
  - Section 4 discusses the results
- Section 5 explores the impact of additional spectrum on the carbon footprint of Wi-Fi access networks
- Section 6 summarises the conclusions.

The report includes a number of annexes containing supplementary material:

- Annex A contains a detailed modelling methodology
- Annex B includes a list of other published studies considered as part of our study
- Annex C provides a bibliography.[6]

[6] Where a report/other source is mentioned in the text, the inclusion of a reference of the form [*n*] indicates that the web address for that document can be found in Annex C.

3 5G mobile network modelling – methodology, inputs and assumptions

This section discusses the methodology, inputs and assumptions used in our modelling of 5G mobile networks and in our assessment of the environmental impact of additional mid-band spectrum assignment. In turn, we:

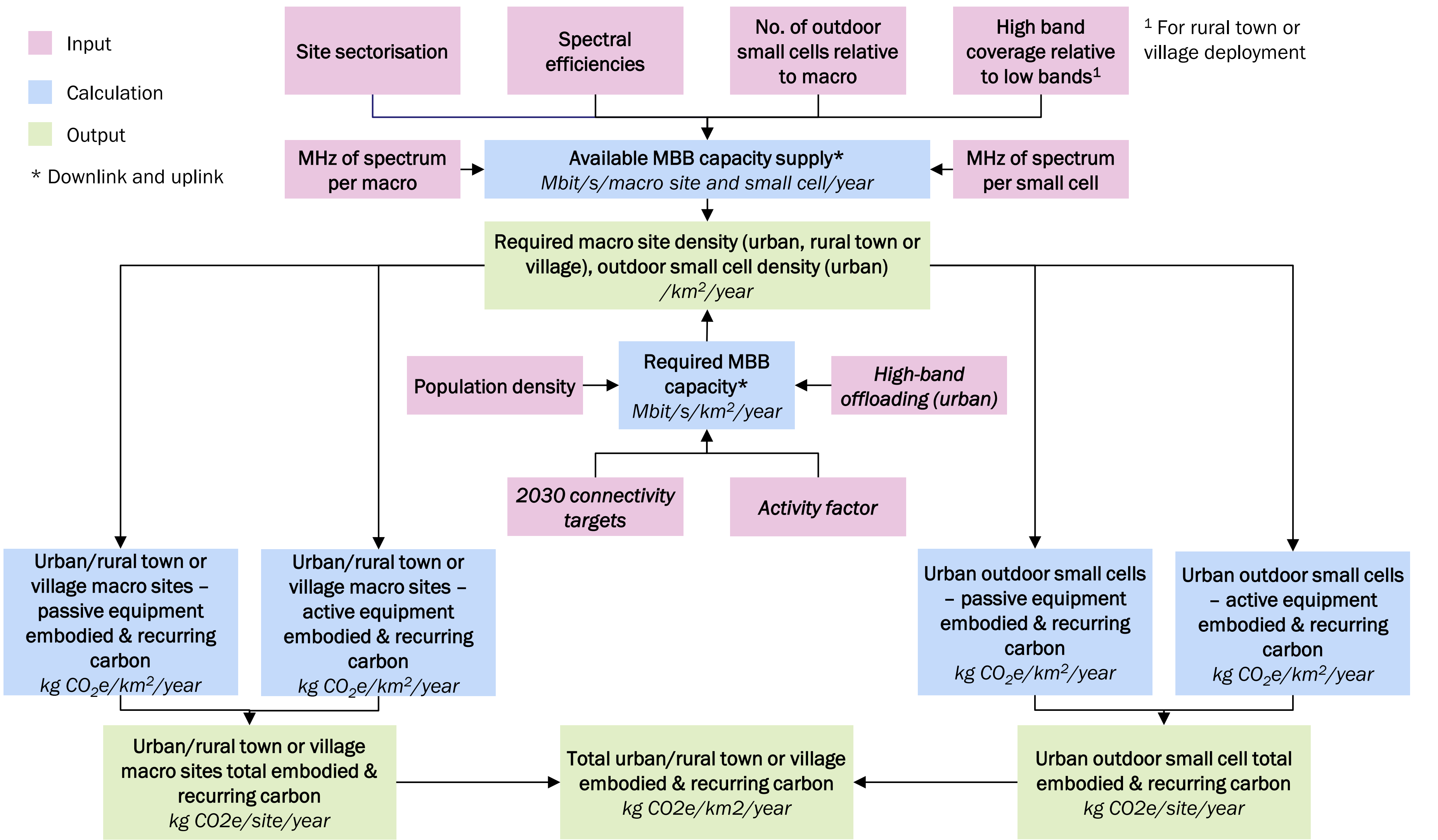
- outline the methodology (Section 3.1)
- describe the characteristics of the two scenarios modelled (Section 3.2)
- discuss the target user experience rate and parameters involved in calculating the required capacity to meet the target user experience, compared to the capacity available in the network in the urban and rural settlements modelled (Section 3.3)
- define the inputs required to determine the capacity of the 5G mobile network (Section 3.4)
- detail the data used to inform our environmental assessment of the 5G mobile network (Section 3.5).

3.1 Overview of approach

The model we have developed provides an estimate of the environmental impacts of different deployment models and scenarios for 5G mobile network evolution from the present time, to meet future connectivity targets defined for 2030.

As shown in Figure 3.1, we use a network model to estimate the sites required per square kilometre assuming the network evolves from today's deployment to meet the European connectivity targets described in the previous section, and then we calculate the associated carbon cost.

Figure 3.1: Overview of modelling approach [Source: Analysys Mason, 2023]



In order to calculate the macro site and outdoor small cell density required to meet the target user experience rate, the target is converted to a capacity density requirement. A per-user growth rate in Mbit/s is applied per year of the model, so that the target user experience rate to be achieved by 2030 is calculated. This required MBB service per active user in a busy hour is then multiplied by the dense urban population density and the proportion of active users (the activity factor) to arrive at a required capacity density. In the dense urban scenario, this capacity density is then adjusted to reflect offloading of traffic to high band, to arrive at the required MBB uplink and downlink capacity density that has to be met by the macro sites and outdoor small cells.

The model output of number of sites is then used to provide an estimate of annualised carbon costs in terms of:

- embodied costs – that is, carbon emissions due to the raw material acquisition, manufacturing, distribution and installation of passive and active equipment at a 5G site, as well as construction of the required site infrastructure
- recurring costs – that is, carbon emissions due to providing energy to operate and maintain the sites.

Total embodied and recurring costs will change depending on the deployment models and variants adopted by different mobile network operators (MNOs) to satisfy coverage or capacity requirements. For example, densification by building new macro sites to add capacity to a 5G mobile network creates embodied costs in the site building, together with increased recurring costs due to the increased number of sites in the network. Instead, MNOs might opt to build fewer new macro sites, and instead densify by building additional outdoor small cells. These small cells would provide less coverage than a macro site, but they would have lower embodied costs per small cell. However, due to the coverage footprint being lower, more small cells would be needed. There are practical difficulties in building both macro sites and small cells, which are summarised in Section 4.3 later. Alternatively, MNOs could add spectrum to existing macro sites and/or small cells, assuming additional spectrum is available, and that existing sites can accommodate further deployment of radio equipment and antennas. Finally, MNOs could upgrade antenna systems and/or baseband processing to improve the spectral efficiency of their network, thus making better use of their available frequency portfolio.

Accordingly, our modelling methodology is based on comparing two alternative deployment models:

- Additional mid-band spectrum is added to existing sites, in combination with a degree of densification (of both macro sites and small cells). We assume the additional mid-band spectrum (i.e. the upper 6GHz band) is available for deployment from 2027.
- More-extensive network densification is carried out, due to no additional mid-band spectrum being made available for 5G mobile networks.

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The model is designed to compare the capacity supplied by a representative 5G network to the capacity needed to meet the future connectivity targets. The capacity supplied by the network is derived from assumptions on the density of macro sites in current 5G mobile networks, together with low-, mid- and high- band spectrum availability, spectral efficiency, number of sectors per cell, and various design assumptions within the mobile network that we summarise in the remainder of this section. The additional capacity needed in the network to meet the European connectivity targets for MBB and for broadband to fixed locations in 2030 is derived based on the connectivity targets, population and household densities, and end-user activity factors.

We model two deployment scenarios: a dense urban area, and a rural town or village, as described further in Section 3.2 below.

3.2 Deployment scenarios

We model two deployment scenarios:

- **a dense urban area**, defined as having a population density of 15 000/km^2 [7]
- **a rural town or village**, defined as having a population density of at least 300/km^2,[8] with an average of 2.8 people per household.[9] This scenario assumes that the population lives outside the reach of fibre networks.

The characteristics of 5G mobile networks vary in each case:

- **Macro sites are more densely deployed in urban areas** than in more rural areas, for two main reasons:
  - due to the greater density of people, a tighter mesh is required to meet aggregated capacity demand
  - the greater density of buildings and street furniture limits signal propagation and yields lower macro-site cell radii.

- **Outdoor small cells are beginning to be deployed in dense urban areas** as an alternative method of increasing capacity, as macro densification is becoming increasingly difficult in these areas for a number of reasons (including finding suitable real estate, obtaining planning permission, and inter-site interference).

- **FWA is being deployed in rural towns and villages and other locations** to provide fibre-like speeds where fibre deployment is uneconomic. FWA deployments can use high-band

7 UN Habitat defines this as the optimum population density for a sustainable city [21], and this value sits fairly centrally in the range of cities looked at in the GSMA report [7]

8 This is the population density of the rural settlement itself, not just the average population density of a largely uninhabited rural area. We use the Eurostat definition of a "moderate density cluster" as having a population density of at least 300km^2 [23].

9 According to the OECD, average households range from two to four people depending on the country [24], whereas according to Ireland's 2016 census urban areas had lower average household sizes than more-rural locations, at 2.7 compared with 2.8 [25].

millimetre-wave (mmWave) spectrum to provide very high speeds, although the propagation of high-band spectrum is worse than low- and mid-band spectrum, thus lowering the cell radius compared to that of a typical rural macro site.

In order to model these different mobile network deployment characteristics we have defined several inputs, as described in Figure 3.2. Where N/A appears in the table, this is because the values are not relevant to the analysis of a given deployment scenario.

Figure 3.2: Summary of 5G mobile network deployment inputs and assumptions by settlement type [Source: Analysys Mason, GSMA [7], 2023]

Input	Dense urban areas		Rural towns and villages	
	Value	Source	Value	Source
Macro-site inter-site distance (ISD)[10]	400m in 2022 (corresponding to a site density of 7.2/km² and a radius of 267m), which reduces over time as the model calculates increased macro-site density	Analysys Mason assumption based on typical European cities	3750m in 2022 (corresponding to a site density of 0.08/km² and a radius of 2500m), which reduces over time as the model calculates increased macro-site density	Analysys Mason assumptions
Small-cell radius	65m, which remains constant across the modelling period[11]	Huawei	N/A	N/A
High-band rural cell radius	N/A	N/A	1000m in 2022, reducing linearly to 500m by 2030 as demand grows and radios prioritise throughput over coverage	Analysys Mason assumptions

3.3 User experience data rate and required capacity

The model calculates the 5G mobile network deployment required to meet a user experience data rate in 2030 in line with the following targets (as explained in Section 2.1):

- 100Mbit/s downlink and 50Mbit/s uplink for MBB
- 1Gbit/s downlink and 200Mbit/s uplink for FWA.

10 We assume that the same ISD is also applied when additional mid-band spectrum is added. When modelling densification scenarios via additional macro cells, the ISD reduces.

11 Our assumptions have been designed to reflect that, in practice, outdoor small cells will be able to supply capacity in limited areas within the macro cell's coverage area. However, the deployment of outdoor small cells will allow the macro cell to make an equivalent capacity supply available in other areas within the cell. For more information, see Section A.1.1.

In line with a previous study conducted on behalf of the GSMA, entitled "Estimating the mid-band spectrum needs in the 2025–2030 timeframe", we note that, whilst a particular data speed cannot be guaranteed by a mobile network, the assumption we make in our modelling is that the network is designed to target this user-experienced speed in the busy hour. This implicitly means that a higher level of capacity is needed compared to a network designed to deliver a best-efforts service (which, for example, might have degraded speeds during the busy hour). [7]

Building upon these targets, we have used a number of further traffic-specific inputs and assumptions in order to determine the network's required capacity.

Inputs and assumptions for modelling MBB capacity demand

In line with the GSMA's report, we have defined an 'activity factor', which is used to determine the maximum number of MBB users accessing the spectrum concurrently. This activity factor takes into account the variability of the user base (i.e. not all the same users access the spectrum at the same times of the day) and is linked to the busy-hour traffic of the network (i.e. the peak capacity requirement for the network). We have assumed a 5% activity factor, applied to the population of the modelled settlement, consistent with typical usage profiles for smartphone users. Since this activity factor is a key dimensioning parameter of the model, we have also considered the impact of applying a higher activity factor (in the sensitivity analysis described in Section 4.1.3).

In addition to this busy-hour traffic, we have also assumed that MBB networks support traffic generated from outside-in coverage. This refers to a 10% increase in the required capacity to reflect that some devices within premises use MBB connectivity, with the traffic carried via base stations located outdoors.

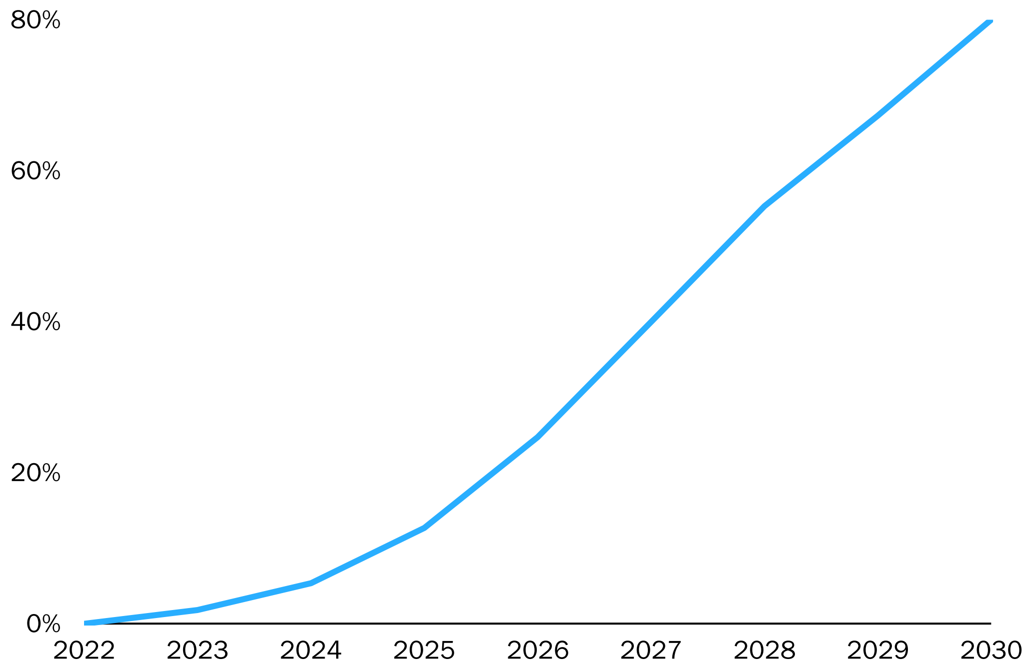
In the dense urban area, the high-band spectrum (mmWave) contribution to network capacity is not explicitly modelled, mainly due to mmWave deployments being concentrated within localised areas of high traffic demand but with more localised coverage compared to 5G mid-band and low-band spectrum. Rather, in the modelled dense urban area, we assume that a portion of the required capacity is met by high-band spectrum being deployed on existing sites, which reduces the capacity to be met through additional mid-band spectrum and/or site densification. We assume that this high-band offloading increases linearly from 0% in 2022 to 10% in five years' time, to reflect the progressive roll-out of mmWave small cells.

Inputs and assumptions for modelling FWA capacity demand

The analysis refers to a rural town or village where the population lives outside the reach of fibre networks and instead receives high-speed broadband connectivity via a 5G-based FWA service. It is assumed that there may be more concurrent FWA users in the busy hour than MBB users, mainly because fixed access usage is generally more continuous (for streaming, gaming, etc.) than mobile usage. As a result, a 10% FWA activity factor is assumed.

We note that not all households in the rural town or village will take up FWA. A sigmoidal penetration curve is assumed, with penetration of 80% of households being achieved by 2030 (as shown in Figure 3.3). In the rural town or village, mmWave spectrum is modelled as part of the macro site spectrum portfolio, rather than as a traffic offload (which is used in the dense urban model).

Figure 3.3: Assumed FWA penetration in a rural town or village receiving high-speed broadband connectivity via a 5G-based FWA network [Source: Analysys Mason, 2023]



3.4 Inputs for modelling MBB and FWA capacity supply

Network capacity density estimation

In order to calculate the macro-site and outdoor small-cell density required to meet a target user experience, the total network capacity density must be estimated. To do so, the capacity that can be provided by each macro site and each small cell must be understood. This individual capacity is directly linked to the available spectrum per network operator (we assume a three-operator market). In our model we consider the following spectrum availability and timelines, which are consistent with typical spectrum availability in European markets (as summarised in Figure 3.4).

- **190MHz of low-band spectrum (700–900MHz)** composed of:
  - 60MHz of 700MHz frequency-division duplexing (FDD) spectrum
  - 60MHz of 800MHz FDD spectrum
  - 70MHz of 900MHz FDD spectrum

- **535MHz of lower mid-band spectrum (1.5–2.6GHz)** composed of:
  - 85MHz of 1500MHz supplementary downlink (SDL) spectrum (although only 40MHz is available until 2027)
  - 150MHz of 1800MHz FDD spectrum
  - 120MHz of 2100MHz FDD spectrum
  - 140MHz of 2600MHz FDD spectrum
  - 40MHz of 2600MHz time-division duplexing (TDD) spectrum
- **400MHz of upper mid-band TDD spectrum (3.4–3.8GHz)**
- **700MHz of additional upper mid-band TDD spectrum (6.425–7.125GHz)** – only available from 2027[12]
- **2400MHz of high-band TDD spectrum (25.1–27.5GHz)** from 2023.[13]

The model considers all available spectrum for public mobile use in a European country, assuming that all operators in a given market operate their own networks. The spectrum availability for public mobile use in European markets is shown in Figure 3.4 below.

Figure 3.4: Maximum spectrum bandwidth available for public mobile use in European markets [Source: Analysys Mason, 2023]

Spectrum	Bandwidth available (MHz)								
	2022	2023	2024	2025	2026	2027	2028	2029	2030
Low bands	190	190	190	190	190	190	190	190	190
Lower mid-bands – FDD	410	410	410	410	410	410	410	410	410
Lower mid-bands – SDL	40	40	40	40	40	85	85	85	85
Lower mid-bands – TDD	40	40	40	40	40	40	40	40	40
Upper mid-bands	400	400	400	400	400	400	400	400	400
Additional upper mid-bands	-	-	-	-	-	700	700	700	700
High bands	-	2400	2400	2400	2400	2400	2400	2400	2400

12 The ITU's World Radiocommunication Conference 2023 (WRC-23) will discuss various frequency bands for IMT use in its agenda item 1.2, including upper 6GHz in ITU Region 1. Depending on the WRC decision, the CEPT European Communications Committee (ECC) might develop a new harmonisation decision(s) concerning use of the 6425–7125MHz band. Allowing time for this to occur, and for devices to become available, we have assumed a 2027 date for the upper 6GHz band deployment.

13 While the 26GHz band is harmonised in Europe from 24.25–27.5GHz, this report assumes that the lower part of the band is assigned for lower-power deployments relying on local area assignments.

In order to determine the uplink and downlink bandwidth the following assumptions are made:

- The use of FDD spectrum is assumed to be split into 50% downlink and 50% uplink
- The use of TDD spectrum is assumed to be 75% downlink and 25% uplink
- The use of SDL spectrum is assumed to be 100% downlink.

While Figure 3.4 summarises the availability of all spectrum bands over time, not all site types across all geographies are assumed to use all available spectrum. Our model considers different types of site (tri-sectored macro sites vs. single-sector small cells) and uses (MBB or FWA), each with its own individual spectrum portfolio, as shown in Figure 3.5.

Figure 3.5: Summary of spectrum availability by site and traffic type [Source: Analysys Mason, 2023]

Spectrum	Available for MBB on urban macro site?	Available for MBB on urban small cell?	Available for MBB on rural town or village macro site?	Available for FWA on rural town or village macro site?
Low-band (700–900MHz)	✓	×	✓	$^1/_3$ [1]
Lower mid-band – FDD (1.5–2.6GHz)	✓	×	✓	×
Upper mid-band (3.4–3.8GHz)	✓	✓	✓	✓
Additional upper mid-band (6.425–7.125GHz)	✓	✓	✓	✓
High-band (25.1–27.5GHz)	× [2]	×	✓	✓

[1] We assume that typically only one low band will be used for FWA, to ensure sufficient capacity in the mobile network for wide-area MBB traffic. Since there are three low-bands in our model, we assume that 1/3 of those, i.e. one band, is available for FWA use

[2] As explained in Section 3.3, the high band is not explicitly modelled in dense urban areas, but rather a high-band offloading factor is used.

Spectrum roll-out assumptions, and time period of the model

Figure 3.4 highlights the points in time when we assume new spectrum bands become available for use. We assume an operator will generally deploy new spectrum onto existing sites progressively across its network, progressing from dense urban areas (where capacity requirements are more stringent) to less dense rural areas, in line with customer needs, and reflecting any regulatory requirements (e.g. roll-out obligations in a spectrum licence) as well as market competition. This progressive roll-out reflects operational and economical constraints: while spectrum may be available nationally, it is not necessarily deployed immediately across all the sites in a national network. To account for this progressive roll-out of new frequency bands, two spectrum deployment profiles are modelled for each new band – one for each settlement type (see Figure 3.6 and Figure 3.7).

Since it was only recently made available, the upper mid-band (3.4–3.8GHz) is included in these progressive roll-out profiles. It is assumed that the additional lower mid-band SDL spectrum can be deployed on all sites with an existing 1500MHz deployment, so no roll-out profile is shown for this band. Because high-band spectrum is not explicitly being modelled for urban areas, it is not included in Figure 3.6. The spectrum roll-out in our model is completed by 2030 and hence the charts below show the profiles up to the final roll-out in 2030. This final roll-out then applies thereafter, until 2032.

The rationale for the spectrum roll-out is as follows:

- We assume that operators have deployed existing upper mid-band spectrum (e.g. 3.5GHz) on all dense urban sites in the initial stages of 5G roll-out and hence the upper mid-band roll-out in the dense urban case is 100% throughout the model. In the rural towns and villages, we assume that operators are still completing 3.5GHz roll-out and hence the upper mid-band roll-out to rural town or village macro sites increases from 2022 until roll-out is complete in 2026.
- We assume that additional upper mid-band spectrum becomes available from 2027 (see Figure 3.4), and is progressively rolled out to sites in both the dense urban and rural town or village scenario. Device roll-out assumptions together with site roll-out assumptions mean that the additional upper mid-band is progressively added to sites from 2027 to 2030.
- The 'high-band' roll-out in the rural town or village refers to mmWave spectrum (see Figure 3.4). In the dense urban modelling scenario we do not explicitly model the mmWave roll-out profile, but instead assume that a portion of the required capacity is met through mmWave. We assume that 20% of rural town or village sites are not suitable for mmWave deployment, and thus roll-out stops at 80% by 2026.

Figure 3.6: New mid-band spectrum roll-out on dense urban macro sites and small cells [Source: Analysys Mason, 2023]

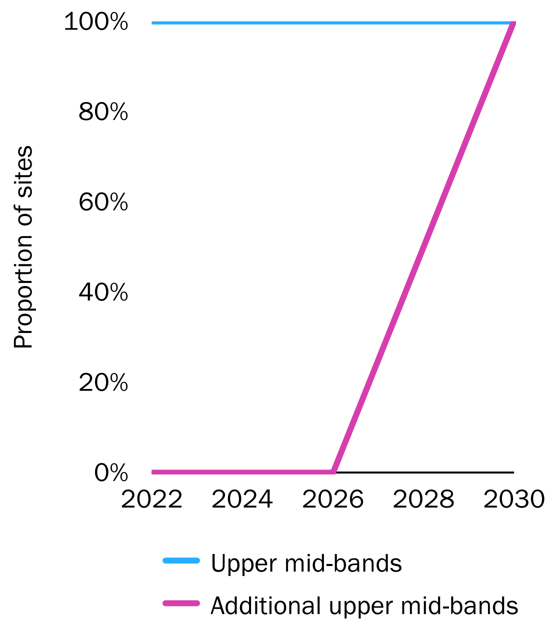
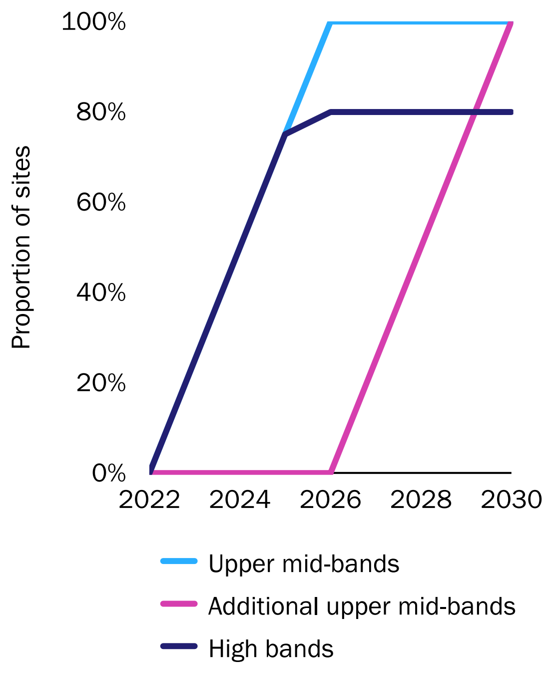
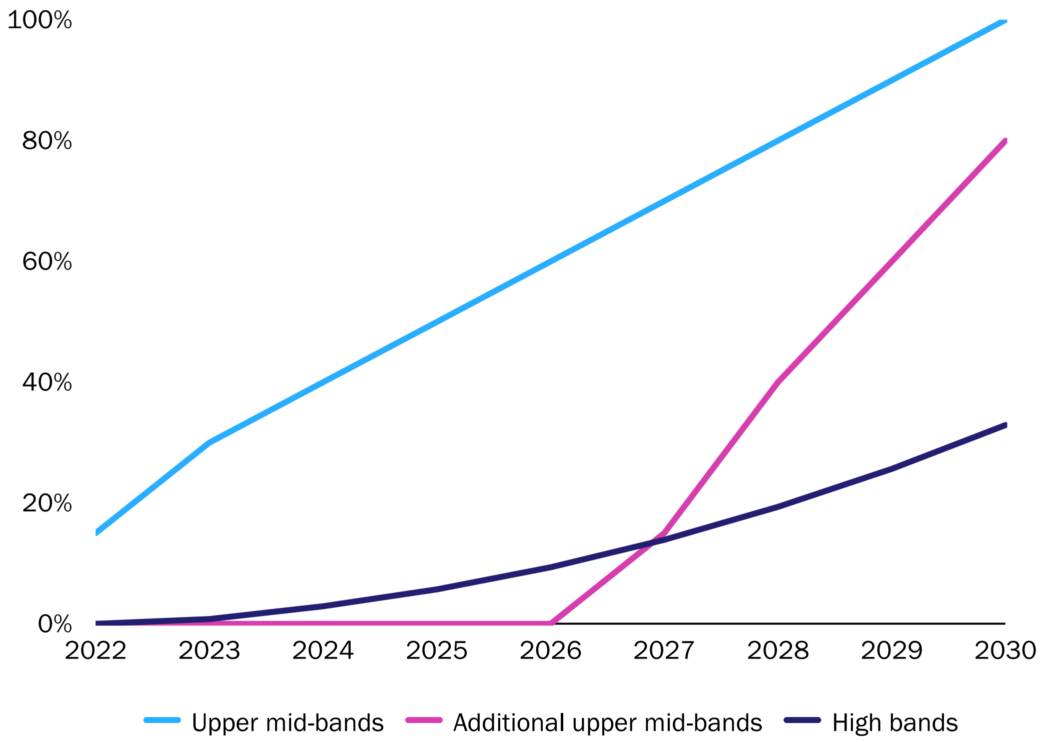


Figure 3.7: New mid-band and high-band spectrum roll-out on rural town or village macro sites [Source: Analysys Mason, 2023]



In addition, we assume that newly assigned spectrum becomes useable once compatible devices are available in sufficient volumes, and that the penetration of devices with new upper mid-band spectrum included will increase over time (see Figure 3.8 below). MBB device penetration growth is assumed to be the same in both urban and rural settlements. As upper mid-band and high-band are already available when FWA deployment begins, we assume that all FWA consumer premises equipment (CPE) is compatible with these bands. However, some CPE will be installed before the additional upper mid-band spectrum is available, and this will only be gradually upgraded to be compatible with the additional upper mid-band spectrum, in line with the MBB device take-up curve. Any new CPE installed after the additional upper mid-band spectrum is available will be compatible. The device penetration curves shown below are Analysys Mason estimates, guided both by our understanding of historical device take-up trends and by current 5G device types. For example, we assume that devices compatible with mmWave will not reach the same levels of penetration as those compatible with upper mid-band, due to a range of factors such as current availability and device cost. We assume that additional upper mid-band spectrum might be added to existing upper mid-band devices, with penetration levels rising more rapidly, assuming that a European harmonisation decision is in place around 2026.

Figure 3.8: Penetration of MBB devices compatible with upper mid-band, additional upper mid-band and high-band [Source: Analysys Mason, 2023]



Note: High-band device penetration is only used in our rural settlement scenario

The available capacity of the macro and outdoor small cell sites modelled in the network are calculated from the spectrum bandwidths and spectral efficiencies. Spectral efficiencies vary between downlink and uplink, and with site type/use, but not by settlement type (see Figure 3.9, Figure 3.10 and Figure 3.11). Spectral efficiency improvement can come from various sources – such as technology improvements, antenna design, network design improvements or other changes affecting the transmitted waveform.

Figure 3.9: MBB macro-site spectral efficiencies [Source: Analysys Mason, GSMA [7],[14] Huawei, 2023]

Spectrum	Downlink spectral efficiency (bit/s/Hz)		Uplink spectral efficiency (bit/s/Hz)	
	2022	2030	2022	2030
Low bands (700–900MHz)*	1.87	1.87	1.03	1.23
Lower mid-bands (1.5–2.6GHz) – FDD*	1.87	3.50	1.03	1.68
Lower mid-bands (1.5–2.6GHz) – SDL*	1.87	3.50	N/A	N/A
Lower mid-bands (1.5–2.6GHz) – TDD*	2.34	3.28	1.05	1.05
Upper mid-bands (3.4–3.8GHz)	5.01	7.15	3.31	4.73
Additional upper mid-bands (6.425–7.125GHz)	5.51	7.87	3.64	5.20
High bands (25.1–27.5GHz)**	3.10	4.65	1.50	2.25

* Non-active antenna system (AAS) base stations are assumed for frequencies below 3.4GHz.

** Only applicable to rural macro-site modelling, as described in Section 3.3.

Figure 3.10: Urban small-cell spectral efficiencies[15] [Source: Huawei, Analysys Mason, 2023]

Spectrum	Downlink spectral efficiency (bit/s/Hz)		Uplink spectral efficiency (bit/s/Hz)	
	2022	2030	2022	2030
Upper mid-bands (3.4–3.8GHz)	1.67	2.38	1.10	1.58
Additional upper mid-bands (6.425–7.125GHz)	1.84	2.62	1.21	1.73

Figure 3.11: FWA macro-site spectral efficiencies [Source: Huawei, Analysys Mason, 2023]

Spectrum	Downlink spectral efficiency (bit/s/Hz)		Uplink spectral efficiency (bit/s/Hz)	
	2022	2030	2022	2030
Low band (e.g. 900MHz)	2.06	2.20	1.13	1.45
Upper mid-bands (3.4–3.8GHz)	5.51	8.40	3.64	5.56
Additional upper mid-bands (6.425–7.125GHz)	6.06	9.24	4.01	6.11
High bands (25.1–27.5GHz)	4.65	6.98	2.25	3.38

14 Note that the lower values for lower mid-bands compared to those for upper mid-bands are because a non-active antenna system base-station deployment is being assumed for lower mid-bands.

15 Improvements in the spectral efficiency of urban small cells are assumed, to reflect advances in technology and antennas leading to improved performance.

In addition, a 15% design margin is applied to the capacity (i.e. only 85% of the capacity can actually be achieved) to account for the reality that in practice capacity at a site/cell in the busy period cannot be fully utilised. This approach is consistent with that used in the GSMA report on estimating mid-band spectrum needs [7] referred to previously.

The model makes assumptions about the number of small cells deployed per macro cell in the urban deployment. Given that individual MNOs will make different deployment choices depending on their network strategy, customer needs and other factors associated with the density of their existing network grids, we model two deployment variants (densification focused on macro cells, and densification focused on small cells), described in Sections 4.1.1 and 4.1.2.

3.5 Inputs and assumptions for modelling the environmental impact

Figure 3.12 details the environmental inputs used in the model. Environmental inputs have been derived from public sources [7] [8] [9] [10] [11] [12], but as far as possible they have been verified as reasonable by Huawei. In some cases estimations have been made (e.g. for future additional upper mid-band equipment).

As noted in Section 3.1 earlier there are two types of carbon cost – embodied and recurring. Embodied carbon costs are incurred once per lifetime, and they have been amortised over that lifetime. In contrast, recurring carbon costs are incurred annually.

To calculate the required infrastructure, we have assumed that the mid-band, upper mid-band and high-band spectrum is deployed on a proportion of sites. For these sites, there is therefore an additional fixed recurring carbon cost associated with the relevant active equipment being used, and there is an incremental recurring carbon cost that varies depending on network loading (both across the day, which has been accounted for in the input value, and in terms of users who can use the spectrum – represented by the compatible device penetration). In our calculation of recurring costs we assume a carbon intensity (a measure of carbon dioxide and other greenhouse gases in energy production) for electricity used by the telecoms sector of 100g/kWh, as we believe that MNOs use a more-green energy mix than that of the typical grid in Europe (currently ~250g/kWh) and that there will be some improvements in emissions by 2030. [13]

The model calculates the number of macro sites and small cells required, on the assumption all spectrum is utilised per site. However, because we consider a three-operator market, in reality each calculated macro site would comprise three macro sites – one per operator – sharing the available spectrum. As such, the environmental inputs shown in Figure 3.12 are the sum for three operators each using a third of the total spectrum.

Figure 3.12: Summary of environmental inputs [Source: Huawei, Analysys Mason, 2023]

Input	Urban macro site	Urban small cell	Rural macro site
Baseline site (excluding upper mid-bands, additional upper mid-bands and high bands) – passive equipment embodied carbon	150 000kg CO_2e	6000kg CO_2e	190 000kg CO_2e
Baseline site (excluding upper mid-bands, additional upper mid-bands and high bands) – active equipment embodied carbon	12 000kg CO_2e	N/A	12 000kg CO_2e
Upper mid-band passive and active equipment embodied carbon	9000kg CO_2e	900kg CO_2e	9000kg CO_2e
Additional upper mid-band passive and active equipment embodied carbon	9000kg CO_2e	900kg CO_2e	9000kg CO_2e
High-band passive and active equipment embodied carbon	N/A	N/A	4500kg CO_2e
Lifetime of passive equipment	20 years	20 years	20 years
Lifetime of active equipment	8 years	8 years	8 years
Baseline site (excluding upper mid-bands, additional upper mid-bands and high bands) – recurring carbon cost	12 000kg CO_2e/year	150kg CO_2e/year	12 000kg CO_2e/year
Upper mid-band recurring carbon cost – fixed component (irrespective of loading)	4000kg CO_2e/year	250kg CO_2e/year	4000kg CO_2e/year
Upper mid-band recurring carbon cost – variable component (loading dependent)	2000kg CO_2e/year	150kg CO_2e/year	2000kg CO_2e/year
Additional upper mid-band recurring carbon cost – fixed component (irrespective of loading)	4000kg CO_2e/year	250kg CO_2e/year	4000kg CO_2e/year
Additional upper mid-band recurring carbon cost – variable component (loading dependent)	2000kg CO_2e/year	150kg CO_2e/year	2000kg CO_2e/year
High-band recurring carbon cost – fixed component (irrespective of loading)	N/A	N/A	2000kg CO_2e/year
High-band recurring carbon cost – variable component (loading dependent)	N/A	N/A	1000kg CO_2e/year

Annex A provides further details of the methodology, including descriptions of where each input is used.

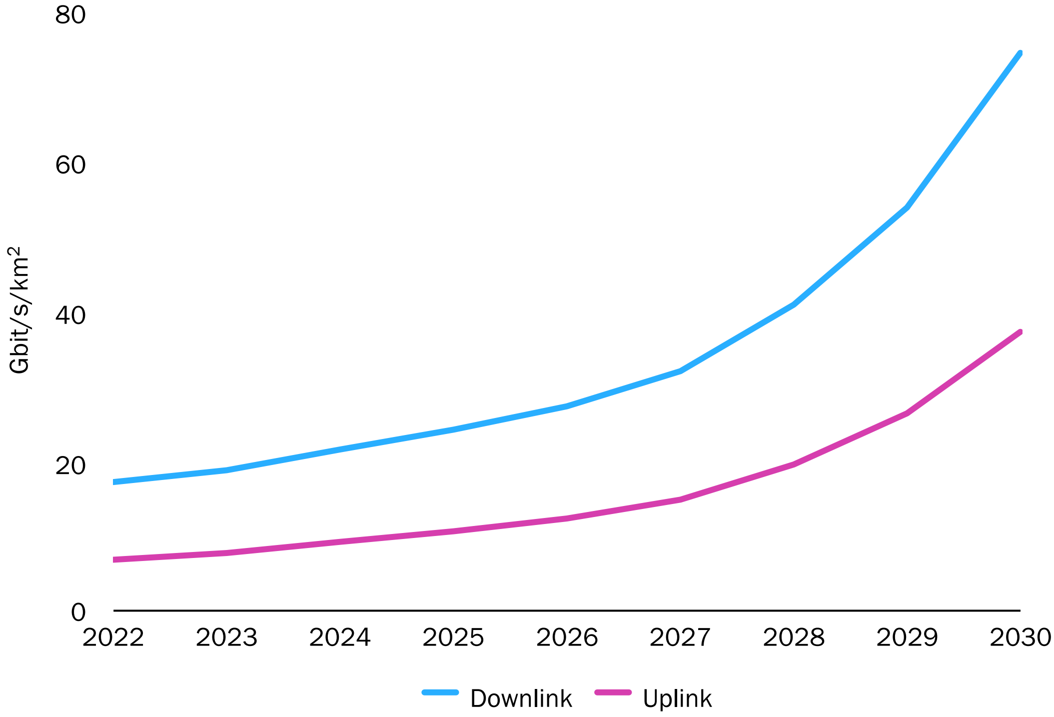
4 5G mobile network modelling – carbon footprint results

This section presents results from the mobile network modelling for the urban and rural settlements (in Sections 4.1 and 4.2 respectively. We then go on to discuss some of the practical issues impacting mobile network densification of the sort modelled in this study, in Section 4.3. Finally we consider how technological improvements are likely to improve the power efficiency of mobile networks as technologies evolve, which is discussed in Section 4.4.

4.1 Dense urban area results

Figure 4.1 shows the progression of the modelled uplink and downlink MBB capacity target for the urban settlement over time. The required downlink MBB capacity reaches nearly 75Gbit/s/km² by 2030.

Figure 4.1: Dense urban MBB required capacity [Source: Analysys Mason, 2023]



In comparison, Figure 4.2 and Figure 4.3 show the dense urban MBB capacity supply per average macro site and small cell respectively. In both figures it can be seen that the capacity provided increases gradually until 2026 as spectral efficiencies increase, and upper mid-band device take-up increases. However, from 2027, the introduction of additional upper-mid band spectrum brings a significant increase in capacity as the new spectrum is rolled out on sites and compatible device penetration increases.

Figure 4.2: Dense urban MBB capacity supply per average macro site [Source: Analysys Mason, 2023]

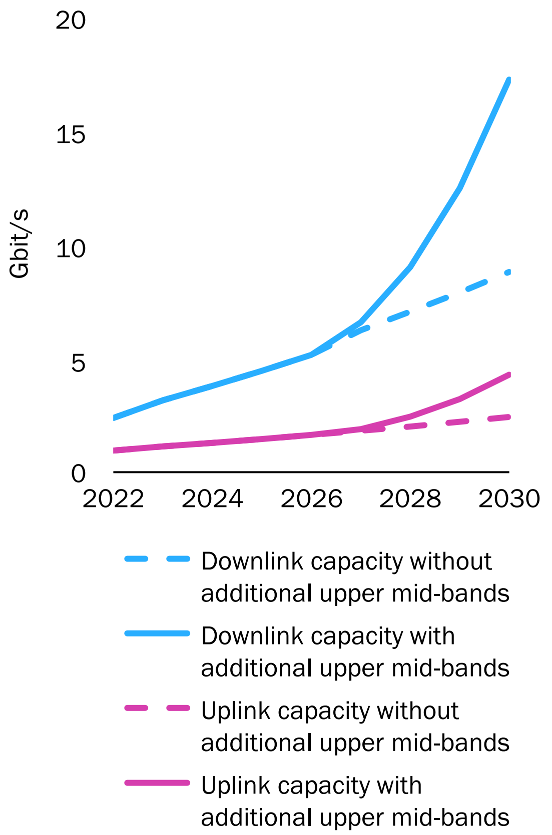
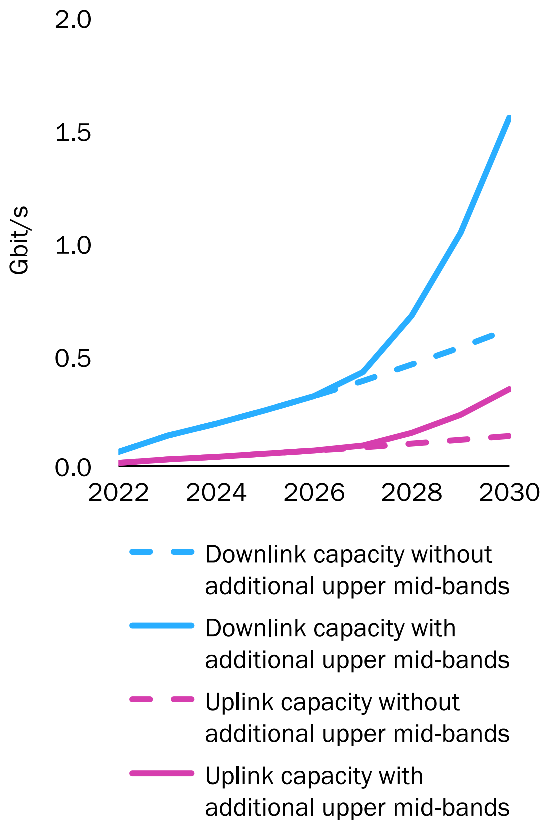


Figure 4.3: Dense urban MBB capacity supply per average small cell [Source: Analysys Mason, 2023]



As discussed below, we have modelled two dense urban deployment variants, the first with a maximum ratio of three small cells per macro site (in line with the GSMA report), and the second with a limit on macro-site densification.

4.1.1 Deployment variant 1 – densification primarily via macro cells

Figure 4.4 and Figure 4.5 show the macro-site and outdoor small-cell density, respectively, required when the level of small-cell densification is limited to three small cells per macro site.

With additional upper mid-band spectrum no macro-site densification is required (as shown on Figure 4.4, macro-site density remains constant at 7.2/km²). As shown on Figure 4.5, at 18.6 small cells/km² the outdoor small-cell densification does not reach the limit of three small cells per macro site; there is a gradual increase in small cells until the new spectrum is deployed, at which point small-cell deployment plateaus for several years while the additional capacity required is met by the additional spectrum, and after this small-cell deployment resumes.

However, without additional upper mid-band spectrum, the small-cell densification cap results in significant macro-site densification in later years in order to provide the required capacity: as shown on Figure 4.4, it increases by 83% by 2030, to reach 13.2 macro sites/km^2 (corresponding to an ISD of 296m). This macro-site densification is in addition to the maximum allowance of small cells (three per macro site), reaching 39.6 small cells/km^2 by 2032 (as shown in Figure 4.5).

Figure 4.4: Density of dense urban macro sites [Source: Analysys Mason, 2023]

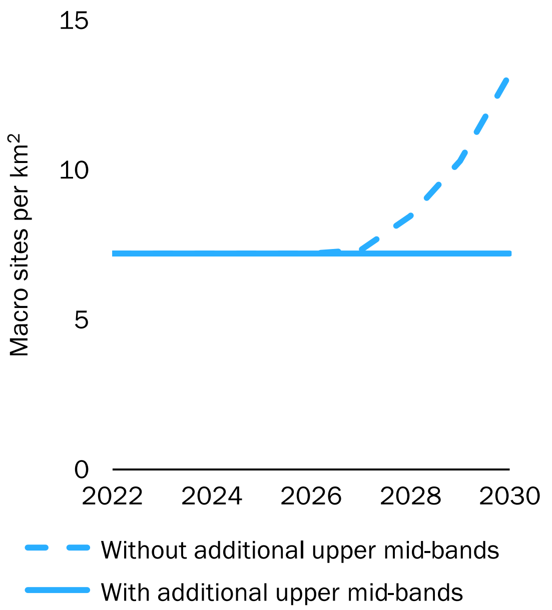
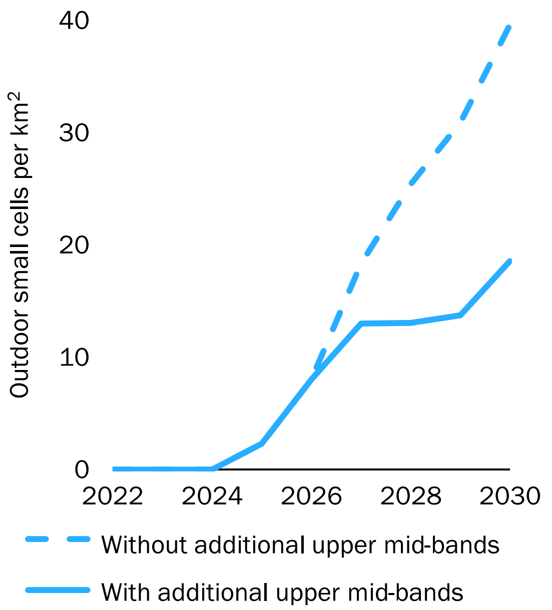


Figure 4.5: Density of dense urban outdoor small cells [Source: Analysys Mason, 2023]



With the assumed downlink to uplink spectrum ratios, it is the case that in order to meet the uplink target, the modelled capacity required is such that the downlink target for the deployment is substantially exceeded. Downlink and uplink capacity assumptions for upper mid-band and additional upper-mid band spectrum are based on currently adopted downlink-centric frame structures[16] in 5G MBB networks. It is noted that alternative frame structures might be adopted in the future as a wider variety of services with bespoke connectivity requirements become more widely available.

Figure 4.6 shows the annual carbon savings achieved by using additional upper mid-bands for IMT-2020/5G (i.e. the amount by which annual carbon footprints are reduced relative to a scenario without additional upper mid-bands) by category per urban km^2. By 2030, the dense urban network's carbon footprint is 131tCO_2e[17]/km^2 lower with additional upper mid-bands than without. Figure 4.6 also shows that the carbon savings from having less densification in 5G mobile networks outweigh the incremental carbon cost of deploying and operating additional mid-band spectrum at existing macro (and small) cells.

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16 Frame structure in a 5G mobile network refers to TDD and FDD transmissions variously used in different frequency bands used for 5G networks. The frame structure for 5G mid-band spectrum is assumed to be based on TDD transmission. In TDD transmission, uplinks and downlinks operate in the same frequency channel at different points in time. The frame structure defines the time allocated to the downlink compared to the uplink. We assume a downlink-oriented frame structure in which downlink transmissions occupy 75% of the available bandwidth and uplink transmissions occupy 25%.

17 Tonnes of carbon dioxide equivalent.

It is noted that the carbon savings will continue beyond 2030. The precise level of these savings is not calculated in our model, due to uncertainty over site build after 2030, and the potential introduction of new mobile access technologies (e.g. 6G) for which performance is as yet undefined. In Figure 4.6 we show what the carbon savings would be in 2031 and 2032 assuming the same level of savings in those years as calculated in our model for 2030.

Figure 4.7 shows the cumulative carbon savings per urban km², reaching 475tCO_2e/km² by 2032 (on the assumption that annual savings in 2031 and 2032 are the same as in 2030).

Figure 4.6: Annual carbon savings per urban km² [Source: Analysys Mason, 2023]

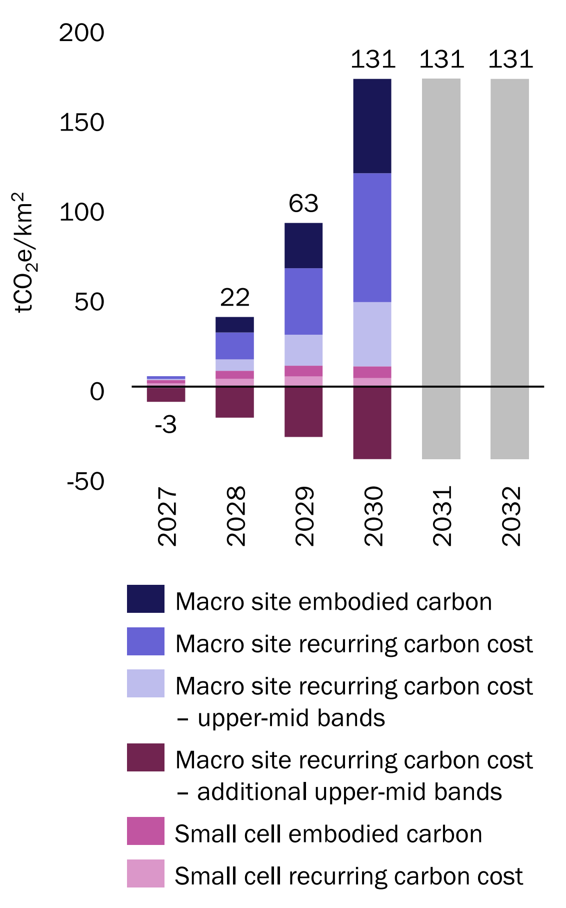


Figure 4.7: Cumulative carbon savings per urban km² [Source: Analysys Mason, 2023]

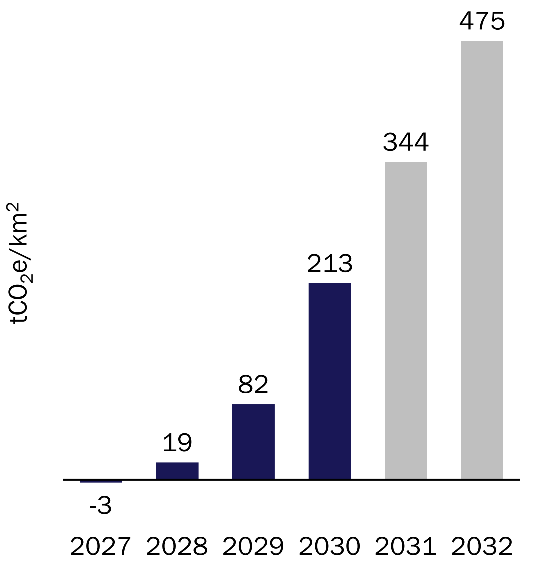


Figure 4.8 and Figure 4.9 illustrate the magnitude of the savings per urban inhabitant, with reference to the modelled urban scenario described in this report (i.e. a population of 15 000 per km²). In 2030, 9kgCO_2e is saved.

Figure 4.8: Annual carbon savings per dense urban inhabitant [Source: Analysys Mason, 2023]

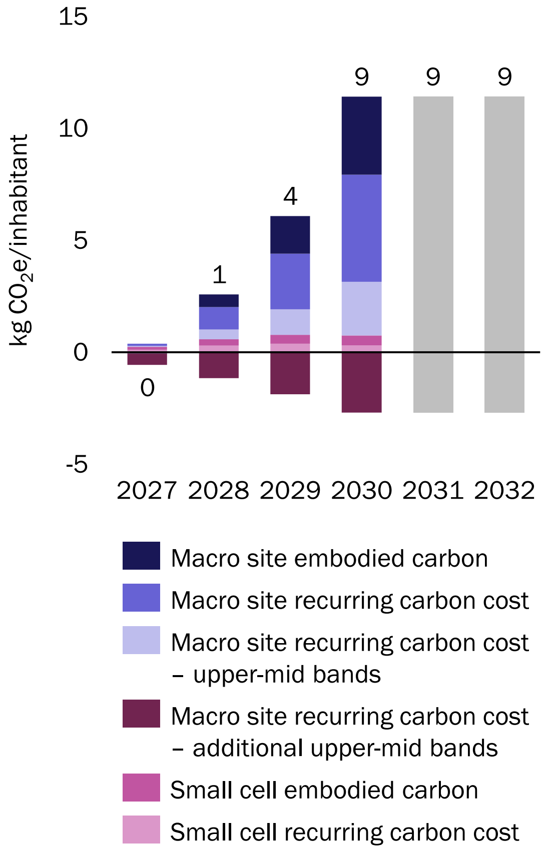
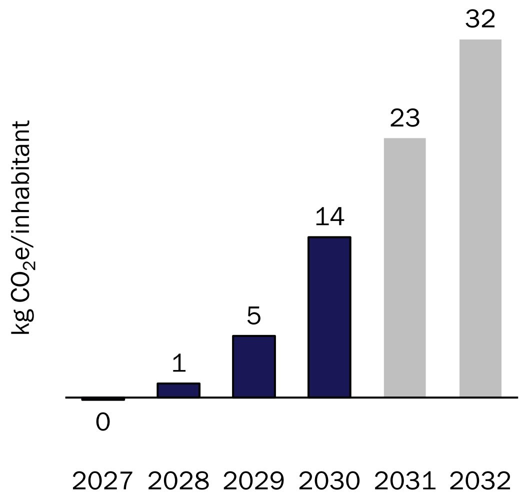


Figure 4.9: Cumulative carbon savings per dense urban inhabitant [Source: Analysys Mason, 2023]



4.1.2 Deployment variant 2 – densification using a higher proportion of small cells

In the second urban deployment variant, macro-site density is capped at 9.4/km², an increase of 31% relative to current macro-site density (corresponding to an ISD of 350m), as shown in Figure 4.10. Figure 4.11 shows the resulting substantial deployment of small cells required to meet the target – exceeding 100 small cells/km².

Figure 4.10: Density of dense urban macro sites [Source: Analysys Mason, 2023]

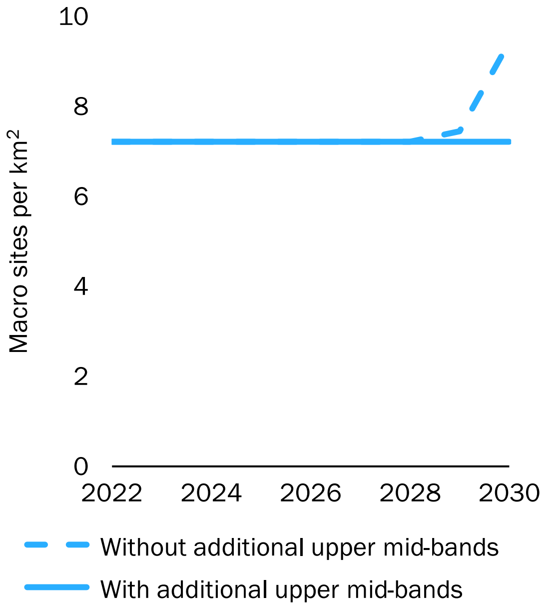
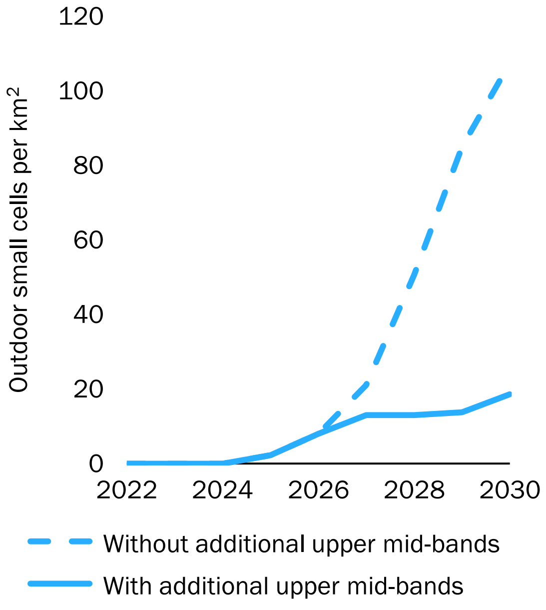


Figure 4.11: Density of dense urban outdoor small cells [Source: Analysys Mason, 2023]



As in deployment variant 1, it is the case that in order to meet the uplink target, the modelled capacity required is such that the downlink target for the deployment is substantially exceeded.

Figure 4.12 to Figure 4.15 show there are still carbon savings from using additional upper mid-bands for IMT-2020/5G under deployment variant 2, but they are around 30% lower than under deployment variant 1.

Figure 4.12: Annual carbon savings per dense urban km² [Source: Analysys Mason, 2023]

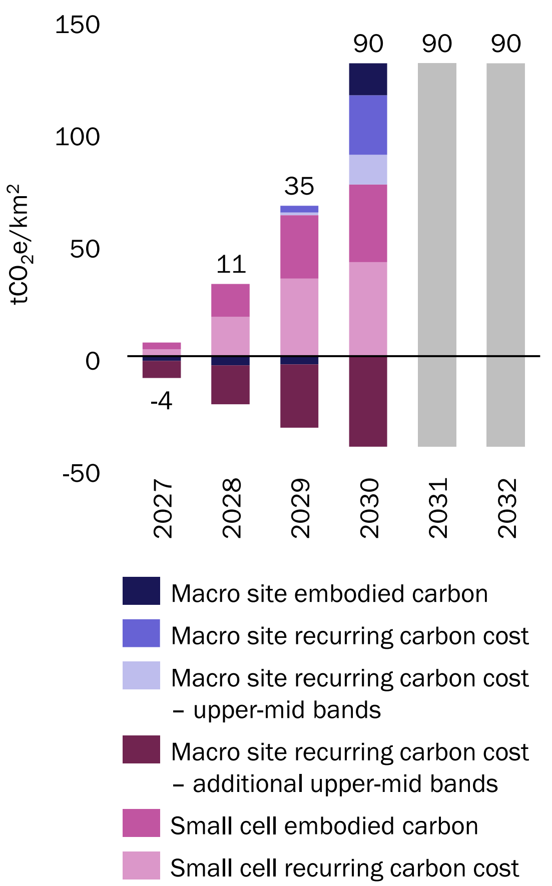


Figure 4.13: Cumulative carbon savings per dense urban km² [Source: Analysys Mason, 2023]

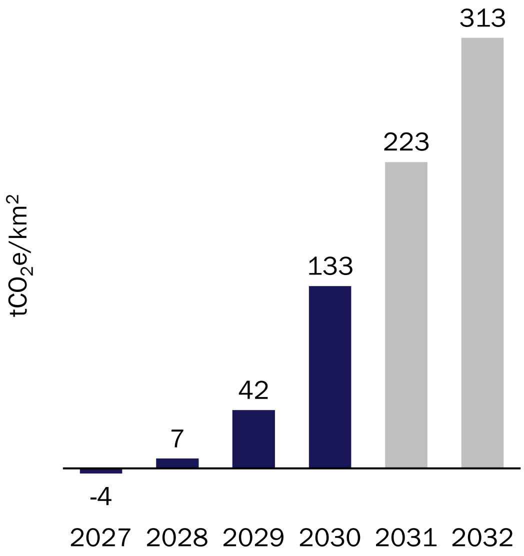


Figure 4.14: Annual carbon savings per dense urban inhabitant [Source: Analysys Mason, 2023]

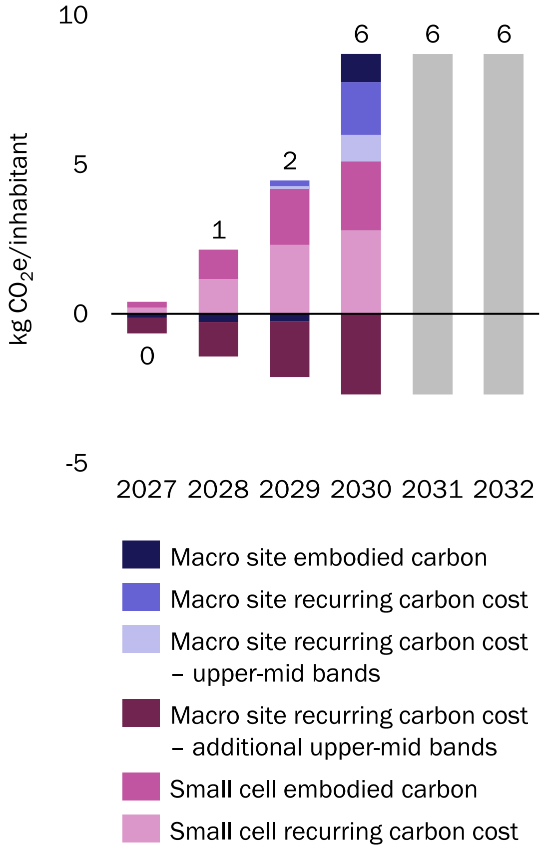
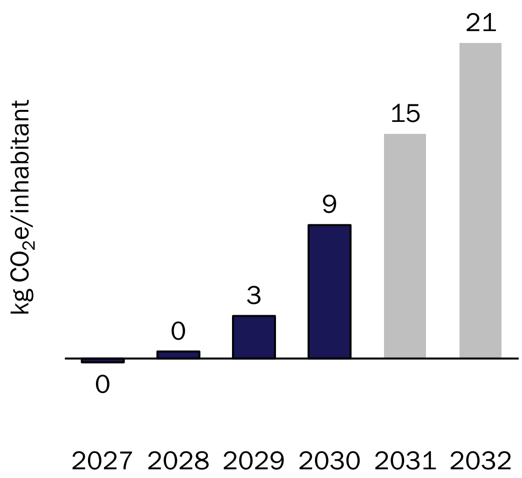


Figure 4.15: Cumulative carbon savings per dense urban inhabitant [Source: Analysys Mason, 2023]



4.1.3 Sensitivity analysis for the dense urban scenario

Figure 4.12 and Figure 4.13 show how the cumulative carbon savings to 2030 vary with activity factor and high-band offloading for dense urban deployment variants 1 and 2 respectively. As expected, a higher activity factor increases the carbon savings. This is because the difference between the volume of site build required with and without additional 5G upper mid-band spectrum is exacerbated as demand on the network increases. Similarly, as high-band offloading increases the carbon savings decrease. This is because there is less demand on the macro sites and small cells, so less densification is required and thus the impact of additional spectrum in terms of mitigating the need for additional site build is reduced. However, we note that high-band offloading is only possible if sites at those specific locations where demand is highest can accommodate high-band deployment, and/or where new mmWave sites can be deployed. It is also noted that the mmWave coverage is lower than the coverage achieved from either 5G mid-bands or from other, lower, frequency bands used in 5G mobile networks. Hence, mmWave offloading can complement 5G mid-band deployment but does not provide a direct substitute for it due to coverage differences.

Figure 4.16: Cumulative carbon savings to 2030 – activity factor and high-band offloading sensitivity on dense urban deployment variant 1 (data point used in Section 4.1.1 highlighted) [Source: Analysys Mason, 2023]

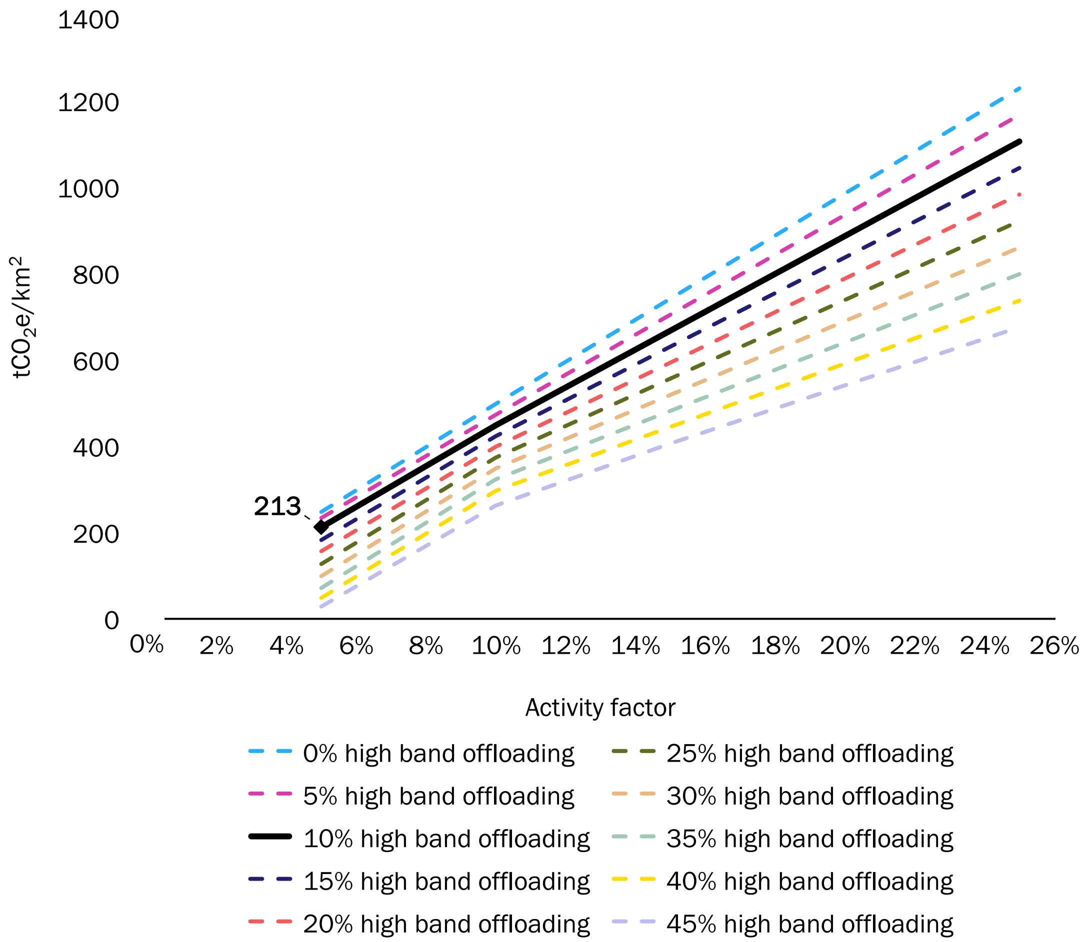
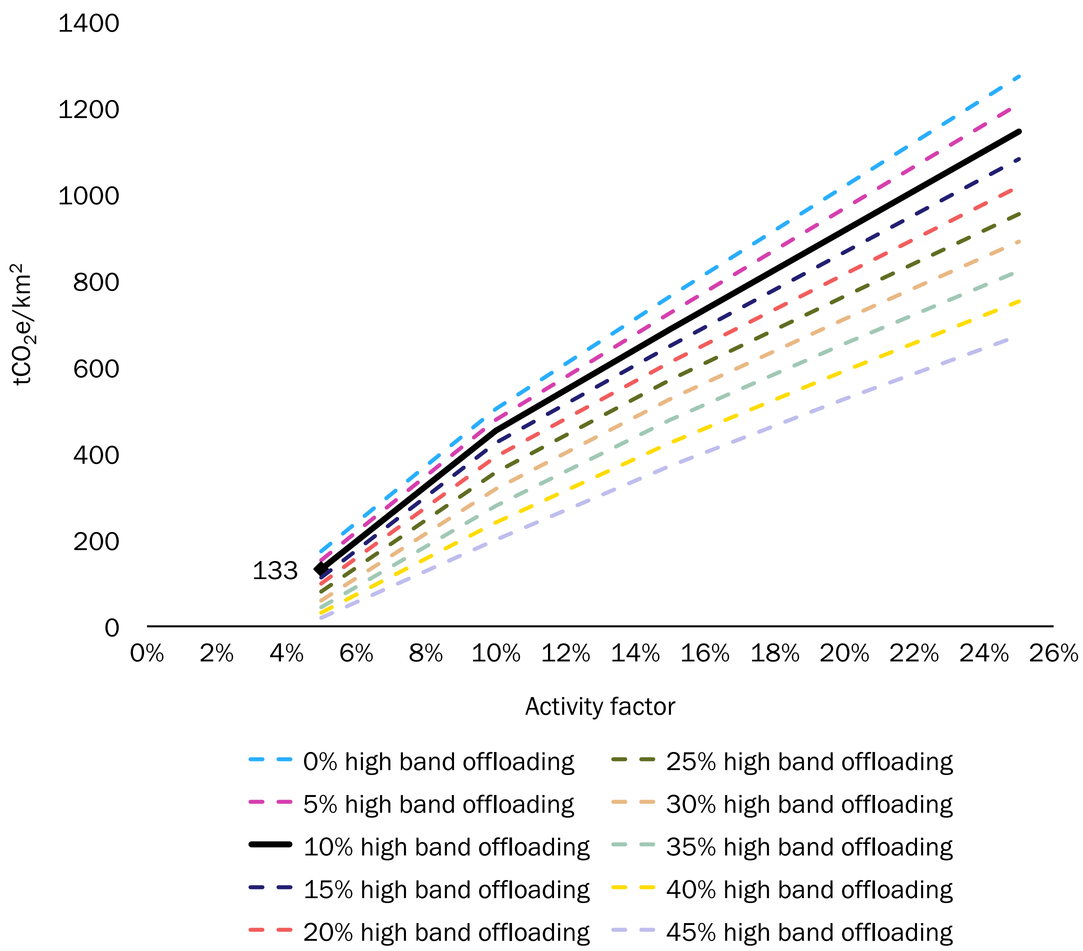


Figure 4.17: Cumulative carbon savings to 2030 – activity factor and high-band offloading sensitivity on dense urban deployment variant 2 (data point used in Section 4.1.2 highlighted) [Source: Analysys Mason, 2023]



4.2 Rural town or village results

Figure 4.18 shows the required uplink and downlink MBB capacity for the rural town or village over time. Likewise, Figure 4.19 shows the FWA required capacity, which accounts for the majority of the total rural required capacity. The required capacity for MBB is calculated based on the assumed population density for the rural town or village, which is 300/km². The required capacity for FWA assumes households in the town or village are beyond the reach of a fixed (fibre) network. We note that not all households will take up a broadband service and hence we assume a penetration of 80% by 2030.

Figure 4.18: MBB required capacity for rural town or village [Source: Analysys Mason, 2023]

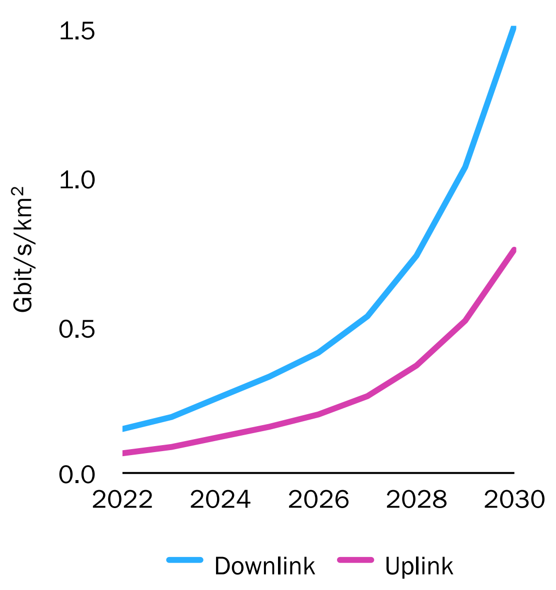
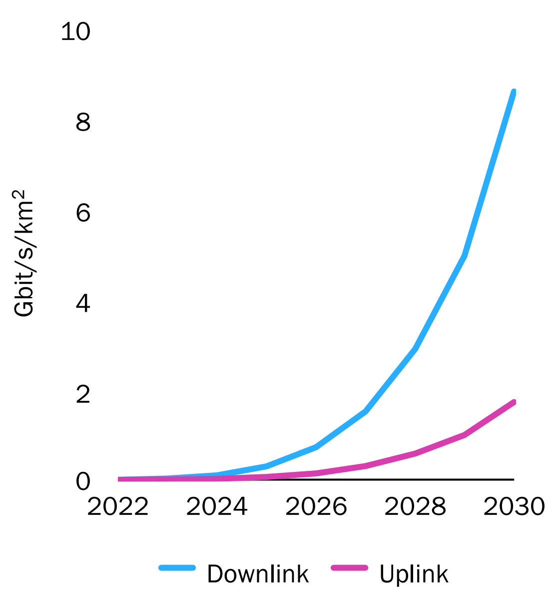


Figure 4.19: FWA required capacity for rural town or village [Source: Analysys Mason, 2023]



In comparison, Figure 4.20 and Figure 4.21 show the MBB and FWA capacity supply per macro site in a rural town or village respectively. Both are fairly similar (there are slight variations due to the different spectrum portfolios and spectral efficiencies), but in reality, rural macro sites will use a combination of MBB and FWA, rather than MBB-only or FWA-only as illustrated here.

Figure 4.20: Maximum MBB capacity supply per macro site for rural town or village [Source: Analysys Mason, 2023]

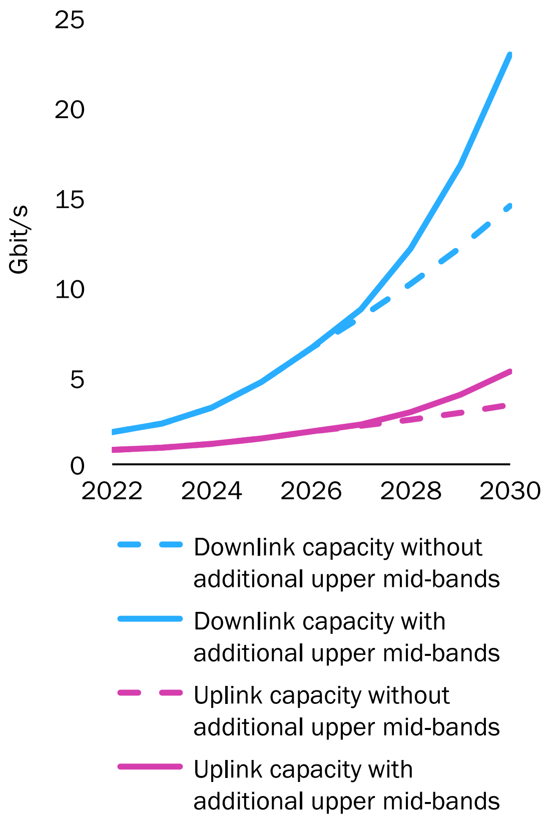
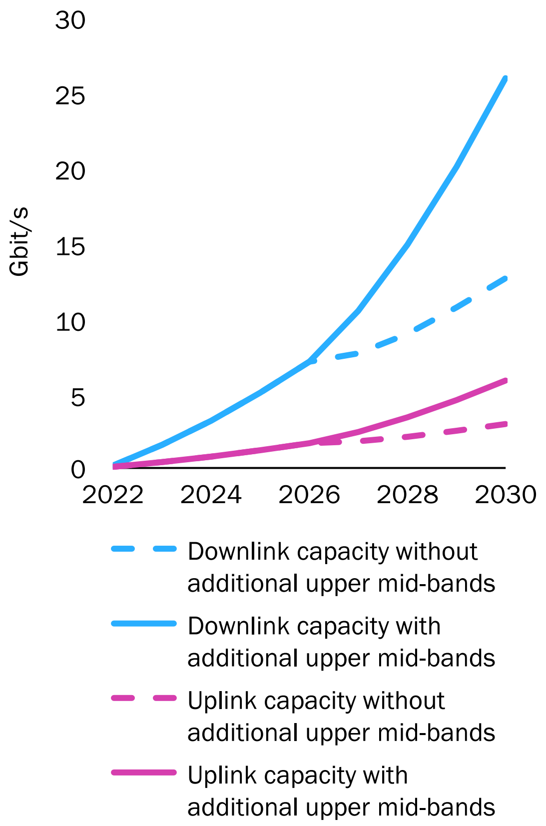
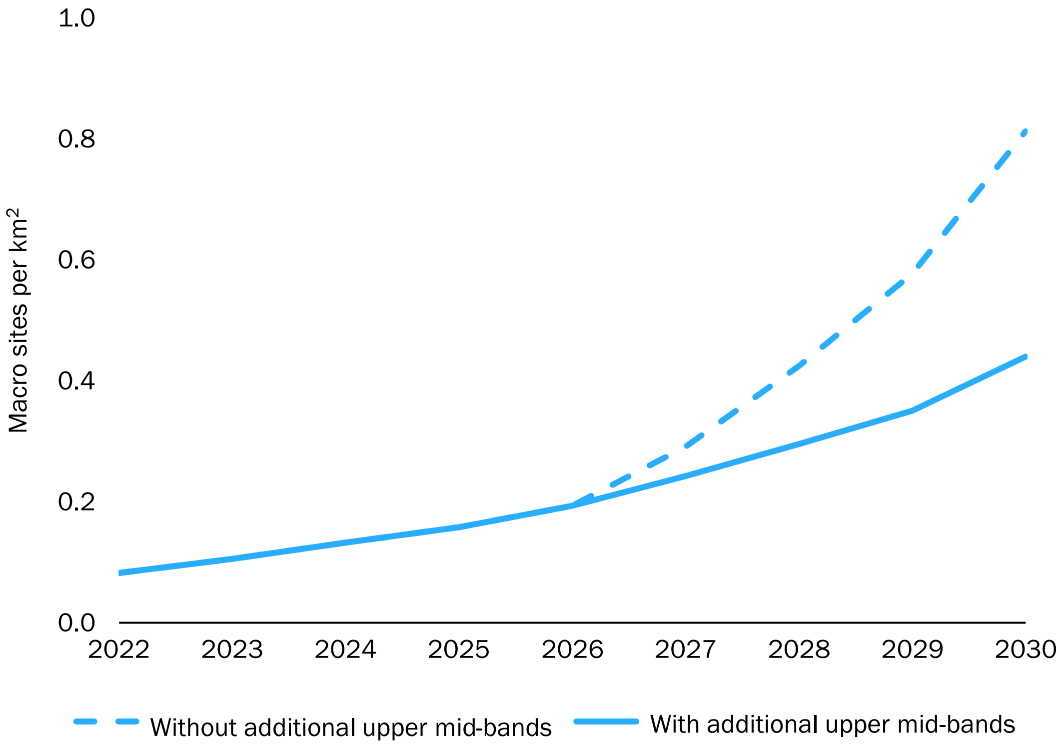


Figure 4.21: Maximum FWA capacity supply per macro site for rural town or village [Source: Analysys Mason, 2023]



In order to meet the total required capacity, macro-site densification is required (see Figure 4.22). With additional upper mid-bands rural macro-site density increases to 0.4/km² by 2030 (an ISD of 1.6km). In comparison, without additional upper mid-band spectrum, rural macro sites reach twice that density, to reach 0.8/km² (an ISD of 1.2km).

Figure 4.22: Density of macro sites for rural towns or villages [Source: Analysys Mason, 2023]



As in the dense urban scenario the downlink target is exceeded; the uplink target is the limiting factor.

Figure 4.23 and Figure 4.24 show the annual and cumulative carbon savings achieved by using additional upper mid-bands for IMT-2020/5G.

It is noted that the carbon savings will continue from 2030. However, the precise level of these savings is not calculated in our model, due to uncertainty over site build after 2030, and the introduction of new mobile access technologies (e.g. 6G) for which performance is as yet undefined. In Figure 4.24 we show what the carbon savings would be in 2031 and 2032 assuming the same level of savings in those years as calculated in our model for 2030.

Figure 4.23: Annual carbon savings per rural town or village km² [Source: Analysys Mason, 2023]

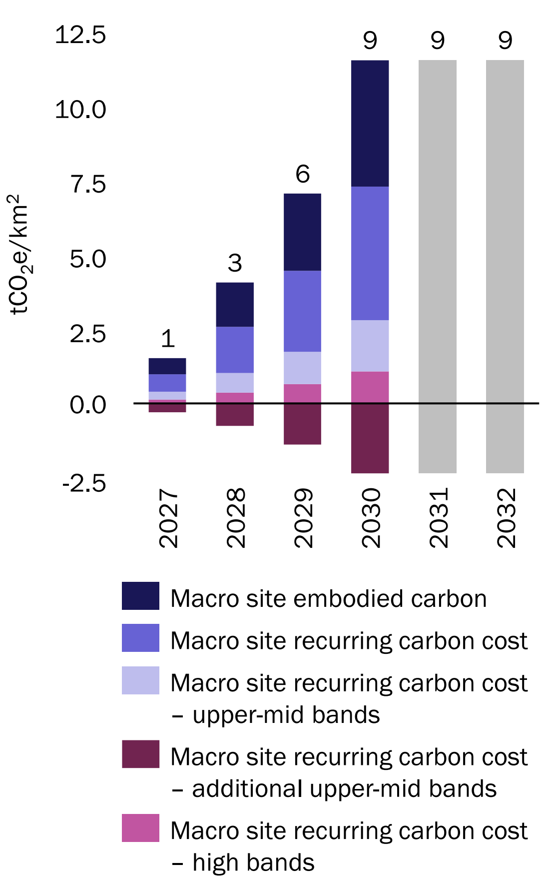
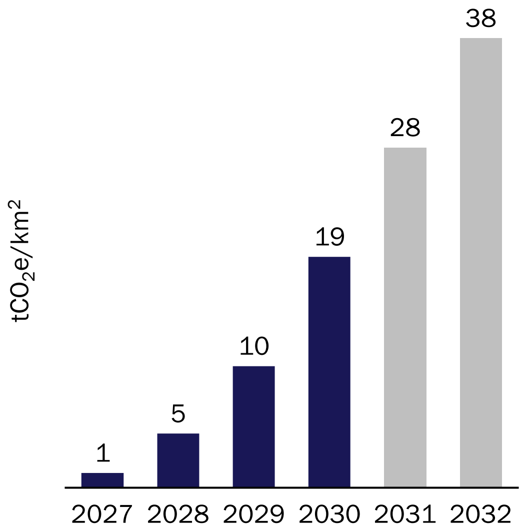


Figure 4.24: Cumulative carbon savings per rural town or village km² [Source: Analysys Mason, 2023]



While from a network point of view these numbers are much lower than the equivalent values in the dense urban scenario, the carbon savings per inhabitant are significantly greater for rural towns or villages (see Figure 4.25 and Figure 4.26). The annual savings per inhabitant are at least three times higher than for a dense urban inhabitant (30kgCO_2e in 2030 in the rural scenario compared with 9kgCO_2e and 6kgCO_2e for urban deployment variants 1 and 2 respectively).

Figure 4.25: Annual carbon savings per rural town or village inhabitant [Source: Analysys Mason, 2023]

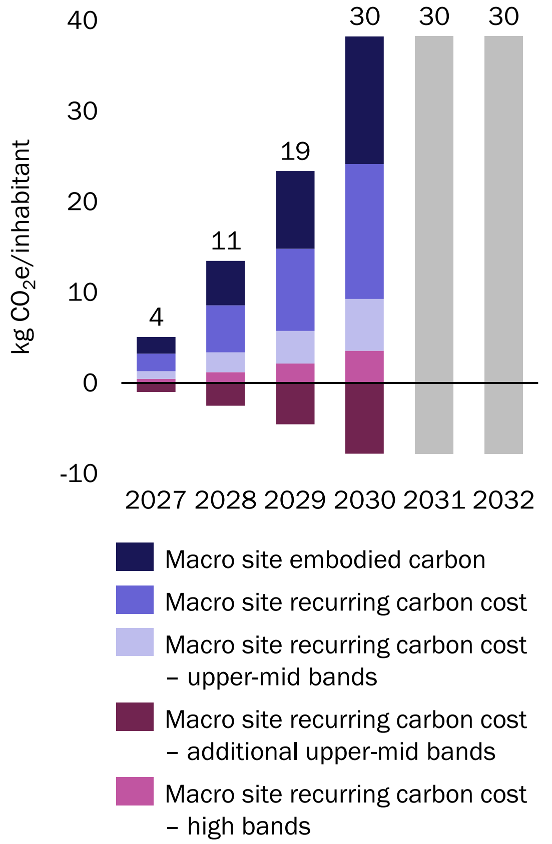
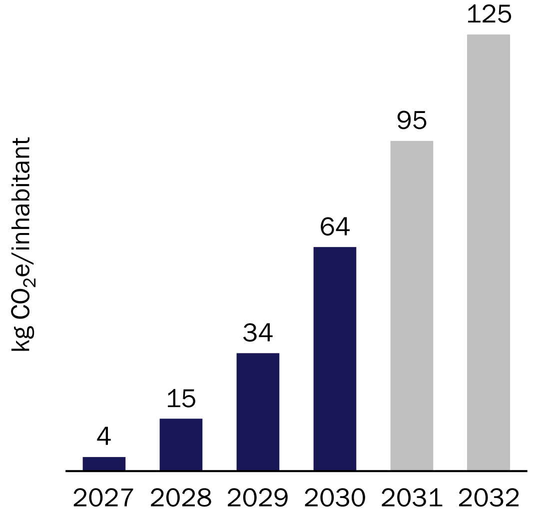


Figure 4.26: Cumulative carbon savings per rural town or village inhabitant [Source: Analysys Mason, 2023]



4.3 Practical issues in building additional macro and small cells

Whilst densifying either macro sites or small cells enables operators to meet increased demand, both options present practical issues in their design, implementation and cost.

In terms of *macro-site densification*, we summarise below examples of the key practical issues:

- Suitable macro-site locations in urban areas are increasingly hard to find
  - few locations that would be suitable for improving existing coverage have sufficient physical space
  - planning issues can delay site acquisition
  - densification may be considered 'unsightly' or the cause of additional electromagnetic radiation, leading to public resistance

- As macro-site density increases, so too does inter-site interference, which reduces the effective site capacity.

In terms of *small-cell densification*, we summarise below examples of the key practical issues:

- Small cells provide lower coverage compared to macro sites, and so many more small cells would be needed to meet future traffic demand, but there may be public resistance to such proliferation
- Identifying enough suitable locations for small cells (which are typically installed on urban furniture or building facades, rather than rooftops) may be difficult
- Local authority co-ordination/planning issues might affect deployment timescales, or even influence whether sites are viable or not, due to the time taken for planning issues associated new sites and/or modifications to existing sites to be authorised
- Small-cell costs can be high relative to the capacity provided, leading to a potentially unsustainable network deployment model as the number of small cells increases.

4.4 Power efficiency measures in mobile network architectures

As mobile networks expand and user demands grow, energy efficiency – and energy saving features – will become even more important to optimise power consumption as networks are densified, and further spectrum is added. Improved technology capabilities to manage power consumption and energy efficiency are an important aspect of how 5G mobile network equipment vendors are evolving their systems to limit the carbon footprint of their clients' networks.

Whist not an exhaustive list, the following are examples of technology features that might be used in 5G mobile networks to manage power consumption and energy efficiency (noting that these features are vendor specific, we include an illustrative list below with specific vendor solutions indicated in the footnote[18]):

- Transmission on demand – for example, dynamic on–off functions in antennas and radio frequency (RF) chains. These dynamic on–off features can be assisted by artificial intelligence (AI) and/or user feedback to anticipate user and traffic patterns and to enable real-time network optimisation (e.g. by analysing historical traffic patterns, busy hours, cell conditions and user needs, and using these in intelligent network optimisation)
- More-efficient power control in networks and devices, adjusting radiated power to actual coverage needs
- Innovative solutions for massive MIMO[19] antennas to increase deployment efficiency and lower power consumption (e.g. through novel optimisation algorithms)[20]

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18 For example, see https://www.huawei.com/en/news/2021/9/most-sustainable-network-solution, https://www.verdict.co.uk/huawei-intelligentran-5g/, https://www.zte.com.cn/global/about/magazine/zte-technologies/2021/1-en/Press-Clipping/1.html, https://www.ericsson.com/en/press-releases/2022/2/ericsson-5g-portfolio-update-puts-energy-efficiency-center-stage and https://www.nokia.com/about-us/news/releases/2022/02/22/nokia-launches-intelligent-ran-operations-to-manage-the-power-of-5g-with-machine-learning-mwc22/

19 MIMO refers to multiple-input, multiple-output, which is the use of multiple transmission and receiving antennas over the same radio channel. A key effect of massive MIMO in 5G is that the capacity of the wireless connection is significantly improved

20 For example, see https://www.huawei.com/en/news/2022/10/5g-innovation-business-success-massive-mimo

- Real-time capture and evaluation of network key performance indicators (KPIs) as an input to network planning, rather than more traditional methods for non-real-time capture of KPIs (e.g. through drive testing).

Other non-technology-related approaches to reduce the carbon footprint of 5G mobile networks may include:

- Use of complementary green energy power sources (e.g. solar or wind power) to limit the use of grid power and replenish back-up batteries
- Power efficiency through spectrum assignment, such as considering the most efficient way to assign spectrum for new mobile technologies (e.g. energy efficiency from wider contiguous carriers rather than aggregation of narrower carriers).

5 Relationship between Wi-Fi carbon footprint and the 6GHz band

5.1 Introduction

Wi-Fi technology is overwhelmingly used for indoor traffic, within homes, public locations or businesses, where the premises are connected to high-speed fixed broadband access networks (generally fibre, but also wireless links or legacy copper technologies) and where Wi-Fi is used to provide high-speed wireless connectivity throughout the premises.

As the market penetration and performance of fixed broadband networks is increasing, with comprehensive fibre roll-out and the progressive introduction of high-speed business-to-consumer (B2C) networks, there is, in turn, a reliance on the evolution of Wi-Fi technologies to deliver the required speed increases within homes and premises.

In Section 4 we assessed the impact on the carbon emissions associated with mobile networks for the scenario in which the upper 6GHz band was used for 5G, as well as the alternative scenario in which the band would not be made available for 5G. In this section we assess the impact on carbon emissions associated with Wi-Fi for the scenario in which the upper 6GHz band is used for WLANs, such as Wi-Fi, as well as the alternative scenario in which the band is not made available for WLANs.

The combination of results from Section 4 and from this section allows us to assess the overall impact on carbon emissions associated with 5G mobile networks and Wi-Fi in the case where the upper 6GHz band is made available for 5G, and the case where the band is made available for WLANs.

Similarly to the analysis presented in Section 4, we have considered the impact (in terms of the number of Wi-Fi access points (APs) needed) of meeting the EC's Digital Decade policy programme target for all end users at fixed locations to have gigabit connectivity at least equivalent in speed to that of 5G. The analysis assumes connectivity within homes and businesses uses Wi-Fi connected to a fixed broadband connection, and we consider Wi-Fi capabilities both with and without the availability of upper 6GHz spectrum, alongside the bands already available for Wi-Fi in Europe (in the 2.4GHz, 5GHz and lower 6GHz bands).

In this section, we further discuss the evolution of fixed broadband connectivity and the role of Wi-Fi, and we elaborate on the implications of the results of modelling performed by Huawei to assess the performance of Wi-Fi APs and terminals (STAs) in typical dense urban and rural dwellings as a function of the available spectrum. We then consider the implications of the modelling outputs in terms of the carbon impact of having additional spectrum available for Wi-Fi use, compared to not having the additional spectrum available.

5.2 Fixed broadband connectivity targets and technology evolution in Europe

A key objective of the EC's Digital Decade vision is for all European households to have access to gigabit connectivity by 2030. Fixed broadband (FBB) technologies are being rolled out across Europe, with fibre to the premises (FTTP) being one of the key solutions to provide gigabit connections close to houses and business premises.

The adoption of fibre-optic technology for FBB connections has developed rapidly in the last 15 years, with the introduction of a new FTTx technology generation every 8 to 10 years, delivering end-user speeds that are around four times higher than the previous generation. For example, G-PON (i.e. gigabit-capable passive optical network, or PON) technology is widely available today delivering up to 1Gbit/s service packages to end users, whereas 10G-PON became available in 2017 and is expected to reach large-scale take-up by 2026, delivering 1-5Gbit/s service packages to end users.

The next generation of PON is the standard defined by the telecommunications sector of the ITU (i.e. ITU-T), called 50G PON. This became available in 2021,[21] and is expected to deliver ~10-20Gbit/s service packages to end users. The first 50G PON products are expected to become commercially available before the end of 2023 and the technology is expected to reach a large-scale market by 2029. Preliminary research is underway for the next PON technology generation (although the ITU-T work towards standard development has not yet started), which will be required to deliver higher speeds to residential users on average, should market demand materialise in the future. However, the market launch for this new technology is unlikely to occur until the next decade.

Accordingly, for the purposes of our analysis, we use a 2030 target of 1Gbit/s within homes and business premises, consistent with the EU's Digital Decade vision.

5.3 Additional spectrum and Wi-Fi throughput for typical premises

Huawei has developed a model for the purpose of understanding the impacts on throughput in typical dense urban and rural premises of both the densification of Wi-Fi APs and the use of additional spectrum for Wi-Fi. This model simulates the operation of the latest type of Wi-Fi equipment, Wi-Fi 6, radios at the physical (PHY) and medium access control (MAC) layers, and accounts for the impact of co-channel and non-co-channel interference in quantifying the achievable data throughputs.

5.3.1 Modelled buildings

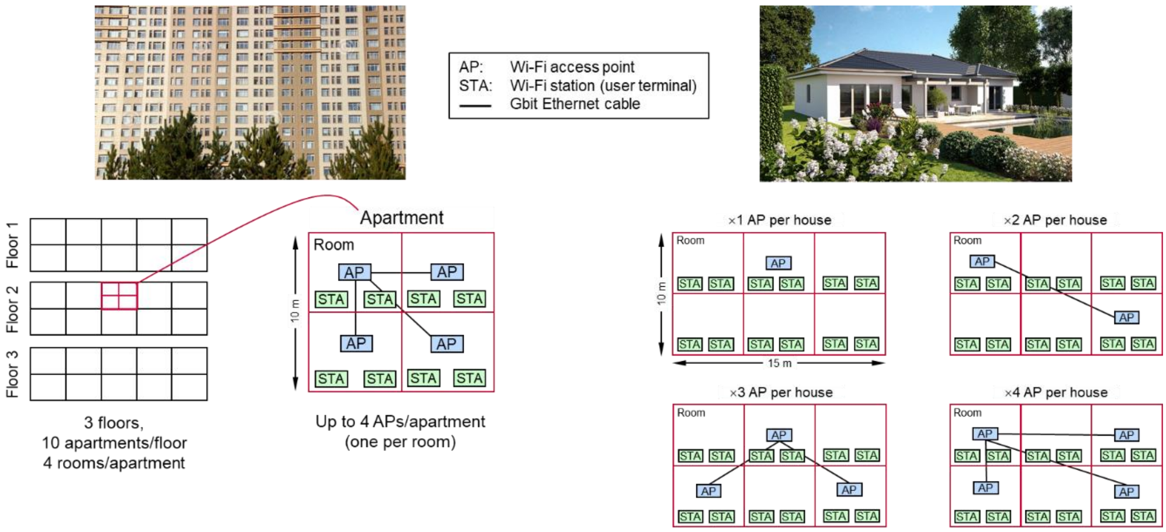
The model has addressed two types of premises, representative of typical urban apartments and rural houses (see Figure 5.1):

21 See https://www.itu.int/hub/2021/06/new-itu-standards-to-boost-fibre-to-the-home-from-10g-to-50g/

- a middle-floor apartment with four 5m×5m rooms, with Wi-Fi used in an apartment block containing nine other similar apartments on the same floor, ten similar apartments on the floor above and ten similar apartments on the floor below
- an isolated single-storey rural house with six 5m×5m rooms.

Radio propagation is modelled based on the New Radio (NR) indoor hotspot (InH) channel simulation model specified by the 3GPP.[22] Penetration loss is modelled as 11dB for the inner walls and 18dB for the floors.

Figure 5.1: Modelled environment – dense urban apartments and rural houses [Source: Huawei, 2023]



5.3.2 Spectrum bands, frequency re-use and antenna technologies

The operation of each Wi-Fi AP and terminal is modelled at the level of the PHY/MAC layers, accounting for co-channel and non-co-channel interference from all other modelled Wi-Fi equipment. In the case of the dense urban apartments, this implies modelling a total of up to 120 Wi-Fi APs (up to four per apartment) and 240 Wi-Fi terminals (two per room).

To assess the impact of available spectrum on aggregate throughput, the availability of the following bands for Wi-Fi is considered: 2.4GHz, 5GHz, lower 6GHz and upper 6GHz. In Europe, all of these bands apart from the upper 6GHz are already available for Wi-Fi use.

The model implements frequency re-use amongst the frequencies used by each Wi-Fi AP, with different re-use factors considered in different bands, and with each AP simultaneously using one channel per band. In addition, the model assumes that APs use a wired backhaul link (i.e. no Wi-Fi spectrum is used for communication between the APs and the on-premises internet router/modem).

Regarding antenna technology, the model accounts for 4×4 MIMO in the Wi-Fi APs and 2×2 MIMO in the Wi-Fi terminals. This is a relatively conservative assumption, considering that larger numbers

22 TR 38.889 and TR 38.901.

of antennas (e.g. 8×8 MIMO), which lead to higher throughputs, are expected to be commonplace in top-of-the-range Wi-Fi APs in future.

5.3.3 Simulation methodology

The simulation methodology is based on a Monte Carlo approach, whereby a large number of trials are performed, each using different locations for Wi-Fi terminals within the premises, in order to build up a statistical distribution of the achievable throughput. For each trial:

- A total of two Wi-Fi terminals per room are randomly positioned in the apartment or house
- The throughput between the terminal and its serving Wi-Fi AP is calculated, under the assumption that all available bands are used, with one channel per band
- The aggregate throughput of all Wi-Fi terminals is calculated in the central apartment or the house (8 terminals in the apartment and 12 terminals in the house), by counting the number of successfully delivered packets over a period of 1 second.

The key parameters for each scenario include:

- The number of Wi-Fi APs, ranging from one to four APs per apartment in the dense urban setting, and from one to six APs per house in the rural setting, with the constraint that there is no more than one AP per room
- The amount of spectrum available to the Wi-Fi APs and terminals
- The antenna technology (4×4 MIMO for APs and 2×2 MIMO for terminals).

All Wi-Fi APs are assumed to serve their respective terminals at the same time (commonly known as a "full buffer" scenario), which represents a conservative assumption.

The result for each modelled environment is a cumulative distribution function giving, under the set of parameters selected, the probabilistic distribution of the aggregated throughput in the apartment or house.

5.3.4 Simulation results

For *dense urban apartments*, the modelling indicates that in 90% of iterations of the model within a household, the target throughput of 1Gbit/s can be achieved with the spectrum currently available for Wi-Fi in the 2.4GHz, 5GHz and lower 6GHz bands. This conservatively[23] assumes that there is only one 4×4 MIMO Wi-Fi AP per apartment simultaneously serving a total of eight 2×2 MIMO Wi-Fi terminals per apartment, relying on multi-user MIMO technology.

To reach or exceed the target throughput of 1Gbit/s in 99% of iterations of the model within an apartment would require two 4×4 MIMO Wi-Fi APs per apartment, whether or not the upper 6GHz band is made available to Wi-Fi.

[23] Conservative, in the sense that larger numbers of antennas can be commonly expected in top-of-the-range Wi-Fi APs in future.

For *rural households*, the simulations indicate that in 99% of all iterations of the model, the target throughput of 1Gbit/s can be readily achieved with the spectrum currently available for Wi-Fi (2.4GHz, 5GHz and lower 6GHz bands) with only one 4×4 MIMO Wi-Fi AP per household simultaneously serving a total of 12 2×2 MIMO Wi-Fi terminals, relying on multi-user MIMO technology.

5.4 Implications for the environmental impact

The results of modelling show that the spectrum currently available to Wi-Fi in the 2.4GHz, 5GHz and lower 6GHz bands is sufficient to deliver the Digital Decade target, and that the use of additional spectrum such as the upper 6GHz band would not result in a lower carbon footprint for Wi-Fi installations, since the same number of access points would be required to reach such a target, irrespective of the utilisation of the upper 6GHz band.

6 Conclusions

Overall, our analysis demonstrates that, from a carbon footprint standpoint, it would be more beneficial to make additional mid-band spectrum available to 5G cellular networks than to rely exclusively on network densification to meet future connectivity targets (in the absence of additional mid-band spectrum).This applies both in the dense urban area and the rural town or village we have modelled in our study.

A summary of our other main conclusions is as follows:

- Our modelling results show that lower network carbon emissions arise in 5G mobile networks with additional mid-band spectrum available to meet the future connectivity targets we have considered in this report, compared to a situation where networks are densified through additional macro and outdoor small cells without the availability of additional mid-band spectrum.
- We calculate that the carbon emission savings from having less densification in 5G mobile networks outweigh the incremental carbon emission costs of deploying and operating new radios (to support the additional mid-band spectrum we have modelled) on macro sites and outdoor small cells for the dense urban area and for macro sites in the rural town or village.
- It should be noted that in the dense urban area we consider two deployment variants for densification (in the absence of additional mid-band spectrum):
  - firstly, densification primarily via macro sites (with some supporting outdoor small cells)
  - secondly, densification primarily via additional outdoor small cells (and thus lower macro-site densification).

  In each case, the incremental carbon emission cost of deploying and operating new upper mid-band radios at the dense urban macro sites and outdoor small cells is lower than the incremental carbon footprint associated with the higher level of densification needed without the additional mid-band spectrum.
- In addition to the increased carbon footprint associated with greater densification, the levels of densification that would be required in 5G mobile networks to meet the connectivity targets in the absence of additional mid-band spectrum would be practically challenging and also potentially technically unfeasible (due to interference between sites that are too close to each other).
- Sensitivity analysis suggests that increasing the activity factor for MBB use in the dense urban environment from 5% to 20% increases the carbon savings. This is because the difference between the volume of site build required with and without additional 5G upper mid-band spectrum is exacerbated as demand on the network increases. Similarly, as high-band offloading

increases the carbon savings decrease. This is because there is less demand on the macro sites and small cells, so less densification is required and thus the impact of additional spectrum is reduced. However, we note that high band offloading is only possible if sites at those specific locations where demand is highest can accommodate high-band deployment, and/or where new mmWave sites can be deployed. It is also noted that the mmWave coverage is lower than the coverage achieved from either 5G mid-bands or from other, lower, frequency bands used in 5G mobile networks. Hence, mmWave offloading can complement 5G mid-band deployment but does not provide a direct substitute for it due to coverage differences.

- For Wi-Fi, based on simulations made available to us and considering the future connectivity targets for fixed broadband (i.e. an aggregated throughput of more than 1Gbit/s per premises), availability of the upper 6GHz band would not translate into any reduction in carbon emissions, given that such targets can be met via the latest Wi-Fi technology using spectrum bands already available for Wi-Fi use in Europe (2.4GHz, 5GHz and lower 6GHz).

While these results have been modelled assuming upper 6GHz deployment (e.g. in terms of the bandwidth available), these conclusions may apply to other upper mid-band spectrum, provided that the alternative upper mid-band spectrum exhibits similar characteristics to those modelled here.

Annex A 5G mobile network modelling methodology

This annex describes the detailed modelling methodology used for the dense urban area (Section A.1) and the rural town or village (Section A.2).

The methodology uses a number of inputs that are described in this annex. The calculations performed by the model are repeated for spectrum configurations with, and without, additional upper mid-band spectrum, and then the difference in potential carbon emissions between the two spectrum configurations is calculated. For the urban settlement the model is run twice to reflect two potential deployment variants in the absence of adding spectrum – densification primarily through macro sites, and densification primarily through outdoor small cells.

A.1 Modelling methodology for dense urban area

In order to calculate the embodied and annual carbon emissions of a particular dense urban access network deployment the density of macro sites and outdoor small cells must be determined. There are several steps to the calculation, as explained below.

Note that the diagrams follow on from one another and that any inputs that have been calculated in a previous diagram are identified via a dark border and the relevant diagram is listed in the legend.

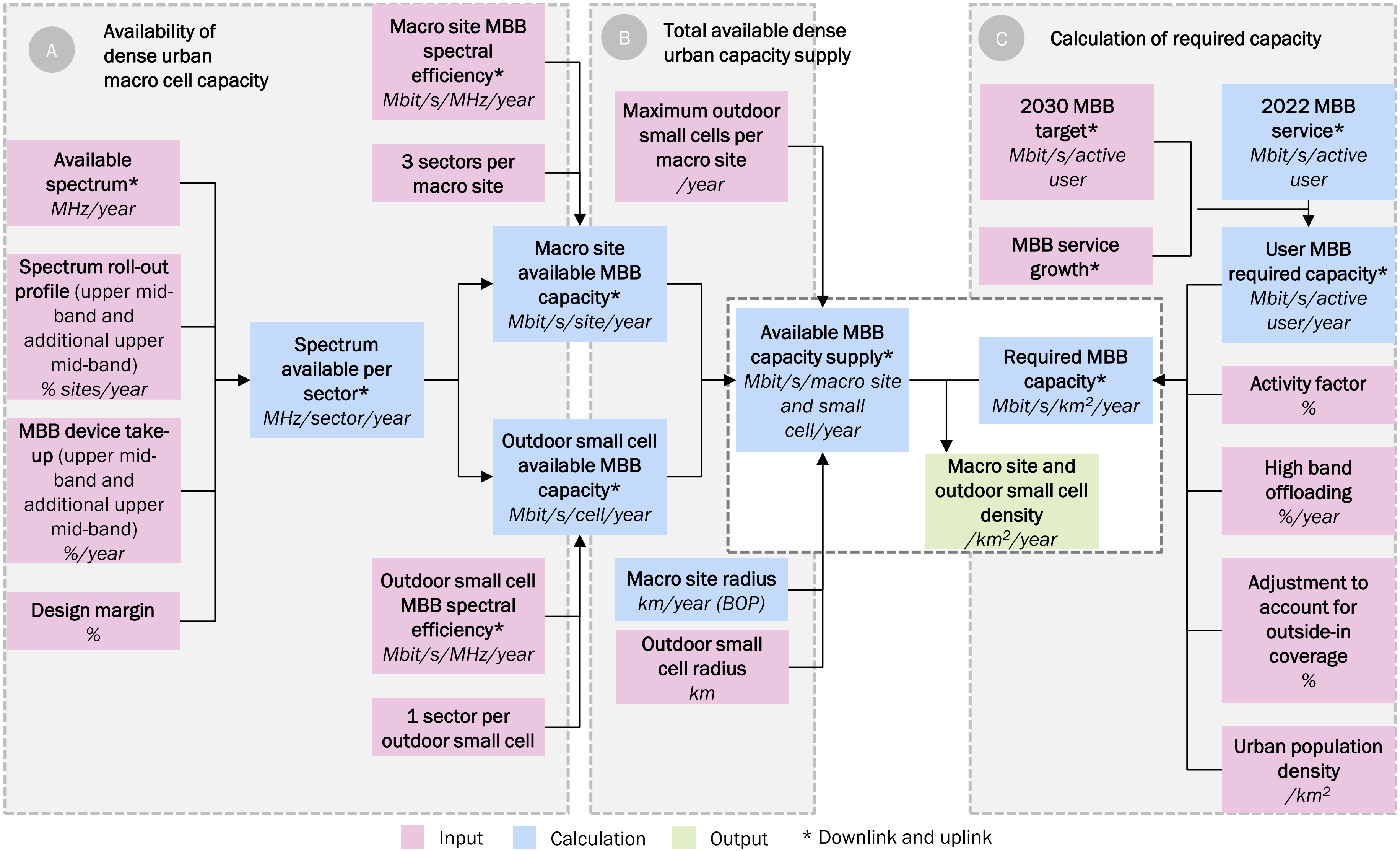
A.1.1 Calculation of dense urban macro-site and outdoor small-cell density

The density of macro sites and outdoor small cells is determined by comparing the uplink and downlink MBB capacity that can be supplied for one macro site and its supplementary outdoor small cells[24] with the required MBB capacity. Figure A.1 shows the wider processing of inputs required to arrive at this overarching calculation (shown in the dashed box with the darker grey outline). This wider processing has been broken down into three constituent components, discussed in turn below.

Values used in the calculation are end-of-period (EOP) unless stated – for example, beginning of period (BOP) is used when calculating macro-cell radius, as shown in Figure A.1 below.

24 We assume an average ratio of small cells per macro site in a given location, noting that in practice the ratio will vary, as small cells are likely to be less evenly distributed than macro sites.

Figure A.1: Calculation of dense urban macro-site and outdoor small-cell density [Source: Analysys Mason, 2023]



Calculation of available dense urban site/cell MBB capacity supply

For each macro site and outdoor small cell, the available downlink and uplink MBB capacity supply is calculated on the basis of the spectrum available to the average site/cell, the number of sectors and the corresponding spectral efficiency. As illustrated in Figure A.2, there are a number of inputs that determine the spectrum deployed on an average site:

- The proportion of sites on which a given band has been deployed – for modelling purposes this is taken to be the percentage of available spectrum deployed on the average site
- The take-up of devices compatible with newly added spectrum bands – this adjusts the available spectrum to represent the spectrum available to the average user
- The design margin, which accounts for the reality that, in practice, capacity at a site/cell in the busy period cannot be fully utilised.

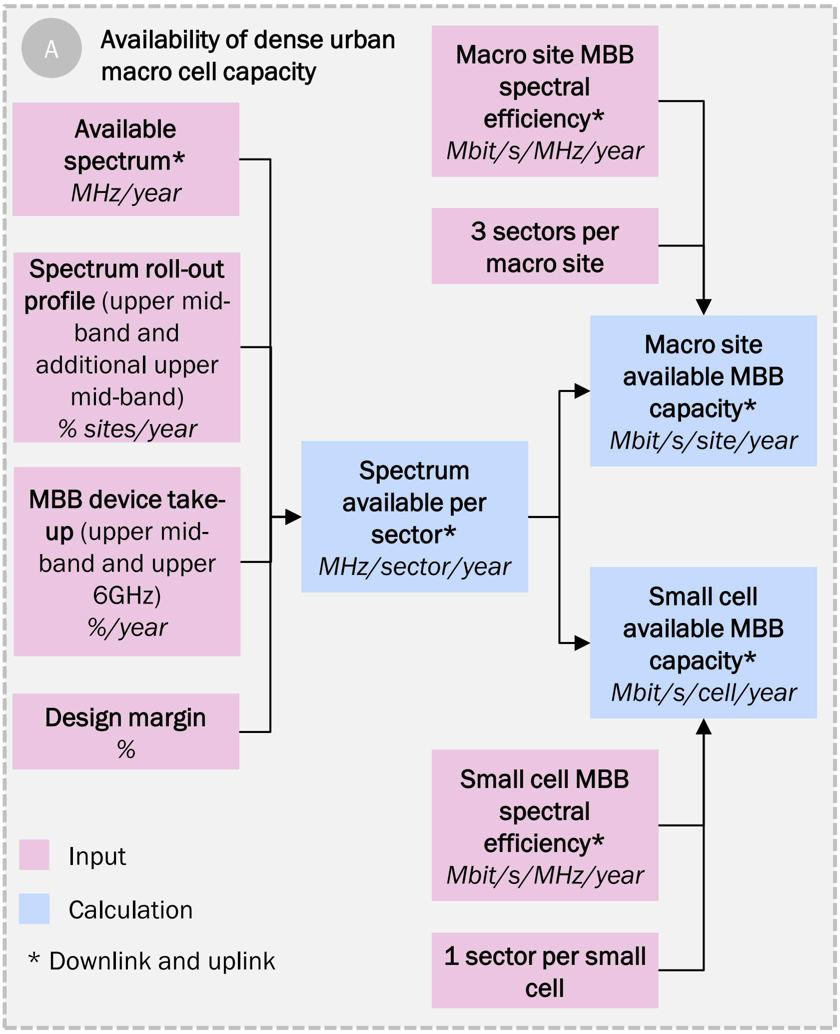


Figure A.2: Calculation of available urban site/cell MBB capacity supply [Source: Analysys Mason, 2023]

Calculation of maximum dense urban network capacity

Once the available uplink and downlink MBB capacity supply of an average dense urban macro site and outdoor small cell have been determined these are combined to calculate the available uplink and downlink MBB capacity of one macro site and its supplementary outdoor small cells. As outlined in Figure A.3, this calculation uses an input assumption for the ratio of outdoor small cells to macro sites, while accounting for small-cell capacity being constrained by coverage (capacity density must be constant in order for the targets to be met ubiquitously in the most efficient manner possible).

Our assumptions have been designed to reflect the fact that, in practice, outdoor small cells will only be able to supply capacity in limited areas within the macro-cell coverage area. However, the deployment of outdoor small cells will allow the macro cell to make an equivalent capacity supply available in other areas within the cell.

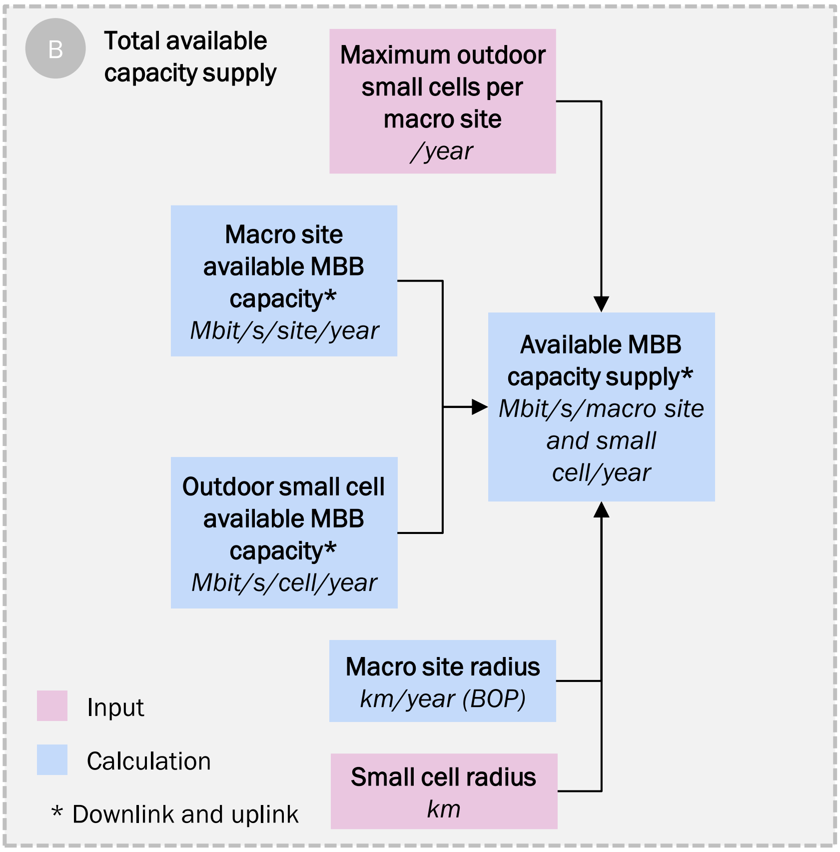


Figure A.3: Calculation of maximum dense urban network capacity [Source: Analysys Mason, 2023]

Calculation of required dense urban MBB capacity

In order to calculate the macro-site and outdoor small-cell density required to meet the target user experience rate, the target is converted to a capacity density requirement. This is shown in Figure A.4. First, the 2022 capacity is calculated on the basis of the 2022 site radius, spectral efficiencies and activity factor. A per-user growth rate in Mbit/s is then applied that will allow the target user experience rate to be achieved by 2030. This required MBB capacity per active user is then multiplied by the dense urban population density and the proportion of active users (the activity factor) to arrive at a required capacity density. This capacity density is then adjusted to reflect offloading of traffic to high bands, to arrive at the required MBB uplink and downlink capacity density that has to be met by the macro sites and outdoor small cells.

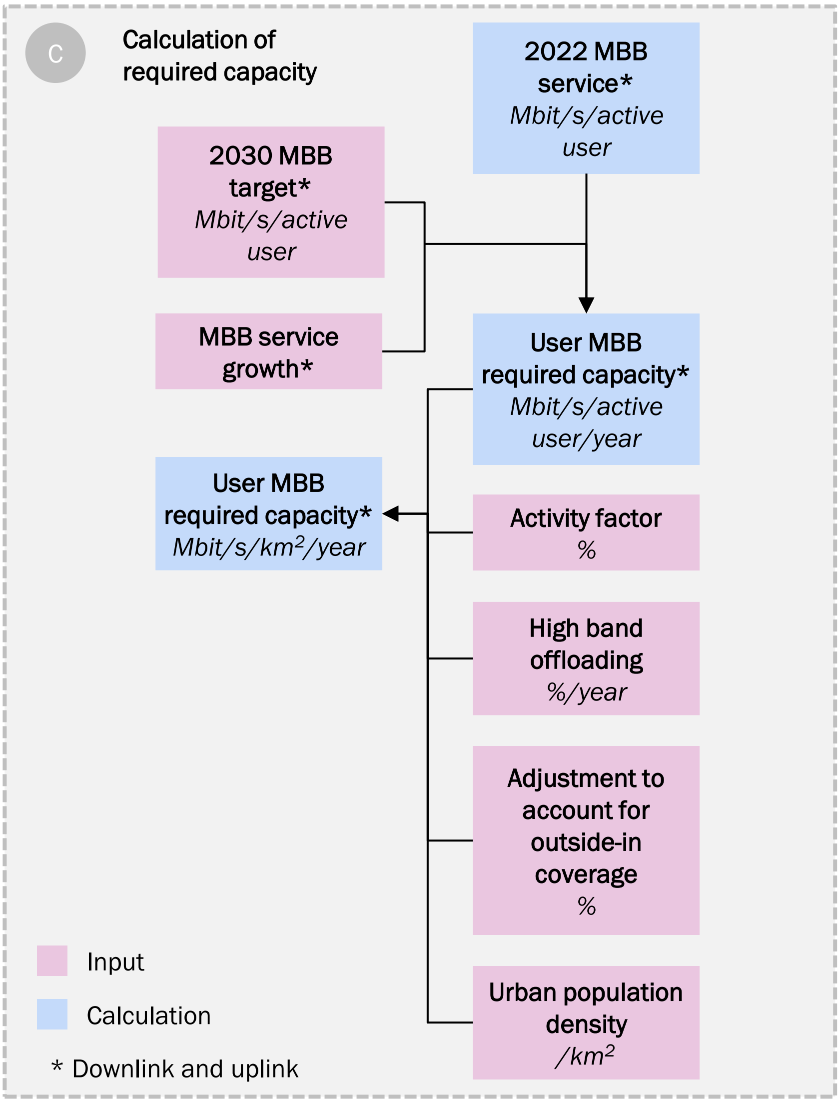


Figure A.4: Calculation of required dense urban MBB capacity [Source: Analysys Mason, 2023]

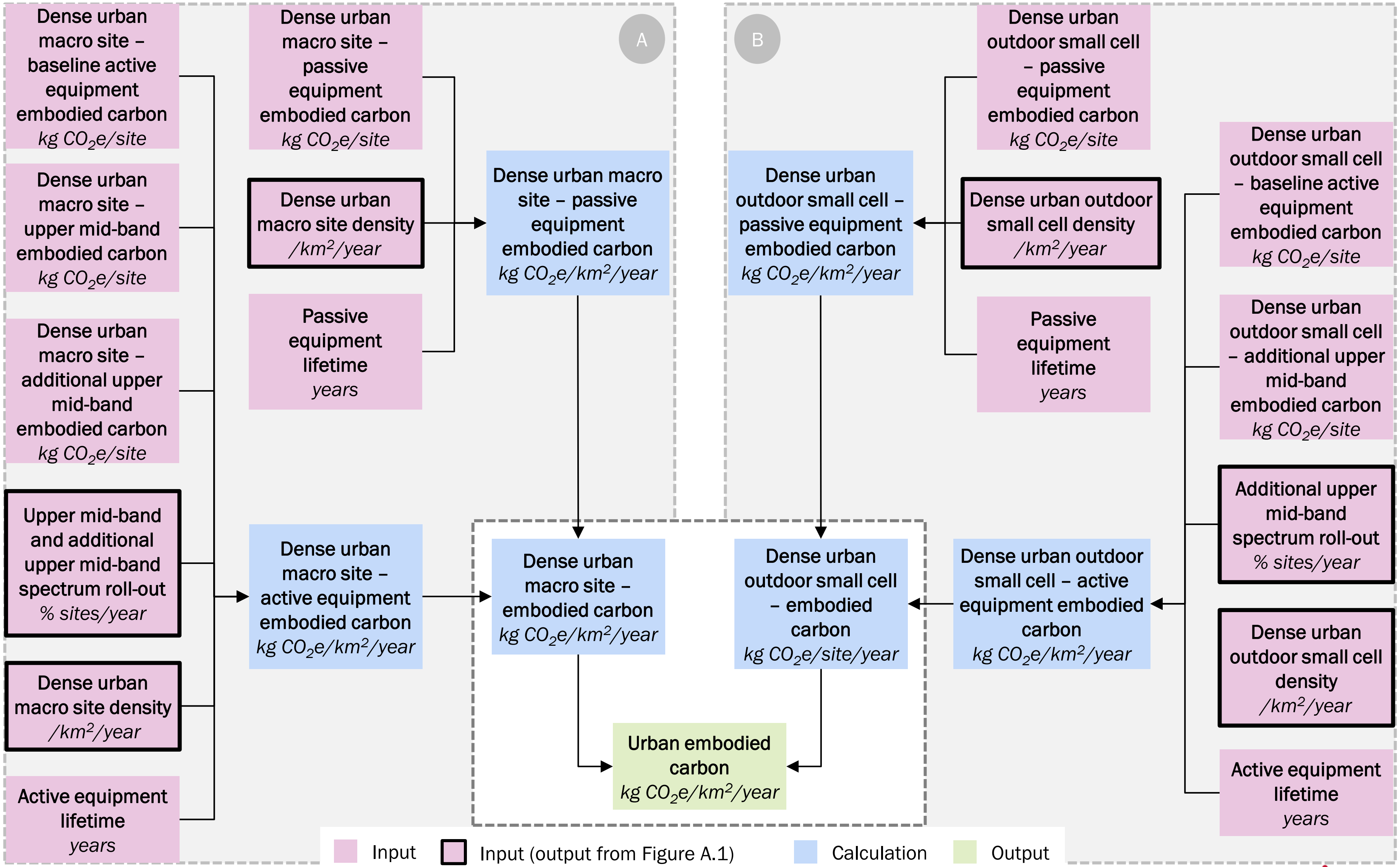
We note that the calculation may forecast a theoretical reduction in site density[25] in certain years, but because this would not typically occur in practice we calculate the actual spectrum roll-out/outdoor small-cell densification required to keep site density constant in these years.

A.1.2 Calculation of embodied carbon for dense urban access network

The embodied carbon emissions of a particular dense urban access network deployment are the sum of the embodied carbon for both the macro sites and outdoor small cells, as shown in Figure A.5.

25 This theoretical reduction in capacity could be triggered in the model if additional spectrum is added to macro cells before the existing capacity supply has reached its full potential, meaning that there is a theoretical reduction in site density because additional capacity is supplied by adding spectrum. However, this is not a real reduction in site density, since capacity demand will grow in subsequent years of the model.

Figure A.5: Calculation of embodied carbon for dense urban access network [Source: Analysys Mason, 2023]



Calculation of embodied carbon for dense urban macro network

Figure A.6 details the calculation of the macro network embodied carbon as the sum of the embodied carbon of passive and active equipment.

The passive equipment has a given embodied carbon per average macro site which is annualised over the passive equipment lifetime and multiplied by the macro-site density to arrive at the annual macro access network passive equipment's embodied carbon.

The active equipment on a given site varies depending on the spectrum deployed. All macro sites have a baseline spectrum deployment for which the active infrastructure has an embodied carbon cost. However, the 5G upper mid-band, and the additional upper mid-band, are only deployed on a proportion of sites, and each infrastructure has its own embodied carbon cost. Again, the embodied carbon cost is summed across all the different site types, and then annualised according to the active equipment's lifetime.

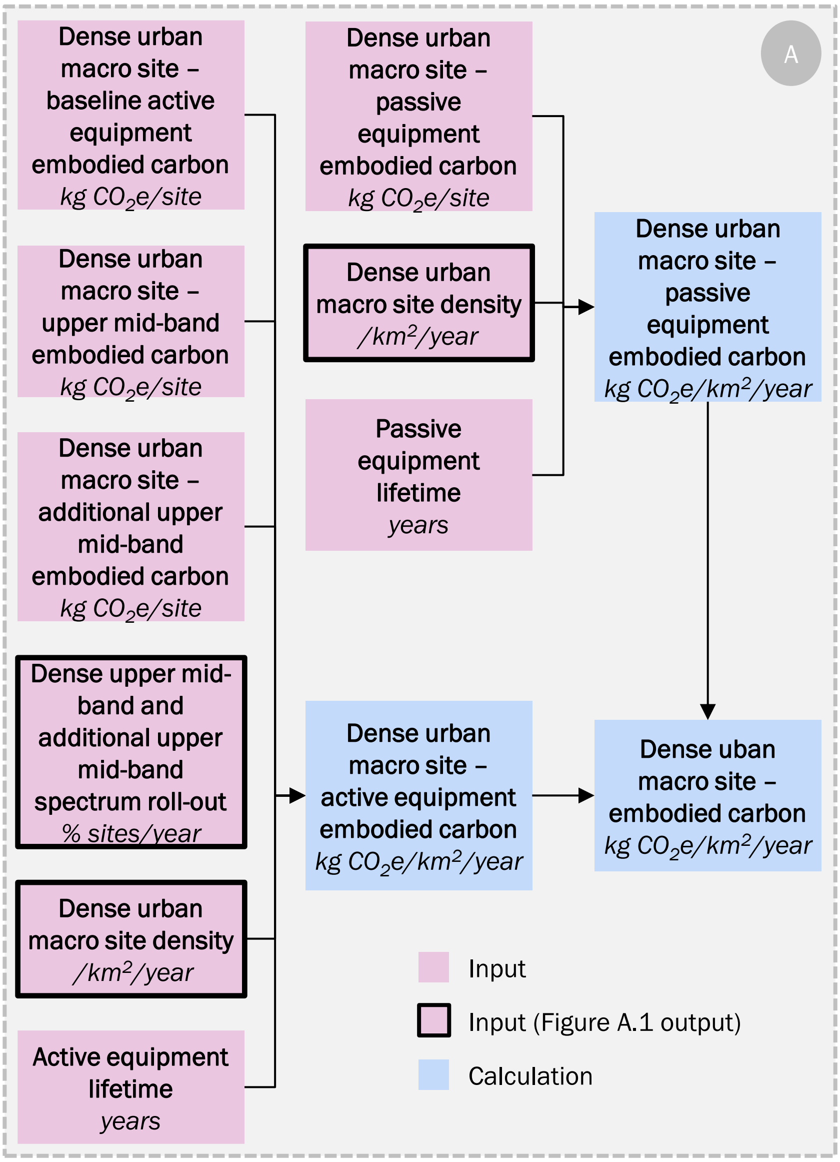


Figure A.6: Calculation of embodied carbon for dense urban macro network [Source: Analysys Mason, 2023]

Calculation of embodied carbon for dense urban outdoor small-cell network

The outdoor small-cell network embodied carbon is calculated in the same manner (see Figure A.7). However, because all outdoor small cells have the upper mid-band deployed, the embodied carbon of upper mid-band active equipment is included in the baseline rather than separated out.

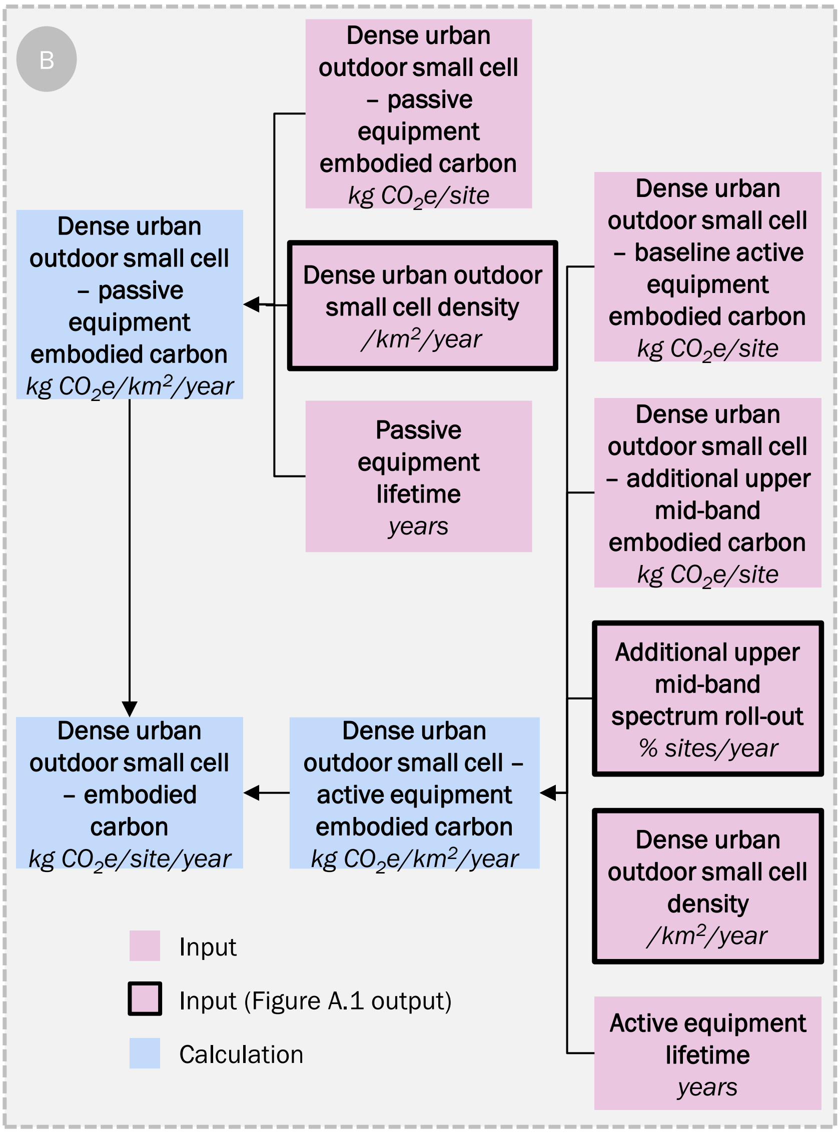
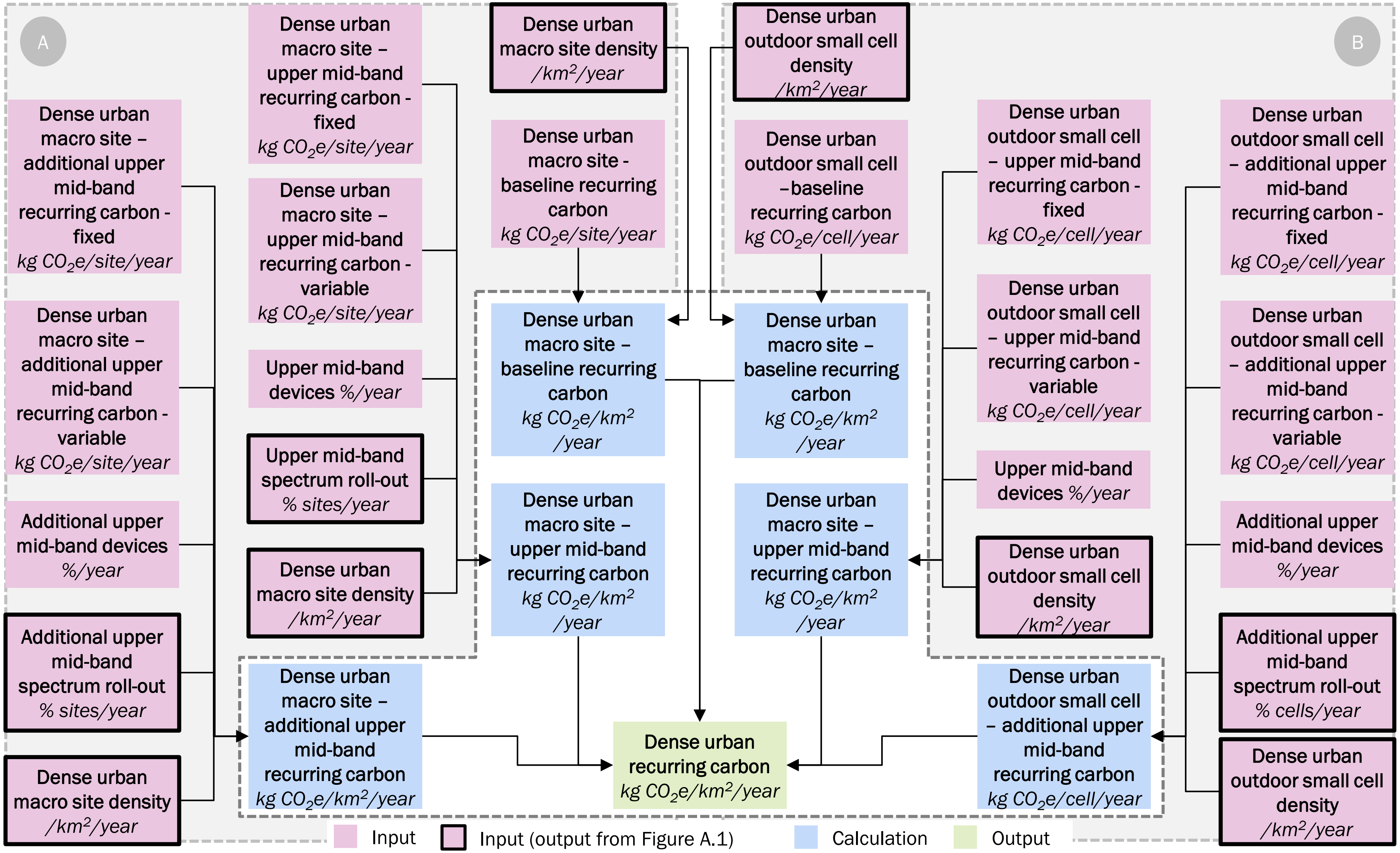


Figure A.7: Calculation of embodied carbon for dense urban outdoor small-cell network [Source: Analysys Mason, 2023]

A.1.3 Calculation of recurring carbon for dense urban access network

Recurring carbon for the dense urban access network (see Figure A.8) is calculated as the sum of recurring carbon for the macro-site network and the outdoor small-cell network. Each of these elements comprises a baseline recurring carbon, and the recurring carbon associated with the deployment of upper mid-band and additional upper mid-band.

Figure A.8: Calculation of dense urban access network recurring carbon [Source: Analysys Mason, 2023]



Calculation of recurring carbon for dense urban macro network

As explained above, there are three components to the macro network recurring carbon:

- the baseline recurring carbon
- the recurring carbon associated with the deployment of upper mid-band
- the recurring carbon associated with the deployment of additional upper mid-band.

These calculations are all shown in Figure A.9 and explained in turn below.

The baseline recurring carbon component is simply the product of a baseline recurring carbon cost per site and the dense urban macro-site density.

The upper mid-band is deployed on a proportion of sites. On these sites there is an additional fixed recurring carbon cost associated with the upper mid-band active equipment being present and turned on, and then there is an incremental recurring carbon cost that varies depending on network loading (both across the day, which has been accounted for in the input value, and in terms of users who can use the spectrum – represented by the compatible device penetration).

Depending on the scenario, there may be a proportion of new macro sites and corresponding outdoor small cells where additional upper mid-band has been deployed. These sites also have an incremental fixed and variable recurring carbon cost, calculated in the same way as for the upper mid-band above.

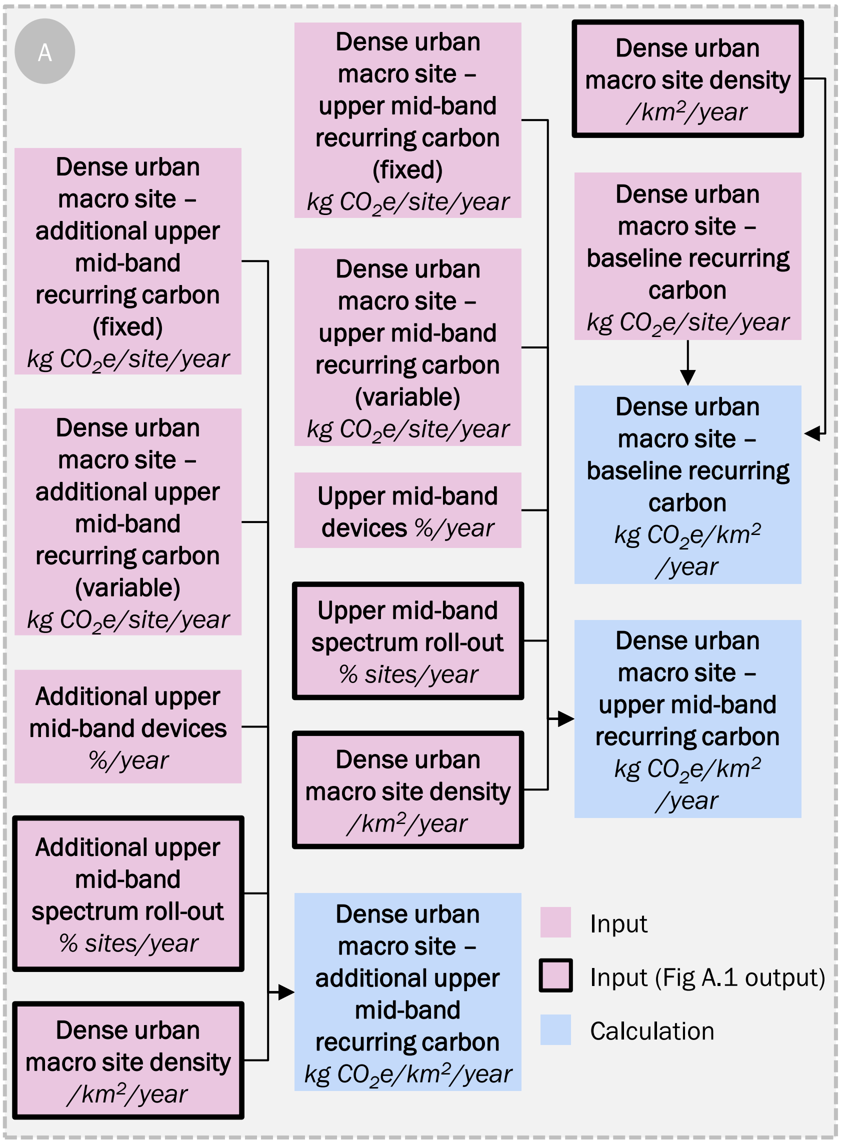


Figure A.9: Calculation of recurring carbon for dense urban macro network [Source: Analysys Mason, 2023]

Calculation of recurring carbon for dense urban small-cell network

Recurring carbon for the small-cell network is calculated in the same manner (see Figure A.10). However, because all outdoor small cells have the upper mid-band deployed, there is no upper mid-band spectrum roll-out input. The recurring carbon for upper mid-band active equipment is kept separate from the baseline, though, as it still varies depending on device penetration.

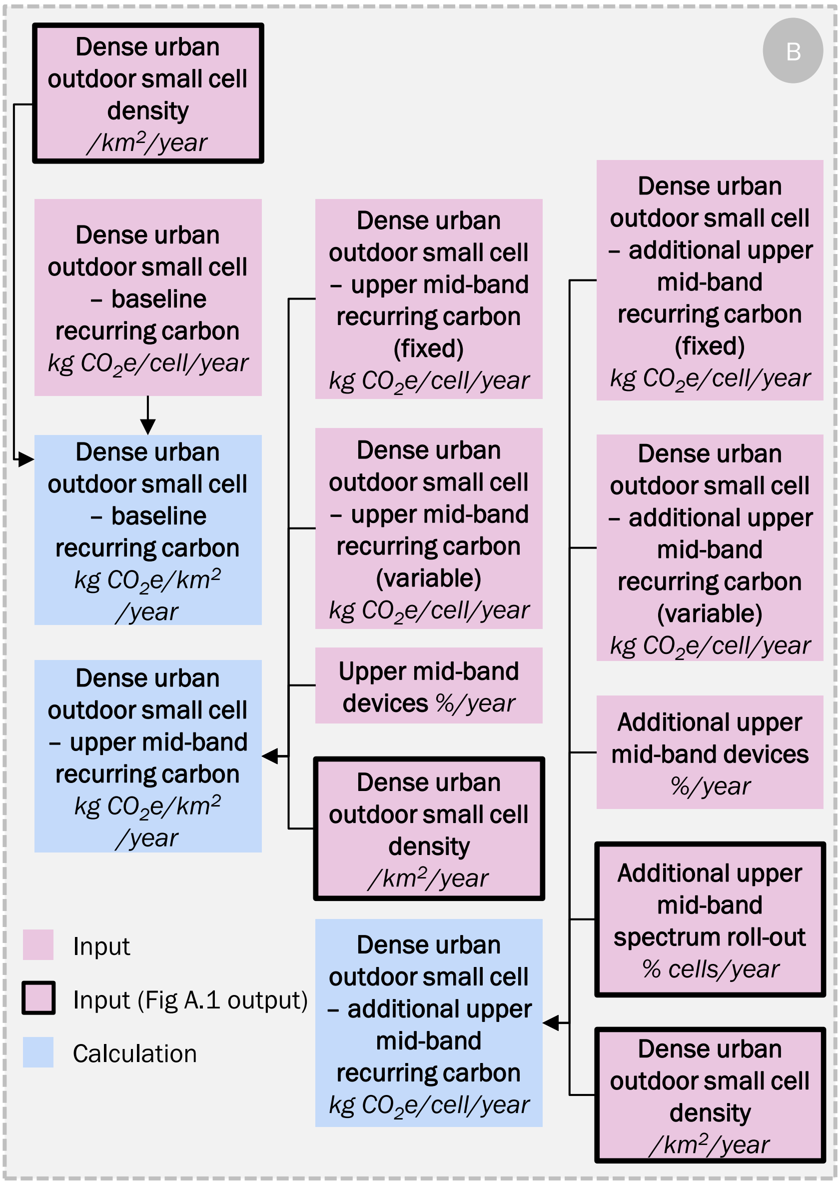


Figure A.10: Calculation of recurring carbon for dense urban outdoor small-cell network [Source: Analysys Mason, 2023]

A.2 Modelling methodology for rural town or village

In order to calculate the embodied and annual carbon emissions of a mobile access network deployment in a particular rural town or village, the density of macro sites must be determined.

A.2.1 Calculation of rural town or village macro-site density

As for the dense urban area, the rural town or village macro-site density is determined by comparing the required capacity with the available capacity supply per site. For the rural town or village, the model calculates the number of macro sites required to meet the combined MBB and FWA service requirements. As explained in Section 3.2 earlier, in the rural town or village settlement it is assumed that the population lives outside the reach of fibre networks and receives high-speed broadband connectivity via a 5G-based FWA network.

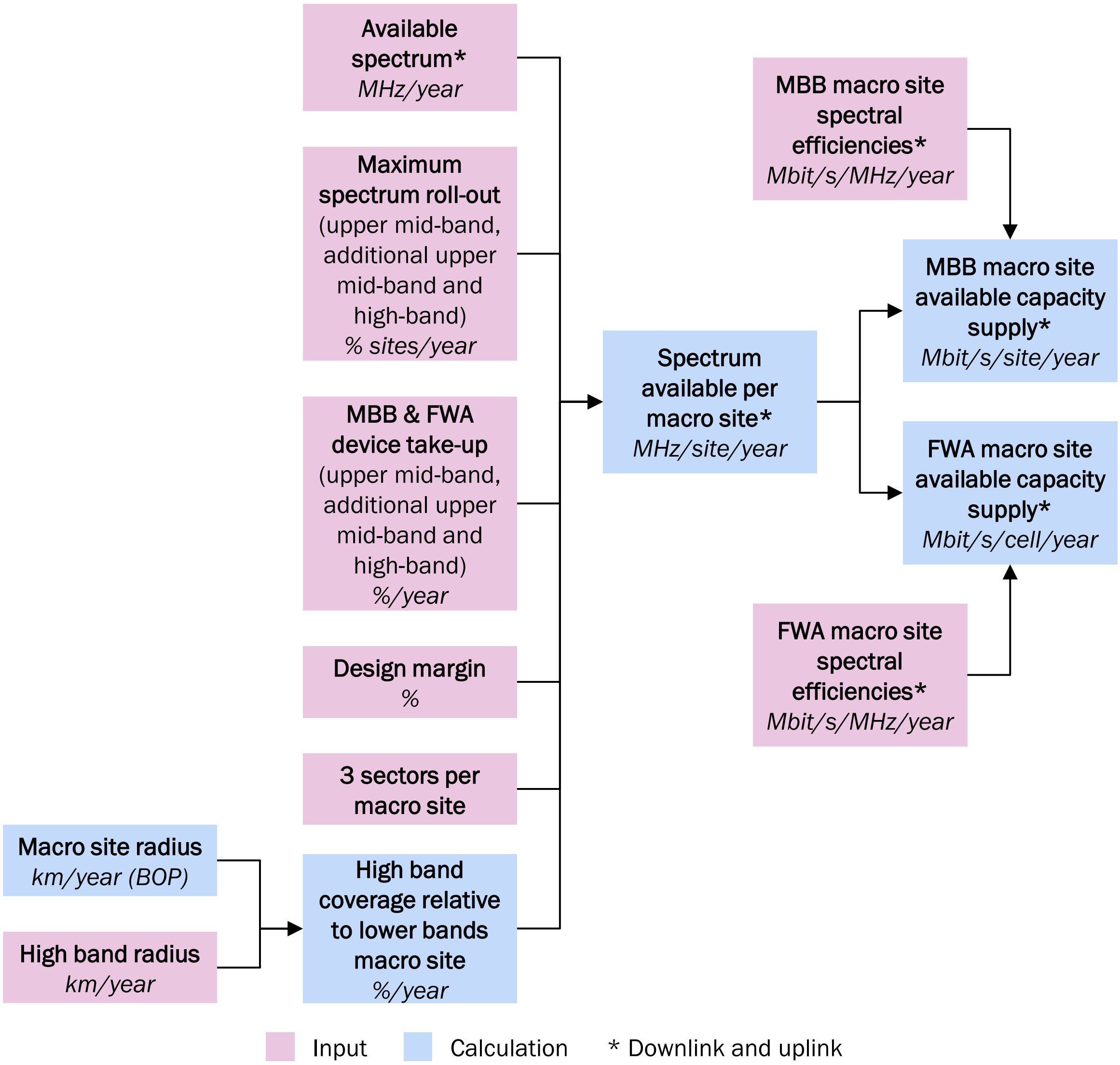
Much of the calculation is the same as described above for the dense urban scenario, with the main differences being as follows:

- There are assumed to be no outdoor small cells in the rural town or village deployment
- High band is modelled as part of the macro-site spectrum portfolio rather than as a traffic offload
- The macro sites serve two types of traffic (MBB and FWA), and capacity is designed to meet the targets for both.

Calculation of available macro-site MBB and FWA capacity supply for rural town or village

The capacity calculation for rural town or village macro sites (see Figure A.11) is the same as that for urban macro sites, although high-band spectrum is now included in the capacity calculation, and thus its roll-out profile and device penetration are factored into the calculation. Similar to the treatment of outdoor small cells in the dense urban settlement, the model accounts for high-band macro-site cell capacity being constrained by coverage (given that the other lower bands deployed at the same base station will deliver wider coverage). Considering that capacity density must be constant in order for the targets to be met ubiquitously in the most efficient manner possible, the lower-band radios of the given macro base-station sector will be relieved from delivering capacity within the high-band coverage area and will instead be able to deliver capacity in other areas within the sector.

Figure A.11: Calculation of available macro-site MBB and FWA capacity for rural town or village [Source: Analysys Mason, 2023]



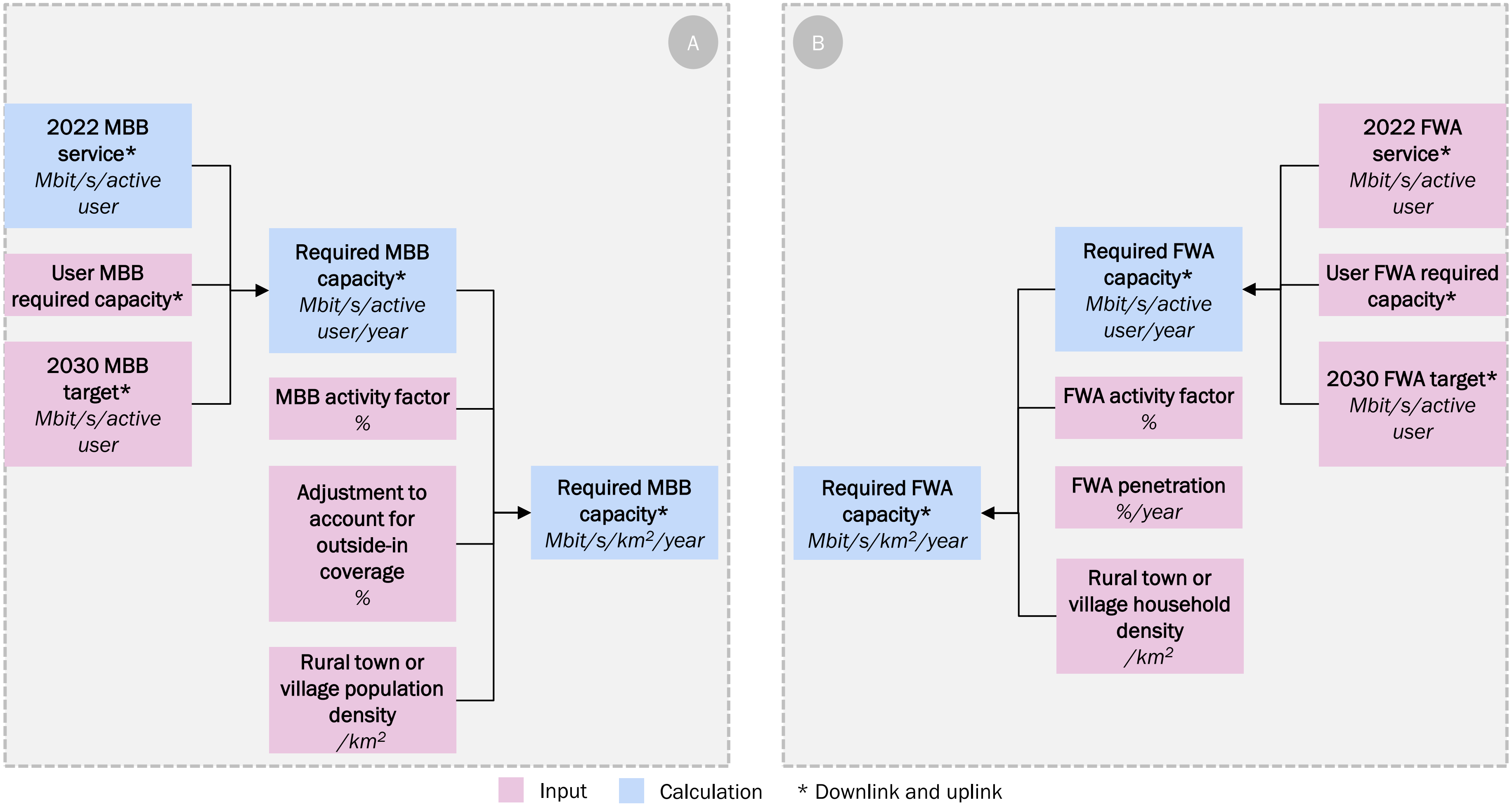
Calculation of required MBB and FWA capacity for rural town or village

Figure A.12 shows how the FWA and MBB target user experience rates are converted to a capacity density requirement for use in calculating the required macro-site density.

The rural town or village MBB target conversion (A) is very similar to the dense urban MBB target conversion, with the exception of the high-band offloading (as the high band is now explicitly modelled).

The rural town or village FWA target conversion (B) follows a similar process to that for MBB. The annual required FWA capacity is determined based on the 2022 service level and a growth rate that allows the 2030 target user experience rate to be achieved. This required FWA service per subscribed household is then multiplied by the rural town or village household density, the proportion of subscribed households (FWA penetration) and the proportion of active users (the activity factor) to arrive at the required capacity density.

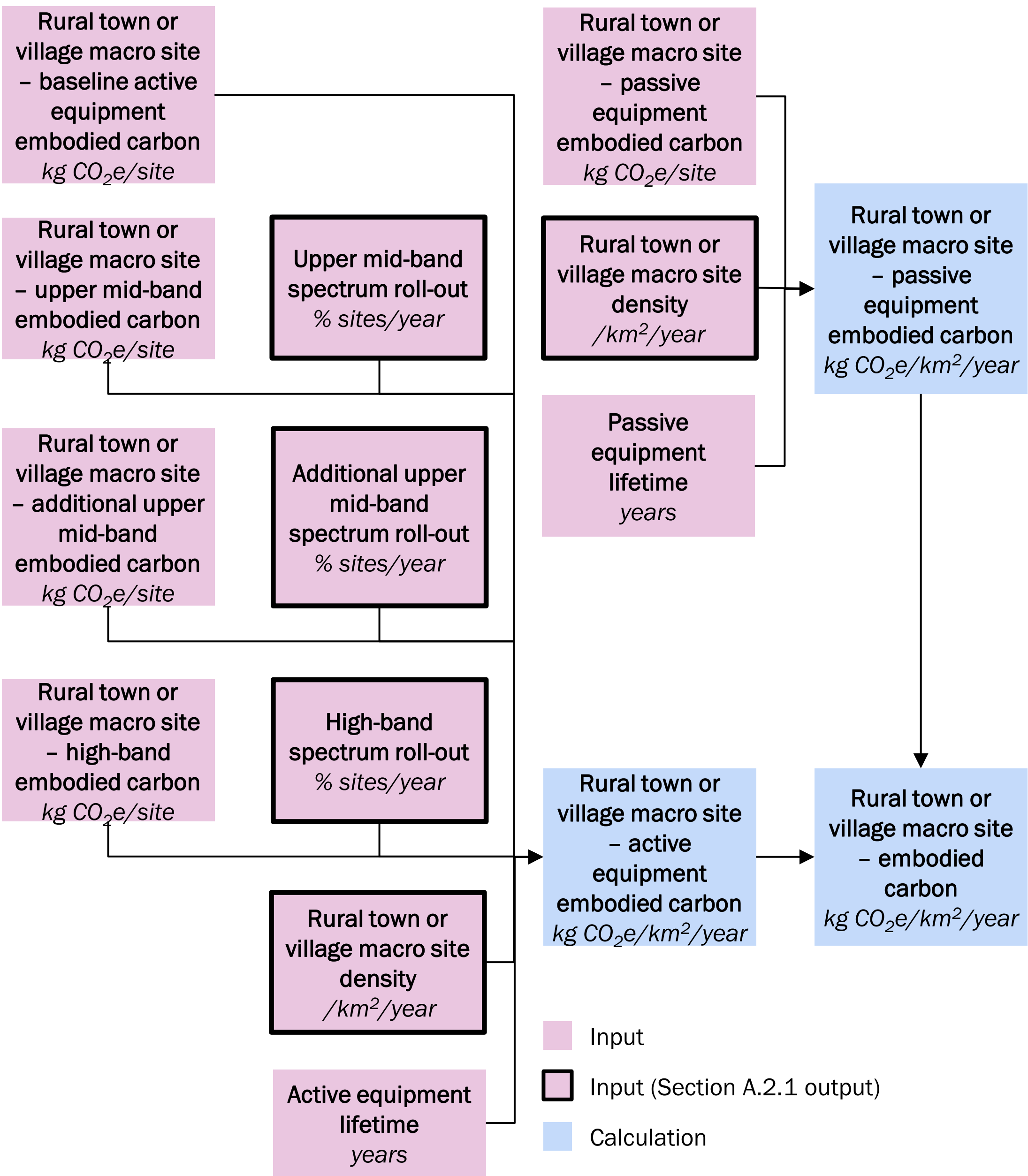
Figure A.12: Calculation of required MBB and FWA capacity for rural town or village [Source: Analysys Mason, 2023]



A.2.2 Calculation of embodied carbon for rural town or village mobile access network

The embodied carbon emissions of a rural town or village mobile access network deployment are calculated in much the same way as the embodied carbon emissions of the macro-site component of the dense urban access network; that is, the sum of the embodied carbon of passive and active equipment. The passive equipment calculation is the same, while the active equipment only differs in its inclusion of high-band infrastructure as an additional source of active equipment embodied carbon. This is shown in Figure A.13.

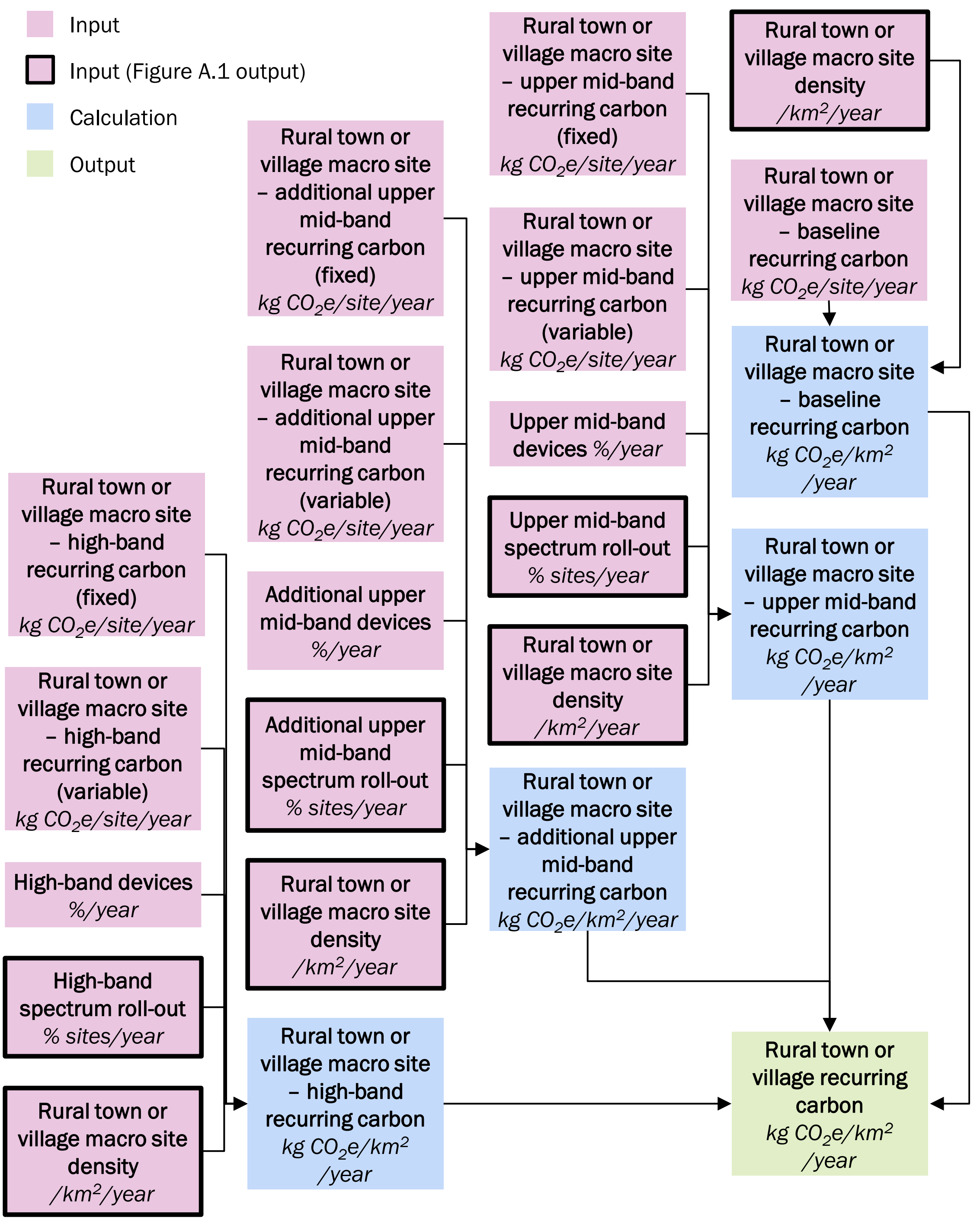
Figure A.13: Calculation of embodied carbon for rural town or village access network [Source: Analysys Mason, 2023]



A.2.3 Calculation of recurring carbon for rural town or village mobile access network

Figure A.14 follows the same principle as Figure A.9 (calculation of recurring carbon for the dense urban macro network), with the addition of the recurring carbon associated with high-band deployment. Within the high-band coverage area there is a possibility that the variable component of upper mid-band and additional upper mid-band recurring carbon will decrease, as the traffic that these bands might otherwise serve is met by the high band.

Figure A.14: Calculation of recurring carbon for rural town or village access network [Source: Analysys Mason, 2023]



Annex B References to other published studies

Several published reports refer to the energy efficiency of fixed networks together with Wi-Fi, but not all studies acknowledge that, over a wider area and for mobility applications, 5G will be needed. For example:

- A study by WIK Consult entitled "Green Wi-Fi" [14] discusses how Wi-Fi enabled applications can help to reduce greenhouse gas emissions in various industries, having a net positive impact on the environment, but without considering the alternative of 5G in delivering these applications. The study focuses on how Wi-Fi 6 can contribute to new applications (such as augmented/virtual reality (AR/VR)) and how these new applications can reduce carbon emissions through, for example, the use of remote working or learning, and specific sector applications, such as in healthcare. The study also assesses the carbon footprint of Wi-Fi and how the carbon footprint varies based on the number of access points (which has an impact on power consumption). It also discusses Wi-Fi technology evolution (e.g. Wi-Fi 6 provides higher data rates than Wi-Fi 4) and the addition of energy-saving technology (e.g. in Wi-Fi 6).

- A report by the Wi-Fi Alliance entitled "6GHz Wi-Fi: connecting to the future" [15] presents various arguments in relation to future use of the upper 6GHz band (6425–7125MHz). The report suggests that Wi-Fi outperforms 5G/IMT in local access network environments in terms of energy efficiency due to its low power transmission (noting that such local area networking will be suited to the next generation of connectivity). However, the report does not address how future wide-area connectivity requirements might be met, other than to assert that the utilisation of spectrum already assigned for 5G use might be increased in future.

- A response from Apple, Broadcom, Cisco, Hewlett Packard Enterprise, Meta and Microsoft to the EC's call for inputs on EU positions for WRC-23 [16] describes how digital technologies including Wi-Fi will contribute to achieving Europe's 'Green Deal', by enabling remote working and therefore reducing travel, and that the energy used for fixed networks (often used together with Wi-Fi) is lower than that of 5G mobile networks. The response also points to several power efficiency measures in the latest Wi-Fi technology. However, the response does not address the question of how MBB networks can best deliver future European connectivity targets in populated areas, and the role of additional spectrum in this.

Other studies provide a more balanced view; for example:

- A study by Arcep [17] entitled "Achieving digital sustainability" challenges the assertion that fibre networks, and Wi-Fi, are more environmentally efficient than 5G mobile networks, and points out that a comparison must be more nuanced (considering factors such as coverage, quality of service and the types of services and environments of deployment). The Arcep report also refers to various power efficiency measures in mobile networks that will improve the network carbon impact of 5G mobile networks (which are also discussed in Section 4.4 of this report).

- A study by the GSMA entitled "The enablement effect report" assesses the enablement impact of mobile networks. It considers two forms of enablement: smart technologies connecting one machine to another (machine to machine, or M2M) and behavioural changes from the use of smartphones. [18]

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