FINAL report for the National Infrastructure Commission

5G wireless infrastructure deployment scenarios over the next decade

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1 Executive summary

This is the final report of a study conducted by Analysys Mason for the National Infrastructure Commission ('the Commission') to investigate scenarios for 5G infrastructure evolution in the UK over the following decade.

The aim of the study has been to calculate the additional cost of 5G deployment (above the current level of 5G infrastructure roll out) in a number of different scenarios that capture a range of the potential evolution scenarios for the market.

The outputs of the study are intended to support the Commission in its development of recommendations for the UK government related to wireless connectivity priorities for the second National Infrastructure Assessment (NIA2), to be published in Autumn 2023.

1.1 Context of 5G network evolution

Successive generations of mobile technology (2G, 3G, 4G and now 5G) have built on the foundations of the previous technology but using new radio and core network technology and bringing additional capabilities, capacity and support for new features. The additional capacity has been enabled partly through improvements in spectral efficiency due to new technology, but also through additional spectrum being awarded in the UK for mobile network operators (MNOs) to use. Successive generations have used wider channels from 200kHz for 2G, to 5MHz or 10MHz for 3G and 4G, and now 5G technology uses very wide contiguous spectrum, such as 100MHz.

While initial 5G services in the UK were rolled out largely to meet consumer mobile broadband (MBB) capacity requirements, enhanced MBB (eMBB) is just one of the three categories of use case defined in the industry's specifications for 5G as developed by the Third Generation Partnership Project (3GPP):

- 5G eMBB allows users to download and stream video, use smartphone applications and browse the internet, and, if within a mid-band 5G coverage area, 5G eMBB should be faster than 4G MBB, and more users can maintain a higher average speed of connection.
- 5G will potentially enable many more IoT devices to be connected in a given location and more demanding IoT applications to be delivered. This is known as massive machine-type communication.

- Ultra-reliable low-latency communication refers to the 5G use cases that are the most demanding in terms of network performance, requiring very low latency and high reliability of connection.

The realization of these use cases depends on the type of 5G network deployment. Different types of 5G network deployment will evolve over the next decade, accommodating a variety of use cases and types of traffic:

- **Wide-area public mobile networks**, primarily built on networks designed to deliver consumer-based mobile services.

- **Wide-area private enterprise networks**, designed to cover multiple specific locations across the UK with the ability for devices to be used between locations (e.g. along transport corridors)

  – these could use either dedicated infrastructure, or a slice of the wide-area public mobile network.

- **Localised private enterprise networks**, site-specific or localised networks designed to only operate in that location (e.g. factories or ports)

  – these could use either dedicated infrastructure, or a slice of the wide-area public mobile network.

These different types of 5G network will have diverse capacity, coverage, and other technical requirements (latency, security, device types, etc.), which are likely to be met through a combination of network infrastructure characteristics, in terms of:

- the number and type of sites deployed, such as public macro sites and public/private small cells (both indoor and outdoor)
- the amount and type of 5G spectrum deployed, including 700MHz, 3.5GHz, millimetre wave (mmWave) and refarming of legacy bands (e.g. 1800MHz and 2100MHz); mmWave refers to spectrum at much higher frequencies than has traditionally been used for mobile services - the primary mmWave band in the UK is 26GHz which Ofcom is planning to auction for mobile use in high-density areas of the country
- the level of 5G standalone (5G-SA) deployment (rather than 5G non-standalone (5G-NSA) deployment) and the capabilities of the 5G core network in a 5G-SA architecture.

In collaboration with the Commission, we have defined five scenarios by varying these network infrastructure characteristics to reflect a range of potential evolution scenarios for 5G networks over the next decade.

1.2 Definition of scenarios

Each scenario builds on the previous one, moving from a lower to a higher level of network deployment/capability.

- **Scenario 1** models the evolution of a nationwide, wide-area public 5G network that improves service capabilities in urban and suburban areas, with a moderate increase in rural coverage. It also models deployment of a limited number of localised private enterprise network deployments (primarily for private sector enterprises, such as factories).
- **Scenario 2** progresses the enterprise segment with more significant deployment of localised private sector 5G networks (e.g. factories, ports, airports) alongside a limited deployment of localised public sector 5G networks (e.g. within and around hospitals) in addition to the nationwide, wide-area public 5G network from Scenario 1.
- **Scenario 3** models the deployment of a contiguous, public 5G MBB coverage layer along key transport corridors across the UK (major roads and railways) and along wide-area utility networks (gas pipelines and overhead electricity lines). This is modelled using the deployment of additional macro sites in the wide-area public 5G network relative to Scenarios 1 and 2.
- **Scenario 4** increases wide-area public 5G network deployment in urban, suburban and rural areas to reflect a higher level of consumer demand in all geotypes.
- **Scenario 5** includes an increased deployment of localised public sector 5G networks (e.g. hospitals) combined with dedicated infrastructure deployed along transport corridors and utility networks providing contiguous 2100MHz 5G coverage for operational use cases.

1.3 Modelling approach

For each scenario, the model we have built:

- starts with the same baseline deployment level (i.e. the currently deployed level of 5G infrastructure)
- calculates the additional deployment required (by 2032) for the given scenario
- defines a time profile for the additional deployment
- uses unit cost inputs to calculate the cost (capex and opex) each year to 2032 for building and operating the additional deployment (with costs split into access, backhaul and core components)
- uses a social discount rate (SDR) to calculate the present value (PV) in 2022 terms of costs over the modelling period. Our approach to calculating PV for this

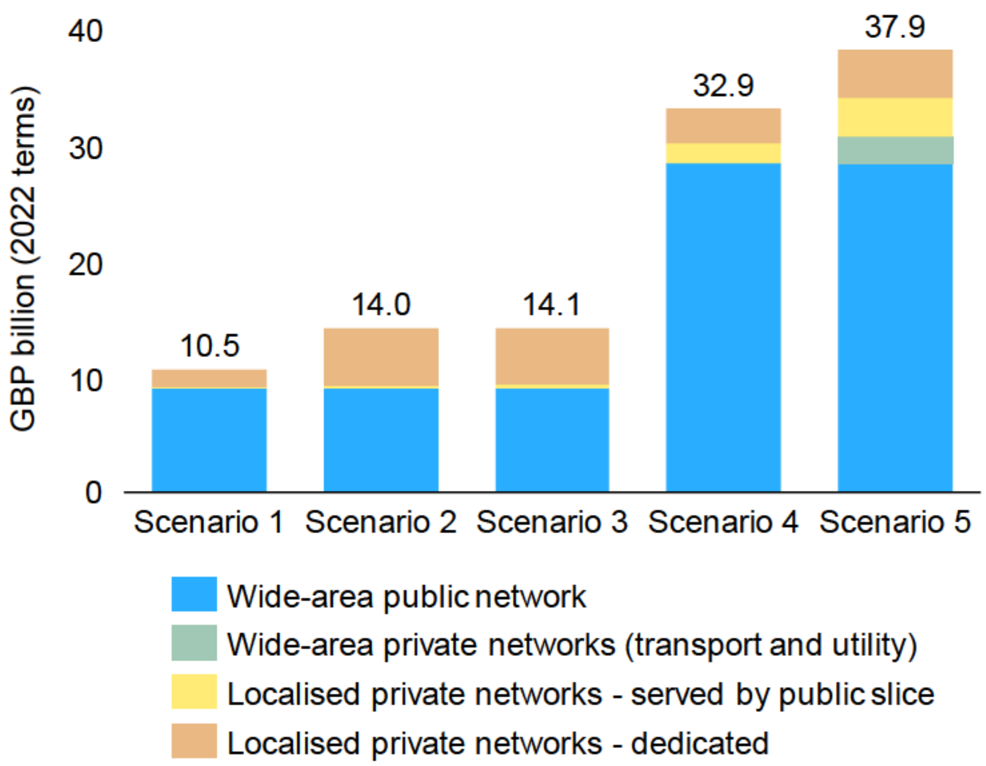
report takes account of how investments would be estimated from the national perspective rather than for an individual firm, using an SDR of 3.5%. This allows for easier comparison of costs between different infrastructure sectors. Sector-specific risk is captured by modelling financing costs using a weighted average cost of capital (WACC).

With the exception of the wide-area core networks, all calculations are split by UK region (North East, North West, Yorkshire and The Humber, East Midlands, West Midlands, East, London, South East, South West, Wales, Scotland and Northern Ireland) and by geotype (urban, suburban and rural).

1.4 Results and conclusions

Figure 1.1 below shows the PV of the capex and opex calculated for each scenario between 2023 and 2032. Figures are for the total UK market (across all four MNOs and private network providers). As can be seen, total PV over the modelling period ranges from GBP10.5 billion to GBP37.9 billion, depending on the scenario.

Figure 1.1: PV of total market 5G investment from 2023–32, by scenario and split by network type [Source: Analysys Mason, 2023]



We estimate total-market PV costs (for incremental 5G deployment over the coming decade) of:

- **GBP10.5 billion in Scenario 1.** The majority of costs arise from the wide-area public network, where 700MHz is deployed on all macro sites, 3.5GHz is deployed on all urban and suburban macro sites, mmWave is deployed on 25% of urban sites and 1800MHz/2100MHz is refarmed on 50% of urban and suburban, and 30% of rural, macro sites. Additionally, 2713 new macro sites and 4195 new outdoor small cells are built per hypothetical MNO. 89 new private sector localised private networks are served by public slice, while 1363 new private sector localised private networks have dedicated infrastructure.

- **GBP14.0 billion in Scenario 2.** The extra GBP3.5 billion (relative to Scenario 1) arises from additional private and public sector localised private networks (totalling 5938 new networks) – 434 served by public slice and 5504 with dedicated infrastructure.

- **GBP14.1 billion in Scenario 3.** There is only a small increase, around GBP40 million, from Scenario 2, which results from building new public 700MHz macro sites outside the existing mobile coverage footprint to provide contiguous MBB coverage along transport corridors and wide-area utility networks. Due to the high level of existing coverage, only a small number of additional infill sites (63) are required, meaning the cost is low.

- **GBP32.9billion in Scenario 4.** The majority of the extra GBP18.8 billion (relative to Scenario 3) arises from the wide-area public network, where 3.5GHz is now also deployed on all rural macro sites, mmWave is deployed on all urban and 50% of suburban macro sites and 1800MHz/2100MHz is refarmed on all urban and suburban, and 50% of rural, macro sites. Additionally, relative to Scenario 3, a further 6287 macro sites are built per hypothetical MNO (9016 in total) and 53 009 new outdoor small cells are built per hypothetical MNO (57 204 in total). Due to the improved public network, a greater share of the 5938 localised private networks are served by a public slice – 2750 – with the remaining 3188 served via dedicated infrastructure (hence the decrease in the share of costs attributed to dedicated local private networks relative to Scenario 3).

- **GBP37.9 billion in Scenario 5**, with the additional GBP5 billion (relative to Scenario 4) arising from the dedicated transport corridor and utility networks and an additional 4925 localised private networks (totalling 10 862 new networks from the current baseline) – 6214 served by public slice and 4648 with dedicated infrastructure.

Our report also examines which use cases might be supported by the different scenarios for each of the key sectors of interest to the Commission (energy, transport, water and wastewater, flood resilience and waste).

2 Introduction

This is the final report of a study conducted by Analysys Mason for the National Infrastructure Commission ('the Commission') to investigate scenarios for 5G wireless infrastructure evolution in the UK.

2.1 Context

The Commission is currently working on the second National Infrastructure Assessment, to be published in Autumn 2023. This follows the first National Infrastructure Assessment published in 2018. The first National Infrastructure Assessment set out a series of recommendations to the UK government on the future of the fixed telecoms network. Many of these recommendations have been taken forward in the UK Government's Future Telecoms Infrastructure Review and subsequently in the National Infrastructure Strategy.

The second National Infrastructure Assessment will make recommendations to the government on the future of wireless telecommunications networks in the UK, including how such networks could support infrastructure needs in different sectors. The Commission is considering the potential role that 5G standalone networks could play in supporting the Commission's objectives to deliver economic growth across all regions of the UK, and support competitiveness and quality of life. The policy recommendations the Commission makes are aimed at furthering these objectives. In this context, the Commission commissioned Analysys Mason to conduct a study that:

- establishes a baseline understanding of current wireless 5G mobile networks in the UK
- models several different scenarios for future 5G infrastructure deployment over the next decade, reflecting a range of possible market outcomes.

2.2 Scope of work

The scope of our analysis has been to conduct modelling of wireless 5G infrastructure roll-out scenarios, and associated costs, to inform the following key issues:

- scenarios of future 5G evolution (e.g. identification of sectors, use cases and deployment locations driving future demand)
- the range of potential network deployments over the coming decade
- costs of additional infrastructure needed under identified scenarios for 5G evolution.

2.3 Structure of this report

The remainder of this document is laid out as follows:

- Section 3 provides a summary of the current 5G wireless connectivity market in the UK.
- Section 4 describes the five scenarios of future 5G deployment over the next decade that we have modelled.
- Section 5 outlines our modelling approach, presents a summary of the modelling results for each scenario, and considers the implications of the different scenarios for key sectors of interest to the Commission.
- Section 6 summarises our overall conclusions.

Supplementary material is included in detailing the network implications of different use cases (excluding digital) in the industry sectors covered by the National Infrastructure Assessment: energy, transport, water and wastewater, flood resilience and waste.

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3 5G wireless connectivity in the UK

Wireless connectivity of different types is increasingly used in the UK market in a range of contexts, and wireless connectivity solutions continue to evolve. There are a number of existing alternative wireless options to 4G/5G cellular (such as short-range wireless technologies used in the Internet of Things (IoT), satellite connectivity, evolution of Wi-Fi, and various bespoke wireless systems) which might be particularly suited to specific coverage environments. These solutions are already widely used in the UK market and are expected to continue playing a role in the future.

The focus of this study is the deployment of mobile (i.e. cellular) 5G solutions. In this section, we provide a background summary of the UK's mobile market and current status of 5G deployment.

- Section 3.1 provides a summary of the UK's mobile market landscape
  - outlining types of player, spectrum available, and selected key issues in the market
- Section 3.2 discusses the current status of 5G deployment.

3.1 UK mobile market landscape

3.1.1 Market players

MNOs

Public cellular services in the UK are provided by four MNOs nationally, each with varying customer bases, network deployments, strategic differentiation and financial performance: the four nationwide providers are Three, VMO2, Vodafone and BTEE. In addition, there are various smaller resellers, mobile virtual network operators (MVNOs). The market share of each MNO is shown in Figure 3.1, with MVNOs split out separately. As discussed in Section 3.1.3, we note that Vodafone and Three are in discussions regarding a merger. For the purposes of this study we will consider a four-MNO market rather than a consolidated three-MNO market.

Figure 3.1: Market share of UK mobile connections (excluding IoT) [Source: Analysys Mason, 2023]

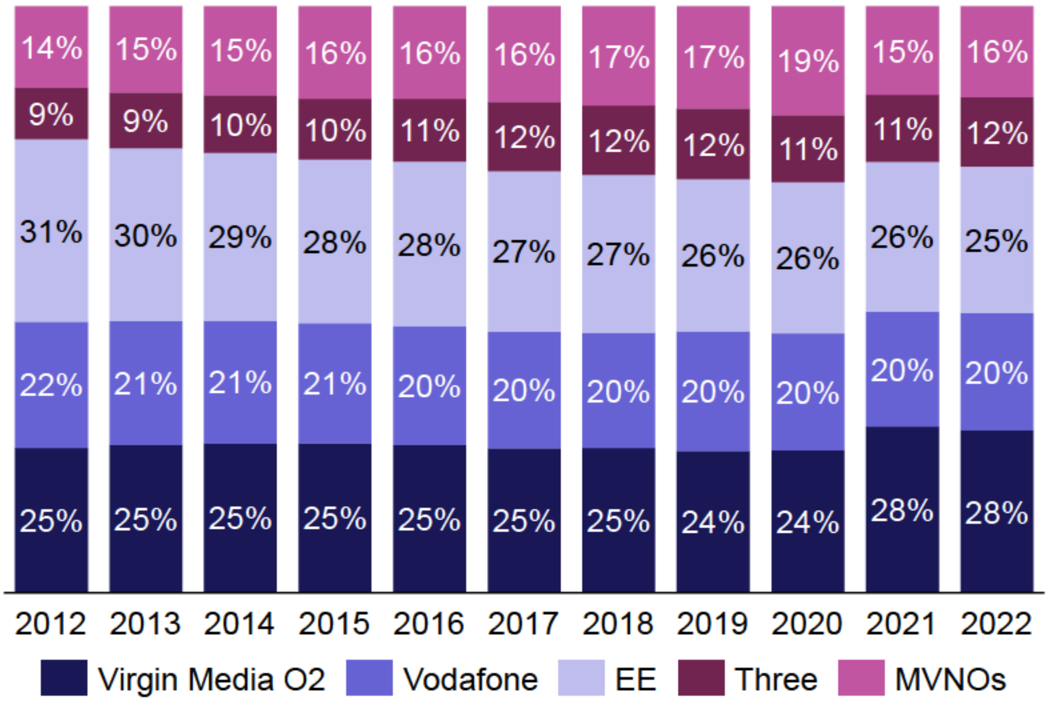
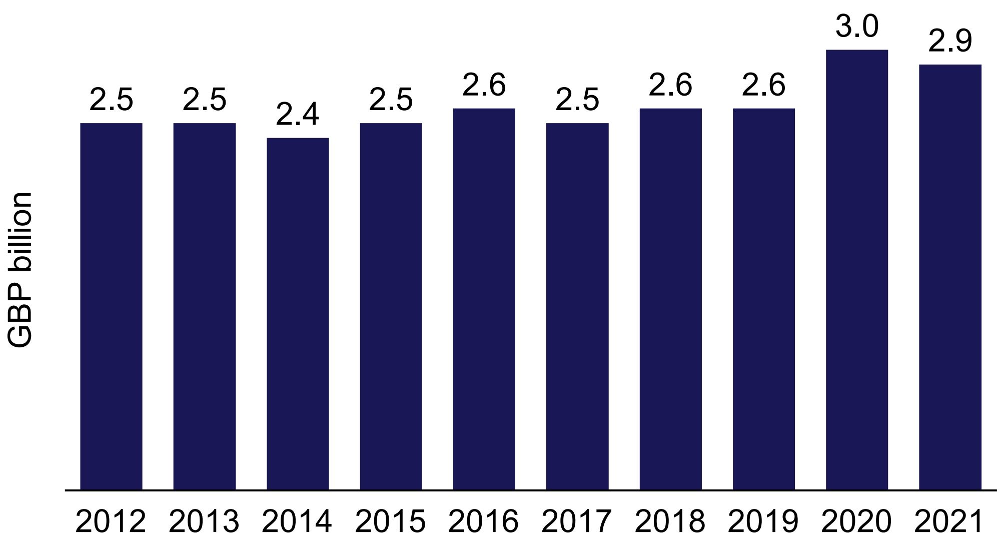


Figure 3.2 below shows that total MNO capex (excluding spectrum acquisition costs) has been relatively flat over the preceding decade, at roughly GBP2.5 billion per annum. However, there was a notable increase in MNO capex in 2020 and 2021, which may be an early indication of increased investment plans/requirements with 5G launch (noting that all four MNOs launched commercial 5G mobile services in 2019/20).

Figure 3.2: Total capex (excluding spectrum) for UK MNOs [Source: reproduced from Figure 4.2, page 19 of 'Discussion paper: Ofcom's future approach to mobile markets' and Figure 4.3, page 22 of 'Conclusions paper: Ofcom's future approach to mobile markets and spectrum']



However, the capex shown in Figure 3.2 includes non-network-specific capex (e.g. IT systems/software upgrades, property/facilities and customer-focused capital expenditure). Ofcom's 2022 Connected Nations report states that GBP2.0 billion was invested in UK mobile network infrastructure in 2021, approximately two thirds of the value shown in Figure 3.2. Of this GBP2.0 billion, GBP1.3 billion was investment in mobile access network (GBP0.2 billion of which was spent on 5G mobile access), and the remaining GBP0.7 billion was spent on core and backhaul. Benchmarks suggest network opex is typically around 10% of network capex.

Private 5G players

A key trend gaining momentum in the UK market is that use cases requiring customisation of wireless connectivity to meet specific user demands (such as factory automation or remote operation of machinery) are likely to be fulfilled through the deployment of private 5G networks. Private 5G networks can be provided by several different types of suppliers: nationwide MNOs as well as 'alternative' providers (including equipment vendors, cloud companies and industrial network specialists).

Three main network deployment models for private 4G/5G networks can be distinguished:

- **Dedicated, on-premises networks:** This type of network is built specifically for the purpose of a single enterprise or industrial user. The network assets are all privately owned and used internally by the enterprise. These networks are already emerging in the UK, and typically use private core deployments, in the (current) absence of widely available standalone 5G (5G-SA) in public mobile networks. Some of these dedicated, on-premises networks are being provided by UK MNOs on behalf of enterprise or industrial users.

- **Network slicing:** Network slicing refers to the segmentation of a 5G network into virtual, bespoke networks that can provide distinct properties and characteristics to specific customers and use cases, without the need to build separate, physical networks. This approach becomes viable for public mobile networks as they migrate to using 5G-SA in combination with 3.5GHz deployment. Private 5G networks can then be provisioned as slices over the public network. This works by existing macro sites or small cells from an MNO providing the radio network (rather than deploying dedicated on-premises sites), used together with the public edge/public core network from that MNO.

- **Hybrid networks:** A hybrid network can be built with a combination of public mobile network elements (via network slicing) and dedicated on-premises elements. For example, a private 5G network might be served via a dedicated private core network, but with a public radio access network (RAN) slice.

3.1.2Spectrum

MNOs

As shown in Figure 3.3 below, each of the four UK MNOs has a different portfolio of licenced mobile spectrum. The quality of service and level of connection achievable by an MNO over time is influenced by their spectrum portfolio and how the spectrum bands are assigned to various technologies. As 3G network shutdowns are planned in the near-term, the spectrum previously used for 3G networks can be reassigned (refarmed) to support 4G or 5G networks, improving 5G coverage and user-experienced speeds. 2G networks are expected to continue into the early 2030s, though some 2G spectrum may be refarmed to 4G/5G prior to 2G shutdown.

Figure 3.3: Summary of MNOs’ current spectrum holdings, MHz [Source: Ofcom, 2023]

Enterprise	EE	Vodafone	VMO2	Three
FDD 700MHz	2×10.0	–	2×10.0	2×10.0
FDD 700MHz SDL	1×20.0	–	–	–
FDD 800MHz	2×5.0	2×10.0	2×10.0	2×5.0
FDD 900MHz	–	2×17.4	2×17.4	–
Total Low Frequency	**50.0**	**54.8**	**74.8**	**30.0**
SDL 1400MHz	–	1×20.0	–	1×20.0

Enterprise	EE	Vodafone	VMO2	Three
FDD 1800MHz	2×45.0	2×5.8	2×5.8	2×15.0
TDD 1.9GHz*	1×10.0	-	1×5.0	1×5.1
FDD 2.1GHz	2×20.0	2×14.8	2×10.0	2×14.6
TDD 2.3GHz	–	–	1×40.0	–
FDD 2.6GHz	2×50.0	2×20.0	–	–
TDD 2.6GHz	–	1×25.0	1×25.0	–
TDD 3.4GHz	1×40.0	1×90 .0	–	1×60.0
TDD 3.6GHz	1×40.0	–	1×80.0	1×80.0
Total High Frequency	**320.0**	**216.2**	**181.6**	**224.3**
Total (MHz)	**370.0**	**271.0**	**256.4**	**254.3**

Note: FDD = frequency division duplexing; TDD = time division duplexing; SDL = supplementary downlink. Three also holds 84MHz in the 3.8GHz band, which is not currently suitable for mobile use in the UK

* The 1.9GHz TDD band is not used in the UK and Ofcom has proposed revoking these licences

Further licenced spectrum is expected to be made available to MNOs (and alternative types of players) in the future. In March 2023, Ofcom published a consultation on auction design and licence conditions for making mmWave spectrum in the 26GHz and 40GHz bands available for mobile use, including 5G. Ofcom has also indicated plans to assign additional spectrum in the 1400MHz band. Assignment of other new spectrum bands for mobile (such as the 600MHz band and upper 6GHz band) is still under consideration and not expected to take place until the next decade.

Private 5G

In addition to the licensed spectrum referred to above, which grants the MNO licensee exclusive use of the spectrum nationwide, shared access licences allow access to spectrum at specific locations (e.g. factories or campuses). Shared access licences (which are available to both MNOs and other types of players) were introduced by Ofcom in 2019, and are available in several bands (including 3.8–4.2GHz and 26GHz), and for outdoor and indoor deployment. The 3.8–4.2GHz has been a key band for the deployment of private 4G/5G networks to date.

3.1.3 Key issues in the UK mobile market

Investment requirements

Ofcom's discussion paper on its future approach to mobile markets states that MNOs typically invest in cycles that are consistent with new technologies becoming available – hence significant investment has already been made in 5G by the UK

MNOs. Despite this significant investment into new technologies, MNO revenues remain static, indicating challenges in gaining returns from investments. MNOs have highlighted various options that they consider might help return on investment and/or the amount of investment, such as removal of annual licence fees (ALFs) on spectrum that they use, discussed below.

ALFs

When Ofcom assigns new mobile spectrum through an auction process, licences are typically indefinite, with an initial term of 20 years. An upfront payment is made for the 20-year licence and this upfront price is determined through bidding in an auction. After the initial term expires, Ofcom's approach is to levy ALFs on the spectrum, which are set to reflect market value of that band/bandwidth. Ofcom calculates full market value using an opportunity cost approach. MNOs collectively paid GBP360million in ALFs in 2022; this figure is due to rise as more spectrum licences reach the end of their initial term (as well as due to inflation).

While Ofcom considers ALFs to be an important tool for promoting efficient use of spectrum, (some) MNOs have argued against ALFs (on the grounds that they reduce investment). In the context of decreasing financial returns for MNOs, increased investment needs as 5G is rolled out, and government objectives to improve digital infrastructure, there has recently been some discussion around replacing ALFs with investment or coverage commitments. This would entail diverting (some of) the GBP360million per annum that MNOs pay in ALFs into additional network investment. We note that as part of the UK Government's Wireless Infrastructure Strategy, Ofcom has been asked to set out its rationale for mobile spectrum fees by the end of 2023 (https://www.gov.uk/government/publications/uk-wireless-infrastructure-strategy/uk-wireless-infrastructure-strategy).

Potential Vodafone/Three merger

In June 2023 Vodafone Group and CK Hutchinson Group formally announced plans to merge their UK mobile operations. The potential merger of Vodafone and Three is now pending regulatory approval. Our modelling approach (described in Section 5) is premised on the current market structure of four operators (meaning a hypothetical single operator has a 25% market share).

Net neutrality, internet players and the impact of internet traffic on networks

The larger international content and application providers that UK consumers enjoy contribute significant amounts of video content to fixed and mobile networks. These 'tech giants' also provide network and other services to MNOs (e.g. data centres, cloud and virtualisation services). Some of these tech giants are also exploring connectivity provision via private 5G networks.

There are currently active debates in some countries over:

- **Network management approaches for use of bandwidth in fixed and mobile networks (and the extent to which these are compatible with, or suggest changes are required to, local rules about 'net neutrality').** The UK and EU have rules in place aimed at protecting the principle of open internet access. These rules provide end users with specific rights (e.g. to use content and applications of their choice, and devices of their choice) but also severely constrain the traffic management that can legally be applied by providers of Internet Access Services (IAS). While the UK and EU do allow service differentiation on network quality terms (potentially by using network slicing) MNOs have raised several arguments in favour of updating regulations in order to improve their consistency and to minimise barriers to deploying services with more varied characteristics (e.g. tariffs offering different peak speeds, data volumes, latency etc.) or specialised services (i.e. services other than IAS).

- **Whether some of the costs of access networks should be borne by the large content and application providers providing streaming services, or whether these costs should fall on end users (as is currently the case).** Some MNOs (and some fixed operators) have argued that since increased internet traffic on their networks – driven by large content providers – requires additional network investment, a co-investment model would be desirable (with large internet content providers contributing to network infrastructure costs in some way). However, others have pointed out that:

  - high demand for video streaming is causing end user demand for operators' high bandwidth services for which end users are already paying
  - internet interconnection between IAS providers is unregulated: there is nothing to stop IAS providers from trying to charge (modest) fees for e.g. paid peering
  - the streaming providers have made very large investments in bringing traffic to the ISPs via their worldwide core networks, greatly reducing the fraction of the traffic for which the operator has to pay.

This debate is by no means resolved either way. Ofcom acknowledges in its consultation paper on the net neutrality review that there could be benefits of such a charging regime but "introducing such a regime would be a significant step and we have not seen sufficient evidence that such an approach would support our objectives at this time".

3.2 Current status of 5G deployment

3.2.1 Site infrastructure

5G RAN equipment will be deployed on the existing (4G) grid of macro sites, as well as on new infill/densification macro sites.

Macro sites

Macro sites are the large sites (with large cell areas) hosting radio equipment (transmitting at high powers) which provide the main grid of coverage and capacity in MNOs' public networks. These can consist of standalone masts or monopoles, or rooftop mounted sites.

We estimate that each MNO currently has active equipment deployed on around 18 000 macro sites. It should be noted that individual macro sites can be shared by MNOs – i.e. the total number of physical macro sites will be less than 4 multiplied by 18 000 (see Section 5.1 for an explanation of how we multiply up costs to estimate a market-total value). EE has stated publicly that it has at least 19 500 macro sites (https://business.ee.co.uk/large-business/esn/esn-ee/), however, this is likely above average for the UK MNOs due to EE's contract to support the Emergency Services Network (ESN), and it is unclear whether any of the ESN sites are shared. Similarly, in April 2020, Vodafone reported that it had 21 000 sites in the UK, although these include "masts as well as smaller mini-masts and antennas", so the number of macro sites will be lower, and again, it is unclear whether or not this number includes shared sites (https://www.vodafone.co.uk/newscentre/smart-living/everything-you-need-to-know-about/a-basic-guide-to-our-network/).

Small cells

We note that the term "small cell" has been used within the industry to describe a range of infrastructure deployments, from single-sector monopoles up to mini-macro sites with multiple high powered, tri-sectored radios mounted on a small tower. For the purpose of this report, small cells are smaller sites (with small cell areas) hosting radio equipment (transmitting at lower powers) which can be used to provide additional capacity in areas of high-demand. These may be mounted on poles, or street furniture or attached to buildings. Small cells are a relatively nascent technology, and, as such, there is limited public data on their deployment to date. VMO2 has reported that it has 1300 live small cells in London as of June 2022; Analysys Mason Research's small cell forecast for the UK estimates around 3300 public outdoor small cells in 2022 (across all operators). However, the UK small-cell sector may experience significant growth in the coming decade, especially once mmWave spectrum is auctioned (scheduled for 2024).

Network coverage and quality

Each MNO in the UK provides near 100% outdoor 4G population coverage from their existing grid of approximately 18 000 macro sites (on which 5G is being deployed). However, 4G outdoor geographical coverage is significantly lower: Ofcom reported that, as of January 2023, the average outdoor 4G geographical coverage provided by MNOs was 83%, ranging from an average of 67% in Scotland to an average of 93% in England (Ofcom Connection Nations report). Indoor coverage is typically lower than outdoor coverage as the spectrum's propagation characteristics make it harder to penetrate physical objects such as walls and windows, than propagate through air.

According to Opensignal's 2023 United Kingdom Mobile Network Experience Report (based on data collected between December 1, 2022 and February 28, 2023), the average download speed achieved across all devices and connections on UK mobile networks ranges from 19.3Mbit/s–47.7Mbit/s depending on the MNO, while the average download speed for a 5G connection ranges from 75.0–237.7Mbit/s. However, download speeds will vary significantly depending on distance from site, spectrum bands deployed on site and number of concurrent users.

The Shared Rural Network (SRN) programme will expand 4G geographical coverage in rural areas. Announced in March 2020, the SRN is an agreement between the UK Government and the four MNOs, in which the government will provide grant funding for new site builds to extend geographical coverage, with the MNOs also committing to improve coverage through individual and collective upgrading of existing networks. Under the terms of the agreement, each MNO has committed to providing 'good quality' 4G data and voice coverage to 88% of the landmass by June 2024, and 90% by January 2027, subject to certain conditions. Overall, the SRN is expected to result in 4G geographical coverage from at least one MNO over 95% of the UK landmass. The government is providing GBP500 million of investment to tackle total 'not spots' (where no MNO currently provides 4G coverage), while the MNOs have committed to GBP532 million of investment to reduce partial not sports (where at least one operator currently provides 4G coverage). Supported by the Home Office, the SRN will also upgrade Extended Area Service (EAS) sites (i.e. ESN extension sites) for use by MNOs.

3.2.2 Public 5G

All four of the UK's MNOs launched commercial 5G mobile services in 2019/2020. Deployment initially focused on towns and cities and, as roll-out continues, coverage will expand into more rural areas. Coverage is being deployed using the recently assigned 700MHz and 3.5GHz '5G bands', as well as through refarming – or dynamic spectrum sharing (DSS) with – 4G bands.

Ofcom's 2022 Connected Nations report provides data on the level of 5G population coverage as of September 2022, which is summarised in Figure 3.4 below.

Figure 3.4: 5G outdoor UK population (premises) coverage [Source: Ofcom Connected Nations report, 2022. Coverage data is for September 2022, and is based on predictions provided by MNOs, whose accuracy is tested by Ofcom]

Operator	5G mobile launch date	All bands		3.5GHz	
		VHC	HC	VHC	HC
At least one MNO	-	67%	77%	N/d	N/d
EE	May 2019	45%	55%	28%	43%
Vodafone	July 2019	31%	42%	25%	38%
VMO2	Oct 2019	36%	39%	17%	22%
Three	Feb 2020	32%	58%	32%	58%
All MNOs	-	11%	20%	N/d	N/d
Average of MNOs		36%	49%	26%	40%

Note: N/d = no data; HC = High Confidence (defined as a signal strength of -110dBm). VHC = Very High Confidence (defined as a signal strength of -100dBm). These confidence levels reflect the likelihood of on-the-ground coverage for consumers in a particular location. Ofcom consider HC to equate to at least an 80% confidence level, and a VHC to equate to a c.95% confidence level

As can be seen, with the exception of Three, MNOs' 3.5GHz 5G footprint is a subset of its total 5G footprint. Ofcom also report that individual MNOs achieved a High Confidence level of geographical 5G outdoor coverage of between 6% and 16%.

All of the 5G coverage reported by Ofcom has been provided using a non-standalone 5G (5G-NSA) architecture. However, since Ofcom published its data in December 2022, Vodafone announced the commercial launch of 5G-SA in several cities in June 2023. None of the remaining three operators have announced any 5G-SA launch plans.

3.2.3 Private 5G

In addition to wide-area public 5G networks, private 5G networks are beginning to be deployed for a variety of bespoke use cases, although the numbers of networks in current deployment is still limited:

- In its 2022 Connected Nations report Ofcom reported that 26 MNO-led private networks were live in the UK. However, Ofcom noted that these may use 4G, 5G, or both. Ofcom also noted that none of these private networks are currently delivered as a slice of a commercially deployed public 5G network.

- The Global mobile Suppliers Association (GSA) publishes a database of private networks, which (as of March 2023) records 38 private networks in the UK (which use a combination of 4G and 5G technologies). Manufacturing and ports are the most common use case (with 15 private networks); other use cases include education, venues and hospitals.

Shared access licences (either low or medium power) in the 3.8–4.2GHz range are available to be used for private 5G networks. (Other bands, including 26GHz, are also available, though there has been limited uptake to date as the equipment ecosystem for this spectrum band is less developed). As of May 2023, Ofcom's spectrum register lists 181 low power and 457 medium power shared access licenses issued in the 3.8–4.2GHz range. These are distributed all over the country (they are not concentrated in dense urban locations as a nascent public mobile network would be).

4 Scenarios for evolution of 5G networks over the next decade

4.1 Context of 5G network evolution

Different types of 5G network deployment will evolve over the next decade, accommodating a variety of use cases and types of traffic:

- **Wide-area public mobile networks**, primarily built on networks designed to deliver consumer-based mobile services.
- **Wide-area private enterprise networks**, designed to cover multiple specific locations across the UK with the ability for devices to be used between locations (e.g. along transport corridors)
  - these could use either dedicated infrastructure, or a slice of the wide-area public mobile network.
- **Localised private enterprise networks**, which refers to site-specific or localised networks designed to operate in a specific location only (e.g. factories or ports)
  - these could use either dedicated infrastructure, or a slice of the wide-area public mobile network.

These different types of 5G network will have diverse capacity, coverage, and other technical requirements (latency, security, device types, etc.), which are likely to be met through a combination of network infrastructure characteristics, in terms of:

- the number and type of sites deployed, such as public macro sites and public/private small cells (both indoor and outdoor)
- the amount and type of 5G spectrum deployed, including 700MHz, 3.5GHz, mmWave and refarming of legacy bands (e.g. 1800MHz and 2100MHz)
- the level of 5G-SA deployment (rather than 5G-NSA deployment) and the capabilities of the 5G core network in a 5G-SA architecture.

We have defined five scenarios by varying these network infrastructure characteristics to reflect a range of potential evolution scenarios for 5G networks over the next decade.

4.2 Summary of scenarios developed

The five scenarios developed are summarised qualitatively below, with more detailed, quantitative descriptions following in turn. Each scenario builds on the previous one, evolving from a lower to a higher level of network deployment and capability.

- **Scenario 1** models the evolution of a nationwide, wide-area public network that improves service capabilities in urban and suburban areas, with a moderate increase in rural coverage. It also models deployment of a limited number of localised private enterprise network deployments (primarily for private sector enterprises, such as factories).
- **Scenario 2** progresses the enterprise segment with more significant deployment of localised private sector 5G networks (e.g. factories, ports, airports) alongside a limited deployment of localised public sector 5G networks (e.g. within and around hospitals).
- **Scenario 3** models the deployment of a contiguous 5G coverage layer along key transport corridors across the UK (major roads and railways) and along wide-area utility networks (gas pipelines and overhead electricity lines). This is modelled using the deployment of additional macro sites in the wide-area public 5G network from Scenarios 1 and 2.
- **Scenario 4** increases wide-area public 5G network deployment in urban, suburban and rural areas to reflect a higher level of consumer demand in all geotypes.
- **Scenario 5** includes an increased deployment of localised public sector 5G networks (e.g. hospitals) combined with dedicated infrastructure deployed along transport corridors and utility networks providing contiguous 5G coverage.

4.2.1 Scenario 1

In Scenario 1 the public network evolves to improve service capabilities, primarily aimed at providing MBB services within wide-area consumer networks in urban and suburban areas. We assume the network also evolves in rural areas through extending low-frequency 5G coverage.

This is representative of a future where consumer demand evolves modestly from today, potentially due to:

- limited uptake of data-intensive applications
- moderate growth in number of connected devices

- increased use of alternative connectivity solutions (e.g. Wi-Fi, fibre, satellite, low power wide-area networks).

This is modelled as follows:

- A 5G cloud-native SA core network (to support the MBB users of a typical UK MNO, as well as any private networks served via a public slice) is deployed to serve urban and suburban areas (by 2025), while rural networks remain deployed via a 5G-NSA architecture.
- Further 5G spectrum roll-out on existing macro sites by 2032:
  - 700MHz is deployed on all sites in each geotype – urban, suburban and rural
  - 3.5GHz is deployed on all urban and suburban sites, but not on rural sites
  - mmWave spectrum is deployed on 25% of urban macro sites
  - 1800MHz and 2100MHz are refarmed to 5G radio on 50% of urban and suburban sites and 25% of rural sites.
- Additional macro sites are deployed with the same 5G spectrum portfolio as outlined above; by 2032:
  - in urban and suburban areas the number of macro sites increases by 25%
  - in rural areas the number of macro sites increases by 10%.
- Additional outdoor small cells are deployed by 2032:
  - we assume two small cells are deployed for every three macro sites in urban areas
  - we assume one small cell is deployed for every three macro sites in suburban areas
  - no outdoor small cells are deployed in rural areas.

There is no targeted deployment to achieve contiguous coverage of transport corridors or utility networks in Scenario 1. However, there is (limited) deployment of localised private enterprise 5G networks (primarily for private sector enterprises, with large factories, ports and mines as the principal adopters). This is illustrated in Figure 4.1 which outlines the proportion of enterprises adopting localised 5G networks, and the split between those using a slice of the public 5G-SA network and those with a dedicated private network (i.e. for 100 large factories, 50 would adopt a localised 5G network, 5 of which would be served via a public slice and the remaining 45 of which would have a dedicated private network). The split between dedicated private networks and those using a public slice is estimated based on consideration of latency requirements (we assume if a low-latency connectivity guarantee is needed, this may require a dedicated private network) and security requirements (for example, if data security concerns make a dedicated private network the preferable solution to deliver the security required by the enterprise user).

There are a number of factors that could result in this limited deployment of localised private enterprise 5G networks. For instance:

- lack of understanding of use cases
- limited evolution in device ecosystems
- high cost of deployment
- poor marketing of solutions
- difficulties in obtaining licences
- concerns about security and privacy
- satisfaction with existing solutions.

Figure 4.1: Overview of Scenario 1: localised enterprise networks [Source: Analysys Mason, 2023]

Enterprise	Percentage of enterprises adopting localised 5G networks	Percentage of localised 5G networks served by public 5G-SA slice
Large factories	50.0%	10.0%
Medium factories	10.0%	10.0%
Ports	50.0%	0.0%
Airports	10.0%	10.0%
Major venues	10.0%	75.0%
Mines	50.0%	0.0%
Hospitals	0.1% (these exist today)	0.0%
Universities/higher education	1.2% (these exist today)	75.0%
Schools	0.0%	N/A
Utility sites	0.0%	N/A
Rail stations	0.0%	N/A
Water treatment sites	0.0%	N/A

4.2.2 Scenario 2

Scenario 2 builds on Scenario 1 by assuming a further evolution of 5G uptake in the enterprise segment, resulting in significant deployment of localised private sector networks as well as a limited deployment of localised public sector networks, as shown in Figure 4.2. As the public network capabilities have not changed from Scenario 1, the split between localised enterprise networks using a slice of public

5G-SA network capacity and those with a dedicated private network remains the same. This scenario could result from private sector businesses being able to overcome some of the challenges identified in localised network deployment identified in Scenario 1, perhaps due to the private sector having

- better investment capabilities
- more relevant use cases
- targeted marketing from private network providers
- greater focus on improving efficiency and maximising profit.

relative to the public sector.

Figure 4.2: Overview of Scenario 2 localised private enterprise networks [Source: Analysys Mason, 2023]

Enterprise	Percentage of enterprises with localised 5G networks	Percentage of localised 5G networks served by public 5G-SA slice
Large factories	75%	10%
Medium factories	50%	10%
Ports	75%	0%
Airports	50%	10%
Major venues	50%	75%
Mines	75%	0%
Hospitals	25%	0%
Universities/higher education	25%	75%
Schools	0%	N/A
Utility sites	25%	10%
Rail stations	0%	N/A
Water treatment sites	25%	10%

4.2.3 Scenario 3

In Scenario 3 we assume additional public macro sites are deployed (relative to Scenario 2) to provide coverage to any uncovered sections of:

- transport corridors (defined as major road and rail routes)
- wide-area utility networks (defined as major gas pipelines and overhead electricity lines).

The length of uncovered transport corridor or utility network is divided by the diameter of a rural 700MHz macro site (see Section 5.2.3) to determine the number of additional macro sites to build. These are all located in rural areas, and provide the same NSA coverage as provided in rural areas in Scenarios 1 and 2.

4.2.4 Scenario 4

In Scenario 4 an increased network deployment in urban, suburban and rural areas (relative to Scenario 3) is modelled to reflect a higher level of consumer demand, perhaps as the result of:

- high uptake of mobile, data-intensive applications, possibly including applications not currently on the market
- considerable growth in number of connected devices
- mobile becoming the default connectivity solution over Wi-Fi, fibre, satellite, low power wide-area networks etc.

This is modelled as follows:

- We assume evolution of the 5G cloud-native SA core modelled previously is implemented (by 2025) with a more distributed architecture to serve increased demand with higher performance in urban, suburban and rural areas.

- Further 5G spectrum roll-out on existing macro sites; by 2032:

  - 700MHz is deployed on all sites – urban, suburban and rural, and on the remote, shared rural network (SRN) sites
  - 3.5GHz is deployed on all urban, suburban and rural sites
  - mmWave is deployed on 100% of urban sites and 50% of suburban sites but not on any rural sites
  - 1800MHz and 2100MHz are refarmed to 5G on 100% of urban and suburban sites and 50% of rural sites.

- More macro sites are deployed with the same 5G spectrum portfolio as outlined above; by 2032:

  - in urban, suburban and rural areas the number of macro sites increases by 50%.

- Additional outdoor small cells are deployed; by 2032:

  - five small cells are deployed for every macro site in urban areas
  - three small cells are deployed for every macro site in suburban areas
  - one small cell is deployed for every macro site in rural areas.

Due to the improved public network capabilities (relative to earlier scenarios), a higher proportion of localised private enterprise networks are served with a slice of the public 5G-SA network (rather than with dedicated private network infrastructure), as shown in Figure 4.3.

Figure 4.3: Overview of Scenario 4 localised enterprise networks [Source: Analysys Mason, 2023]

Enterprise	Percentage of enterprises with localised 5G networks	Percentage of localised 5G networks served by public 5G-SA slice
Large factories	75%	50%
Medium factories	50%	50%
Ports	75%	0%
Airports	50%	50%
Major venues	50%	90%
Mines	75%	0%
Hospitals	25%	0%
Universities/higher education	25%	90%
Schools	0%	N/A
Utility sites	25%	25%
Rail stations	0%	N/A
Water treatment sites	25%	50%

4.2.5 Scenario 5

In Scenario 5, we make an assumption that dedicated low frequency infrastructure is deployed along the full length of transport corridors and utility networks to provide contiguous, dedicated, coverage suitable for operational use cases. One possible spectrum band that might be used for this infrastructure is the unpaired 2100MHz spectrum (i.e. 1900–1920MHz) that is currently not used for mobile services. In a consultation on the unpaired 2100MHz band in March 2023, Ofcom stated its provisional view that "national infrastructure uses […] focused on public safety, such as rail and utilities, may be the most optimal future use of the 1900–1915MHz spectrum" (https://www.ofcom.org.uk/__data/assets/pdf_file/0028/255835/future-use-2100-MHz-spectrum-condoc.pdf). Ofcom consider that the 1900–1915MHz band could be used for high power uses, while the 1915–1920MHz would only be suitable for low power uses (due to interference concerns with the adjacent paired 2100MHz band that is used in public mobile networks). As part of its consultation, Ofcom states that "prototype future rail equipment operating in the unpaired 2100MHz spectrum is being developed and tested with planned European trials based on upgraded 5G equipment around 2024". Ofcom also notes that "there are ongoing standardisation efforts to facilitate 5G in a 3MHz channel bandwidth for railways, utilities and emergency services".

Additionally, Scenario 5 assumes an increased demand for deployment (relative to earlier scenarios) of localised private networks for public sector enterprises (e.g. hospitals), as shown in Figure 4.4, as the challenges identified in Scenario 1 are overcome.

Figure 4.4: Overview of Scenario 5 localised enterprise networks [Source: Analysys Mason, 2023]

Enterprise	Percentage of enterprises with localised 5G networks	Percentage of localised 5G networks served by public 5G-SA slice
Large factories	75%	50%
Medium factories	50%	50%
Ports	75%	0%
Airports	50%	50%
Major venues	50%	90%
Mines	75%	0%
Hospitals	75%	0%
Universities/higher education	75%	90%
Schools	10%	90%
Utility sites	75%	25%
Rail stations	25%	90%
Water treatment sites	25%	50%

4.3 Possible 'exceptional events'

The scenarios developed cover a range of eventualities but are not intended to be exhaustive. They have been designed to explore the impact of likely variations in network infrastructure characteristics. However, there could be 'exceptional events' or variations that might result in a future not captured within these scenarios. The principal such variation relates to the future level of data traffic, which is discussed below.

4.3.1 Traffic variations

The data traffic carried by wide-area public mobile networks could deviate from the variations modelled in several ways.

- There could be significantly increased data traffic if 5G is used more extensively by consumers, businesses or for different types of connection (e.g. between machines, or IoT), resulting in a level of network densification required that is greater than that of Scenarios 4 and 5 – either due to additional use cases or more simultaneous usage.

- There could be a different geographical distribution of wide-area public mobile network traffic – not concentrated around densely populated areas, but distributed across geotypes. This could occur if different connection types (such as machine to machine) become widely used outside of dense urban areas, or due to changing working patterns (i.e. remote working). Delays to fibre roll out in the fixed broadband market could result in higher demand and take-up of 5G-based fixed wireless access (FWA).

Likewise, with wide-area private enterprise networks, there could be an increased or accelerated demand for higher throughput and coverage requiring additional capacity to be provisioned, and further densification beyond that of Scenario 5.

Traffic generated by dedicated private networks and the private network traffic carried by public network slices in localised areas for private enterprise customers could also vary in a number of ways.

- The demand may be significantly greater if 5G performance is proven to meet customer needs, requiring higher levels of infrastructure per enterprise than modelled (either in terms of indoor small cells, outdoor small cells or core network). This could be due to new use cases, lower latency or higher throughput requirements, or more simultaneous usage.
- The share of enterprises taking up private 5G-SA networks may be higher than that captured in Scenario 5 – any future government policies making 5G take-up more attractive for enterprises could have an impact on this.
- The public sector demand might materialise in the absence of private sector demand – future government policies might also play a role here.
- The ratio we have modelled between dedicated localised private enterprise networks and those using public network slices could be lower than Scenarios 1–3, resulting in a different distribution of costs in those scenarios between private, and public, networks, for example due to insufficient evidence of the security/reliability/availability of public slices or due to differing cost structures of users leading to a preference for one solution over another.
- The ratio we have modelled between dedicated localised private enterprise networks to those using public network slices could be higher than Scenarios 4–5, resulting in a different distribution of costs, due to extensive marketing of the suitability of 5G network slicing or due to differing cost structures of users.

4.3.2 Other variations

Other potential variations include:

- spectrum availability
- government interventions.

Spectrum availability

The **spectrum available** could differ from that modelled:

- More spectrum could become available for mobile use (e.g. the upper 6GHz which is due to be considered at the 2023 World Radiocommunications Conference). This would provide additional capacity, reducing the macro site and/or small cell densification required to meet increased consumer traffic, although additional costs would be incurred to deploy the new active equipment.

- mmWave deployment might not materialise (e.g. due to high equipment costs, difficulty accessing licenses, stringent obligations associated with licenses, high auction costs, or lack of mmWave-enabled devices). This would reduce the capacity available on small cells and urban macro sites in all scenarios, and on suburban macro sites in Scenarios 4 and 5, increasing the required macro site and/or small cell densification.

Government interventions

Government interventions may result in an infrastructure deployment outside those modelled.

- Policies that provide, or reward, investment in a particular region, or sector, could result in a disproportionate level of infrastructure deployment in these areas. For example, the UK government has recently announced that new hospitals will be enabled with 5G or equivalent wireless technology (https://www.gov.uk/government/publications/uk-wireless-infrastructure-strategy/uk-wireless-infrastructure-strategy). If instead the government decided that all hospitals, new and old, had to be 5G, then this would take the future outside of the maximum 75% of hospitals currently modelled in Scenario 5, and incur a greater cost.

- New coverage or network resilience obligations might be imposed on operators. For instance, if redundant backhaul was required to ensure network resilience in the face of physical infrastructure damage (e.g. due to a storm), costs would increase.

5 Modelling approach and results

5.1 Summary of modelling approach

For each scenario, the model:

- starts with the same baseline deployment level (i.e. the currently deployed level of 5G infrastructure, as described in Section 3)
- calculates the additional deployment required (by 2032) for the given scenario
- defines a time profile for the additional deployment
- uses unit cost inputs to calculate the cost (capex and opex) each year to 2032 for building and operating the additional deployment (with costs split into access, backhaul and core components of the network deployment).

With the exception of the wide-area core networks, all calculations are split by UK region (North East, North West, Yorkshire and The Humber, East Midlands, West Midlands, East, London, South East, South West, Wales, Scotland and Northern Ireland) and by geotype (urban, suburban and rural – see Figure 5.1 for geotype definitions).

Beginning with the **wide-area public network**, the model calculates the number of macro sites to be upgraded with the various spectrum bands, and the number of new macro sites and small cells to be built by 2032 for the given scenario. For modelling purposes, we assume macro site upgrades are distributed over time according to a defined spectrum roll-out profile (which may vary by band), while new macro sites and small cells are built linearly over time. Each spectrum band upgrade has its own associated access and backhaul cost over time per geotype, as does a new macro site or small cell, although the macro site cost may vary between scenarios as different spectrum portfolios are applied (see Section 5.2 for cost inputs). These deployments and costs are multiplied to give a total cost per region, geotype and network component (i.e. access, backhaul and core). For the core component there is a nationwide cost (which varies by scenario), and the 5G cloud-native core functionality is modelled as being rolled-out linearly between 2023 and 2025. We model a hypothetical operator with 25% market share. We calculate total-market costs by multiplying costs for the hypothetical operator by four in non-rural areas, and two in rural areas (to represent increased levels of network sharing in rural areas compared to non-rural, and to reflect that landmass coverage in rural areas varies more between networks than it does in non-rural areas).

The model then calculates the number of macro and bespoke sites required to cover the specified length of **transport corridors, and utility network,** by 2032. These sites are built according to a roll-out profile that simulates faster initial deployment in more easy-to-access areas followed by a slower build-out rate to achieve coverage in less accessible areas (noting that the infill sites outside the current footprint are all equally inaccessible and thus are built in a linear profile) over the modelling period. The site build profile is then multiplied by the associated site access and backhaul cost over time (per geotype) to give a total cost per region, geotype and network component. (The macro site cost may vary between scenarios as different spectrum portfolios and deployment models are applied). If the scenario requires a dedicated wide-area network, then a simplified core cost is also incurred per network (i.e. per road, rail, gas and electricity network), and this is modelled as being rolled-out linearly between 2023 and 2025.

Localised private enterprise networks are modelled beginning with those served via a public slice. These are assumed to require 3.5GHz coverage (from the public network). A portion of users are modelled as having a dedicated private core, with the remainder using the public 5G-SA core (i.e. end-to-end slice).

The model estimates how many indoor small cells are required to augment outside-in coverage already provided by the public network. These are then divided by four to arrive at the number of small cells the hypothetical operator (with a 25% market share) is required to build (each private network would be served by one operator and as such the indoor cells would not be shared with other operators), and these are distributed linearly over time. The access and backhaul costs are calculated per enterprise, region and geotype.

Finally, the model considers localised private enterprise networks that are served via dedicated private infrastructure. These do not use public 3.5GHz coverage nor the public core. Instead, private outdoor small cells and private 5G core deployments are assumed, in addition to indoor small cells. Section 5.2 details the number of indoor and outdoor small cells and the type of core required per enterprise, and these are multiplied by the total number of enterprises (using dedicated private infrastructure) and built in a linear profile over time. The access, backhaul and private core costs are calculated per enterprise, region and geotype.

5.2 Key inputs and assumptions

Key modelling inputs and assumptions are discussed below.

5.2.1 Baseline assumptions

The ‘baseline’ defines the current level of 5G infrastructure deployment in the UK (discussed in Section 3.2) from a hypothetical nationally deployed network. The model then calculates the cost of incremental 5G deployment above this baseline.

Our baseline assumptions for the hypothetical MNO modelled are as follows:

- A current site portfolio of:
  - 18 000 macro sites across the UK (distributed across regions and geotypes as explained in the following section)
  - 1000 small cells in the most dense urban areas
  - a small number of NSA core nodes distributed across the UK.
- A spectrum portfolio representative of the UK MNOs, including:
  - 2×10MHz of 700MHz and 100MHz of 3.5GHz available on macro sites for 5G; 3.5GHz may also be deployed on small cells. (Vodafone does not hold any 700MHz spectrum, but can be expected to use an alternative low frequency band to provide 5G coverage).
  - mmWave spectrum, available following the forthcoming Ofcom mmWave auction, to be deployed on macro sites and small cells. (We assume that the hypothetical operator will win a 'fair share' of the 26GHz spectrum that Ofcom will make available via auction in high-density areas of the UK).
  - spectrum in other bands to be refarmed to 5G over time. In the UK, operators are expected to switch off their 3G networks by 2024, while 2G networks will continue into the early part of the next decade. For modelling purposes, we include the cost of refarming two legacy spectrum bands to 5G (which we label as 1800MHz and 2100MHz, but bands may vary by operator, and further bands will be refarmed to 5G over time).
  - for wide-area private enterprise networks that are built using dedicated infrastructure, we make an assumption that suitable dedicated spectrum is available on a wide-area basis (possible options for achieving this might include 2.1GHz unpaired spectrum, which Ofcom is currently consulting on).
- A baseline coverage level in line with that typically achieved by MNOs today, achieving average speeds of tens of Mbit/s (see Section 3.2.1):
  - the existing (4G) grid on which it is assumed 5G is deployed has an outdoor population coverage (UK-wide) of >99% and an outdoor geographical coverage (UK-wide) of around 83%; outdoor geographical coverage has been calibrated by nation at 93%/77%/66%/91% in England/Wales/Scotland/Northern Ireland respectively (in line with data from the 2022 Ofcom Connected Nations report).

- 5G outdoor population coverage of 50% from 700MHz, and 40% from 3.5GHz (the average of the MNOs' High Confidence coverage levels from all bands and 3.5GHz as reported by Ofcom – see Section 3.2).
- coverage is assumed to be rolled out starting from the most dense areas of the UK.

Our baseline also assumes that a limited number of 5G private networks have been deployed to date across a variety of enterprise types: 10 large factories, 5 ports, 4 venues, 1 hospital, and 6 universities.

5.2.2 Geographical distribution of macro sites

The geographical distribution of the 18 000 sites is calculated on the basis of how traffic (and thus population) is distributed across sites. We assume MBB demand is distributed across the full portfolio of macro sites using a logarithmic curve. In lieu of actual site-location data, our approach simulates the geographical distribution of existing sites. The logarithmic curve has been calibrated based on actual data on the MBB traffic distribution across sites within MNOs' networks available to Analysys Mason. These sites are then mapped to a region and geotype using a geographic information system (GIS) calculation undertaken as follows:

- We start with a high-resolution population distribution map of the UK, which divides the UK population into 30×30m grid squares (using open source data provided by Meta – see https://dataforgood.facebook.com/dfg/tools/high-resolution-population-density-maps).
- Population is aggregated into larger 10km×10km grid squares. This reduces the computational complexity (compared to a more granular grid square approach) and is also relevant to the analysis in that the grid squares are roughly commensurate with macro-site cell areas.
- The 10km×10km grid squares are 'masked' by a GIS outline of the UK. This step reduces the area of the grid squares where they extend beyond the land boundary of the UK.
- The population density of the masked grid squares is calculated, and ranked from highest population density to lowest population density. This allows the 5G population coverage to be mapped onto geographical coverage. It also allows geotypes to be defined on the basis of population density (see Figure 5.1). The number of sites per grid square is then calculated based on the cumulative population ranked from most dense to least dense.

- Finally, a regional mask is applied, allowing the area, population and number of macro sites with various spectrum portfolios to be determined for each region and geotype.

Figure 5.1: Geotype definitions [Source: Analysys Mason, 2023]

Geotype	Minimum population density (population per km^2)
Urban	1000
Suburban	600
Rural	0

Other GIS datasets can be overlaid on the GIS file of grid squares in the UK to determine their regional and geotype distribution. For example, GIS files of major roads and railways in the UK were overlaid and used to calculate the length of the road or railway within each grid square and thus each region and geotype. A similar approach was used to determine the length of utility networks, and the number of various enterprises in each region and geotype.

5.2.3 Macro site characteristics

In order to calculate the number of macro sites required to cover a length of road, rail or utility network, the macro site diameter is required. The values used are shown in Figure 5.2 below, and use Analysys Mason estimates from similar past projects. Theoretical cell radii were derived from link budget/radio planning software, and these were then adjusted to reflect actual MNO coverage data.

Figure 5.2: Macro site diameter [Source: Analysys Mason, 2023]

Geotype	700MHz macro site diameter (km)	2100MHz macro site diameter (km)
Urban	2.4	2
Suburban	4.6	2.6
Rural	14.0	7

5.2.4 Localised private enterprise networks

For certain types of enterprise (namely ports, airports, hospitals, universities/higher education institutes, utility sites, rail stations and water treatment sites) the number per region and geotype was determined using publicly available GIS datasets (see Section 5.2.1). However, for other types of enterprise regional distribution was based on publicly available data (see Figure 5.3), but the geotype distribution was assumed as shown in Figure 5.4.

Figure 5.3: Regional distribution of enterprises [Source: Analysys Mason, 2023]

Region	Number of large factories	Number of medium factories	Number of major venues	Number of mines	Number of schools
Source	ONS 2022 UK business dataset Table 18, SIC codes 10–32 with ≥250 employees	ONS 2022 UK business dataset Table 18, SIC codes 10–32 with 50–249 employees	Stadiums' websites (collated on Wikipedia)	ONS 2022 UK business dataset Table 18, SIC codes 7–9 with ≥50 employees	National government websites
North East	75	345	24	0	1177
North West	180	905	40	10	3420
Yorkshire and The Humber	150	875	11	5	2374
East Midlands	140	835	22	20	2219
West Midlands	150	905	16	5	2607
East	80	650	3	5	2754
London	35	250	35	0	3071
South East	110	725	17	5	3872
South West	115	570	26	15	2575
Wales	85	415	22	0	1544
Scotland	95	545	38	45	2422
Northern Ireland	60	240	22	5	1029

Figure 5.4: Estimated geotype distribution of enterprises [Source: Analysys Mason, 2023]

Geotype	Large factories	Medium factories	Major venues	Mines	Schools[1]
Urban	5.0%	10.0%	50.0%	0%	58.8%
Suburban	47.5%	45.0%	50.0%	0%	16.2%
Rural	47.5%	45.0%	0%	100.0%	25.0%

1 In England and Wales 25% of schools are located in rural areas (https://explore-education-statistics.service.gov.uk/find-statistics/school-pupils-and-their-characteristics), the remainder have been distributed between urban and suburban areas in line with population.

Estimates of the typical area and infrastructure requirements of different types of enterprise are shown in Figure 5.5 below. These estimates are aligned with the private networks tracker and forecast prepared by Analysys Mason's Research division.

Figure 5.5: Estimate of localised enterprise network space and infrastructure requirements [Source: Analysys Mason, 2023]

Enterprise	Area (km^2)	Public indoor small cells	Private outdoor small cells	Private indoor small cells	Private core size[1]
Large factories	1.50	30	1	30	Medium
Medium factories	0.25	10	1	10	Small
Ports	30.00	50	15	50	Large
Airports	1.00	20	1	20	Medium
Major venues	0.25	10	1	10	Small
Mines	35.00	60	15	60	Large
Hospitals	0.25	10	1	10	Small
Universities/higher education	1.00	20	1	20	Medium
Schools	0.25	10	1	10	Small
Utility sites	1.50	30	1	30	Medium
Rail stations	0.25	10	1	10	Small
Water treatment sites	1.50	30	1	30	Medium

1 A small private 5G core can support 10 small cells, 200 SIMs and provide 2Gbit/s, a medium core can support an unlimited number of small cells, 500 SIMs, and provide 5Gbit/s, and a large 5G core can support an unlimited number of small cells, 1000 SIMs, and provide 10Gbit/s.

5.2.5 Cost inputs

Figure 5.6 below summarises the unit cost estimates for the various access network components modelled.

Figure 5.6: Access network cost estimates [Source: Analysys Mason based on confidential inputs from a number of modelling projects in Europe, 2023]

Component[1]	Capex (GBP 2022)	Opex (GBP 2022 per annum)	Capex price trend (real terms)	Opex price trend (real terms)
Passive macro site components				

Component[1]	Capex (GBP 2022)	Opex (GBP 2022 per annum)	Capex price trend (real terms)	Opex price trend (real terms)
Site civils and acquisition and operation/rental – rooftop	50 000 per site	10 000 per site	0%	0%
Site civils and acquisition and operation /rental – greenfield	100 000 per site	5000 per site	0%	0%
Civils/acquisition cost for sites outside baseline MBB coverage area	200 000 per site	25 000 per site	0%	0%
Site civils and acquisition and operation /rental – dedicated transport corridor/utility network site	50 000 per site	10 000 per site	0%	0%
mMIMO site strengthening	20 000 per site	1000 per site	0%	0%
Active macro site components				
mMIMO antenna + 3.5GHz carrier cost	50 000 per site	2500 per site	-2%	-2%
Sub-1GHz antenna + 5G remote radio unit (RRU)	30 000 per sub-1GHz band	2000 per sub-1GHz band	-2%	-2%
1–3GHz antenna + 5G RRU	17 500 per 1–3GHz band	1750 per 1–3GHz band	-2%	-2%
Baseband unit	5000 per site	0 per site	-2%	-2%
Carrier activation charge (for all bands other than 3.5GHz and mmWave)	2500 per sub-3GHz band	500 per sub-3GHz band	-2%	-2%
Upgrade to mmWave	35 000 per site	500 per site	-5%	-2%
2100MHz antenna + RRU + BBU + carrier charge	40 000 per site	4000 per site	0%	0%
Small cell components				

Component[1]	Capex (GBP 2022)	Opex (GBP 2022 per annum)	Capex price trend (real terms)	Opex price trend (real terms)
Outdoor small cell deployment cost	18 000 per cell	2500 per cell	7.5% until 2025 then -5%	-2%
Indoor small cell deployment cost	15000 per cell	2000 per cell	7.5% until 2025 then -5%	-2%
Private outdoor small cell deployment cost	19 800 per cell	2750 per cell	7.5% until 2025 then -5%	-2%
Private indoor small cell deployment cost	16 500 per cell	2200 per cell	7.5% until 2025 then -5%	-2%

[1] Note that components are for public access networks unless specified otherwise

The estimated backhaul network costs are shown in Figure 5.7.

Figure 5.7: Backhaul network cost estimates [Source: Analysys Mason based on confidential inputs from a number of modelling projects in Europe, 2023]

Component[1]	Capex (GBP 2022)	Opex (GBP 2022)	Capex price trend (real terms)	Opex price trend (real terms)
Macro site backhaul – microwave	15 000 per site	3000 per site	-2%	-2%
Macro site backhaul – fibre	25 000 per site	1000 per site	-2%	-2%
Dedicated transport corridor/utility network backhaul	15 000 per urban site, 30 000 per suburban or rural site	3000 per urban site, 6000 per suburban or rural site	-2%	-2%
Small cell backhaul	2000 per cell	2000 per cell	-2%	-2%
Private small cell backhaul	2200 per cell	2200 per cell	-2%	-2%

[1] Note that components are for public access networks unless specified otherwise

Figure 5.8 shows the estimated costs for different deployments of 5G-SA core. The simplified core network assumption is that used for dedicated wide-area private enterprise networks (transport corridors/utility networks), while the standard and advanced core assumptions are those used for wide-area public networks. Our cost inputs are internal estimates, informed by discussion with industry players (see

Analysys Mason's article, 'Building cost-efficient cloud-native 5G-SA networks: a TCO comparison', published in February 2023).

Figure 5.8: Public SA core cost estimates [Source: Analysys Mason, 2023]

Type of core	Nodes	Capex per node (GBP 2022)	Opex per node (GBP 2022)	Capex price trend (real terms)	Opex price trend (real terms)
Simplified	1	15 000 000	7 500 000	-1%	-2%
Standard	3	12 000 000	6 000 000	-1%	-2%
Advanced	6	16 000 000	8 000 000	-1%	-2%

The private 5G core costs shown in Figure 5.9 are based on the monthly price for Azure Pro 5G Core plus the monthly Azure Stack Edge pro with GPU cost and the shipping fee, while the price trends are Analysys Mason estimates.

Figure 5.9: Private core cost estimates [Source: https://azure.microsoft.com/en-us/pricing/details/private-5g-core/, Analysys Mason, 2023]

Private 5G core size	Capex (GBP 2022)	Opex (GBP 2022)	Capex price trend (real terms)	Opex price trend (real terms)
Small	280	33 000	-%	-%
Medium	280	47 000	-%	-%
Large	280	82 000	-%	-%

5.2.6 Social discount rate (SDR) and weighted average cost of capital (WACC)

In order to allow the comparison of costs between national infrastructures in different sectors, we use an approach specified by the NIC in which investments are modelled from a national perspective using a real SDR of 3.5%.

The sector-specific risk is then captured by modelling financing costs in addition to capital costs using an average of the pre-tax real WACC over the modelling period. We calculate a pre-tax real WACC that evolves over the modelling period to reflect the forecasted evolution of the risk-free rate, as follows:

- We start with an industry pre-tax nominal WACC of 7.8%. This is the value used by Ofcom in its most recent charge control decisions (e.g. for mobile call termination), published in March 2021. Ofcom also references this rate in its Future of mobile conclusions paper (published December 2022).

- The premium of the pre-tax nominal WACC above the 2022 risk-free rate is calculated. (The risk-free rate is calculated as a 5-year forward-looking average over the forecasted gilt rate). This premium is assumed to be constant going forward, and is added onto the forecasted risk-free rate. Gilt rates are taken from the Office for Budget Responsibility's (OBR's) July 2022 Long-term economic determinants file (see https://obr.uk/data/#lted).

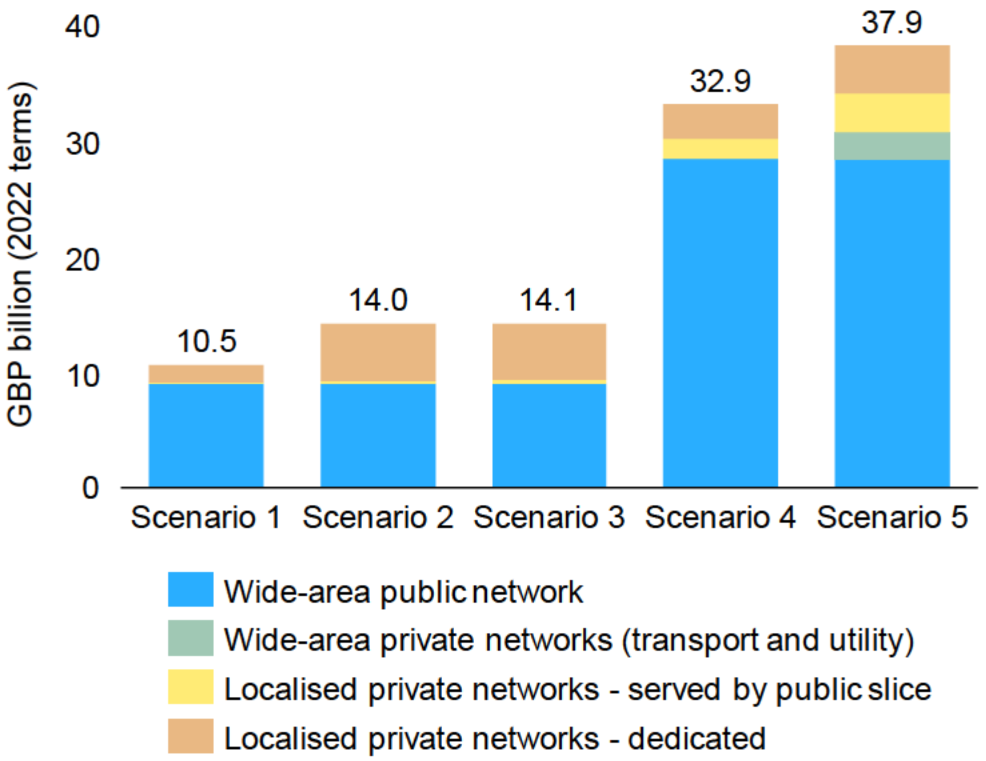
- The pre-tax nominal WACC is converted to a pre-tax real WACC using yearly GDP deflators (also from the OBR's July 2022 Long-term economic determinants file).

We assume a 10-year financing period for site upgrades, and a 30-year financing period for new sites.

5.3 Summary of results

Figure 5.10 below shows the present value (PV) of the market-total (across all four MNOs and private network providers) capex and opex calculated for each scenario between 2023 and 2032.

Figure 5.10: PV of total market 5G investment from 2023–32, by scenario and split by network type [Source: Analysys Mason, 2023]



We note that these PV of costs are higher than if they were modelled from an industry perspective. If the PV of costs was calculated with a simple discounted cash flow analysis, using the industry pre-tax nominal WACC of 7.8% converted to a pre-tax real WACC using yearly GDP deflators, then the PV of the market total capex and opex between 2023 and 2032 ranges from GBP8.45 million in Scenario 1 to GBP29.85 million in Scenario 5. Annex B provides further details.

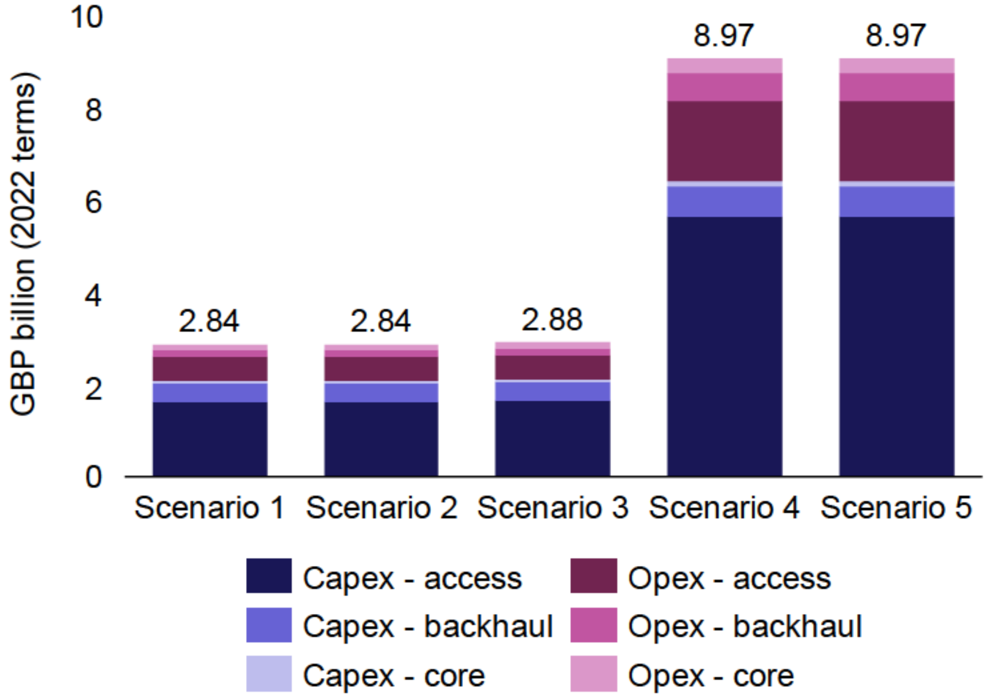
Each network type is discussed in turn below.

5.3.1 Wide-area public network

Figure 5.11 below shows the PV (per network) of the capex and opex calculated for each scenario's wide-area public network between 2023 and 2032. This cost arises from upgrading existing sites (with additional spectrum/active equipment), building new densification macro sites and small cells, as well as backhaul and core upgrades. Scenarios 1 and 2 are identical in this regard and hence have the same PV (of GBP2.84 billion in 2022 terms per network). Scenario 3 includes an additional 16 macro sites covering transport corridors and utility networks outside the current MBB coverage footprint, and has an incrementally larger PV than Scenarios 1 and 2 as a result (GBP2.88 billion in 2022 terms per network). Scenarios 4 and 5 are also identical (these have an PV of GBP8.97 billion in 2022 terms per network).

- In Scenarios 1 and 2, by 2032:
  - 14 407 existing sites are upgraded to have 700MHz deployed
  - 3535 existing sites are upgraded to have 3.5GHz deployed
  - 996 existing sites are upgraded to have mmWave deployed
  - 1800MHz and 2100MHz are refarmed to 5G on 6617 existing sites
  - there are 20 713 macro sites (2713 new sites)
  - there are 5195 small cells (4195 new cells).
- In Scenario 3, by 2032:
  - 14 407 existing sites are upgraded to have 700MHz deployed
  - 3535 existing sites are upgraded to have 3.5GHz deployed
  - 996 existing sites are upgraded to have mmWave deployed
  - 1800MHz and 2100MHz are refarmed to 5G on 6617 existing sites
  - there are 20 775 macro sites (2775 new sites)
  - there are 5195 small cells (4195 new cells).
- In Scenarios 4 and 5, by 2032:
  - 14 565 existing sites are upgraded to have 700MHz deployed
  - 15 449 existing sites are upgraded to have 3.5GHz deployed
  - 5034 existing sites are upgraded to have mmWave deployed
  - 1800MHz and 2100MHz are refarmed to 5G on 12 043 existing sites
  - there are 27 063 macro sites (9063 new sites)
  - there are 58 204 small cells (57 204 new cells).

Figure 5.11: Wide-area public network PV, per network [Source: Analysys Mason, 2023]



For all scenarios, the largest cost arises from the access component of the network. Access costs are broken down further in Figure 5.12 and Figure 5.13 below. As can be seen, in Scenarios 1, 2 and 3 the largest contributors to the access cost are the 700MHz upgrades and the densification macro sites. In Scenarios 4 and 5, the densification macro sites are the largest contributor, followed by 3500MHz upgrades. In both cases the PV of operating costs is between one third and half of the PV of capital costs. (The cost of infill macro sites for providing continuous coverage along transport routes and utility networks – applicable for Scenarios 3, 4 and 5 – is too small to be seen on the charts, but is discussed separately in the following section).

Figure 5.12: Wide-area public network access capex PV, per network [Source: Analysys Mason, 2023]

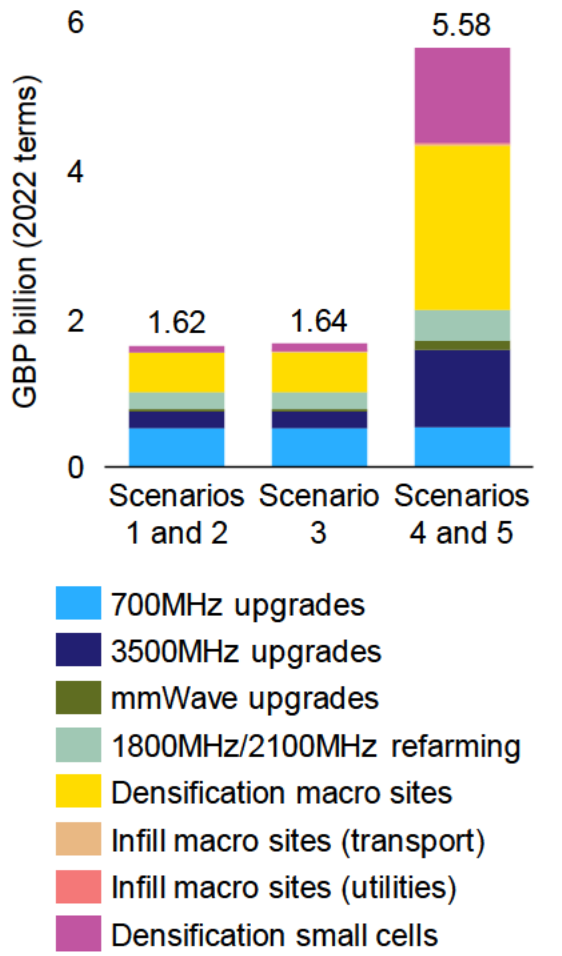
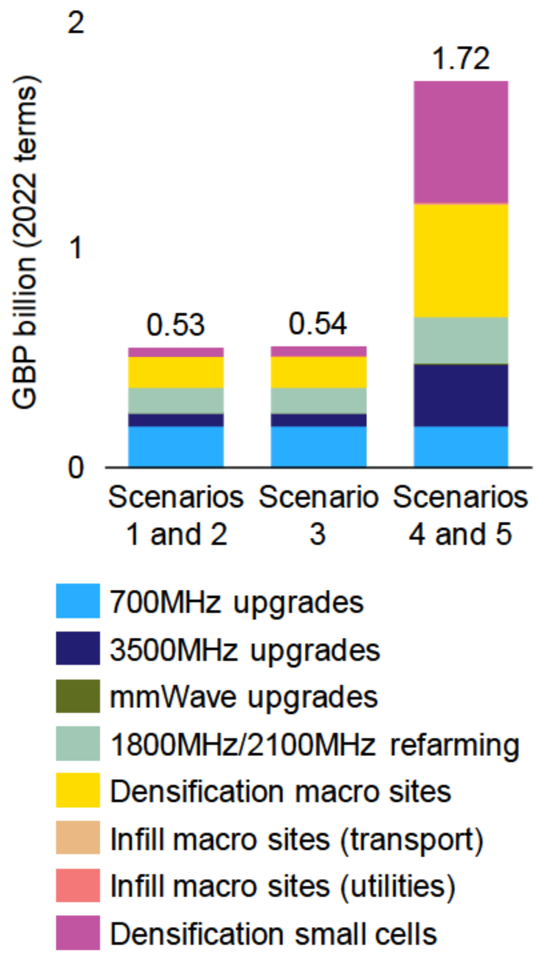


Figure 5.13: Wide-area public network access opex PV, per network [Source: Analysys Mason, 2023]



Backhaul capital and operating costs are broken down in Figure 5.14 and Figure 5.15 below. As for the access network, operating costs are between one third and half of capital costs for macro site densification and macro site upgrades. However, the small cell densification operating costs are several times higher than capital costs.

Figure 5.14: Wide-area public network backhaul capex PV, per network [Source: Analysys Mason, 2023]

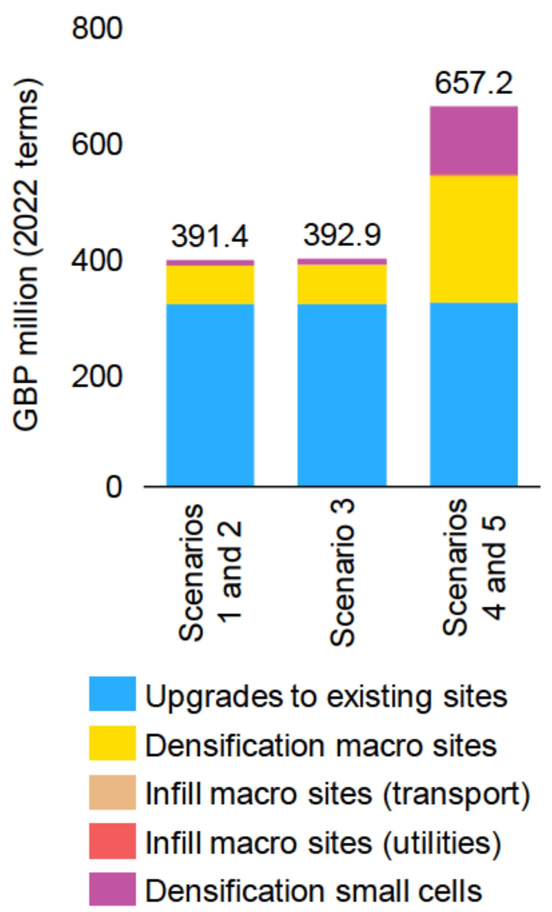
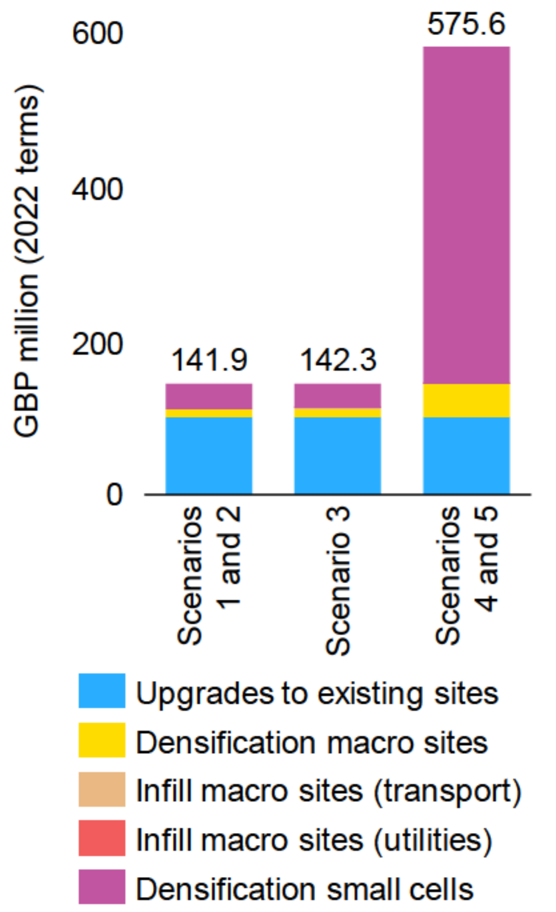


Figure 5.15: Wide-area public network backhaul opex PV, per network [Source: Analysys Mason, 2023]

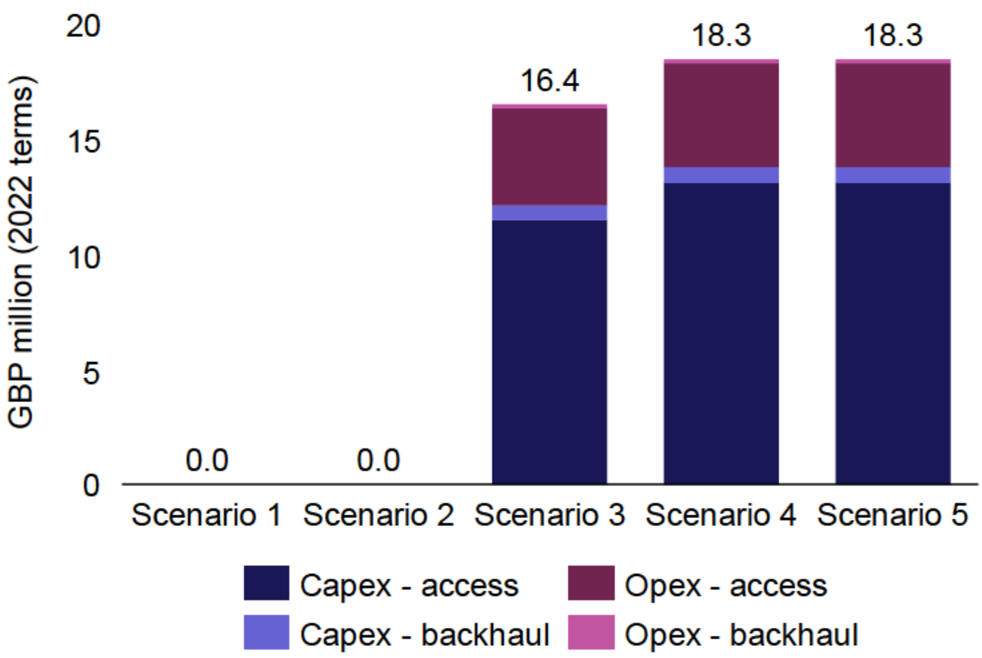


The core required to support Scenarios 1, 2 and 3 has a capex PV of GBP45.5 million and an opex PV of GBP118.2 million per network. Equivalent values for Scenarios 4 and 5 are GBP121.4 million and GBP315.2 million per network respectively.

5.3.2 Wide-area private networks (transport and utility)

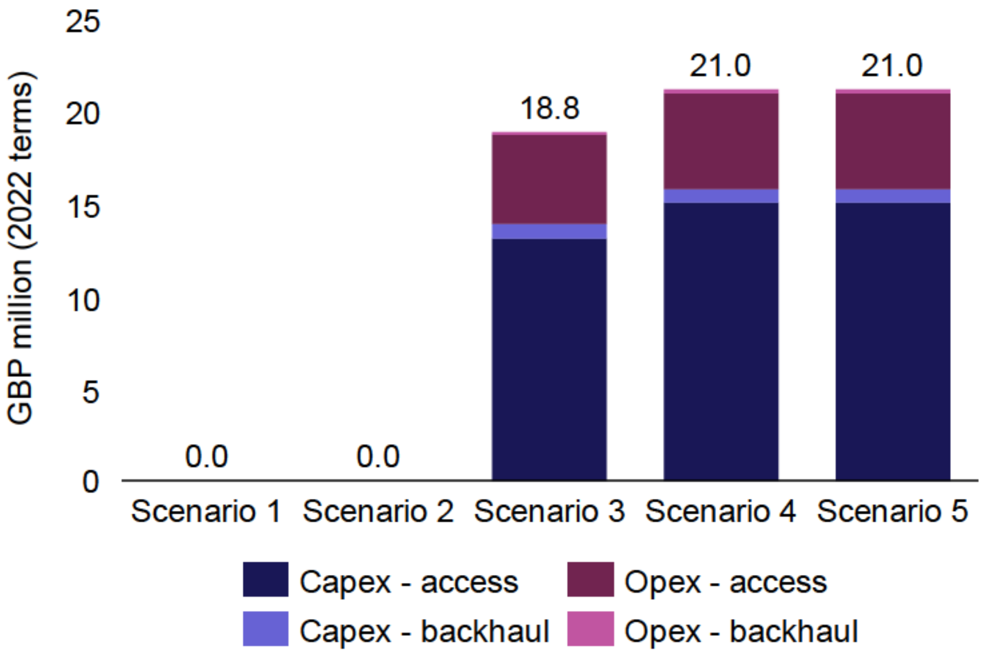
Figure 5.16 shows the total costs associated with building one network of infill macro sites to provide MBB coverage from the wide-area public network along lengths of transport corridors that are currently outside the public network's coverage footprint (only applicable to Scenarios 3, 4 and 5). This is equivalent to each hypothetical MNO bearing the cost for a quarter of the network, as shown in Figure 5.12–Figure 5.15. More active equipment is deployed on these sites in Scenarios 4 and 5 than Scenario 3 resulting in a slightly higher cost per site (e.g. Scenarios 4 and 5 include 3.5GHz, but Scenario 3 does not).

Figure 5.16: Wide-area public network infill along transport corridors PV [Source: Analysys Mason, 2023]



A similar result can be seen in Figure 5.17 below, which shows the cost of public network infill to provide contiguous coverage along utility networks.

Figure 5.17: Wide-area public network infill along utility networks PV [Source: Analysys Mason, 2023]



In Scenario 5, a dedicated network of new (2100MHz-only) sites is deployed to provide operational coverage across the entire length of transport corridor and wide-area utility networks. While these sites have a much lower unit cost than the public infill sites, the total number of sites is much greater, resulting in a much higher total cost than for the public infill sites (see Figure 5.18 and Figure 5.19 below).

Figure 5.18: Wide-area transport network PV [Source: Analysys Mason, 2023]

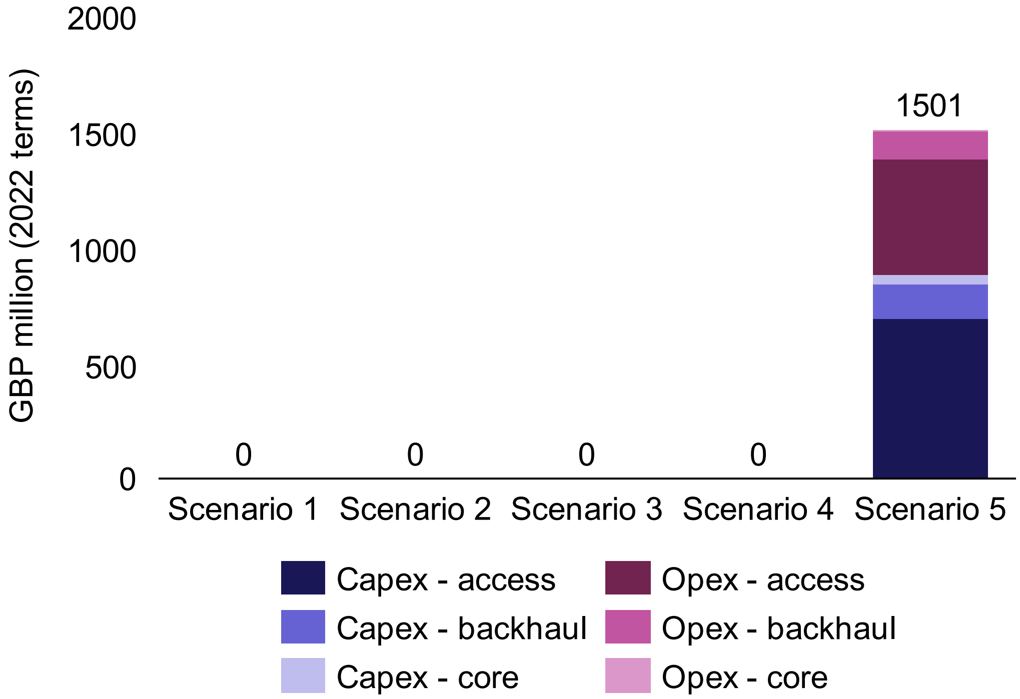
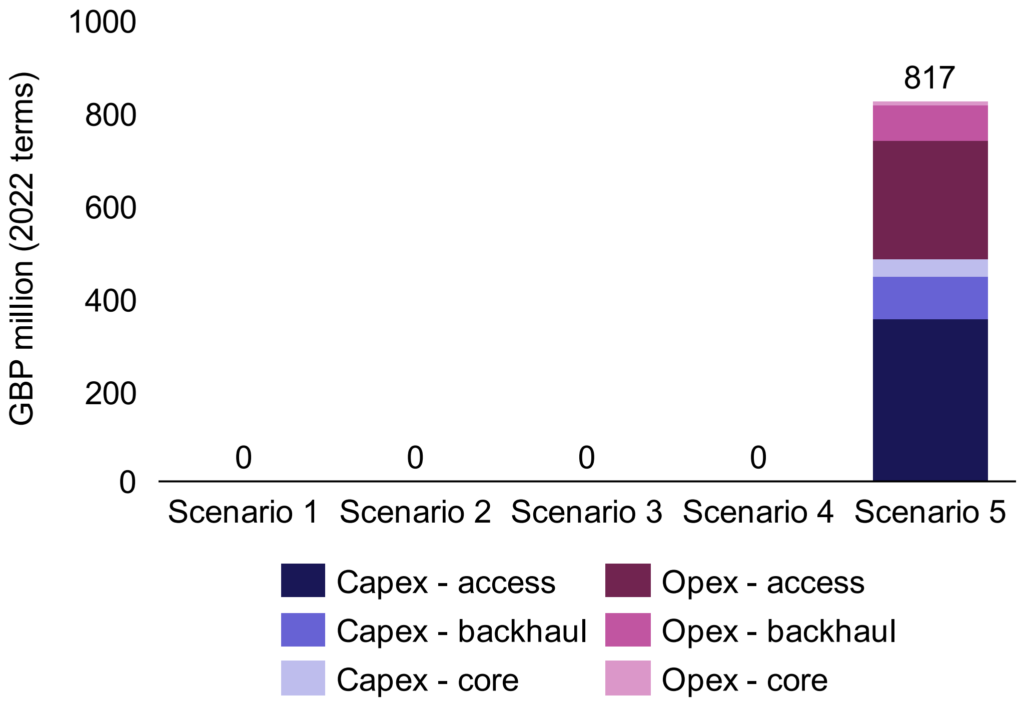


Figure 5.19: Wide-area utility network PV [Source: Analysys Mason, 2023]



If a network of private outdoor small cells was required at intervals of 500m along major roads, perhaps to support a greater volume of autonomous vehicles (see Section 5.4.2), 18,770 small cells would be needed to cover the 9385km of major road (motorways including motorway stretches of A roads) we have modelled (out of a total of approximately 425,000km of UK road). Based on the same access, backhaul and core cost assumptions we have used for private outdoor small cells in other scenarios, this would have a network PV of GBP1 billion, composed of:

- GBP499 million for access capex
- GBP258 million for access opex
- GBP46 million for backhaul capex
- GBP206 million for backhaul opex
- GBP19 million for core capex
- GBP3 million for core opex.

5.3.3 Localised private networks – served via public network slices

In our analysis, by 2032, the following number of new localised private networks will be served via 5G-SA public network slices per hypothetical MNO:

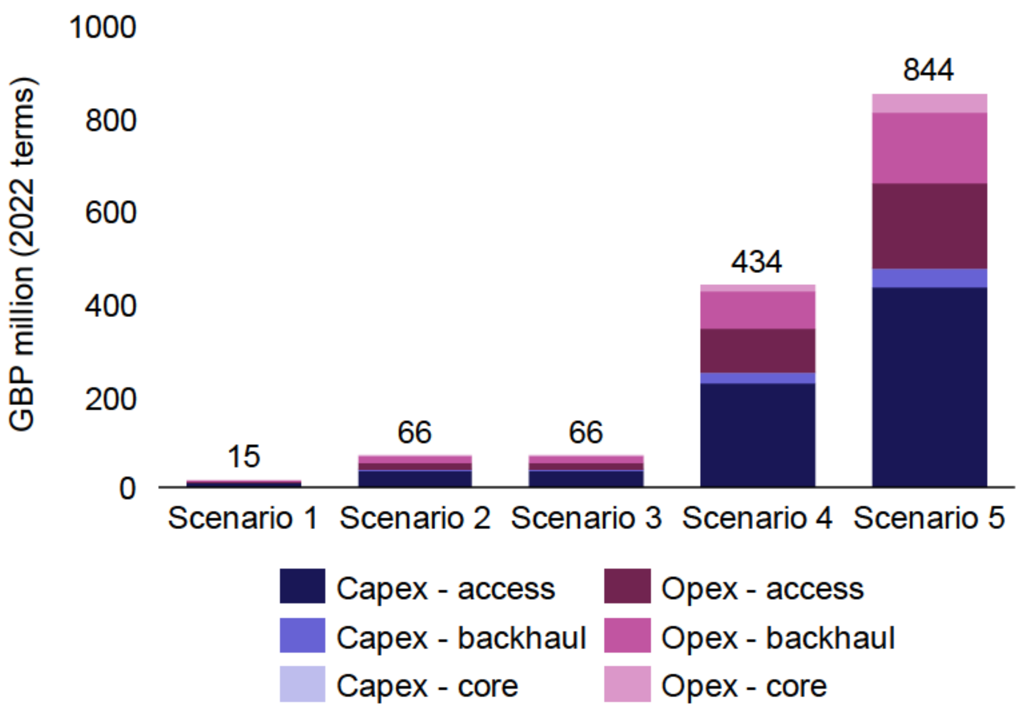
- 22 in Scenario 1
- 108 in Scenarios 2 and 3
- 687 in Scenario 4

- 1553 in Scenario 5.

The number of private 5G networks served by public slices increases from Scenario 1 to 2 as more enterprises (both private and public sector) adopt private 5G networks. Scenarios 2 and 3 are identical. The increase from Scenario 4 to 5 occurs for similar reasons – an increase in public sector enterprises adopting private 5G networks. The increase from Scenario 3 to 4, however, is the result of an increase in the proportion of enterprises with private-5G-network demand who choose to use a public slice due to the improved capabilities of the public network.

Figure 5.20 below shows the corresponding PV (by scenario) of the access, backhaul and core costs per network.

Figure 5.20: PV (per network) of localised private networks served via public slice [Source: Analysys Mason, 2023]



5.3.4 Localised private networks – dedicated

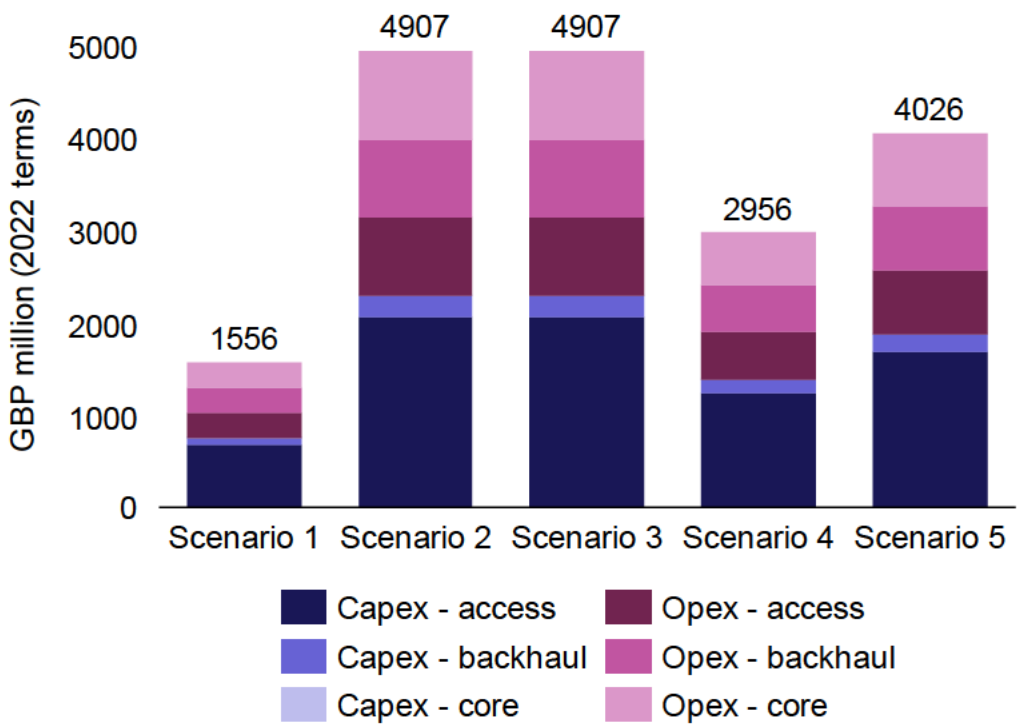
By 2032, we model the following number of new dedicated localised private 5G-SA networks (total market):

- 1363 in Scenario 1
- 5504 in Scenarios 2 and 3
- 3188 in Scenario 4
- 4648 in Scenario 5.

Figure 5.21 shows the corresponding PV of the dedicated private networks.

Moving to higher scenarios, the total number of private networks increases, but so does the portion of private networks that can be served by a public slice (due to the enhanced capabilities of the public network). As such, the number of dedicated private networks is lower in Scenarios 4 and 5 than in Scenarios 2 and 3. This is reflected in the PV values shown below.

Figure 5.21: Total market PV of dedicated localised private networks [Source: Analysys Mason, 2023]



5.4 Extent to which scenarios support use cases in different industry sectors

The figures in the following sub-sections describe the extent to which different use cases within industry sectors of interest to the Commission might be supported by the five different 5G-evolution scenarios that we have modelled. Sub-sections cover the six different industry sectors (excluding digital) covered by the Commission's National Infrastructure Assessment: energy, transport, water and wastewater, flood resilience and waste.

It should be noted that where operational use cases can be supported by both public and private networks, there may be other considerations for why private networks may be needed (such as security or resilience considerations, which can be particularly important for critical features).

5.4.1 Energy

Figure 5.22: Supporting scenarios for energy sector use cases [Source: Analysys Mason, 2023]

Use case	Summary of network implications (see Annex A for detail)	Supporting scenarios
Augmented reality (AR) / virtual reality (VR) for augmented operational support on site, e.g. digital twins	• low–mid capacity • low latency • localised	**Supported by public and private networks in:** • urban and suburban areas in all scenarios • rural areas in Scenarios 4 and 5 **Supported by private networks only in:** • rural areas in Scenarios 1, 2 and 3
Ultra-high definition (UHD) video for surveillance	• low capacity • wide-area	**Supported by public and private networks in:** • all areas within the current mobile network footprint in all scenarios • areas outside the current mobile network footprint in Scenarios 3, 4 and 5 **Not supported in:** • areas outside the current mobile network footprint in Scenarios 1 and 2
Sensor networks used for fault detection, predictive maintenance and process optimisation (e.g. smart grid management)	• low capacity • wide-area	**Supported by public and private networks in:** • all areas within the current mobile network footprint in all scenarios • areas outside the current mobile network footprint in Scenarios 3, 4 and 5 **Not supported in:** • areas outside the current mobile network footprint in Scenarios 1 and 2
Remote machine manipulation for remote control, inspection and maintenance of site equipment	• mid capacity • very low latency • likely to require high security • localised	**Supported by private networks only in:** • all areas in all scenarios
Robotics for automated	• mid capacity	**Supported by private networks only in:**

Use case	Summary of network implications (see Annex A for detail)	Supporting scenarios
processes on site	• very low latency • likely to require high security • localised	• all areas in all scenarios
Drones for remote video inspections of equipment	• low–mid capacity • low latency • wide-area	**Supported by public and private networks in:** • urban and suburban areas within the current mobile network footprint in all scenarios • rural areas within the current mobile network footprint in Scenarios 4 and 5 • areas outside the current mobile network footprint in Scenarios 4 and 5 **Not supported in:** • rural areas within the current mobile network footprint in Scenarios 1, 2 and 3 • areas outside the current mobile network footprint in Scenarios 1, 2 and 3

5.4.2 Transport

Figure 5.23: Scenario relevance for the transport sector [Source: Analysys Mason, 2023]

Use case	Summary of network implications (see Annex A for detail)	Scenario relevance
UHD video for surveillance	• low–mid capacity • wide-area	**Supported by public and private networks in:** • urban and suburban areas within the current mobile network footprint in all scenarios • rural areas within the current mobile network footprint in Scenarios 4 and 5 • areas outside the current mobile network footprint in Scenarios 4 and 5 **Not supported in:** • rural areas within the current network footprint in Scenarios 1, 2 and 3

Use case	Summary of network implications (see Annex A for detail)	Scenario relevance
		• areas outside the public network footprint in Scenarios 1, 2 and 3
Sensor networks for traffic monitoring, smart traffic management, smart motorways and predictive maintenance	• low capacity • wide-area	**Supported by public and private networks in:** • all areas within the current mobile network footprint in all scenarios • areas outside the current mobile network footprint in Scenarios 3, 4 and 5 **Not supported in:** • areas outside the current mobile network footprint in Scenarios 1 and 2
Smart tracking for vehicles, cargo and carriages	• low capacity • wide-area	**Supported by public and private networks in:** • all areas within the current mobile network footprint in all scenarios • areas outside the current mobile network footprint in Scenarios 3, 4 and 5 **Not supported in:** • areas outside the current mobile network footprint in Scenarios 1 and 2
Autonomous vehicles	• low–mid capacity • very low latency • high security • contiguous wide-area	**Supported by dedicated transport corridor deployment:** • in low volumes (e.g. certain types of public authority, HGC or coach vehicles only, not all privately owned cars along railways and major roads in Scenario 5 **Not supported in:** • all areas in Scenarios 1, 2, 3 and 4 • large volumes along railways and roads in Scenario 5

Based on existing research on vehicle to everything (V2X) communication, it is assumed autonomous vehicles must have the capability to communicate between vehicles, as well as infrastructure, objects around vehicles and the roadside. Thus, the infrastructure connectivity aspect is only one part of a V2X solution and autonomous vehicle operation on roads will not be enabled solely through having connectivity dedicated along transport corridors.

5.4.3 Water and wastewater

Figure 5.24: Scenario relevance for the water and wastewater sector [Source: Analysys Mason, 2023]

Use case	Summary of network implications (see Annex A for detail)	Scenario relevance
UHD video for surveillance	• low capacity • localised	**Supported by public and private networks in:** • all areas in all scenarios
Sensor networks for monitoring flow	• low capacity • localised	**Supported by public and private networks in:** all areas in all scenarios
Drones for video inspections	• low–mid capacity • low latency • localised	**Supported by public and private networks in:** • urban and suburban areas in all scenarios • rural areas in Scenarios 4 and 5 **Supported by private networks only in:** • rural areas in Scenarios 1, 2 and 3

5.4.4 Flood resilience and waste

Both the flood resilience sector and the waste sector only have one identified use case, sensor networks, as shown in Figure 5.25 and Figure 5.26 below.

Figure 5.25: Scenario relevance for the flood resilience sector [Source: Analysys Mason, 2023]

Use case	Summary of network implications (see Annex A for detail)	Scenario relevance
Sensor networks for early warning systems	• low capacity • localised	**Supported by public and private networks in:** • all areas in all scenarios

Figure 5.26: Scenario relevance for the waste sector [Source: Analysys Mason, 2023]

Use case	Summary of network implications (see Annex A for detail)	Scenario relevance
Sensor networks for smart bins, intelligent monitoring of materials and end to end tracking	• low capacity • wide-area	**Supported by public and private networks in:** • all areas within the current mobile network footprint in all scenarios • areas outside the current mobile network footprint in Scenarios 3, 4 and 5 **Not supported in:** • areas outside the current mobile network footprint in Scenarios 1 and 2

6 Conclusions

The aim of the study has been to calculate the incremental cost of 5G deployment (above the current level of 5G infrastructure roll out) in a number of different scenarios that capture a range of the potential evolution scenarios for the UK market.

The model developed as part of the study calculated an PV of between GBP10.5 billion and GBP37.9 billion in 2022 terms for the total UK market (across all four MNOs and private network providers) over the modelling period (2023–2032), depending on the scenario.

- **Scenario 1,** which models improved urban/suburban service capabilities, moderate rural roll-out, and a limited number of localised private sector network deployments **estimates total-market PV costs of GBP10.5 billion** (for incremental 5G deployment over the coming decade). The majority of costs arise from the access and backhaul capex of extending low- and mid-band 5G coverage (700MHz is deployed on all macro sites, 3.5GHz is deployed on all urban and suburban macro sites), and building 2713 new macro sites per MNO.
- **Scenario 2** models more significant deployment of localised private sector 5G networks alongside a limited deployment of localised public sector 5G networks (totalling 5938 new networks, 434 served by public slice and 5504 with dedicated infrastructure). In this scenario the model **estimates total-market PV costs of GBP14.0 billion.** The extra GBP3.5 billion (relative to Scenario 1) principally arises from the capex of the new access network, although the opex of the new access network, backhaul and private core is a significant component of the cost.
- **Scenario 3,** which models the deployment of additional macro sites in the wide-area public 5G network to provide contiguous 5G MBB coverage along key transport corridors and wide-area utility networks across the UK also **estimates total-market PV costs of GBP14.1 billion.** There is only a small increase, around GBP40 million, from Scenario 2, because the high level of existing coverage means that only a small number of additional infill sites (63) are required.
- **Scenario 4,** which increases wide-area public 5G network deployment in urban, suburban and rural areas to reflect a higher level of consumer demand in all geotypes, **estimates total-market PV costs of GBP32.9 billion**. The majority of the extra GBP18.8 billion (relative to Scenario 3) arises from the capex and opex associated with the densification of the access network, both of macro

sites (6287 more macro sites per MNO than in Scenario 3) and small cells (53 009 new outdoor small cells per MNO) and the capex associated with deploying 3.5GHz on all rural macro sites.

- **Scenario 5** includes an increased deployment of localised public sector 5G networks combined with dedicated infrastructure deployed along transport corridors and utility networks providing contiguous 5G coverage for these use cases. The model **estimates total-market PV costs of GBP37.9 billion**, with the additional GBP5 billion (relative to Scenario 4) arising from the dedicated access network along transport corridors and utility networks and the improvements in the wide-area public access network in order to support an additional 4925 localised private networks.

Annex A Sector and use case network implications

This annex provides further detail on the network implications of each sector's use cases.

- Section A.1 provides details of network implications for each of the Commission's industry sectors (excluding digital) covered by the National Infrastructure Assessment: energy, transport, water and wastewater, flood resilience and waste.
- Section A.2 provides a bibliography of sources used for Section A.1.

A.1 Sector and use case network implications

Figure A.1: Energy sector use case network implications [Source: see bibliography in A.2, 2023]

Use case	Capacity (Mbit/s)	Latency (ms)	Security	Coverage
AR/VR for augmented operational support on site, e.g. digital twins	2.5–50	<100	-	Localised
Ultra-high definition (UHD) video for surveillance	3–5	<1000	-	Localised and wide-area
Sensor networks used for fault detection, preventative maintenance and process optimisation (e.g. smart grid management)	≤1	<3000	-	Localised and wide-area
Remote machine manipulation for remote control, inspection and maintenance	1–100	1–10	Likely to require high security	Localised

Use case	Capacity (Mbit/s)	Latency (ms)	Security	Coverage
of site equipment				
Robotics for automated processes on site	1–100	1–10	Likely to require high security	Localised
Drones for remote video inspections of equipment	1–50	1–100	-	Wide-area

Figure A.2: Transport sector use case network implications [Source: see bibliography in A.2, 2023]

Use case	Capacity (Mbit/s)	Latency (ms)	Security	Coverage
UHD video for surveillance	5–30 (roads) >4Mbit/s (rail)	<2000 (road) <500ms (rail)	–	Localised
Sensor networks for traffic monitoring, smart traffic management, smart motorways and predictive maintenance	<1	<1000	–	Localised
Smart tracking for vehicles, cargo and carriages	<1	<10 000	–	Continuous along transport corridors
Autonomous vehicles	1–1000 (road) <1 (rail)	10–100 (road) <100 (rail)	Ultra-high security	Continuous along transport corridors

Figure A.3: Water and wastewater sector use case network implications [Source: see bibliography in A.2, 2023]

Use case	Capacity (Mbit/s)	Latency (ms)	Security	Coverage
UHD video for surveillance	5–30	<2000	–	Localised
Sensor networks for	<1	<1000		Localised

Use case	Capacity (Mbit/s)	Latency (ms)	Security	Coverage
monitoring flow				
Drones for video inspections	1–50	1–100		Localised

Figure A.4: Flood resilience sector use case network implications [Source: see bibliography in A.2, 2023]

Use case	Capacity (Mbit/s)	Latency (ms)	Security/ reliability	Coverage
Sensor networks for early warning systems	<1	<1000		Localised

Figure A.5: Waste sector use case network implications [Source: see bibliography in A.2, 2023]

Use case	Capacity (Mbit/s)	Latency (ms)	Security/ reliability	Coverage
Sensor networks, networks for smart bins, intelligent monitoring of materials and end to end tracking	<1	<1000		Localised

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Annex B Costs from an industry perspective

The results presented in this report use an approach specified by the NIC in which investments are modelled from a national perspective using a real SDR of 3.5%. Sector-specific risk is captured by modelling financing costs using a weighted average cost of capital (WACC).

These costs are higher than if costs were modelled from an industry perspective. Figure B.6 below shows the PV of the market-total (across all four MNOs and private network providers) capex and opex calculated for each scenario between 2023 and 2032 when using the industry pre-tax nominal WACC of 7.8% converted to a pre-tax real WACC using yearly GDP deflators.

Figure B.6: PV of total market 5G investment from 2023–32, by scenario and split by network type – from an industry perspective[Source: Analysys Mason, 2023]