Resilient Time Dissemination Market Study

Final report

London Economics

July 2024

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About ReThinkPNT

ReThinkPNT is a consultancy that provides technical and strategic level services to clients in areas of space and PNT, with the goal of promoting resilience in navigation and timing systems and approaches. They provide technical assessments, assurance, business, and market analysis for both technology and business. The principal of ReThinkPNT, Andy Proctor, is a former Technical Director of the UK Space Agency, and a board member at the European Space Agency.

Acknowledgements

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Key findings

- There were indications that the direct economic incentives to procure resilient time were not sufficient to mitigate the broader economic impact in the event of a disruption – i.e. there appears is a market failure for resilient time in the UK (this will be investigated in the study's Part B)
- The total addressable market (TAM) for resilient time in the UK over the 2024 - 2030 period is estimated to be worth £1.4bn or £201m/year.
- The major use cases contributing were found to be: Mobile communications network; Exchange and Trading Systems; Future Trading; and Energy, monitoring, measurement and analysis solutions.
- Two key attributes of these markets were found to make these markets large. First, they have demanding resilient time accuracy requirements that require a degree of sophistication from the time infrastructure. Second, large numbers of geographically separated locations that require synchronized time, as market size increases at least proportionally with the number of locations.
- All use cases identified used GNSS to some extent to provide time dissemination given its low cost and broad availability.
- In general, all use cases were found to already have solutions robust enough to manage disruptions only lasting less than two to five days but not weeks – this report assumed disruption of two days when estimating the willingness to pay.
- The most common method for achieving resilience was installing local atomic clocks, the type varying according to the accuracy requirements of the use case. The price of these clocks in general set a ceiling on the willingness to pay for time resilience from the user.
- The expected probability and duration of time disruption has a major impact on the market size for resilient time dissemination. Should the national threat environment increase, the incentive to participate in the market for time dissemination would increase as a minimum proportionally, but potentially exponentially, if new technological solutions must be adopted.

Context

Positioning, Navigation and Timing (PNT) services are vital to modern economies, the UK included. While positioning and navigation receive much attention and publicity, time is often overlooked. However, time underpins key parts of the economy particularly for critical national infrastructure (CNI). From power transmission and distribution, mobile communications, datacentres, financial markets, aviation, and emergency services – time is required to ensure reliable operation of the UKs physical and digital infrastructure.

However, many of these applications that require time currently use Global Navigation Satellite Systems (GNSS) which are vulnerable to being disrupted, degraded, or denied. With no widely adopted backup system in place for time in the UK, GNSS has become a potential point of failure for critical infrastructure. The sources of these threats include jamming, spoofing, atmospheric anomalies (e.g., space weather), multipath, and cyber-attacks.

It is therefore vital that the UK understands how time is used, the scale of its demand and the commercial willingness to pay if the UK is to ensure that any market opportunity, resilience improvement opportunity, or vulnerability mitigation can be actioned.

Study objectives

This report seeks to improve the understanding on the nature of resilient timing markets in the UK by identifying the most critical use cases for time, understand how time is used and improve the UKs understanding for a resilient time dissemination services.

The specific research questions answered by this project are:

- What are the most important uses of time dissemination in the UK?
- What are the use case requirements for time dissemination in the UK?
- What is the current and future Total Addressable Market (TAM) for resilient time dissemination in the UK and internationally until 2030?
- What are the drivers and blockers for the adoption and growth of resilient time dissemination in the UK?

This report (Part A) is the first of a two-part investigation into the UK timing market and focuses on the size of the market opportunity. Part B will focus on exploring the impact of potential UK government interventions to increase the UKs time resilience and to grow the size of the timing market in the UK.

Scope and methodology

The methodology for this report involved identifying and evaluating high-priority use cases for resiliently disseminated time in the UK. Ten high-priority use cases were identified through a comprehensive ranking and rigorous assessment. Each of these ten priority use cases then underwent detailed sizing to determine the total addressable market (TAM). This was achieved through the following structured approach:

1) **Understanding the use of time**: Detailed research was carried out to identify how time was used, which included understanding the use case requirements and the trends and drivers which affect customer’s willingness to pay for resilient time;

2) **Market sizing methodology**: A bespoke market sizing methodology was developed for each use case incorporating how time was used and market trends and drivers;
3) **Data collection**: Data was collected to carry out the market sizing leveraging proprietary and open sources. For example, revenues of financial firms were collected to understand the scale of fines that could be imposed on them for improper timestamping;
4) **Stakeholder consultation**: Stakeholder consultations to verify and update the information and assumptions used in the analysis;
5) **Market sizing**: Market sizing was carried out for the UK using quantitative methods. Following this, the international market TAM was estimated, using the UK TAM as a reference and multiplying it by a scalar e.g. ratio of the number of 5G based stations between UK and EU27.

The process was repeated for the following ten selected use cases:

Table 1 Time dissemination use cases selected for market assessment

Sector	Use case	Definition
Finance	UC1: Exchange and trading systems	Regulatory compliance to facilitate and execute trading activities involving various financial instruments within organised marketplaces or exchanges.
	UC2: Future trading	Future of trading in financial markets, the advancements of technologies and trading techniques, particularly high frequency trading.
Telecoms	UC3: Mobile communications network (5G)	5G mobile communication technology and standard that represents the latest evolution, advancement, and innovation in cellular network technology.
	UC4: Next generation telecom (6G)	The deployment of sixth generation (6G) wireless communication systems. Like its predecessors, 6G networks will be broadband cellular network, in which the service area is divided into small geographical areas called cells.
Energy	UC5: Energy, monitoring, measurement and analysis solutions	Systems designed to monitor, analyse, and manage energy consumption, usage patterns, performance metrics, or operational parameters including the integration of alternative energy sources into the grid.
	UC6: National grid CNI network and systems	Network of power stations, powerlines and electricity infrastructure that allows electricity to be generated, transported, and used across the country and its systems and procedures that facilitate its operation.
Aviation	UC7: Air traffic control radar systems	Air traffic control radar systems. Comprises Primary Surveillance Radar (passive or non-cooperative) and Secondary Surveillance Radar (active or cooperative), which relies on aircraft having a transponder (Mode A/C/S).
	UC8: Air traffic control WAM systems	Wide Area Monitoring (WAM) systems that make use of signals transmitted by an aircraft to calculate the aircraft's position. It is a distributed surveillance technology that works by deploying multiple sensors throughout an area to provide coverage of the desired airspace. WAM can be used as a replacement for secondary radar or complementary to ADS-B.
	UC9: Timing systems for airborne applications	Time required on-board and to communicate with aircraft. Aircraft require a time source to ensure the accuracy, reliability, and efficiency of various systems, operations, and functionalities onboard aircraft and to communicate with the ground.
Information Technology	UC10: Data centres (Ecommerce)	Data centres for Ecommerce which are designed to house and maintain networked computer servers, and infrastructure that support and facilitate the storage, processing, retrieval, and dissemination of digital data over the internet or other interconnected networks.

The EU27 was selected as the international reference for 9 out of 10 of these use cases principally due to the similarity of its market and regulatory environment. For example, in the finance sector institutions in the UK and the EU must comply with MiFID II requirements. For the aviation sector, the UK is a member of Eurocontrol, and the UK airspace is closely integrated with the EU, and faces similar market trends such as levels of traffic and threats. Moreover, telecommunications operators in the UK often also have operations extending to the EU, and the UK electricity grid features interconnections with Europe, as opposed to the other regions. The only use case which was not compared to the EU27 was the data centre use case. Instead, it was compared to five eyes countries as there was some level of synchronization requirement across regions and the importance and scale of the US market.

Results

Finance, Telecoms and Energy sectors are the key markets for time in the UK. The total addressable market (TAM) for resilient time in the UK over the 2024 - 2030 period is estimated to be worth £1.4bn or £201m/year.

The following section outlines results of the study. The major use cases contributing were found to be: Mobile communications network; Exchange and Trading Systems; Future Trading; and Energy, monitoring, measurement and analysis solutions. The combined market of these use cases accounted for **98.8%** of the UK TAM of the ten use cases investigated. These use cases have a significant importance on the time dissemination market, and their importance is not expected to diminish even if more use cases were considered. The remaining six uses by comparison have markets that are orders of magnitude smaller. Sensitivity analysis was undertaken, the key results presented are based on the central estimate for UK total addressable market for resilient time (£m).

Figure 1 Total addressable market for ten identified time dissemination use cases

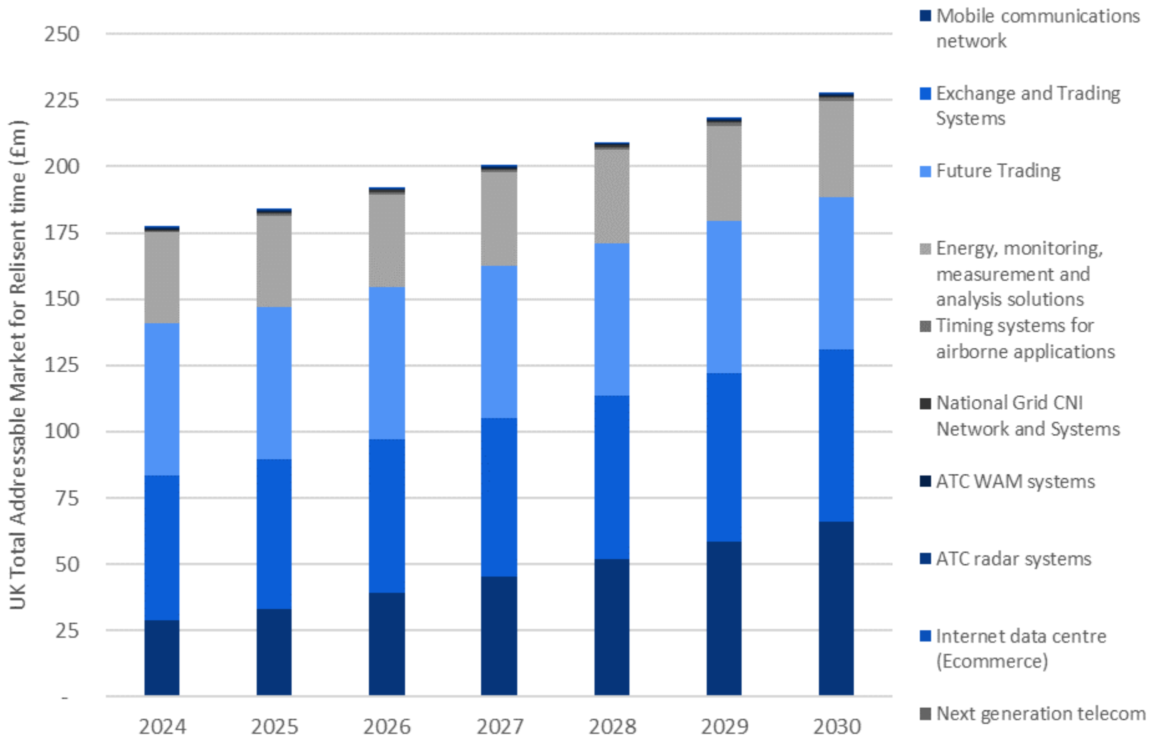
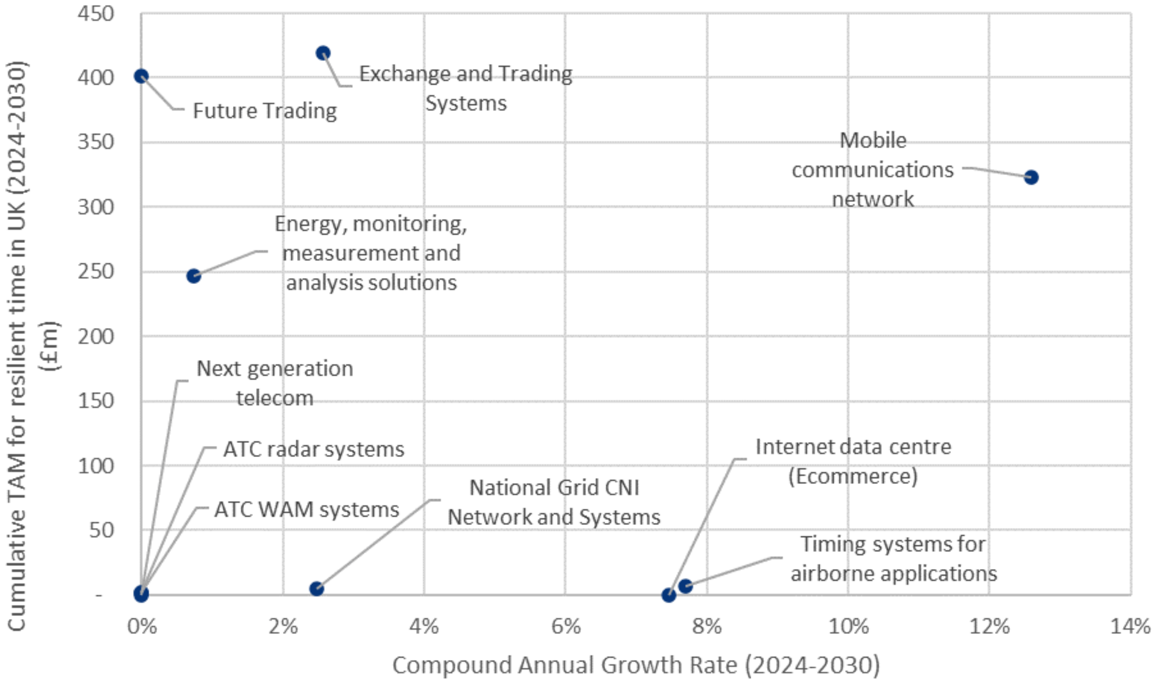


Figure 2 Central estimate for UK total Addressable Market (TAM) for Resilient time (£m)



Note: Rollout for 'Next generation telecom' does not begin until end of 2030. The cumulative TAM and CAGR for this use case from 2030-2034 are £58.5m and 89% respectively.

Table 2 Use case assessment summary

Sector	Use case	Use of time	Drivers for adopting resilient time	Blockers for adopting resilient time	Cumulative TAM (£K) (2024 - 2030)	Average TAM/yr. (£K)	Average TAM/yr. (EU27) (£K)
Finance	Exchange and trading systems	Finance firms require time to log and synchronise transactions under MiFID II regulations, track ordering routing and execution and synchronise market data feeds.	Financial firms face severe financial penalties under MiFID II regulations for failing to accurately time stamp transactions, required to assist in regulatory enforcement by regulators. The fines can be up to 10% of global annual turnover of the financial firm.	Compliance with MiFID II timing requirements is not demanding, and as such can be readily achieved with low-cost solutions. There have been no historic fines for breaches of MiFID II relating to time, which reduces the perception of regulatory threat.	420,000	60,000	61,700
	Future trading	Finance firms require accurate time to operate high frequency trading (HFT) algorithms such as monitoring transaction network latency and server to server synchronisation.	Willingness to pay is driven by the commercial incentive to ensure the continuity of revenues being generated by HFT algorithms. The number of firms engaging in HFT is expected to increase over the coming decade	HFT was initially a highly profitable enterprise when it was first introduced but much of the excess return has been arbitraged away from increased competition. This is compounded by a small number of HFT firms in the UK.	400,000	57,000	221,000
Telecoms	Mobile communications network (5G)	Timing synchronisation is required across the 5G network to meet radio network-driven synchronization requirements. Specifications for 6G are currently unknown but would be at least as demanding than 5G, likely more demanding.	The UK government has made a commitment to rolling out 5G to all populated areas by 2030, this increases the number of base stations that require timing synchronisation which is underpinned by the growing demand for mobile data. 6G rollout is expected to start 2030 depending on growth rate of mobile data usage.	There is significant business model pressure on mobile network operators who have seen falling mobile telephony revenues across the UK. This financial pressure is forcing them to reduce the scope and speed of the 5G rollout, particularly small cells.	320,000	46,000	558,000
	Next generation telecommunications (6G)				N/A	12,000	141,000
Energy	Energy, monitoring, measurement and analysis solutions	Time is required to achieve grid stability and efficient operations of power grid. Resilient time is required at substations for monitoring systems and to enable the system to respond to faults. The requirement becomes more critical the larger the substation.	As power grids are natural monopolies, they are heavily regulated, with fines available for up to of 10% of operator's turnover. Grid modernisation and the overall increase in electricity consumption driven by emissions targets offer opportunities to insert new technologies	Power grid infrastructure is expensive with long asset lifetimes, this limits the uptake of new timing and monitoring techniques. Moreover, existing time resiliency measures such as Caesium clocks are already incorporated into the grid to provide redundancy to a GNSS outage.	250,000	35,000	121,000
	National grid CNI network and systems				4,600	660	6,560

Sector	Use case	Use of time	Drivers for adopting resilient time	Blockers for adopting resilient time	Cumulative TAM (£K) (2024 - 2030)	Average TAM/yr. (£K)	Average TAM/yr. (EU27) (£K)
Aviation	ATC radar systems	Required to modulate the RF signal emitted from the radar and time of flight calculations for each pulse. Time is also required to synchronise aircraft locations with other assets in the ATC radar network.	Increasing threats affecting air traffic management highlighted by the war in Ukraine and GNSS jamming in Baltic is increasing the demands from airlines and regulators for ATC network resilience. Stringent regulatory oversight of air navigation services providers gives financial incentives to ensure networks operate reliably and with high availability.	ATC radars operate monostatically which substantially eliminates any stringent radar-radar synchronisation requirements. Low ATC network synchronization requirements (~1 second) enable holdover clocks to provide near indefinite holdover capacity. Finally, ATC networks particularly in the UK already have a resilient system of systems approach which reduces willingness to pay for further timing resilience. Finally, there are a limited number of Radar and WAM systems across the UK which reduces the market opportunity.	2,200	310	3,700
	ATC WAM systems	Aircraft position is calculated based on the time differences between signals received by multiple antennas. By comparing these time differences, the system can trilaterate the aircraft's position in three-dimensional space.			2,300	330	4,730
	Timing systems for airborne applications	Air to ground communications synchronisation and timestamping (similar to 4G/5G), flight management system synchronisation, date link communications and 4D navigation	Increasing threats affecting air traffic highlighted by the war in Ukraine and GNSS jamming in Baltic. Moreover, increasing levels of complexity in airborne avionics technologies.	As a mobility use case, time has a much lower value, with time only signals providing limited benefits over those that can provide PNT. Moreover, the redundancy of onboard navigation systems to external disruption mitigates any value of resilient time.	7,200	1,000	6,900
Information Technology	Data centres (Ecommerce)	Time is used for correlating and ordering simultaneous events between distributed servers. Accurate time reduces packet loss, improves network performance and increases network security	Losing synchronised time for an extended period increases the operational costs of running data centres at the best or even a degraded user experience. For Ecommerce this can result in lower levers of sales conversions.	Accurate timing and synchronisation are already addressed within many data centres through backup atomic clocks which are inexpensive and capable of holding time for a few days. This sets a ceiling on the willingness to pay for short disruptions.	120	17	513

Note: Value reported for 6G corresponds to the average TAM over 2030 – 2034 period as 6G is not expected to being its rollout until 2030; International value stated for data centres refers to five eyes countries excluding the UK (USA, Canada, Australia and New Zealand) instead of EU27

Project caveats

The research has been conducted by a team of independent professional economists, engineers, and market analysts with specialist knowledge of the space industry, PNT use cases, and market modelling in these contexts. Best practice and judgment have been used throughout the study, and the methodology used, and assumptions made are described for each use case individually in Section 1)3 of this report in a transparent manner, with caveats noted as required. Nonetheless, the reader should bear in mind the following high-level limitations and caveats of this study throughout:

- **The project assumed two days of GNSS disruption:** This assumption was required to estimate the TAM for resilient time. This assumption had a major impact on the TAM quoted in this report as even for use cases that require high timing precision, technical and financially viable solutions can readily be found to manage disruptions of a few days. This is possible because of the widespread access to reliable atomic clocks, which limit the amount that users are willing to pay for robust time as a service. However, if the assumed duration of disruption was increased, it would be expected to increase the market values stated here exponentially, especially if the duration goes beyond the period the widely adopted types of holdover clocks can cover.
- **National risk register:** This report has used the national risk register[1] to assess the probability of GNSS disruption which has a direct impact on the willingness to pay for resilient time. It should be noted that this report has a relatively low probability of GNSS disruption, which as outlined, is a worst case a 1% annual probability for GNSS disruption. Should this probability increase, the TAM would be expected to increase proportionally with risk as a minimum and potentially in a non-linear way if technology solutions need to be adopted. Noting ongoing jamming campaigns in the Baltic, it is conceivable that jamming could be a future risk factor for UK access to GNSS.
- **Perception of risk does not necessarily equal reality:** Willingness to pay is based on the aggregated perception of risk that customers have within each market. However, this perception does not necessarily equal the actual risk and hence willingness to pay for resilient time services. This means that market sizes estimated here, calculated based on the national risk register could deviate from the actual market willingness to pay for resilient time dissemination, if the users had perfect appreciation for the risk.
- **Only direct customer willingness to pay is considered**: External impacts on the willingness to pay was not assessed in calculating TAMs for each use case. E.g., a financial firm may have regulatory incentive to procure resilient time to avoid a fine. However, the impact or value to the wider market if transactions could not occur could be much larger than the fine incentive for the financial firm. This study considers only the willingness to pay from the perspective of the economic agent that can procure resilient time.
- **The value of future applications is unknown:** User requirements for time evolve with markets and technology. This is especially challenging for use cases which have yet to fully mature. For example, high frequency trading algorithms are constantly evolving to maintain performance in response to changing market conditions.
- **Qualitative variables are difficult to quantify:** Key variables that determine the precise nature of the future market for time dissemination can be defined in qualitative terms but are much harder to quantify. Market sizing has necessitated quantification of these

[1] National Risk Register 2023 edition. Available at: https://assets.publishing.service.gov.uk/media/64ca1dfe19f5622669f3c1b1/2023_NATIONAL_RISK_REGISTER_NRR.pdf

variables, but this has been done to demonstrate which services represent the most promising opportunities and which variables are the biggest revenue drivers. The detail and nuance present in the narrative that accompanies this analysis should be studied by decision makers as closely as the revenue estimates themselves.

- **International reference was calculated from the UK as a baseline:** The priority of this study was to understand the UK timing market. As such, effort was prioritised on sizing and characterising the UK over international markets. The market sizing approach therefore used the UK as a reference and was scaled to the international market, for example the ratio of the number of 5G base stations in UK compared to the EU27.

1 Introduction

Positioning, Navigation and Timing (PNT) services are vital to the functioning of technology and infrastructure, including the electrical power grid, communications infrastructure and mobile devices, all modes of transportation, precision agriculture, weather forecasting, and emergency services. The proliferation of GNSS as a source of precise timing data is extensive, with GNSS becoming the dominant solution when building systems requiring position and/or timing.[2] Its global coverage, low implementation cost, and usually high availability and reliability mean that this proliferation is to be expected.

However, as the reliance on GNSS has increased, particularly in critical national infrastructure (CNI), so too has the exposure to the weaknesses of the system. Many systems and applications which use precise timing data from GNSS are vulnerable when GNSS is disrupted, degraded, or denied. With no widely adopted backup system in place, GNSS has become a potential single point of failure for important infrastructure. The sources of these threats include jamming, spoofing, atmospheric anomalies (e.g., space weather), multipath, and cyber-attacks.

There is a growing resilience gap as hazardous disruptions become more diverse, prolific, and capable. Calls for robust and assured timing and synchronisation (T&S) to enhance or back up existing solutions in CNI and commercial users are increasing in frequency and strength with the scale and sophistication of threats to existing PNT systems.

The Blackett Review[3] into critical dependencies on GNSS in 2018 recognised that in recent years both the threats to the UK and the infrastructure upon which modern life depends have evolved. The Blackett Review was accompanied by the London Economics report on the economic impact of a five-day loss of GNSS[4], highlighting the economic vulnerability to a loss of GNSS and presenting the widely quoted result of £5bn loss from a five-day outage. London Economics produced an updated report in 2021 (published in 2023)[5]. Several actions have been taken by stakeholders to raise awareness of the vulnerabilities of GNSS and push for the development of alternative systems. For example, in the UK, the Critical Infrastructure Resilience Programme[6] was begun in 2010 to address vulnerabilities, and Executive Order 13905 from the US Government in February 2020 aims to strengthen national resilience through responsible use of PNT services.

This report seeks to continue this process of improving resilience of PNT to a GNSS disruption by identifying and understanding the market dynamics of use of resilient time and improve our knowledge of the market for a resilient time dissemination services. This research will contribute to understanding the Total Addressable Market (TAM) for resilient time dissemination for UK stakeholders, with obvious international applicability.

The specific research questions of the project were:

- What are the most important uses of time dissemination in the UK?

[2] Government Office for Science. (2018). 'Blackett Review – Satellite-derived Time and Position: A study of critical dependencies'
[3] Government Office for Science. (2018). 'Blackett Review – Satellite-derived Time and Position: A study of critical dependencies'
[4] London Economics (2017). 'The economic impact on the UK of a disruption to GNSS'. Available at: https://londoneconomics.co.uk/blog/publication/economic-impact-uk-disruption-gnss/
[5] London Economics (2023) .'The economic impact on the UK of a disruption to GNSS, 2021'. Available at: https://www.gov.uk/government/publications/report-the-economic-impact-on-the-uk-of-a-disruption-to-gnss
[6] Cabinet Office. (2010). 'Strategic Framework and Policy Statement on improving the resilience of Critical Infrastructure to disruption from natural hazards'

- What are the use case requirements for time dissemination in the UK?
- What is the current and future Total Addressable Market (TAM) for resilient time dissemination in the UK and internationally until 2030?
- What are the drivers and blockers for the adoption and growth of resilient time dissemination in the UK?

The methodology for this project involved a structured approach to identify and evaluate high-priority use cases for resiliently disseminated time. Initially, ten high-priority use cases were identified through a comprehensive ranking and stakeholder engagement process. Each of these priority applications underwent detailed sizing to determine the total addressable market (TAM) for resilient time dissemination. The value proposition of a resilient time dissemination service was analysed by examining the trends and drivers of demand, as well as conducting a competitive assessment to understand the ability to meet this demand. This process included stakeholder validation to verify and update the information and assumptions used in the analysis – see Annex 2.

2 Methodology

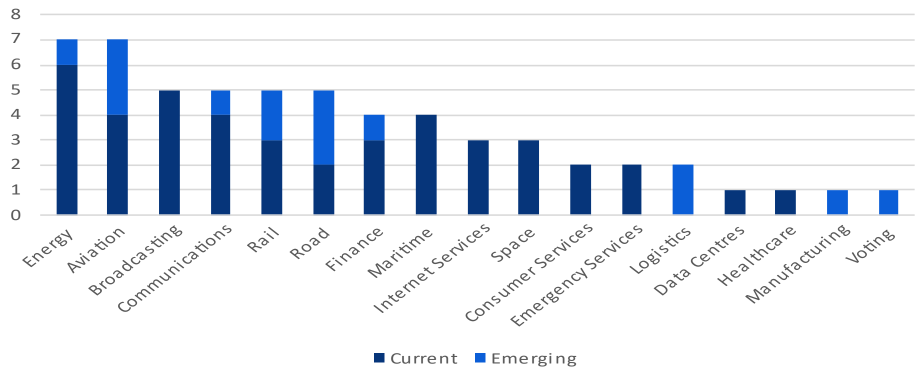
The following section outlines the methodology for the project including definitions of the selected use cases.

2.1 Approach to selecting priority use cases

The selection of use cases for this project was governed by a set of specific parameters that defined its scope. This report concentrated on the timing market, deliberately excluding positioning and navigation use cases. The focus was placed on identifying use cases with significant growth potential for the timing and dissemination market, rather than those requiring more robust solutions to address vulnerabilities.

The process began with the development of an extensive list of timing applications, leveraging existing knowledge databases from London Economics, RethinkPNT, and the Royal Institute of Navigation (RIN), supplemented by additional desk-based research. This comprehensive list encompassed 96 applications of timing, which were then aggregated into 58 distinct markets (use cases) across 17 sectors. The aggregation process considered factors such as the end user responsible for procuring timing solutions, the specific locations where timing signals would be utilised, and the similarity in requirements across applications. For instance, the National Grid requires precise time for various applications within individual substations. These applications were aggregated into a single use case because providing timing for one application would inherently provide timing for all applications within the substation.

Figure 3 Markets per sector (current and emerging)



Each use case was evaluated and ranked based on the perceived impact of a timing disruption and the likelihood of such a disruption occurring. Figure 4 shows how this ranking was implemented. From this ranking, 15 use cases for resilient timing and dissemination were shortlisted– see Figure 5 for full detailed and descriptions of the use cases.

Figure 4 Descriptive example of how use cases were ranked

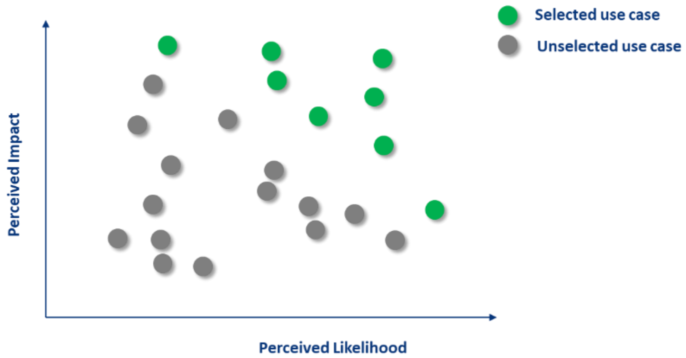
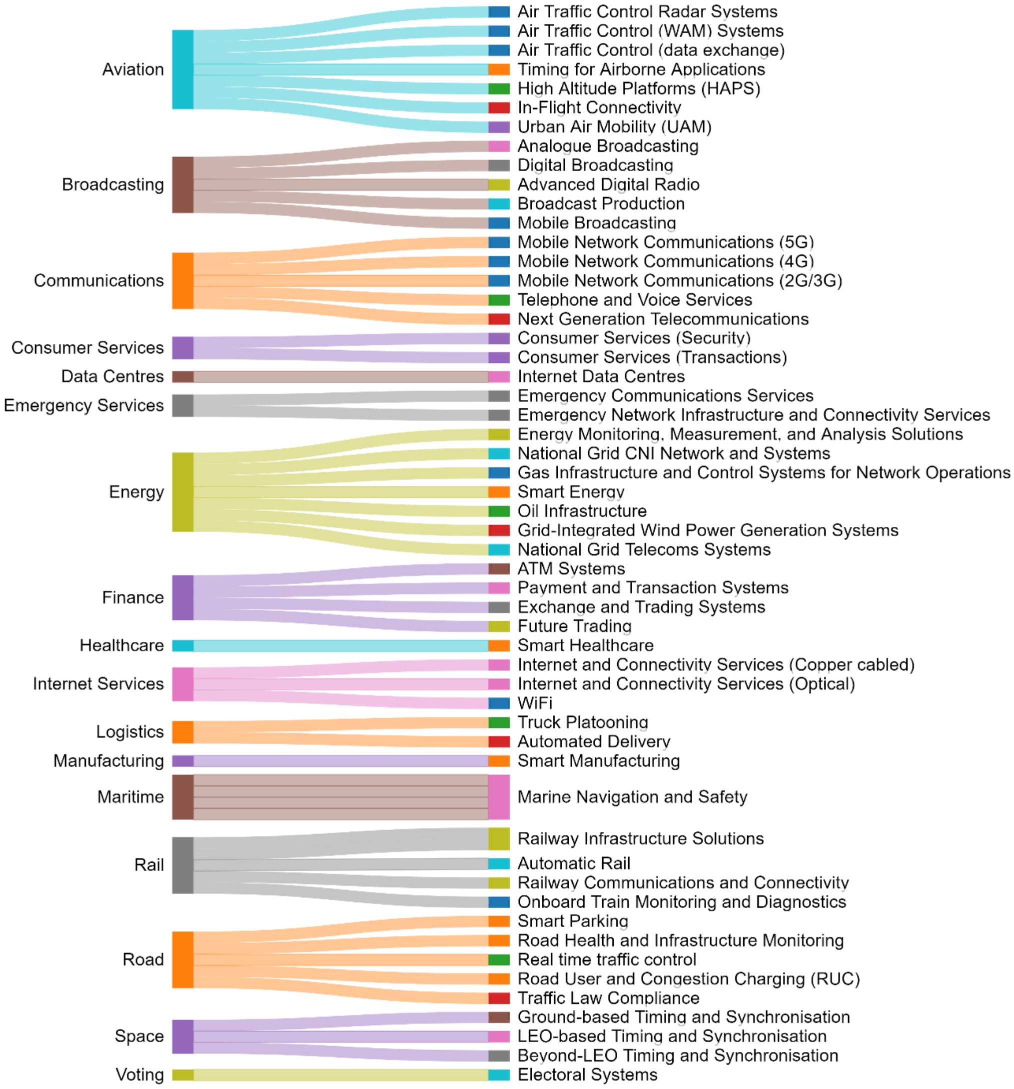


Figure 5 Timing markets (use cases) and sectors



Sources: London Economics and ReThinkPNT analysis

These shortlisted use cases were then presented to key industry stakeholders in a workshop setting, where ten priority use cases were identified. The prioritisation criteria included:

- **Willingness to pay:** Users within the market perceive resilient time to have a high value and are willing to spend money on a product or service.
- **Market size:** Total potential demand for a resilient timing product or service.
- **Growth potential:** The likelihood or capacity of the market to experience expansion in the future.
- **Barriers to entry:** The absence or minimal presence of challenges that may hinder new entries from capturing users within the market.
- **Customer base:** Diverse range of users within market who would purchase a resilient timing solution, controlling the bargaining power of buyers.

This structured and systematic approach ensured that the selected use cases aligned with the project's objectives, focusing on high-impact, high-potential areas within the time dissemination market. Detailed analysis was performed on each selected use case, presented in Section 2.3.

2.2 Use case selection summary

The selected top ten priority use cases are outlined in Table 3:

Table 3 Priority use cases

Sector	Use case	Maturity	Definition
Finance (trading)	Exchange and trading systems	Current	The integrated platforms, infrastructures, technologies, or networks designed to facilitate and execute trading activities involving various financial instruments within organised marketplaces or exchanges.
	Future trading	Emerging	Refers to the future of trading in financial markets, the advancements of technologies and trading techniques, as well as the evolution of the regulatory environment.
Telecommunications	Mobile communications networks (5G)	Current	Fifth-generation mobile communication technology and standard that represents the latest evolution, advancement, and innovation in cellular network technology, enabling transformative capabilities, performance, and experiences for voice, data, and connected services.
	Next generation telecommunications (6G)	Emerging	The next generation of cellular technology that envisions the evolution of existing 5G technologies towards the deployment of sixth-generation (6G) wireless communication systems. Like its predecessors, 6G networks will be broadband cellular network, in which the service area is divided into small geographical areas called cells.
Energy	Energy monitoring, measurement, and analysis solutions	Current	Systems designed to monitor, analyse, and manage energy consumption, usage patterns, performance metrics, or operational parameters including the integration of alternative energy sources into the grid.
	National grid CNI network and systems	Current	Refers to the network of power stations, powerlines and electricity infrastructure that allows electricity to be generated, transported and used across the country and its systems and procedures that facilitate its operations.

Sector	Use case	Maturity	Definition
Aviation	Air traffic control (ATC) radar systems	Current	The Air Traffic Control Radar Beacon System (ATCRBS) is a critical component of modern air traffic management, facilitating the detection, tracking, and identification of aircraft through radar technology. Comprises Primary Surveillance Radar (passive or non-cooperative) and Secondary Surveillance Radar (active or cooperative), which relies on aircraft having a transponder (Mode A/C/S). Accurate timing and frequency is critical for SSR operation (frequency generated by internal source). Standard practice is to derive this from the airport's Master Clock System.
	ATC Wide Area Multilateration (WAM) systems	Current	WAM systems makes use of signals transmitted by an aircraft to calculate the aircraft's position. It is a distributed surveillance technology that works by deploying multiple sensors throughout an area to provide coverage of the desired airspace. WAM can be installed in areas of challenging terrain which limits the use of secondary radar. It can also be used as a replacement for secondary radar or complementary surveillance to ADS-B.
	Timing systems for airborne applications	Current	Aircraft require a time source to ensure the accuracy, reliability, and efficiency of various systems, operations, and functionalities onboard aircraft. When available, aircraft flight management systems and navigation solutions will be used to provide aircraft time source. Current requirements are satisfied with a mechanical clock (mandatory fit). However, mechanical clocks are unable to provide data outputs for future avionics that support airspace integration.
Information technology	Data centres (Ecommerce)	Current	Facilities designed to house and maintain a large collection of networked computer servers, and other related infrastructure components that support and facilitate the storage, processing, retrieval, and dissemination of digital data over the Internet or other interconnected networks. Examples include cloud storage and processing systems (Eg AWS) and core hosted network processing for areas like current and future trading.

Note: Maturity is categorised into two categories: Current use cases are adopted. Emerging use cases are yet to be widely adopted.

The table below summarises the high-level results from each of the case studies.

Table 4 Summary of results

Use Case	Results
Exchange and trading systems	Estimated annual TAM: ■ UK: £54.7 m rising to £65.3 m in 2030 ■ Pan-European: £189.2 m rising to £225.9 m in 2030 ■ EU: £56.3 m rising to £67.3 m in 2030
Future trading	Estimated annual TAM: ■ UK: up to £57 m. ■ EU: up to £221 m.
Mobile communications networks (5G)	Estimated annual TAM: ■ UK: £29 m rising to £65 m in 2030 ■ EU: £475 m rising to £640 m in 2030
Next generation telecommunications (6G)	Estimated annual TAM (in 2034): ■ UK: between £16 m - £29 m ■ EU: between £156 m - £287 m
Energy monitoring, measurement, and analysis solutions	Considerable potential for resiliently disseminated time exists in this market, however, market growth is tied to the expansion of the customer base. This expansion is experiencing limited growth due to factors such as modest

Use Case	Results
	household and business growth, and in the case of the EU a declining population. The market is therefore projected to experience minimal growth during the forecast period.
National Grid CNI network and systems	Estimated annual TAM: ■ UK: £609 k and is anticipated to reach £724 k in 2030 ■ EU: £5.72 m and is anticipated to reach £7.39 m in 2030.
ATC radar systems	Estimated annual TAM: ■ UK: £308 k ■ EU: £3.7 m Negligible nominal growth is expected in 2024-2030 period – the total number of ATC radars are not expected to increase, nor are the requirements expected to increase.
Wide Area Multilateration (WAM)	Estimated annual TAM: ■ UK: between £184 k - £468 k ■ EU: between £1.2 m - £8.2 m
Timing systems for airborne applications	Estimated annual TAM (for emergency services): ■ UK: Approximately £783 k, projected to reach £1.3 m in 2030. ■ EU: Approximately £5.2 m projected to reach £8.8 m in 2030.
Data centres (Ecommerce)	Estimated annual TAM: ■ UK: Approximately £13k, projected to reach £21k in 2030. ■ Five Eyes countries: Approximately £362k and is projected to reach £695k in 2030.

Note: EU refers to EU27 countries

Source: LE Analysis

2.3 Approach to analysing use cases

The primary goal of the analysis was to determine the total addressable market (TAM) for resiliently disseminated time across various use cases. The TAM was defined as the total revenue opportunity available if a resilient time dissemination service were to capture 100% market share. The analysis prioritised opportunities within the UK, with international opportunities considered as a secondary focus. The EU27 was selected as the international reference for 9 out of 10 of these use cases due to the similarity in the market and regulatory environment. For example, in the finance sector institutions in the UK and the EU must comply with MIFID II requirements. In general, EU27 also has more consolidated datasets for comparison to the UK. Data centres was chosen as an exception and compared to five eyes countries as data centres require synchronisation across the globe.

To ensure a comprehensive and unbiased assessment, the analysis was conducted in a technology-agnostic manner, without presuming any specific technological solutions. The regulatory environment was assumed to remain stable, and potential regulatory changes were not factored into the analysis. Both existing and prospective use cases within the relevant timeframe, extending up to 2030, were considered. Additionally, the analysis assumed a scenario of disruptions lasting less than 48 hours, without delving into detailed risk assessments for longer disruptions.

Customer engagement was an important part of the analysis, as not all information required for detailed TAM analysis was available in the public domain. Interviews with relevant customers were held, with a focus on the largest and/or most representative customers. These interviews were used to validate and update the categories used in the matrix analysis, to understand the specific user requirements, and to examine the complementary timing sources to GNSS that are employed in each use case. Further details on customer engagement can be found in Annex 2.

The analysis of each use case follows a structured and consistent approach in which the value proposition of resilient time dissemination service is articulated by comparing the user requirements to the degree to which these are met. In addition, market drivers, enablers, and blockers specific to each use case are assessed.

3 Detailed use case analysis

This section presents qualification and quantification of the TAM for each individual use case. Each use case is structured as follows:

- Overview: Provides a non-technical background and context to introduce the use case, including why timing is important for that specific application.
- Use of time: Describes how time is currently obtained / used within the use case.
- User requirements: Describes minimum user requirements for timing of the use case.
- Drivers and enablers for adopting resiliently disseminated time: Contextual factors that drive the need for resilient timing in that specific use case.
- Blockers for adopting resiliently disseminated time: Contextual factors that block / reduce the need for resilient timing within the specific use case.
- Market sizing methodology: Describes the method used to estimate the potential size of the market in the UK and internationally. These sections also describe the assumptions made and, where relevant, stakeholder engaged.
- Market sizing results: Provides the final results of the analysis, including an estimate of TAM in 2024 and forecasted to 2030.
- Conclusion: Discussion of the results and how they should be interpreted.

3.1 UC1: Exchange and trading systems

This use case focuses on the utilisation of time signals by market infrastructure providers within the financial sector. These entities play crucial roles in the functioning, transparency, and regulatory compliance of financial markets. They provide essential services and platforms that facilitate trading, reporting, and transparency in financial instruments. Entities within this category include trading venues and systematic internalisers (SIs).

Trading venues

Trading venues are organised markets where transferable securities and other financial contracts, like derivatives, are bought and sold. There are 3 categories of trading venues:

1. **Regulated markets (RM):** Also known as stock exchanges, regulated markets are highly organised and centralised trading venues where securities such as stocks, bonds, and derivatives are traded. Examples include the Intercontinental Exchange (ICE) Futures Europe and the London Stock Exchange (LSE).
2. **Multilateral trading facility (MTF):** MTFs are electronic trading platforms that bring together multiple buyers and sellers of financial instruments. They operate similarly to traditional stock exchanges but are typically less regulated and offer lower barriers to entry for market participants. Examples include BATS Europe and Chi-X Europe.

3. **Organised trading facility (OTF):** OTFs are trading venues for non-equity instruments such as bonds, derivatives, and structured finance products.

The three types of trading venue differ in the types of financial instruments they can offer and the rules they operate under. Regulated markets have stringent listing requirements for companies wishing to list securities on the exchange compared to MTFs and OTFs which may include higher financial thresholds, stricter governance standards, and more extensive disclosure obligations. These financial instruments go through a vetting process by the Listing Authority before they are admitted to trading[7]. The primary distinction between OTFs and MTFs lies in the scope of financial instruments they can offer and facilitate trading for[8]. OTFs are designed specifically for trading non-equity instruments, such as bonds, derivatives, and other financial instruments that do not fall within the category of equities. On the other hand, MTFs have broader capabilities and can facilitate the trading of both equity and non-equity instruments. In addition to non-equity instruments like bonds and derivatives, MTFs also allow for the trading of equities, including stocks and shares.

Systematic internalisers

Systematic internalisers are investment firms that execute client orders internally against their own capital, rather than routing them to external trading venues such as stock exchanges or electronic trading platforms. They act as counterparties to client orders and provide liquidity by quoting bid and ask prices for financial instruments they trade. Large investment banks such as JP Morgan and Goldman Sachs act as SIs for their clients, executing orders using their own capital and infrastructure.

3.1.1 Use of time

Since the introduction of direct electronic trading of financial instruments in the 1990s, the speed of transactions within financial markets has surged exponentially.

Table 5 Trading speed changes over the last two decades

2005-2010	2011	2015	2016
97 ms	7 ms	< 1ms	< 0.001ms

Source: Martins, C.J.L. (2018). Regulations and Technology Behind HFT Latency, Batch Auctions and Payments for Order Flow in the US and EU. e-Finanse, 14(2), pp.34–46. doi:https://doi.org/10.2478/fiqf-2018-0010.

This rapid pace has culminated in the current scenario where trading decisions are formulated and trades executed within nanoseconds[9]. As such, accurate timing and synchronisation plays a crucial function in multiple dimensions of market infrastructure provider operations.

Ordering routing and execution: Time is employed in timestamping orders accurately to ensure their proper sequencing. This precise timing guarantees that orders are executed in the intended order, guarding against potential issues like trade misalignment or front-running. Synchronised clocks across trading venues and systems facilitate the measurement of latency. Traders closely

[7] MFSA. (n.d.). Regulated vs Non-Regulated Market. [online] Available at: https://www.mfsa.mt/service-detail/investor-awareness-campaign/ [Accessed 24 Apr. 2024].
[8] www.spectrum-markets.com. (n.d.). Multilateral Trading Facility - What is an MTF? | Spectrum. [online] Available at: https://www.spectrum-markets.com/en/what-is-an-mtf [Accessed 24 Apr. 2024].
[9] Brière, S. (2023). The impact of ultra-low latency and FPGAs on the trading industry. [online] Orthogone. Available at: https://orthogone.com/whats-the-impact-of-ultra-low-latency-and-fpgas-on-the-trading-industry/ [Accessed 24 Apr. 2024].

monitor latency to identify any delays in order routing and execution, enabling them to adjust strategies in real-time and optimise trade performance.

Market data feeds: Time is critical in market data feeds for accurate sequencing of market events through precise timestamping. Low-latency feeds enable traders to react swiftly to market changes, while synchronised clocks ensure consistency across systems and venues. Time-stamped data facilitates historical analysis and algorithmic trading strategies, empowering traders to make informed decisions and capitalise on market opportunities.

Regulatory compliance: Financial trading organisations face rigorous regulatory requirements concerning the accuracy of timestamping financial transactions. In the European Union (EU), institutions are legally obligated to adhere to the Markets in Financial Instruments Directive (MiFID II) standard. MiFID II mandates precise timestamping of transactions to ensure transparency, market integrity, and investor protection. The MiFID II requirements for clock synchronisation are set out in Commission Delegated Regulation (EU) 2017/574, commonly known as RTS 25. The maximum divergence from Coordinated Universal Time (UTC) (accuracy) specified for different types of trades is 100 microseconds for High Frequency Trading (HFT), 1 millisecond for non-HFT trades, and 1 second for human trades[10]. The UK follows its own version of MiFID II known as the UK MiFID, a near-identical, parallel framework. Following Brexit, the UK onshored MiFID II into its regulatory framework, starting with a unified rulebook. However, slight divergence between frameworks has occurred since.

Pershing Limited have created a divergence tracker that provides a detailed overview of how EU and UK MiFID requirements differ as at May 2022[11]. The table below has been adapted from this divergence tracker.

Table 6 Divergence between EU MiFID II and UK MiFID

Theme	What is changing?	EU/UK divergence notes
Investor reporting	The MiFID II 'Quick Fix' Directive, effective February 2022, mandates electronic communication for client reporting. However, UK regulations, such as the Markets in Financial Instruments (Capital Markets) (Amendment) Regulations 2021, allow for free paper copies upon retail client request. HM Treasury may further explore electronic communication for retail clients.	EU firms had to transition to electronic communication methods for all clients (except where retail clients choose paper) by February 2022 under the EC 'Quick Fix' requirements. Conversely, UK firms switch to electronic communication with wholesale clients only, effective 26th July 2021. The UK may extend this to retail clients pending further review.
Costs and charges	The EC's MiFID II 'Quick Fix' Directive, implemented in February 2022, exempts professional clients and eligible counterparties (except for investment advice or portfolio management) from costs and charges disclosures. Similarly, UK amendments effective 26th July 2021 exempts professional clients (except for investment advice and portfolio management) from providing all costs and charges information.	The EU and UK align in exempting professional clients and eligible counterparties (except for investment advice and portfolio management) from costs and charges disclosure requirements. EU firms complied from 28th February 2022, while UK firms adopted the changes from 26th July 2021.
Ex-post reporting requirements	The EC's MiFID II 'Quick Fix' Directive, implemented in February 2022, exempts professional clients and eligible counterparties from certain ex-post requirements, such as periodic custody statements,	Firms affected by the changes introduced by both the EU Quick Fix and the UK's Statutory Instrument should carefully assess the impact

[10] European Commission. (2014). Supplementing Directive 2014/65/EU of the European Parliament and of the Council with regard to regulatory technical standards for the level of accuracy of business clocks Available at: https://ec.europa.eu/finance/securities/docs/isd/mifid/rts/160607-rts-25-annex_en.pdf [Accessed 24 Apr. 2024].

[11] Pershing. (n.d.). *MiFID II and MiFIR Reviews*. [online] Available at: https://www.pershing.com/uk/en/perspectives/market-regulatory-risk-planning/mifid-ii-and-mifir.html [Accessed 25 Apr. 2024].

Theme	What is changing?	EU/UK divergence notes
(10% drop reporting)	contract notes, portfolio management periodic reports, and 10% drop reports (though professional clients can opt in). UK firms, under the UK's Statutory Instrument, differ slightly in their changes regarding ex-post reporting to wholesale clients. While detailed contract notes are no longer required, professional clients must still receive 'essential information' on order execution. Regarding portfolio management periodic reports, professional clients receive periodic statements, but detailed reporting requirements are switched off. Unlike the EU Quick Fix, the UK Statutory Instrument retains custody statement requirements. The FCA had temporary measures for 10% depreciation portfolio notifications to professional and, under certain circumstances, retail clients until the end of 2022. The UK's Statutory Instrument removes the 10% depreciation notification requirement for investment firms providing portfolio management services to professional clients. HM Treasury is considering how this rule should apply to retail clients in the future, potentially abolishing it.	on their operations under differing regulatory frameworks.
Product governance	The EC's MiFID II 'Quick Fix' Directive, implemented in February 2022, removed product governance requirements for simple corporate bonds with "make-whole clauses". ESMA has also collaborated with National Competent Authorities (NCAs) to evaluate the implementation of product governance rules, with potential guidance and changes anticipated. In the UK, the FCA's February 2021 Review assessed asset management firms' compliance with MiFID II's product governance regime (FCA PROD) and its consideration of end-client interests throughout the product lifecycle. This area remains a focal point for the FCA, with potential adjustments to PROD rules for distributors under consideration based on the report findings.	For UK firms, HM Treasury is expected to consult on any changes to the UK PROD rules on the back of the 'Quick Fix' change, and the FCA is also expected to do a broader review.
Transaction reporting	In March 2021, ESMA published its Final Report proposing changes to the MIFIR Transaction Reporting (TR) Regime. The review aimed to refine and clarify certain data fields based on over two years of transaction reporting experience under MiFIR. Proposed changes include replacing the trading on a trading venue (TOTV) concept with the SI approach for OTC derivatives, removing the short sale indicator, aligning with reporting regimes such as MAR, EMIR, and the Benchmark Regulation, relying on international standards like LEIs, ISINs, and CFIs, and adding three additional data elements to harmonise reporting practices and prevent inconsistent and duplicative reporting.	If ESMA's proposals are adopted, it could lead to divergence between EU and UK transaction reporting regimes unless the FCA aligns with them.
Best execution	The EC's MiFID II 'Quick Fix' Directive suspended the obligation to produce best-execution reports under RTS 27 for execution venues, market makers, and SIs from 28 February 2022. The UK Government's Markets in Financial Instruments (Capital Markets) (Amendment) Regulation, along with the FCA's policy statement (PS21/20), confirmed the removal of the RTS 28 reporting obligation for investment firms' top 5 execution venues, as well as the removal of the RTS 27 reporting obligation for venues.	The UK's approach differs by solely removing the RTS 27 obligation for venues, creating a rule divergence between the EU and UK.

Theme	What is changing?	EU/UK divergence notes
Transparency regime	The European Commission's November 2021 proposals aim to revise MIFIR requirements, including reducing the dark trading double volume cap (DVC) from 8% to 7% and removing the venue-specific 4% DVC. Changes to the systematic internaliser regime may redirect volumes from venues to lit markets. In the UK, the Wholesale Markets Review proposes simplifying transparency requirements, enhancing competitiveness, and improving consumer outcomes. Areas of focus include recalibrating transparency for fixed income and derivatives, amending the Reference Price Waiver for better execution, and simplifying the SI regime, among others.	Dark pools: While the UK confirmed the removal of the DVC requirement, the EU's approach differs as the EU wants to retain this tool and only proposed to adjust the limits slightly. The UK removed the DVC requirement, while the EU proposed minor adjustments to its limits. ESMA suggests narrowing the scope of the share trading obligation (STO) to shares with an European Economic Area (EEA) ISIN and disagrees with prioritising best execution obligations over the STO, unlike the UK's decision to abolish the UK STO for UK shares.

Source: Adapted from Pershing. (n.d.). MiFID II and MiFIR Reviews. [online] Available at: https://www.pershing.com/uk/en/perspectives/market-regulatory-risk-planning/mifid-ii-and-mifir.html [Accessed 25 Apr. 2024].

3.1.2 User requirements

Table 7 User requirements for use case

Application	Timing accuracy	Availability	Integrity	Continuity	Indoors (Y/N)
Time stamping	1ms	99.9%	Y	The timing & sync system shall provide continuity of service	Y

Source: MiFID II RTS-25 and European Union Agency for the Space Programme (EUSPA). User Needs and Requirements #EUSpace Report on Insurance and Finance. Available at: https://www.euspa.europa.eu/sites/default/files/report_on_insurance_and_finance_user_needs_and_requirements.pdf [Accessed 4 Jun. 2024].

3.1.3 Drivers and enablers for adopting resiliently disseminated time

Large corporate stakes at risk

With substantial investments and assets on the line, institutions are acutely aware of the potential financial repercussions of timing disruptions. A pertinent example of such consequence is the penalty imposed for failure to comply with the strict regulatory framework established by the MiFID II framework. Companies failing to adhere to the stipulated regulations face maximum fines of up to 10% of their global annual turnover[12]. Moreover, operational disruptions stemming from timing outages can lead to revenue losses during the affected period, due to the inability to execute trades. Additionally, some trading venues, such as the London Stock Exchange, offer exchange hosted services[13]. These services include offering cabinet space within their data centres and providing market connectivity services, including time synchronisation. This facilitates low-latency trading for their clientele. Beyond direct financial setbacks, entities within the sector depend significantly on credibility and reputation to establish and retain the trust of their investors, assuring them of the security of their funds. A prolonged outage due to the loss of time will impact investor confidence on the robustness of the financial organisation's operations.

[12] European Commission (2014). *DIRECTIVE 2014/65/EU OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 15 May 2014 on markets in financial instruments and amending Directive 2002/92/EC and Directive 2011/61/EU*

[13] EXCHANGE HOSTING SERVICE - LONDON (Including the LSEG TRADING LAUNCHPAD SERVICE) PRICE LIST. (2023). Available at: https://docs.londonstockexchange.com/sites/default/files/documents/exchange-hosting-service-price-list-jan-2024_1.pdf [Accessed 9 Apr. 2024].

Increasing regulatory oversight on trading venue outages

Technical outages at stock exchanges have become a relatively common occurrence[14], often deemed inevitable due to the complexities of modern financial systems. During the latter part of 2023, the London Stock Exchange (LSE) encountered two instances of outages affecting Alternative Investment Market (AIM) stocks between October and December[15], while in June 2023 the SIX Swiss Exchange experienced its worst outage in over 10 years, halting trading for three hours[16]. These outages, which disrupt trading operations outright or impede the orderly conduct of trading venues, can have far-reaching implications for market integrity, resilience, and investor confidence. Market outages can significantly impact price discovery mechanisms, hinder firms' risk hedging capabilities, and erode market confidence, ultimately jeopardising the functioning of global capital markets. The financial ramifications of IT downtime within trading environments can be large, with potential losses as high as £7.43 million per hour[17].

Recognising the critical importance of trading venue resilience, regulatory bodies such as the Financial Conduct Authority (FCA) and the European Securities and Markets Authority (ESMA) have intensified their focus on enhancing market resilience during outages. The FCA has established a taskforce on "good practices" to address conduct during outages and has released a report outlining strategies to improve market resilience[18]. Similarly, ESMA has published recommendations for trading venues to follow in the event of a market outage, urging National Competent Authorities (NCAs) to ensure that trading venues have appropriate outage plans in place[19]. Considering these developments, the regulatory emphasis on enhancing market resilience amidst outages serves as a clear indication to market infrastructure providers that resilience is increasingly essential. This presents an opportunity for market infrastructure providers to prioritise the adoption of resiliently disseminated time services as a proactive resiliency measure to mitigate the impact of outages and safeguard the integrity and stability of global financial markets.

Safeguard against market manipulation practices

Market manipulation persists in financial trading, propelled by profit-seeking incentives. Despite heightened regulatory scrutiny, the increasing speed and volume of trading orders necessitate more advanced technology to detect and uphold fair market practices, ensuring integrity amidst evolving challenges. One of the most insidious forms of market manipulation is spoofing. Spoofing in the finance context, not to be confused with GNSS spoofing, involves traders placing orders with the intention to cancel them, thereby influencing prices in a desired direction. Detecting such activity poses challenges due to the complex nature of electronic platforms and the rapid speeds at which orders are executed. A number of large fines have been handed out in recent years for firms found

[14] Cboe Exchange, (2021). *Recommendations to Improve Market Resilience to Venue Outages*. [online] Available at: https://cdn.cboe.com/resources/participant_resources/Market_Outages_Paper.pdf [Accessed 15 Apr. 2024].

[15] euronews. (2023). *LSE outage: What happened and which companies were impacted?* [online] Available at: https://www.euronews.com/business/2023/12/06/lse-outage-what-happened-and-which-companies-were-impacted [Accessed 15 Apr. 2024].

[16] www.thetradenews.com. (n.d.). *SIX Swiss Exchange experiences worst outage for over a decade - The TRADE*. [online] Available at: https://www.thetradenews.com/six-swiss-exchange-experiences-worst-outage-for-over-a-decade/ [Accessed 15 Apr. 2024].

[17] Amulet Hotkey. (n.d.). *Investing In Reliability: Why Downtime Is Not An Option*. [online] Available at: https://www.amulethotkey.com/news-events/investing-in-reliability-why-downtime-is-not-an-option/ [Accessed 25 Apr. 2024].

[18] Financial Conduct Authority, (2023). *Improving Equity Secondary Markets*. [online] Available at: https://www.fca.org.uk/publication/policy/ps23-4.pdf [Accessed 15 Apr. 2024].

[19] European Securities and Market Authority, (2023). Final Report on market outages. [online] Available at: https://www.esma.europa.eu/sites/default/files/2023-05/ESMA70-156-6458_Final_Report_on_market_outages.pdf [Accessed 15 Apr. 2024].

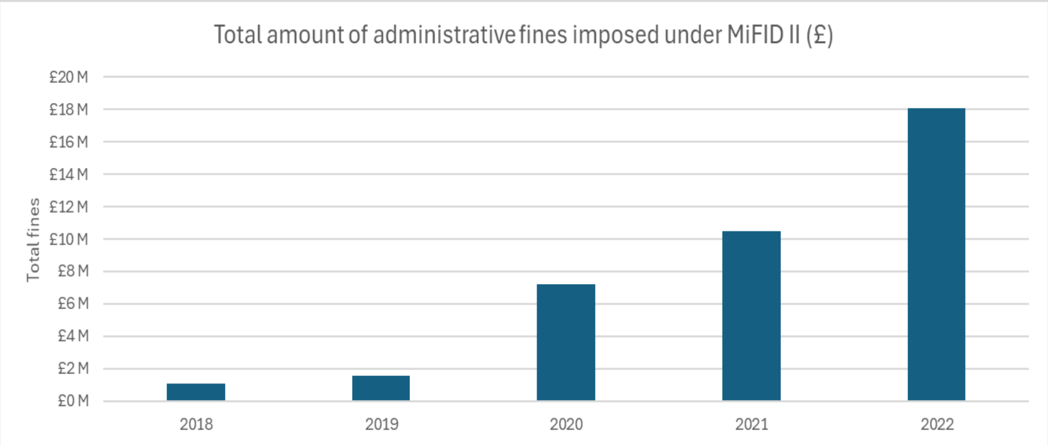
engaging in spoofing activities, including JP Morgan ($920M)[20], Deutsche Bank ($130M)[21] and Bank of America ($24M)[22]. High resolution and reliable timestamps enable trading venues to detect and prevent spoofing by analysing order book activity in real-time, conducting post-trade analysis, and sharing accurate data with regulators. It enhances market integrity, fosters trust among participants, and demonstrates a commitment to fair and orderly trading practices. As technologies to manipulate time become more prolific and accessible, it is imperative for market participants to remain vigilant and continuously enhance surveillance measures to safeguard market integrity.

3.1.4 Blockers for adopting resiliently disseminated time

Lack of fines imposed for breaches of MiFID II

The value of fines imposed under MiFID II on companies from 2018 to 2022[23] as shown in Figure 6 below, could potentially indicate a broader issue related to the willingness to invest in a resiliently disseminated time service. While fines have been levied in certain instances, their magnitude appears modest when compared to the substantial global revenues generated by major financial firms operating within the purview of MiFID II. The relatively low level of fines may suggest that some companies would not see an urgency in prioritising investment in such services. The minimal fines could stem from either the adequacy of existing measures established by trading venues and SIs to comply with MiFID II regulations. Alternatively, it could indicate that no incidents occurred that compromised the existing timing solution, or it may suggest a potential lack of supervisory oversight. Despite an increase in the total amount of administrative fines imposed during this period, the European Securities and Markets Authority (ESMA) advises caution when interpreting this data. This increased total may be skewed by a few instances of exceptionally high fines imposed by the National Competent Authorities (NCAs) of only a few member states.

Figure 6 Fines imposed under MiFID II on companies within the EU



Source: Anon, (2023). Sanctions and measures imposed under MiFID II in 2022 . [online] Available at: https://www.esma.europa.eu/sites/default/files/2023-07/ESMA35-335435667-4321_Report_MiFID_II_sanctions_2022.pdf [Accessed 9 Apr. 2024].

[20] www.cftc.gov. (n.d.). *CFTC Orders JPMorgan to Pay Record $920 Million for Spoofing and Manipulation | CFTC*. [online] Available at: https://www.cftc.gov/PressRoom/PressReleases/8260-20#:~:text=CFTC%20Orders%20JPMorgan%20to%20Pay [Accessed 8 Apr. 2024].

[21] Nasdaq.com. (2021). *News and Insights*. [online] Available at: https://www.nasdaq.com/articles/deutsche-bank-db-settles-spoofing-case-to-pay- [Accessed 8 Apr. 2024].

[22] Stempel, J. (2023). *US regulator fines Bank of America $24 mln for Treasuries spoofing*. [online] Available at: https://www.reuters.com/business/finance/us-regulator-fines-bank-america-24-mln-treasuries-spoofing-2023-11-30/ [Accessed 4 Aug. 2024].

[23] Anon, (2023). *Sanctions and measures imposed under MiFID II in 2022* . [online] Available at: https://www.esma.europa.eu/sites/default/files/2023-07/ESMA35-335435667-4321_Report_MiFID_II_sanctions_2022.pdf [Accessed 9 Apr. 2024].

Switching costs from current timing solutions

When contemplating the transition to a new timing service, trading venues and SIs will assess the balance between the enhanced value offered by the new service and the expenses incurred during the switch. These expenses encompass various facets, including any costs associated with retraining employees to adapt to the new technology and acquiring new equipment to support the transition. Additionally, there may be write-offs required for investments made in outdated technology, further adding to the financial considerations. Moreover, depending on the user, implementing a new timing service may require a range of support services, including engineering support and repair services to address any issues that may arise. Furthermore, conducting thorough vendor evaluations and due diligence processes will be an essential but time-consuming activity for implementing a new service to its operations, adding to the complexity of the decision-making process. Operational disruptions, such as downtime and data migration, and system reconfigurations further compound the challenges faced during the transition.

3.1.5 Market sizing methodology

TAM assessment approach

The Total Addressable Market (TAM) for trading venues and Systematic Internalisers (SIs) for timing is influenced by the potential fines they might face for violating MiFID II regulations. These fines can amount to 10% of their annual global turnover.

When a parent company or any of its subsidiaries are fined, the fine is determined based on the total annual turnover outlined in their consolidated financial statements prepared under Directive 2013/34/EU. This turnover is taken from the most recent financial statements approved by the parent company's management. Therefore, the turnover subject to fines is that of the parent company, even if the fine is related to a subsidiary's breach of regulations.

To prevent double counting in market sizing exercises, where parent companies have subsidiaries in both the UK and the EU, the market sizing considers three categories of trading venues/SIs: those solely based in the UK, those solely based in the EU, and a pan-European category for companies with presence in both regions.

Willingness to pay for a resiliently disseminated time service is then determined in a low, central, and high scenario by multiplying the fine for each company by the annualised probability of GNSS loss, taken from the National Risk Register.

Forecasting turnover growth

The turnover growth is forecast using an annual growth range of 2% to 4% for the market infrastructure industry forecast by Oliver Wyman[24]. Employing this range, a sensitivity analysis is conducted, with the low scenario assuming a 2% growth rate, the central scenario considering a 3% growth rate, and the high scenario anticipating a 4% growth rate.

[24] www.oliverwyman.com. (n.d.). Global Market Infrastructure: How MI Providers Can Achieve Breakthrough Growth. [online] Available at: https://www.oliverwyman.com/our-expertise/insights/2018/oct/global-market-infrastructure-industry-analysis-2018.html [Accessed 12 Apr. 2024].

Figure 7 Market sizing approach

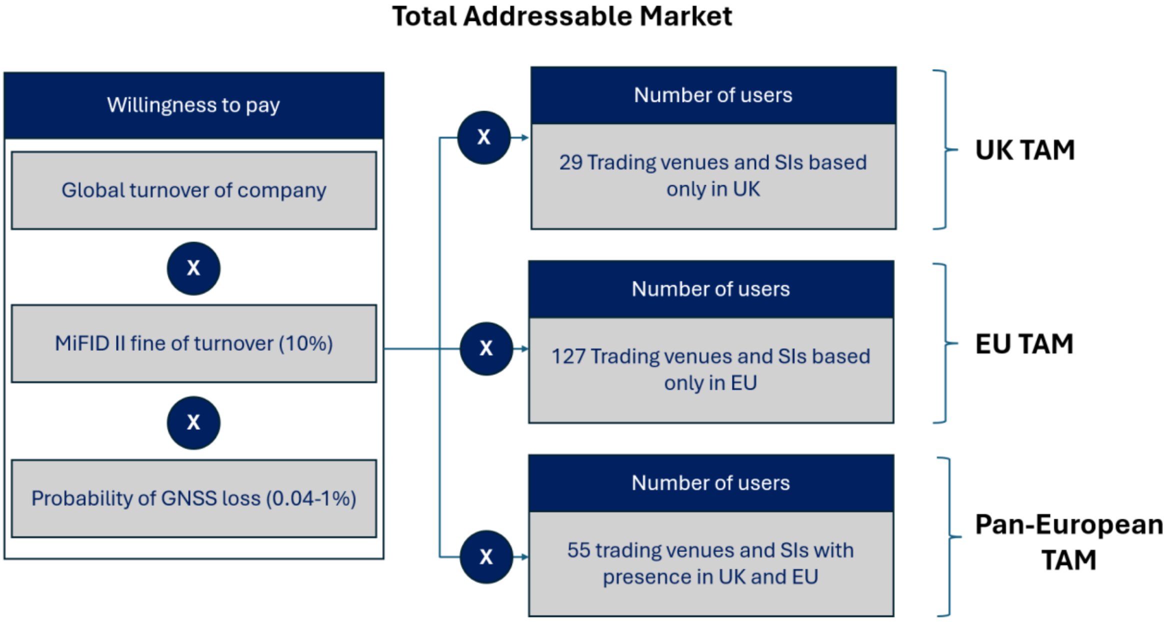


Table 8 Market sizing parameters

Parameter	Description	Source
(1) Global turnover of company	Annual total revenue generated by the company from all its operations worldwide	FAME database and LE analysis
(2) Regulatory fine of turnover	The fine imposed by regulators under MiFID (10% of global turnover).	European Securities and Markets Authority (ESMA)
(3) Probability of GNSS loss	Annualised probability of loss of GNSS services (0.04-1%)	National Risk Register
(4) Number of trading venues and SIs	Count of trading venues and systematic internalisers within a financial market or regulatory framework	FCA - UK ESMA - EU

Note: The National Risk Register assessed likelihood of loss of GNSS over 5 years, so the published probabilities in the register were divided by five to calculate the annual risk.

Source: Financial Conduct Authority (FCA). NewRegister. [online] Available at: https://register.fca.org.uk/s/resources [Accessed 26 Apr. 2024]; European Securities and Market Authority (ESMA). ESMA Registers. [online] Available at: https://registers.esma.europa.eu/publication/searchRegister?core=esma_registers_upreg [Accessed 26 Apr. 2024].

3.1.6 Market sizing results

The forecasted total addressable market (TAM) for pan-European, UK, and EU markets are projected across low, central, and high scenarios, incorporating the range of industry growth rates and the annualised probability of GNSS loss from the National Risk Register as sensitivity variables (0.04%, 0.2%, and 1%, respectively). European markets were considered for international comparison due to the similarities in regulatory environments between the UK and Europe under MIFID II.

Total addressable market – Pan-European

In the central scenario, the TAM for trading venues and SIs based in both the UK and EU (pan-European) is currently valued at approximately £189.2 million, and is projected to reach £225.9 million in 2030, with a compound annual growth rate (CAGR) of 3%.

Table 9 Range of TAM estimates for pan-European market (2024-2030)

Scenario	2024	2025	2026	2027	2028	2029	2030
Low	£37.47m	£38.22m	£38.99m	£39.77m	£40.56m	£41.37m	£42.20m
Central	£189.21m	£194.88m	£200.73m	£206.75m	£212.96m	£219.34m	£225.92m
High	£955.23m	£993.44m	£1,033.17m	£1,074.50m	£1,117.48m	£1,162.18m	£1,208.67m

Figure 8 Growth of pan-European TAM under low scenario

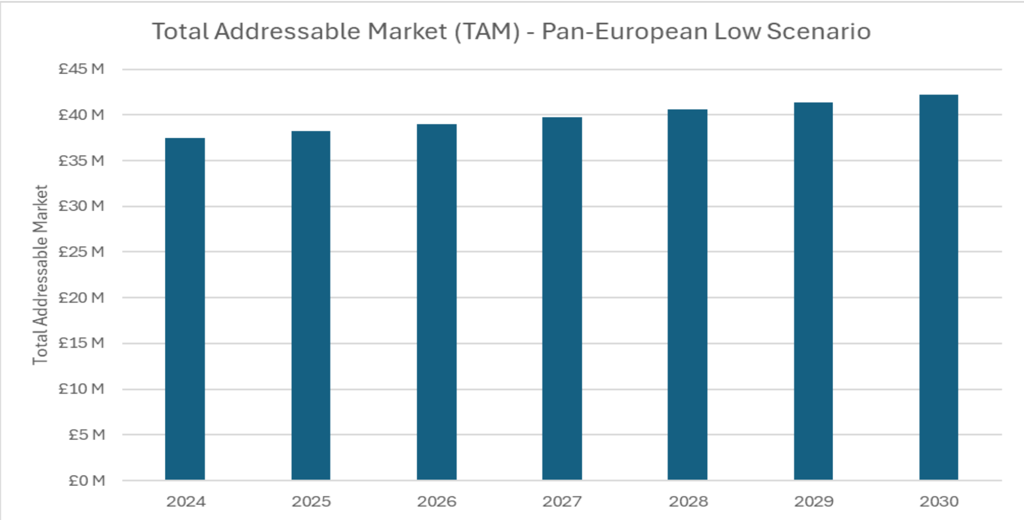


Figure 9 Growth of pan-European TAM under central scenario

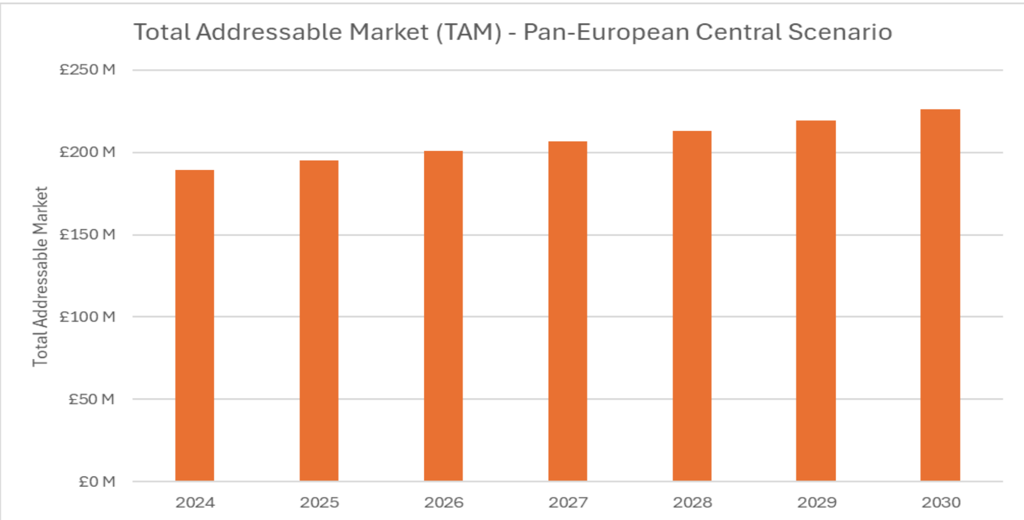
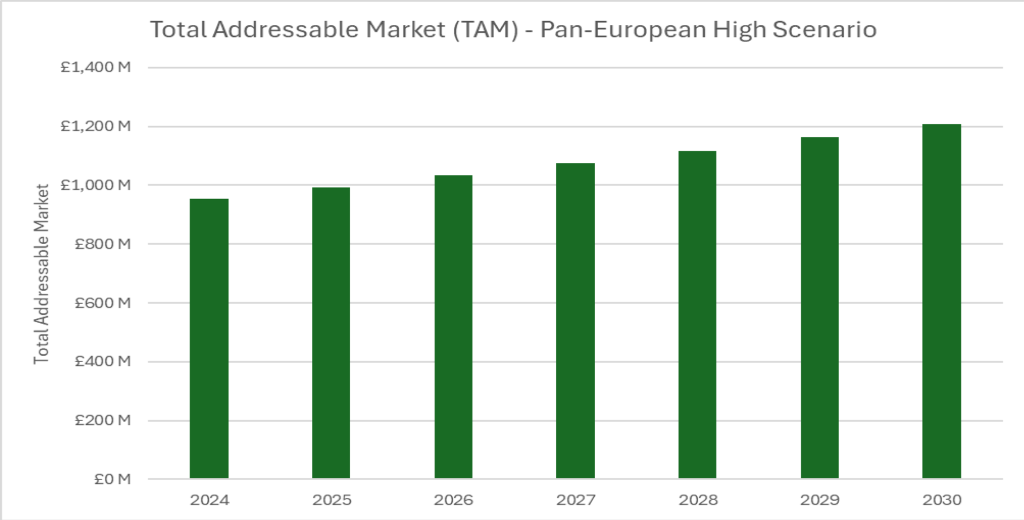


Figure 10 Growth of pan-European TAM under high scenario



Total addressable market - UK

In the central scenario, the TAM for trading venues and SIs based in the UK only is currently valued at approximately £54.7 million, and is projected to reach £65.3 million in 2030, with a compound annual growth rate (CAGR) of 3%.

Table 10 Range of TAM estimates for UK market (2024-2030)

Scenario	2024	2025	2026	2027	2028	2029	2030
Low	£10.84m	£11.05m	£11.27m	£11.50m	£11.73m	£11.96m	£12.20m
Central	£54.71m	£56.35m	£58.04m	£59.78m	£61.58m	£63.42m	£65.33m
High	£276.21m	£287.26m	£298.75m	£310.70m	£323.12m	£336.05m	£349.49m

Figure 11 Growth of UK TAM under low scenario

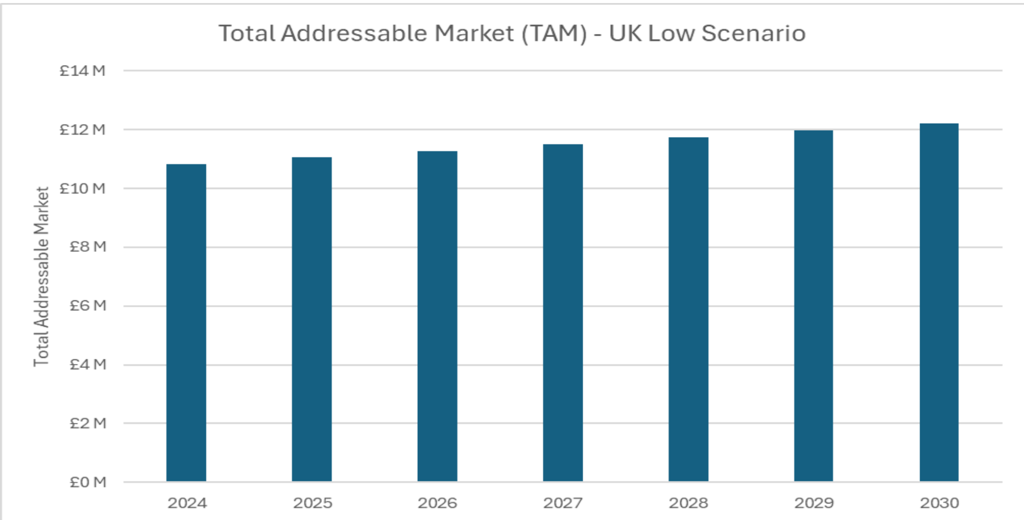


Figure 12 Growth of UK TAM under central scenario

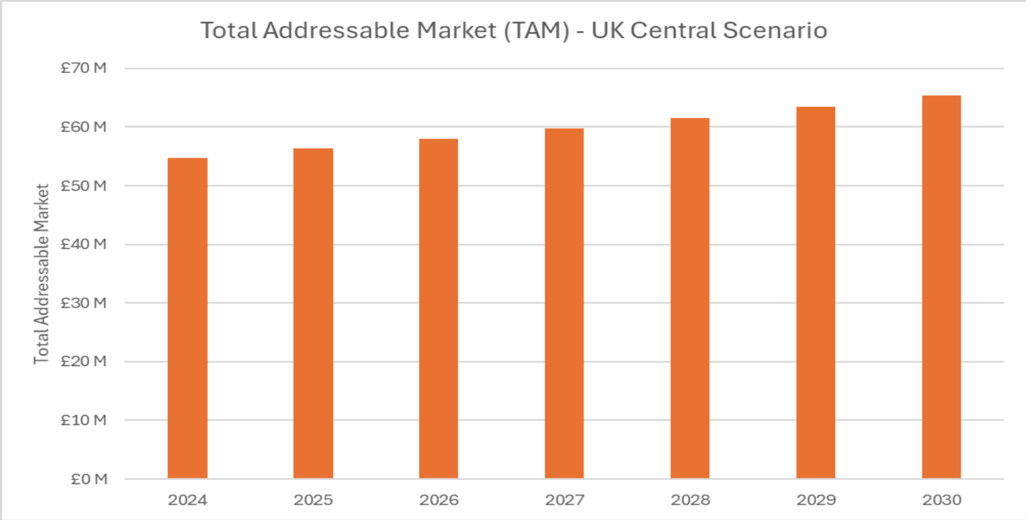
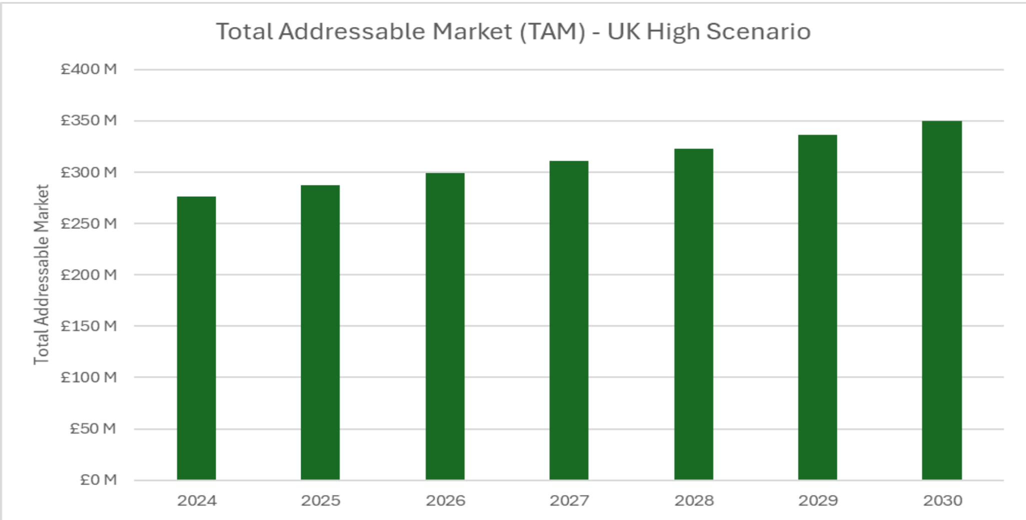


Figure 13 Growth of UK TAM under high scenario



Total addressable market - EU

In the central scenario, the TAM for trading venues and SIs based in the EU only is currently valued at approximately £56.3 million, and is projected to reach £67.3 million in 2030, with a compound annual growth rate (CAGR) of 3%.

Table 11 Range of TAM estimates for EU market (2024-2030)

Scenario	2024	2025	2026	2027	2028	2029	2030
Low	£11.16m	£11.38m	£11.61m	£11.84m	£12.08m	£12.32m	£12.57m
Central	£56.33m	£58.02m	£59.76m	£61.56m	£63.40m	£65.31m	£67.27m
High	£284.40m	£295.78m	£307.61m	£319.92m	£332.71m	£346.02m	£359.86m

Figure 14 Growth of EU TAM under low scenario

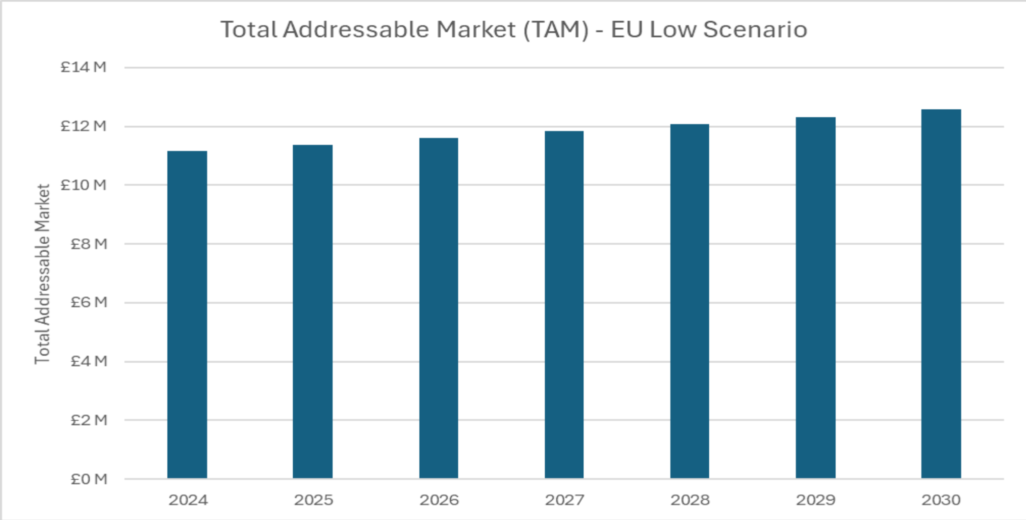


Figure 15 Growth of EU TAM under central scenario

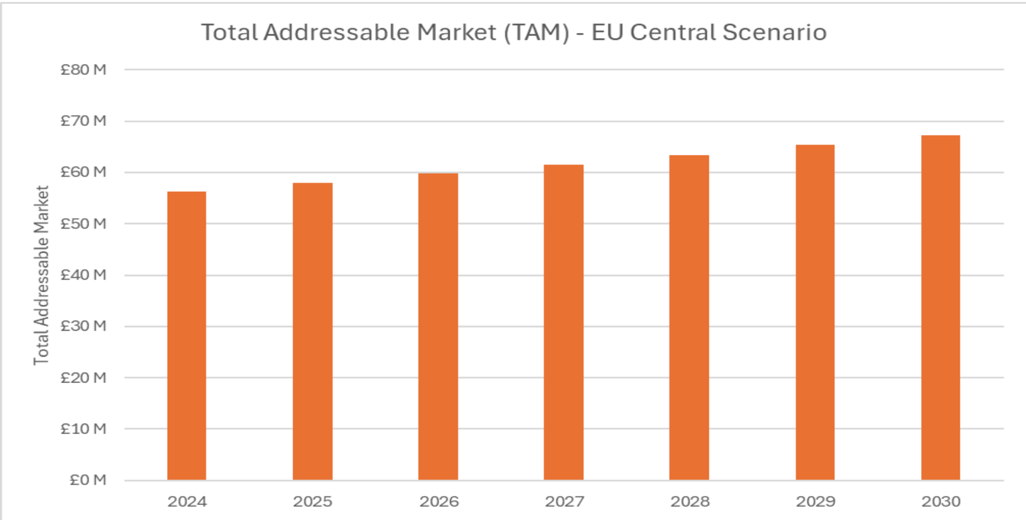
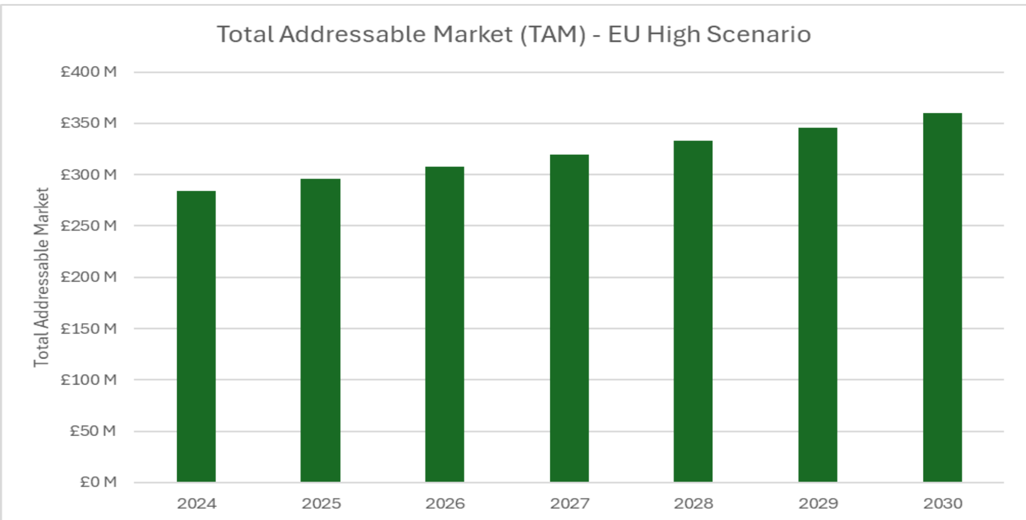


Figure 16 Growth of EU TAM under high scenario



3.1.7 Conclusions

- Timing is **crucial for daily operations of trading venues and SIs** to ensure they can provide participants with uninterrupted access to the markets and meet regulatory obligations.
- While nanosecond resolution provides extremely high precision, **non-HFT trading activities** and **regulatory requirements** are adequately served by **microsecond** or **millisecond resolution**.
- There are **large corporate stakes at risk** in the event of a loss of the ability to timestamp accurately that act as strong incentives for the adoption of resiliently disseminated time:
  - The potential of **hefty fines levied under MiFID regulations** of up to 10% of global annual turnover, should these market infrastructure providers be unable to timestamp transactions to the required accuracy serve as a direct financial incentive.
  - Those offering timing services through hosted services, such as the LSE, are motivated to uphold robust timing infrastructure to avoid **breaching service level agreements** with co-located customers.
  - To **maintain trust** with market participants and **prevent disruptions** that could lead to dissatisfaction among customers and erode competitive standing, market infrastructure providers will need to prioritise reliability.
- However, the apparent **lack of regulatory fines** imposed under MiFID may suggest a lower willingness to pay for a resiliently disseminated time service.
  - The absence of significant disruptions attributable to timing issues and the perceived adequacy of existing timing infrastructure could pose challenges to market adoption.
  - Furthermore, the inertia associated with switching to new timing solutions due to entrenched systems and perceived low urgency may hinder widespread adoption.
- Nonetheless, **regulatory focus on market outages is intensifying**, with bodies like the FCA and ESMA taking proactive measures to enhance market resilience.
  - The establishment of task forces to develop good practices and issuance of guidelines in the event of outages signal a growing recognition of operational resilience as a critical market issue.
- For each market, the central estimate of the TAM is:
  - Pan-European: **£189.2 million in 2024** rising to **£225.9 million by 2030**.
  - UK-only: **£54.7 million in 2024** rising to **£65.3 million by 2030**.
  - EU-only: **£56.3 million in 2024** rising to **£67.3 million by 2030**.
- While the EU-only market has more trading venues and SIs (29 vs 127), the marginal difference in the TAMs can be attributed to **the significantly higher average revenue of UK-only firms** compared to their EU-only counterparts (~£9.3 billion versus ~£2.2 billion).
  - In context of the TAM, revenue emerges as the primary determinant of willingness to pay for a resiliently disseminated time service, largely influenced by the fines imposed by MiFID based on revenue.
- Unsurprisingly the **pan-European market holds the greatest market opportunity**, as these organisations have a global presence and are household names in the finance industry (e.g. JP Morgan, Bank of America, Citigroup, etc.).

3.2 UC2: Future trading

Actors within the Future Trading use case are those financial organisations that are engaged in High-Frequency Trading (HFT). High-Frequency Trading is a sophisticated trading strategy employed by firms that leverage cutting edge technology and ultra-low latency infrastructure to execute trades with unparalleled speed and efficiency, often within microseconds or even nanoseconds. These firms invest heavily in cutting-edge hardware, advanced software, and direct market access (DMA) to minimise latency and gain a competitive edge in the market. HFT strategies are designed to capitalise on small price discrepancies, arbitrage opportunities, and market inefficiencies across various trading venues.

Article 4 of the MiFID II Directive[25] defines a firm engaging in high frequency algorithmic trading as those firms that:

(a) Use infrastructure intended to minimise network and other types of latencies, including at least one of the following facilities for algorithmic order entry: co-location, proximity hosting or high-speed direct electronic access.
(b) Employ system-determination of order initiation, generation, routing, or execution without human intervention for individual trades or orders.
(c) High message intraday rates which constitute orders, quotes, or cancellations.

There are three typical categories of HFT firms[26]:

1. **Proprietary firms:** This is the largest segment, and consists of companies carrying out HFT using their own capital. They typically focus on market making, arbitrage, and other quantitative trading strategies to generate profits from the financial markets.
2. **Broker-dealer proprietary desks**: Traditional broker-dealer firms maintain distinct proprietary trading desks dedicated to HFT, which operate independently from their client-facing businesses. This setup is observed in major investment banks, among others.
3. **Hedge funds**: Hedge funds can employ HFT as part of their investment strategies, generally focusing on statistical arbitrage, where they exploit short-term price discrepancies between related securities.

Within this landscape, companies are characterised by their innovative approaches and methods in several areas including:

Algorithmic trading and artificial intelligence (AI): Algorithmic trading and AI is at the forefront of the HFT market, serving as a pivotal component in executing vast quantities of trades swiftly and efficiently. These algorithms operate on predetermined rules and parameters, harnessing intricate mathematical models, statistical analyses, and AI methodologies, including machine learning (ML). By integrating AI capabilities, algorithmic trading systems can dynamically adapt to changing market conditions, learn from historical data, and refine their strategies in real-time. This enables them to accurately identify lucrative trading opportunities, seamlessly execute orders, and proficiently manage risk with a high degree of precision and automation.

[25] DIRECTIVE 2014/65/EU OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 15 May 2014 on markets in financial instruments and amending Directive 2002/92/EC and Directive 2011/61/EU (recast) (Text with EEA relevance). (n.d.). Available at: https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32014L0065.

[26] Capgemini (2017). Available at: https://www.capgemini.com/wp-content/uploads/2017/07/High_Frequency_Trading__Evolution_and_the_Future.pdf.

Alternative data: HFT companies incorporate alternative and novel data sources, such as satellite imagery, social media sentiment, geolocation data, news feeds, and communications metadata to supplement traditional market data and enhance trading strategies. In the coming years, progress in storage, capture, and analysis technology is anticipated to fuel a significant increase in both the volume and accessibility of data. Access to the fastest, most reliable, and most relevant information will become ever more crucial to firms seeking to maximise their competitive advantage.

3.2.1 Use of time

Latency measurements

In HFT, latency is critical – a millisecond decline in a decision latency may support a HFT firm's revenue by around £100 million a year. Understanding the latencies of the network's component systems is crucial to determine where improvement efforts should be directed, emphasising the importance for precise latency measurements[27]. Any discrepancy in time accuracy can lead to a significant deterioration in the statistical foundation upon which HFT trading decisions are based. This is because HFT algorithms heavily rely on statistical data, like how often trades happen and the time it takes for information to travel between exchanges, building these into execution logic in models. Ensuring the delivery of accurate timing to the application level of these algorithms is crucial. By providing real-time latency data, HFT firms can integrate these metrics directly into their trading decisions. The importance of accuracy extends throughout the entire decision-making process, as any inaccuracies can introduce inconsistencies and degrade algorithm performance. Additionally, understanding true latency enables greater risk management. By understanding the exact timing of trade executions, algorithms can gauge the freshness of market data and assess the potential risks associated with outdated information.

Server to server synchronisation

The increasing demands on algorithm performance in HFT have resulted in greater numbers of servers and greater numbers of processing platforms within each server[28]. To ensure efficient operation of this distributed processing model, precise time synchronisation between servers is essential. Accurate timing ensures that trading algorithms receive consistent and reliable data, enabling them to make informed decisions based on the most up-to-date market information. In the fast-paced environment of HFT, where split-second decisions are commonplace, any discrepancies in timing synchronisation can lead to inefficiencies and potentially missed opportunities for profitable trades.

Regulatory compliance: Financial trading organisations face rigorous regulatory requirements concerning the accuracy of timestamping financial transactions. In the European Union (EU), institutions are legally obligated to adhere to the Markets in Financial Instruments Directive (MiFID II) standard. MiFID II mandates precise timestamping of transactions to ensure transparency, market integrity, and investor protection. The MiFID II requirements for clock synchronisation are set out in Commission Delegated Regulation (EU) 2017/574, commonly known as RTS 25. The precision specified for different types of trades is 100 microseconds for High Frequency Trading (HFT), 1

[27] The Application of Network Based Synchronisation in HFT Infrastructure. (2011). Available at: https://www.korusys.com/wp-content/uploads/2019/08/Korusys-Network-Sync-In-HFT.pdf [Accessed 16 Apr. 2024].

[28] Equinix, (n.d.). *Rewriting the rules for financial trading infrastructure*. [online] Available at: https://info.equinix.com/rs/equinixinc/images/WhitePaper_M2M%202-0.pdf?mkt_tok=3RkMMJWWfF9wsRonvqjLZKXonjHpfsX77OQsXqKwlMI%2F0ER3fOvrPUfGjI4CRcNjI%2BSLDwEYGJlv6SgFS7jFMbNs1rgNWRA%3D [Accessed 16 Apr. 2024].

millisecond for non-HFT trades, and 1 second for human trades[29]. The UK follows its own version of MiFID II known as the UK MiFID, a near-identical, parallel framework.

3.2.2 User requirements

Table 12 User requirements for use case

Application	Timing accuracy	Availability	Integrity	Continuity	Indoors (Y/N)
Time stamping	100µs	99.9%	Y	The timing & sync system shall provide continuity of service	Y

Source: MiFID II RTS-25 and European Union Agency for the Space Programme (EUSPA). User Needs and Requirements #EUSpace Report on Insurance and Finance. Available at: https://www.euspa.europa.eu/sites/default/files/report_on_insurance_and_finance_user_needs_and_requirements.pdf [Accessed 4 Jun. 2024].

3.2.3 Drivers and enablers for adopting resiliently disseminated time

Technology and regulatory evolution

The HFT market is characterised by the pursuit of outperforming competitors and exploiting market arbitrage opportunities ahead of rivals through a latency "arms race". Over the years, there has been significant improvements in trading speeds[30]. For instance, between 2005 and 2011, trading speed decreased from 97 milliseconds to 7 milliseconds. By 2015, it had already dropped to less than 1 millisecond, and by 2016, less than one microsecond. Technology plays an increasingly crucial role in this endeavour. Network equipment providers are responding to demands for reduced latency and better traffic management, improving the speeds at which market data can be received[31]. High frequency traders employ various methods to reduce latency, utilising different communication technologies such as fibre optics, as well as open-air communication systems like microwaves and lasers, to achieve faster speeds. As the industry continues to evolve and strive for a competitive advantage in latency reduction, the speed of HFT will continue to increase, leading to tighter tolerances for time synchronisation.

In 2023, a coalition of HFT firms, known as the Shortwave Modernisation Coalition (SMC), petitioned the Federal Communications Commission (FCC) to utilise the shortwave band of the radio spectrum for transmitting data between major financial sectors[32]. This initiative aims to achieve faster data transmission compared to higher-frequency signals used in fibre optic or satellite transmissions. This is likely to result in heightened timing and synchronisation requirements. As trading speeds increase, it is expected that regulation will evolve to uphold market transparency and fairness. The UK's Financial Conduct Authority has pledged to "keep pace with evolving market abuse techniques" as outlined in their strategy for 2022-2025[33].

Additionally, in the past, there was a significant reliance on FPGAs (Field-Programmable Gate Arrays) to maintain time accuracy when transitioning between software and hardware. This reliance is due

[29] A complete guide to time stamping regulations in the financial sector Contents. Available at: https://www.npl.co.uk/getattachment/products-services/Time-frequency/npltime/NPLTime-Certified/NPLTime-Brochure.pdf.aspx?lang=en-GB [Accessed 9 Apr. 2024].
[30] Martins, C.J.L. (2018). Regulations and Technology Behind HFT Latency, Batch Auctions and Payments for Order Flow in the US and EU. *e-Finanse*, 14(2), pp.34–46. doi:https://doi.org/10.2478/fiqf-2018-0010.
[31] SiliconANGLE. (2023). *It's back to the future for Arista with new high-frequency trading switches*. [online] Available at: https://siliconangle.com/2023/10/11/back-future-arista-new-high-frequency-trading-switches/ [Accessed 16 Apr. 2024].
[32] www.garp.org. (n.d.). *Could Speedier High-Frequency Trading Prompt the Next Market Meltdown?* [online] Available at: https://www.garp.org/risk-intelligence/technology/speedy-trading-meltdown-102023 [Accessed 17 Apr. 2024].
[33] Our Strategy Our Strategy. (2022). Available at: https://www.fca.org.uk/publication/corporate/our-strategy-2022-25.pdf.

to the fact that software-generated timestamps have inherent delays and inaccuracies as time signals were slow to reach CPUs.[34] The software-hardware border refers to the interface where software (programmes, operating systems, applications) interacts with hardware (physical components like CPUs, memory, and input/output devices). This interaction is crucial for the overall performance and accuracy of computing systems, especially when precise timing is required. Timestamps were generated by software, which necessitated synchronisation with the operating system clock to ensure accuracy. Software timestamping involves generating timestamps using the system's software. When an event occurs, the software records the current time based on the operating system clock.

Today, the situation is improving dramatically. Hardware-based timestamps are becoming more widely available[35], providing a more reliable and precise way to handle time signals. Hardware timestamping involves generating timestamps directly at the hardware level. When an event occurs, the timestamp is created by dedicated hardware components, such as network interface cards (NICs) or motherboards with PPS (Pulse Per Second) inputs and outputs. Modern motherboards now often come equipped with PPS input and output capabilities, allowing for highly accurate time synchronisation directly via hardware. As a result, the ability to utilise precise time has greatly increased. What used to be the exclusive domain of specialised FPGAs for precise timekeeping is now becoming almost ubiquitous in off-the-shelf hardware. This shift means that precise time management is more accessible and easier to implement across a broader range of applications and devices.

As hardware-based timestamping capabilities become more accessible and widely available in off-the-shelf components, there will be a greater reliance on these technologies across various applications. This increased adoption may drive the need for resiliently disseminated time services to ensure efficient and reliable operation.

Certified time source adoption for improved reliability

HFT firms need to minimise latency as much as possible to gain a competitive advantage in executing trades. This is why they collocate their trading systems within or near the exchanges' data centres, minimising the distance and travel time for data and trade orders. Exchanges offer colocation services, which allow HFT firms to host their trading systems within the exchange's data centre facilities[36] (please see Use Case 8 for more detail on Data Centres). These services include providing low-latency network connectivity, computing resources, and other infrastructure necessary for HFT operations. As part of the colocation services, exchanges often provide time synchronisation services to ensure that the trading systems of HFT firms are accurately synchronised with the exchange's reference time. This is crucial for timestamping trades and maintaining fairness in the order execution process.

While some colocation facilities offer precise time synchronisation, they often do so on a "best effort" basis[37]. Unlike certain colocation centres that use certified time sources like those from the National Physical Laboratory (NPL) and can guarantee how closely they adhere to Coordinated Universal Time (UTC), many facilities cannot commit to a stringent performance Service Level

[34] Molenaar, R. (2023). Introduction to Precision Time Protocol (PTP). [online] NetworkLessons.com. Available at: https://networklessons.com/cisco/ccnp-encor-350-401/introduction-to-precision-time-protocol-ptp.
[35] Conversation with former Director of Network Engineering at NYSE
[36] Londonstockexchange.com. (2024). London Stock Exchange | London Stock Exchange. [online] Available at: https://www.londonstockexchange.com/equities-trading/market-connectivity/exchange-hosting [Accessed 22 May 2024].
[37] Conversation with former Global Head of Network Services at NYSE Euronext

Agreement (SLA). This is because their time sources are not certified, and thus they cannot provide the highest assurance of accuracy and reliability[38].

Exchanges providing time synchronisation offer a convenient "set and forget" solution for HFT firms, which simplifies operations and reduces the need for additional infrastructure. However, this convenience may limit the uptake of external, potentially more reliable timing services that could offer better performance guarantees.

Therefore, despite the convenience of exchange-provided time sources, some HFT firms may prefer to maintain their own time servers and Global Navigation Satellite System (GNSS) feeds. By doing so, they can ensure guaranteed performance levels, optimise their algorithms, and enhance their trading systems. Certified time sources are generally more reliable and can provide the high level of accuracy required for HFT operations. This approach allows firms to have greater control over their time synchronisation and can be critical for those who seek to maintain a competitive edge through superior technology and precision.

3.2.4 Blockers for adopting resiliently disseminated time

Declining profits in HFT

HFT was initially a highly profitable enterprise when it was first introduced in the financial markets. The speed advantages afforded by cutting-edge technology and infrastructure allowed HFT firms to get ahead of other market participants and exploit fleeting price discrepancies across different trading venues. In 2009, at the peak of HFT's profitability, revenues from HFT activities in the U.S. equities market alone were estimated to be around $7.2 billion[39]. However, this figure has since declined significantly, falling to below $1 billion by 2017. A couple of driving factors have contributed to this substantial drop in HFT revenues:

Increased competition: As more firms adopted HFT strategies and invested in low-latency infrastructure, the speed advantages that initially fuelled HFT profits began to diminish. If all market participants operate at similar speeds, the HFT advantages disappear. There is a limit to how much latency can be shaved off before being constrained by technological limitations.

Higher costs: To stay competitive and maintain their speed edge, HFT firms had to continually upgrade their technology and infrastructure, incurring significant costs. Additionally, the costs of data feeds and co-location fees charged by exchanges for low-latency access doubled or tripled between 2010 and 2015[40], further eroding profit margins.

This decline in profit margins affects the market size for a resiliently disseminated timing service and may reduce uptake, as cost-conscious HFT firms prioritise investments in other areas that might offer more direct performance benefits.

Lack of transparency and openness in industry

The definition of high-frequency trading (HFT) has faced pushback in response to an ESMA consultation, with only around half of respondents expressing broad satisfaction with their

[38] Conversation with former Director of Network Engineering at Intercontinental Exchange - NYSE
[39] IG. High-frequency trading explained: why has it decreased? [online] Available at: https://www.ig.com/uk/trading-strategies/high-frequency-trading-explained--why-has-it-decreased--181010.
[40] Deutsche Bank. Research briefing: High-frequency trading, reaching the limits (2016). [online] Available at: https://www.dbresearch.com/PROD/RPS_EN-PROD/PROD0000000000454703/Research_Briefing_High-frequency_trading.pdf

definition[41]. This lack of clarity contributes to the challenge of discerning the exact strategies and technologies employed by market participants, and how resilient timing services can be of value. In this highly competitive and secretive environment, firms may be less inclined to adopt an external service or cooperate and share details about their trading infrastructure. The competitive nature of the industry means that firms are wary of revealing proprietary information that could potentially give their competitors an advantage. Additionally, concerns about data privacy and security may further deter firms from embracing external timing services, as they may prefer to maintain control over their trading operations and data. Overall, the lack of transparency and openness in the industry creates hurdles for the adoption of resilient timing services, as firms navigate the complexities of maintaining a competitive edge while safeguarding their proprietary trading strategies and technologies.

Small number of HFT participants in UK market

High-frequency trading holds a less dominant position in the UK compared to the US[42], influenced by several factors. Firstly, the UK's stricter regulatory environment poses challenges for firms looking to engage in HFT activities. Additionally, the UK's financial markets exhibit lower liquidity and greater consolidation than their US counterparts, diminishing the appeal for HFT firms to operate within them. Moreover, the technological infrastructure in the UK may lag behind that of the US, making it more difficult for HFT firms to execute trades swiftly and efficiently. While the US invests heavily in infrastructure optimisation, such as dynamiting and cutting through terrain to shave off microseconds between trading hubs, the UK's progress in this regard appears comparatively nascent. Furthermore, the UK's brokerage landscape offers greater freedom in routing strategies, fostering unpredictability, and purportedly reducing vulnerability to HFT activity[43]. Geographically, the UK's trading venues are closely clustered within approximately 20 miles, contrasting sharply with the vast distances separating some US exchanges, which can exceed 700 miles. Such proximity in the UK minimises the potential for speed advantages, making it challenging for HFT firms to exploit time differentials to the same extent as in the US. The amalgamation of these factors contributes to a smaller HFT market size in the UK, potentially leading to limited demand for resilient timing services.

Lack of well-defined method of auditing time synchronisation performance

There is a lack of a well-defined and standardised method for reporting and auditing time synchronisation performance in the high-frequency trading (HFT) industry[44]. While HFT firms are required to demonstrate compliance with regulations and document their system designs, the process of self-certification and reporting is not comprehensive.

Typically, HFT firms go through a self-certification effort annually, where they fill out forms stating, to the best of their knowledge and ability, that they meet the necessary requirements. In these forms, they outline their time source, its traceability to Coordinated Universal Time (UTC), and how it is performing. However, there is no ongoing reporting or auditing of timing performance beyond these self-reported figures.

[41] MiFID II Review Report MiFID II/MiFIR review report on Algorithmic Trading. 2021. Available at: https://www.esma.europa.eu/sites/default/files/library/esma70-156-4572_mifid_ii_final_report_on_algorithmic_trading.pdf.
[42] Financial, C. to T.L. (2023). High-Frequency Trading: The Algorithm-Driven Future Of Financial Markets | The London Financial. [online] Available at: https://thelondonfinancial.com/markets/high-frequency-trading-the-algorithm-driven-future-of-financial-markets.
[43] FCA Insight. (2017). Under the spotlight: high frequency trading. [online] Available at: https://www.fca.org.uk/insight/under-spotlight-high-frequency-trading.
[44] Conversation with former Director of Network Engineering at Intercontinental Exchange - NYSE

Compliance monitoring systems, such as MiFID dashboards, rely on self-reported figures from various components within the HFT firms' systems. These monitoring systems do not measure true accuracy or conduct independent verification of time synchronisation performance. To accurately assess timing accuracy, a dedicated probe or measurement device is required.

Currently, there is no well-defined form of auditing or independent verification of time synchronisation performance in the finance industry, particularly in the HFT sector. Only a handful of individuals or organisations conduct spot checks by visiting data centres and comparing the Pulse Per Second (PPS) output on network cards of example servers to assess their accuracy.

This lack of a well-defined reporting and auditing framework for time synchronisation performance could lead to a lack of incentive for HFT firms to adopt resilient and highly accurate time services. Without a rigorous auditing process or independent verification, firms may be content with self-reported figures and less inclined to invest in more robust and resilient time synchronisation solutions.

3.2.5 Market sizing methodology

The total addressable market (TAM) for a resiliently disseminated timing service is estimated by analysing the costs associated with both the implementation and maintenance of timing infrastructure, assuming that the HFT company opts to develop and operate its own timing system. This estimation sets a market ceiling, as any new timing service must be competitive in terms of cost effectiveness.

The Financial Industry Regulatory Authority (FINRA) proposed a tightening of clock synchronisation requirements and sought industry responses to this proposal through a survey[45]. Survey respondents indicated that meeting the most stringent proposed standards would cost over £1.1 million to implement, with an annual maintenance cost of £530,000 (in 2024 pounds sterling). These figures are used to estimate the cost of developing and operating timing infrastructure for the market sizing exercise. The lifetime of the timing infrastructure is assumed to be 15 years, which is used to annualise the capital expenditures (CAPEX) to provide a yearly cost.

The number of HFT firms is estimated as a proportion of the total number of investment firms in the UK that provide or perform MiFID investment services or activities, based on data from the FCA investment register[46]. The European Securities and Markets Authority (ESMA) register provides the number of investment firms in the EU[47]. The proportion of these firms that engage in HFT is estimated under three scenarios: low (1%), central (3%), and high (5%). Multiplying the number of HFT firms by the yearly cost of implementing and operating timing infrastructure gives a ceiling value for the TAM.

The future growth of the market depends on the number of firms employing HFT. This is subject to market dynamics such as consolidation and new entrants, which are not estimable over an extended period. Thus, the analysis provides three scenarios: one where the number of HFT firms declines by 2% per year, one where the number remains flat, and one where the number grows by 2%.

[45] Financial Industry Regulation Authority. Notice of Filing of a Proposed Rule Change To Reduce the Synchronization Tolerance for Computer Clocks That Are Used To Record Events in NMS Securities and OTC Equity Securities [online] Available at: https://www.federalregister.gov/documents/2016/02/25/2016-03960/self-regulatory-organizations-financial-industry-regulatory-authority-inc-notice-of-filing-of-a#footnote-42-p9554

[46] Financial Conduct Authority (FCA). Investment firms register. [online] Available at: https://register.fca.org.uk/s/resources.

[47] European Securities and Markets Authority (ESMA). ESMA register. [online] Available at: https://registers.esma.europa.eu/publication/searchRegister?core=esma_registers_upreg

Table 13 Market sizing assumptions

Assumption	Value
Timing infrastructure CAPEX	£1.1 million
Timing infrastructure lifetime	15 years
Annualised timing infrastructure CAPEX	£73k
Timing infrastructure OPEX	£550k
Number of FCA registered investment firms	3051
Number of ESMA registered investment firms	11846
Proportion of investment firms engaged in HFT (low/central/high)	1%/3%/5%
Number of UK investment firms engaged in HFT (low/central/high)	31/92/153
Number of EU investment firms engaged in HFT (low/central/high)	118/355/592
Market growth (declining, flat, growing)	-2%/0%/2%

3.2.6 Market sizing results

UK TAM

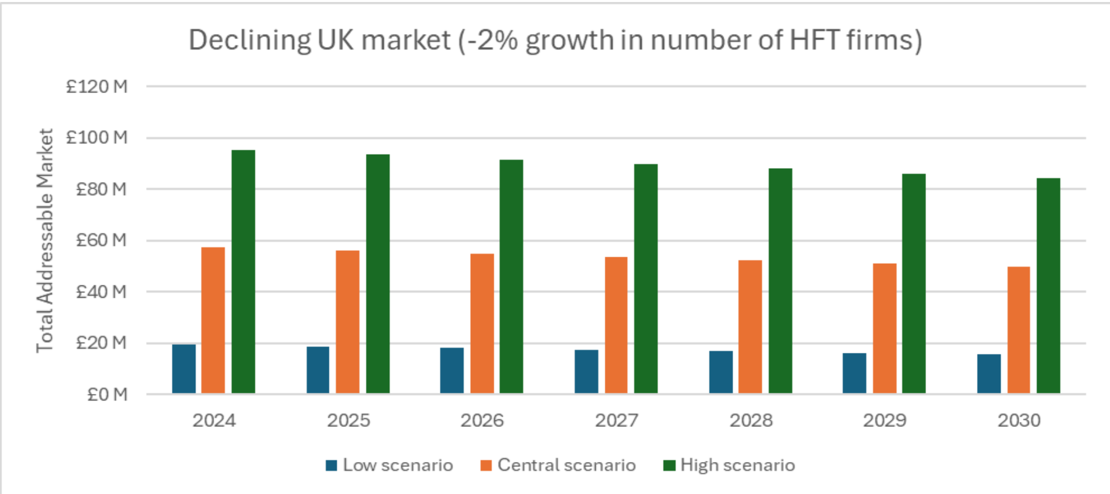
In the central scenario, assuming a flat market growth, the UK total addressable market is estimated to be worth approximately £57 million annually. Results for the different scenarios are presented in the tables below.

Declining UK market

Table 14 UK total addressable market declining growth scenario

Scenario	2024	2025	2026	2027	2028	2029	2030
Low	£19.32m	£18.70m	£18.08m	£17.45m	£16.83m	£16.21m	£15.58m
Central	£57.35m	£56.10m	£54.85m	£53.61m	£52.36m	£51.11m	£49.87m
High	£95.37m	£93.50m	£91.63m	£89.76m	£87.89m	£86.02m	£84.15m

Figure 17 UK total addressable market declining growth scenario

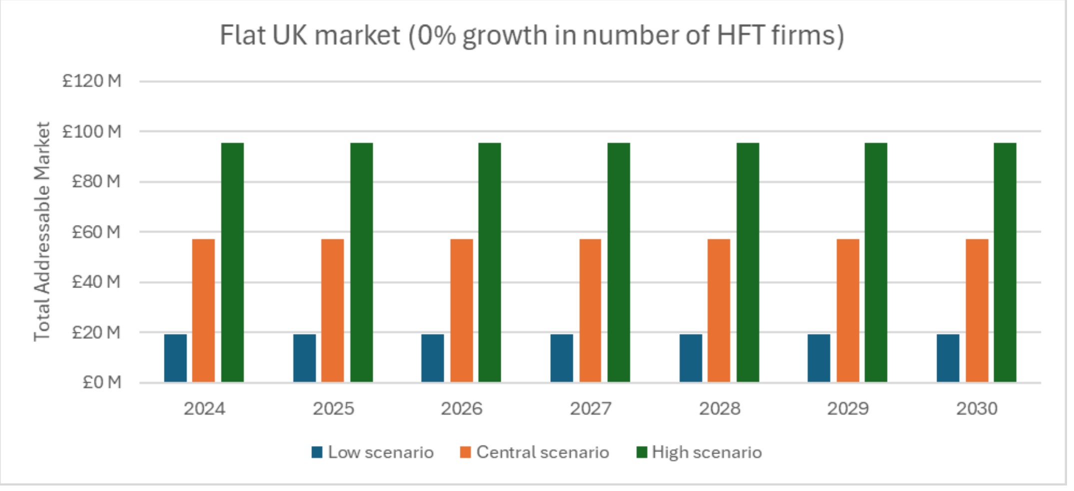


Flat UK market

Table 15 UK total addressable market flat growth scenario

Scenario	2024	2025	2026	2027	2028	2029	2030
Low	£19.32m	£19.32m	£19.32m	£19.32m	£19.32m	£19.32m	£19.32m
Central	£57.35m	£57.35m	£57.35m	£57.35m	£57.35m	£57.35m	£57.35m
High	£95.37m	£95.37m	£95.37m	£95.37m	£95.37m	£95.37m	£95.37m

Figure 18 UK total addressable market flat growth scenario

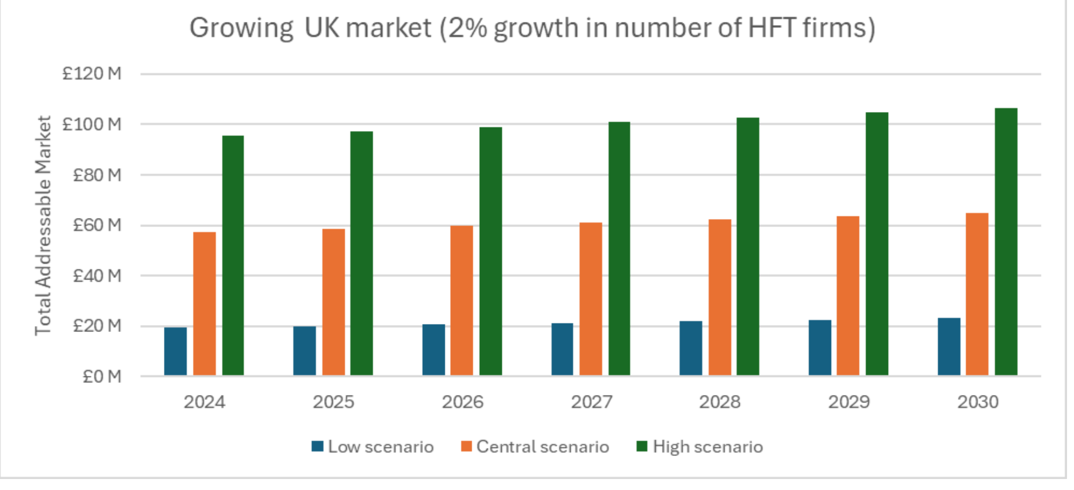


Growing UK market

Table 16 UK total addressable market growth scenario

Scenario	2024	2025	2026	2027	2028	2029	2030
Low	£19.32m	£19.95m	£20.57m	£21.19m	£21.82m	£22.44m	£23.06m
Central	£57.35m	£58.59m	£59.84m	£61.09m	£62.33m	£63.58m	£64.83m
High	£95.37m	£97.24m	£99.11m	£100.98 m	£102.85m	£104.72m	£106.59m

Figure 19 UK total addressable market growth scenario



EU TAM

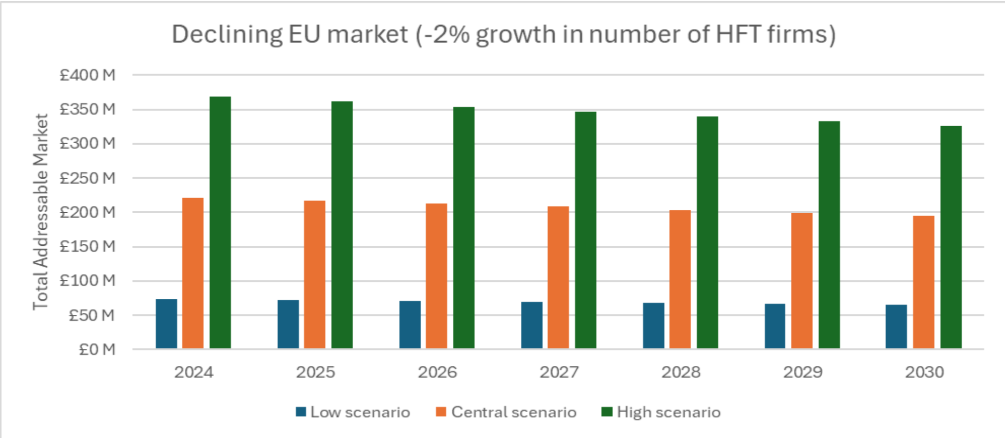
In the central scenario, assuming a flat market growth, the EU total addressable market is estimated to be worth approximately £221 million annually. Results for the different scenarios are presented in the tables below.

Declining EU market

Table 17 EU total addressable market declining growth scenario

Scenario	2024	2025	2026	2027	2028	2029	2030
Low	£73.55m	£72.31m	£71.06m	£69.81m	£68.57m	£67.32m	£66.07m
Central	£221.28m	£216.92m	£212.56m	£208.19m	£203.83m	£199.47m	£195.73m
High	£369.01m	£361.53m	£354.05m	£347.20m	£340.34m	£333.48m	£326.63m

Figure 20 EU total addressable market declining growth scenario

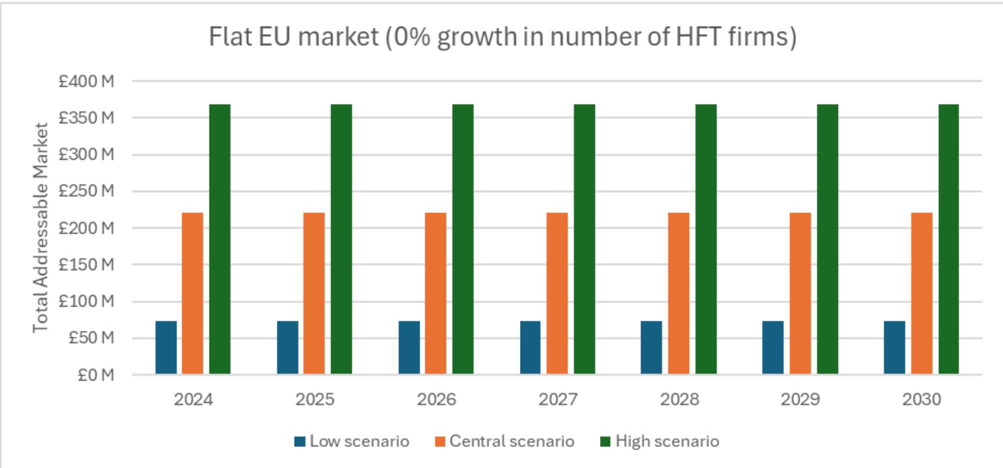


Flat EU market

Table 18 EU total addressable market flat growth scenario

Scenario	2024	2025	2026	2027	2028	2029	2030
Low	£73.55m	£73.55m	£73.55m	£73.55m	£73.55m	£73.55m	£73.55m
Central	£221.28m	£221.28m	£221.28m	£221.28m	£221.28m	£221.28m	£221.28m
High	£369.01m	£369.01m	£369.01m	£369.01m	£369.01m	£369.01m	£369.01m

Figure 21 EU total addressable market flat growth scenario

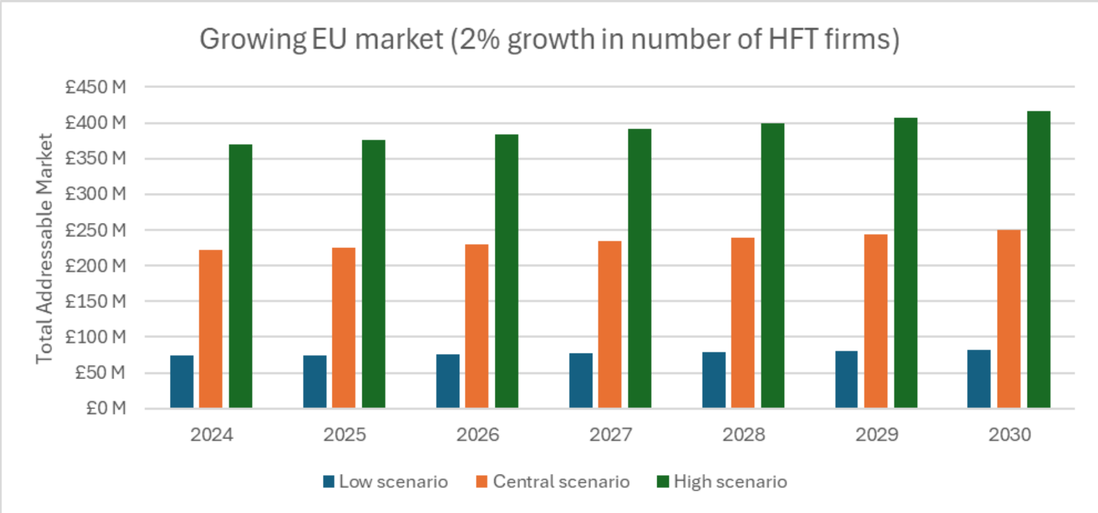


Growing EU market

Table 19 EU total addressable market growth scenario

Scenario	2024	2025	2026	2027	2028	2029	2030
Low	£73.55m	£74.80m	£76.05m	£77.29m	£78.54m	£80.41m	£82.28m
Central	£221.28m	£225.65m	£230.01m	£234.37m	£239.36m	£244.35m	£249.33m
High	£369.01m	£376.49m	£383.97m	£391.45m	£399.56m	£407.66m	£415.76m

Figure 22 EU total addressable market growth scenario



3.2.7 Conclusions

- **Timing is a critical component of HFT operations**, where a difference of nanoseconds can provide a competitive edge. The ability to execute trades faster than competitors is often the key to success in this highly dynamic and competitive field.
- As technologies advance and trading speeds increase, the **need for precise timing becomes even more crucial**. Accurate timing is essential for measuring latency, optimising algorithm performance, and ensuring overall trading efficiency. Without precise timing, HFT firms risk losing their competitive advantage.
- Despite the importance of precise timing, **declining profits in the HFT sector** may affect companies' willingness to invest in resiliently disseminated timing services. Firms may **prioritise other investments** that have a more direct impact on trading performance and offer more immediate and tangible benefits. This shift in investment priorities could lead to reduced spending on timing infrastructure.
- Current regulatory mechanisms and auditing processes are inadequate. The reliance on self-certification and the lack of comprehensive auditing mean that firms are **not incentivised to invest in precise and resilient timing for regulatory purposes**.
- Despite these challenges, the future trading market presents a significant opportunity.
  - In the central scenario, the total addressable market for a resiliently disseminated timing service is estimated to be up to **£57 million annually** in the UK and up to **£221 million annually** in the EU.

3.3 UC3: Mobile communications networks (5G)

This use case covers the fifth-generation (5G) standard that represents the latest evolution, advancement, and innovation in cellular network technology, enabling transformative capabilities, performance, and experiences for voice, data, and connected services. Compared to 4G, it can provide faster speeds with much higher capacity and faster response times. This allows many more users and devices to access fast internet connections and large amounts of data at the same time.

As of 2023, 4G continues to provide the bulk of consumers' mobile experience with 4G accounting for 81% of total data traffic[48]. In the UK there are currently four organisations or mobile network operators (MNO's) who are rolling out 5G networks (Vodafone, Three (3), EE and Virgin-O2)[49].

Bandwidth for 5G services utilise the 3 GHz and 700 MHz bands auctioned by Ofcom in 2021[50]. The 3 GHz band offers high capacity to support large numbers of demanding users across smaller areas, and consequently has to date been deployed predominantly in high traffic locations, with at least 61% of 3 GHz site deployments in urban areas. Lower frequency bands such as 700 MHz may provide a similar performance to existing 4G coverage – with additional capacity where such spectrum is used – and is suitable for in-building and wide area coverage, so is increasingly present in both urban and more rural environments.

3.3.1 Use of time

Accurate and reliable synchronization is a prerequisite for the operations of telecommunications networks. Time for synchronisation importance grew with 4G, and is even more important for 5G networks. The radio access networks (RAN) used in 5G use various sources of time to provide synchronization performance to match the network use case and services delivered. For MNOs, finding the right balance between timing accuracy, availability and cost is key to adoption.

The uses of time and hence their requirements can be split into two areas[51]:

- **Radio network-driven synchronization requirements**: There are two uses for time for radio synchronisation requirements 1) Time division duplex (TDD) cell phase synchronization and 2) communication features based on coordinated transmission or reception from multiple Transmission Reception Points;
- **Application-driven synchronization requirements**: Examples include time-sensitive networks (TSNs), smart grid applications and the UE device-positioning use cases.

3.3.2 User requirements

Radio network-driven synchronization requirements

Time division duplex (TDD) cell phase synchronization

Time signals are a fundamental requirement to the operation of 5G networks. 5G networks use TDD to coordinate signals between radio cells to prevent interferences and loss of traffic i.e. enable data

[48] Ofcom Connected Nations 2023 Annual report: Available at: https://www.ofcom.org.uk/research-and-data/multi-sector-research/infrastructure-research/connected-nations-2023
[49] As of writing Vodafone and Three are proposing a merger which has yet to be approved by regulators
[50] Ofcom auto stage results. Available at: https://www.ofcom.org.uk/news-centre/2021/spectrum-auction-principal-stage-results
[51] 5G synchronisation requirements. Available at: https://www.ericsson.com/en/reports-and-papers/ericsson-technology-review/articles/5g-synchronization-requirements-and-solutions

to be segmented in the time domain. For TDD synchronicity and interference management, the critical points are when switching between transmission and reception. This means for 5G base stations operating at the same or adjacent frequencies in overlapping coverage areas require time domain isolation to prevent base-station-to-base-station and user-equipment-to-user-equipment radio frequency (RF) interference.

The requirement for this timing is outlined in 3GPP mobile broadband standards[52]. In 3GPP cell phase synchronization is specified as 3µs. i.e. the requirement on cell phase synchronization is ultimately specified in terms of maximum deviation in relation to a common absolute timing requirement and dividing the requirement by half (±1.5µs).

Coordinated transmission or reception from multiple Transmission Reception Points (TRxP)

Coordinating transmission and reception from multiple TRxPs brings many benefits and features to mobile networks. These include allowing total higher bandwidth, carrier aggregation[53], dual connectivity[54] and improving link performance to name a few.

Control of relative time error between antennas is therefore required. The key is maintaining relative frame timing alignment at the receiver antennas. 3GPP has therefore defined a maximum receive timing difference (MRTD) as a maximum relative received timing difference the user's equipment must be capable of handling.

Application-driven synchronization requirements

Some 5G applications can have stringent timing accuracy requirements on the synchronization of the 5G nodes. Generally these are enterprise features and are not required for the wider consumer market. Examples include time-sensitive networks (TSNs), smart grid applications and the UE device-positioning use cases, described below in more detail.

- **Time-sensitive networks**: Industrial applications generally require the distribution of time synchronization to the industrial subnetworks used for functionality such as robot control or autonomous vehicles. Synchronization requirements are in the microsecond range between nodes in the network;
- **Smart grid applications**: 5G can be used to support smart grid applications. The 3GPP synchronization architecture can be used to support the distribution of timing to the synchro-phasors that in this way can measure the phase relationships in the AC power distribution network;
- **Positioning of user devices**: Some applications use time from a 5G network to position user devices. Depending on the required positioning accuracy, these may not always result in cost-efficient solutions. For example, 1m corresponds to a synchronization accuracy of around 3ns, which is orders of magnitude more stringent than other radio network synchronization requirements.

[52] 3GPP – The Mobile Broadband Standard: Available at: https://portal.3gpp.org/desktopmodules/Specifications/SpecificationDetails.aspx?specificationId=3204
[53] Carrier aggregation is a technique used to increase the data rate per user, whereby multiple frequency blocks (called component carriers) are assigned to the same user.
[54] Dual connectivity is a key feature in 5G that enables simultaneous connection to multiple base stations for user equipment

3.3.3 Drivers and enablers for adopting resiliently disseminated time

UK government commitment to 5G rollout

As discussed, accurate reliable time is a fundamental requirement for the 5G networks to operate. The total addressable market (TAM) for 5G timing is heavily influenced by the rate of rollout of 5G, particularly any equipment revenues which are directly proportional to the number of 5G base stations.

The UK government has targeted for "all populated areas" in the UK, including rural communities, to have standalone[55] 5G coverage by 2030[56]. However, this does not mean that the entire 5G rollout will be completed by 2030, with Vodafone-Three targeting 2034 for reaching 99% of the population with standalone 5G[57]. As stated, the rollout is being carried out by the UKs four MNOs (Vodafone, Three, EE, and Virgin-O2). The rate of this rollout is determined by the level of infrastructure investment by these companies; in 2022 their total investment in 5G access networks totalled over £240m[58].

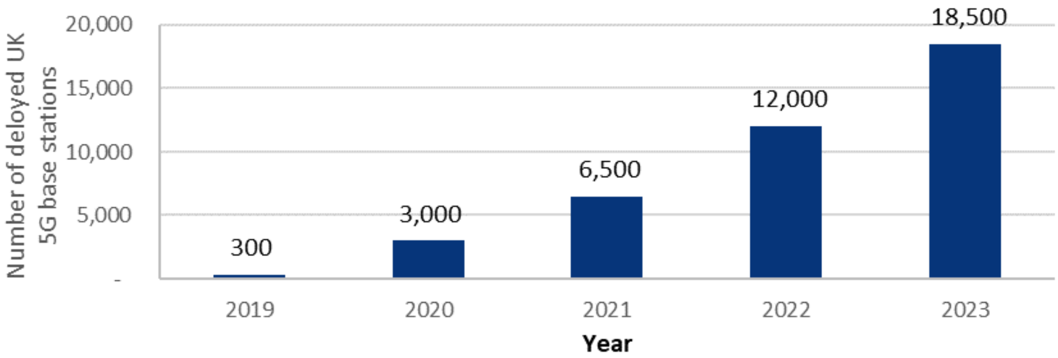
In 2022, 5,500 new 5G base stations were deployed at an average cost of £43.6K per deployment[59]. The total number of 5G deployments in the UK, at the end of 2023 now totals 18,500, up from 12,000 in 2022. LE analysis based on this rollout rate and the total 5G deployments forecasts 104,500 5G deployments in the UK by 2030[60]

As of 2023, 5G is now deployed on sites in 34%, 20% and 10% of urban, suburban, and rural areas respectively. Ofcom currently estimates that between 6 – 26% of the UK landmass now has a very high confidence of a 5G signal[61]. A report commissioned by DCMS in 2018 estimated that approximately 31,000 large cell and 303,000 small cell sites would be required to provide nationwide full 5G performance.[62]

According to one UK MNO the 5G network has a synchronisation of 500ns, with time division requirements of less than 100ns. Currently GNSS is used for timing, however with increasing risks of GNSS, alternative solutions are being sought. It is possible for an MNO to self-disseminate time throughout their network, without requiring time inputs at all base stations. Instead, a time source is taken in at 2 to 3 core locations, and then distributed using fibre optics. This capability depends on the fibre network in place, which will vary across MNO and country. GNSS receivers are still used at the edge of the network alongside fibre, however, these are likely to become back-ups. This would likely impact the business model adopted by a resilient time service provider, considering the few base stations that require timing inputs, and the ultimately much larger end user base.

[55] Involves the deployment of a new 5G core network. This could enable new use cases such as Augmented Reality (AR) /Virtual Reality (VR) and robotics, supported by the broader capabilities of 5G including ultra-low latency, advanced virtual network (slicing) functions, and potentially improved coverage
[56] 5G in the UK. Common library – Available at: https://commonslibrary.parliament.uk/research-briefings/cbp-7883/
[57] Vodafone press release. Available at: https://www.vodafone.co.uk/newscentre/press-release/uk-small-biz-missing-out-8-6bnquid-annually-5gsa-slow-roll-out/
[58] Ofcom Connected Nations 2023 Annual report: Available at: https://www.ofcom.org.uk/research-and-data/multi-sector-research/infrastructure-research/connected-nations-2023
[59] 5G coverage reported here is currently provided on a Non-Stand Alone basis – although trials of Stand Alone 5G are underway. Non-Stand Alone 5G relies on a 4G core network and uses 4G for signalling and network control functions
[60] LE extrapolation of number of deployed 5G base stations in the UK using a polynomial regression see Figure 30
[61] Ofcom Connected Nations 2023 Annual report: Available at: https://www.ofcom.org.uk/research-and-data/multi-sector-research/infrastructure-research/connected-nations-2023
[62] DCMS report, UK Mobile market dynamics, , July 2018: Available at: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/728816/Frontier_report_on_Mobile_Market_Dynamics.pdf

Figure 23 Number of 5G deployments in the UK



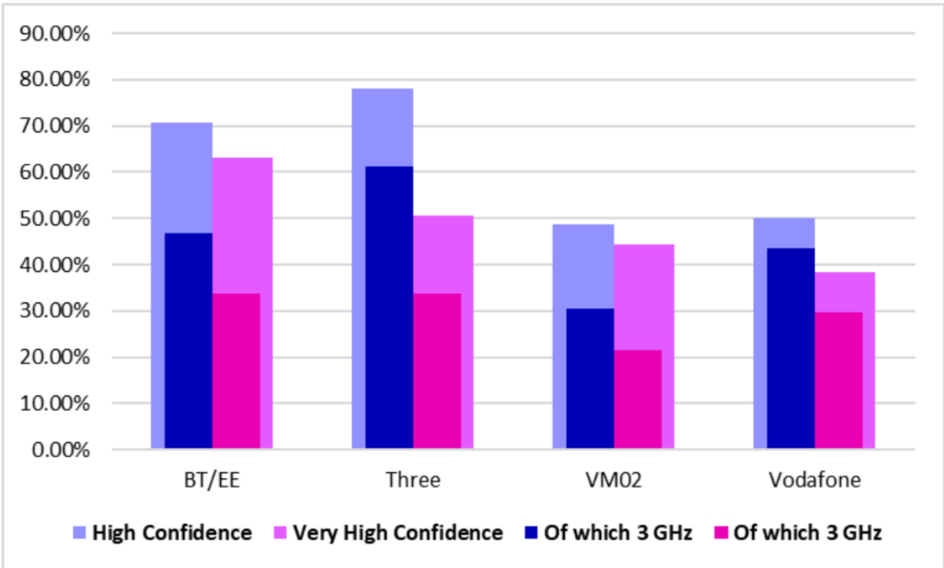
Source: LE analysis of Ofcom annual Connected Nations reports, available at: https://www.ofcom.org.uk/phones-and-broadband/coverage-and-speeds/infrastructure-research

Table 20 Number of small cell sites required for complete UK coverage

Clutter type	Land area (Km square)	Cell radii (Km)	Number of small cell sites
Dense urban	176	0.09	9,296
Urban	3,686	0.09	194,635
Suburban	6,309	0.17	93,359
Villages	4,955	0.62	5,514
Total			302,804

Source: DCMS report, UK Mobile market dynamics, ***, July 2018: Available at: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/728816/Frontier_report_on_Mobile_Market_Dynamics.pdf***

Figure 24 MNO 5G coverage outside of UK premises with a spotlight on 3GHz



Note: Coverage outside of UK premises refers to coverage predicted in a 100x100m area around a UK dwelling, and is used as a measure of outdoor coverage of populated areas; High Confidence associated with a signal strength (-110 dBm), to equate to at least an 80% confidence level. Very High Confidence associated with a higher signal strength (-100 dBm), to equate to a circa 95% confidence level.

Source: Ofcom Connected Nations 2023 Annual report: Available at: https://www.ofcom.org.uk/research-and-data/multi-sector-research/infrastructure-research/connected-nations-2023

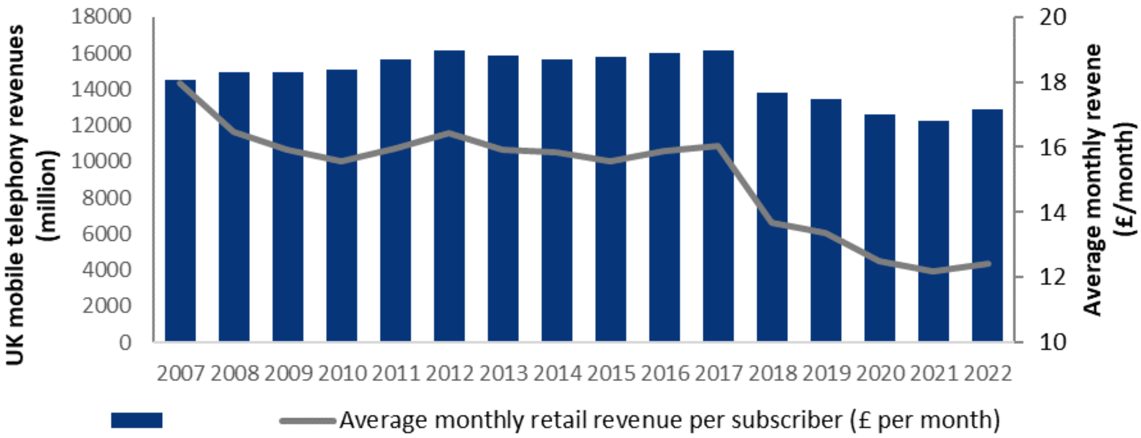
3.3.4 Blockers for adopting resiliently disseminated time

MNO financial and business model pressure

UK MNOs business models are under increasing pressure. EBITDA margins have, in general, been below European mobile operators, with some operations in other European markets earning EBITDA margins that are nearly double those in the UK[63]. In addition, estimates of Return on Capital Employed ("ROCE") show that some UK MNOs earn an overall return below the cost of capital i.e. the cost for financing their operations[64].

Key to this pressure has been consistently declining revenues for UK MNOs which has been particularly prevalent in the last 5 years, as shown in Figure 25. The loss of revenue has been driven by consistently falling average monthly pricing per user as MNOs have struggled to monetise this increased demand for mobile data connectivity and to rebalance revenue generation from voice services to data services.

Figure 25 UK mobile telephony revenues (million)



Source: LE analysis of OFCOM Telecommunications Market Data Updates, available at: https://www.ofcom.org.uk/phones-and-broadband/telecoms-infrastructure/

This leaves MNOs in a challenging position of needing to fund the continued rollout of 5G – estimated to have a total cost of around £6.5bn[65] for a single MNO network[66]. However, the ability of MNOs to monetize these investments gets more and more challenging as the rollout continues into less densely populated regions. This is underlined by the current magnitude of CAPEX being deployed by the MNOs, which combined in 2022 totalled only £240m.

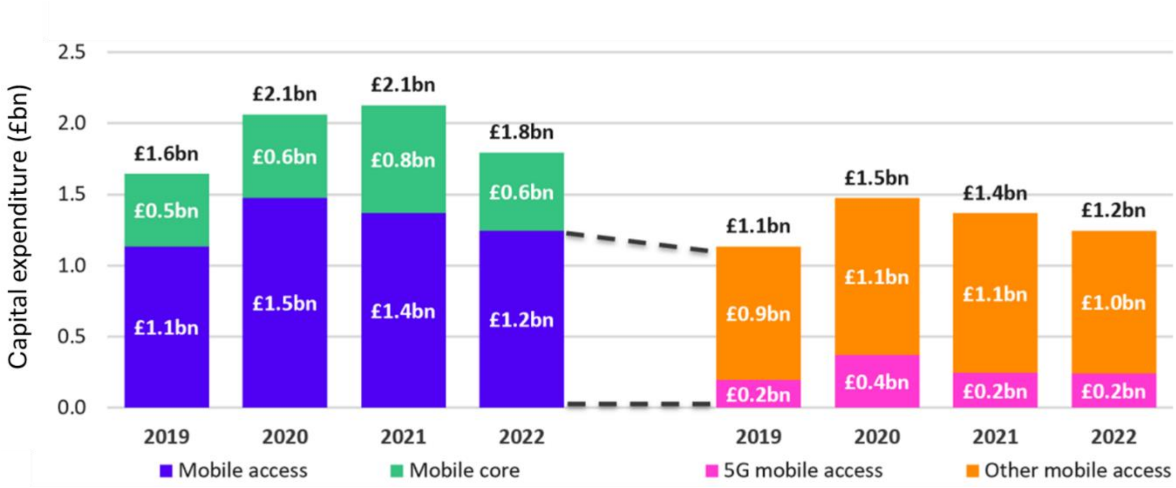
[63] Deloitte – The future of UK mobile value chain, February 2022. Available at: https://www2.deloitte.com/content/dam/Deloitte/uk/Documents/financial-advisory/deloitte-uk-future-of-the-uk-mobile-value-chain-feb-2022.pdf

[64] A report by Enders Analysis estimated that the ROCE (using spectrum at current value) for two of the four UK MNOs was below Ofcom's pre-tax nominal cost of capital (9%), and the ROCE (using spectrum at historic costs) was at or below the cost of capital for three of the four UK MNOs. See: Enders Analysis, "What's to become of H3G", 25 January 2022.

[65] This value is an upper bound for full network coverage of both large and small cells. Estimations used for the TAM are lower as they rely on more realistic forecasts based on actual 5G rollout.

[66] DCMS report, UK mobile market dynamics, July 2018: Available at: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/728816/Frontier_report_on_Mobile_Market_Dynamics.pdf

Figure 26 Estimated mobile telecoms network capital expenditure: 2019 to 2022



Note: Adjusted for CPI (2022 prices)

Source: Ofcom Connected Nations 2023 Annual report: Available at: https://www.ofcom.org.uk/research-and-data/multi-sector-research/infrastructure-research/connected-nations-2023

As a result, the expectation is that the government target for 2030 will be met largely by 700MHz for rural areas which will not give the same user experience as urban environments[67]. For timing this means fewer 5G base stations and a smaller market when compared to a full 3GHz rollout.

Limited deployment of private 5G networks

Private networks are a key but niche feature of the mobile market, offering customised connectivity for various sectors and use cases, such as ports, airports, factories, and smart agriculture. These networks can benefit from 5G capabilities, such as ultra-low latency, and involve different types of providers, including both MNOs and non-MNO entities. However, the number of commercial private networks deployed by MNOs is still low, with less than 20 reported as of September 2023 (a decrease from the 26 reported in the previous year)[68]. Most of these networks use a combination of 4G and 5G technologies and operate on different frequency bands, such as N77, N78, B40 and B41. Only a few of them are 5G SA and only one is delivered as a slice of the public 5G network.

Lack of regulatory compensation for loss of mobile service provision

Ofcom, the industry regulator, currently has no industry-standard compensation scheme for the loss of mobile service. Ofcom's statement is that, depending on the circumstances, it could be appropriate for a mobile provider to give compensation while repairs are being made[69]. However, this statement does not represent a commitment for compensation. In any event, compensation for the loss of mobile services would likely be limited even if paid.

As a point of comparison, Ofcom does have a 'fixed-line' broadband / landline compensation scheme which pays £9.76 per day that a service is not repaired after two full working days[70]. As such, even

[67] Ofcom connected nations 2023 report statement: "Important to recognise that there is a diversity of deployment strategies leading to potentially different consumer experiences within coverage footprints"
[68] Ofcom Connected Nations 2023 Annual report: Available at: https://www.ofcom.org.uk/research-and-data/multi-sector-research/infrastructure-research/connected-nations-2023
[69] Ofcom Mobile phone service faults and problems. Available at: https://www.ofcom.org.uk/phones-telecoms-and-internet/advice-for-consumers/problems/mobile-faults-guide
[70] Ofcom automatic compensation: Available at: https://www.ofcom.org.uk/phones-telecoms-and-internet/advice-for-consumers/costs-and-billing/automatic-compensation-need-know

if existing fines "fixed-line" scheme was applied to mobile, no compensation would be paid for a <48hr disruption for mobile services. Ofcom has however levied fines for failing to provide adequate mobile services as they did on Three in 2017 for failing to maintain 999 access for its customers[71]

MVNO service level agreements and competition

Mobile Virtual Network Operators (MVNO) are companies that offer mobile phone services but do not own the network infrastructure. Instead, MVNOs lease wireless network capacity from Mobile Network Operators (MNOs) at wholesale rates and then repackage and resell those services under their own brand to end-users. MNOs in the UK provide services to 69% of users the remaining 31% provided for by MVNOs[72].

The MVNO business model offers companies the ability to enter the mobile telecommunications market without needing to invest in the infrastructure and resources of physical networks. The MNOs meanwhile gain the wholesale revenue from the MVNOs, but do not incur any costs associated with customer acquisition and retention, ideally with a marginal increase in competition. This model becomes increasingly compelling where the MNO has unutilised capacity on its network, or the cost of customer acquisition and retention is high[73]. A summary of the selected MVNO and MNOs are shown in Figure 27:

Figure 27 The UK's MVNOs and the networks they use (selected)

EE	Three	VM O2	Vodafone
• 1p Mobile • Axis Telecom • BT Mobile * • China Mobile • Cinos • CMLink • Ecotalk • Lyca Mobile • Now Mobile • Pelion • Plan.com • Plusnet Mobile * • Spitfire • Tango Networks • Telecom Plus (Utility Warehouse) • The Phone Co-Op • To The Moon Mobile • Truphone • Vectone Mobile • Wireless Logic	• FreedomPop • iD Mobile • SMARTY * • Superdrug Mobile	• Giffgaff * • Sky Mobile • Tesco Mobile * • Virgin Mobile *	• Asda Mobile • Lebara Mobile • Talkmobile * • VOXI *

Source: Telcotitans, BT boats of MVNO wins but UK competition hots up. Available at: https://www.telcotitans.com/btwatch/bt-boasts-of-mvno-wins-but-uk-competition-hots-up/6826.article

For timing, service agreements between the MNOs and the MVNOs provide an incentive to the MNO to ensure the terms of the service agreements are met risking either penalties under the service agreement or the loss of wholesale revenue should the MVNO change MNO provider[74]. This line of business is highly competitive and is a major source of competition in UK mobile telecoms market. Table 21 shows the number of MVNO customers served by EE, alongside the total mobile revenue and the wholesale mobile revenue from MVNOs illustrating the magnitude of this source of revenue for MNOs.

[71] Guardian. Ofcom fines Three £1.9m for failing to maintain 999 access. Available at: https://www.theguardian.com/business/2017/jun/16/ofcom-fines-three-19m-failing-maintain-999-access
[72] Ofcom data tech tracker 2022 - QM4. Which mobile network do you use most often?. Available at: https://www.ofcom.org.uk/__data/assets/pdf_file/0022/239431/Tech-Tracker-2022-Main-Data-Tables.pdf
[73] Herbert Smith Freehills (2017). MVNOS: negotiating an optimum wholesale agreement. Available at: https://hsfnotes.com/tmt/2017/05/15/mvnos-negotiating-an-optimum-wholesale-agreement/
[74] Lyca mobile swap from VironO2 to EE. Available at: https://www.ispreview.co.uk/index.php/2023/06/confusion-as-uk-lyca-mobile-users-swap-from-o2-to-ee-mvno.html

Table 21 EE MVNO financial performance

	FY19–20	FY20–21	FY21–22	FY22–23
MVNO customers	3,882,000	4,114,000	2,706,000	696,000
Mobile revenue	£1,281m	£1,189m	£1,133m	£1,062m
Of which wholesale mobile	£245m	£255	£182m	£66m

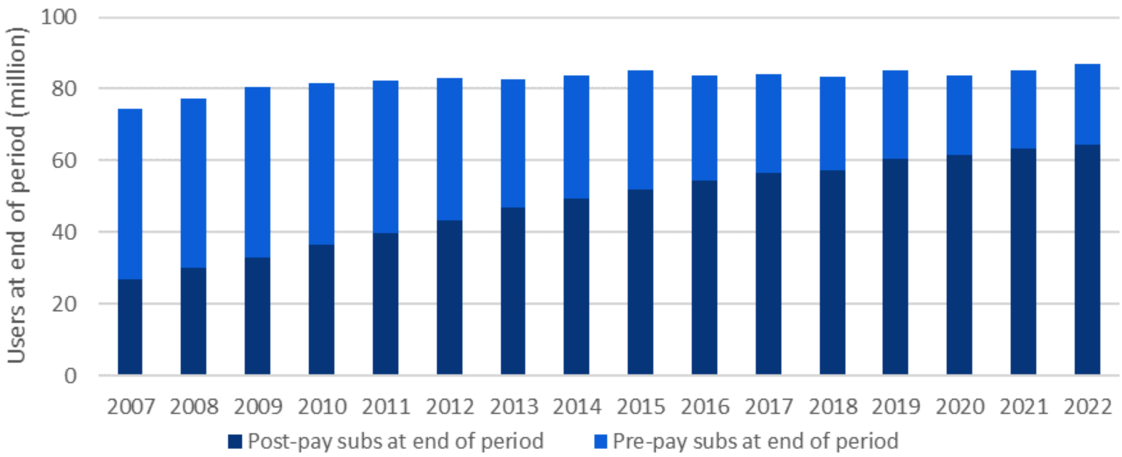
Note: General decline of revenues shown is due to loss of Virgin Mobile contract in 2020 and is not evidence of declining MVNO business in the UK

Source: Joseph Purnell (2023). 'BT boasts of MVNO wins but UK competition hots up'. Available at: https://www.telcotitans.com/btwatch/bt-boasts-of-mvno-wins-but-uk-competition-hots-up/6826.article

Prevalence of monthly contracts

Pay monthly contracts have consistently been replacing pay-as-you-go tariffs in the UK for well over a decade. Pay monthly contracts are now how the vast majority of consumers pay for their mobile data, with around 80% of users paying on a monthly basis with the remaining on pay-as-you-go or top up tariffs,[75] as shown in Figure 28.

Figure 28 UK subscriber numbers by type (millions)



Source: LE analysis of OFCOM Telecommunications Market Data Updates, available at: https://www.ofcom.org.uk/phones-and-broadband/telecoms-infrastructure/

Due to this, MNOs have a reduced incentive to ensure continuity of service as customers would still pay for their services even if they lost connectivity for an extended period of time. In contrast, if a pay-as-you-go customer went without signal, the MNO operator would have direct impact to revenue as customers would not completely make up for their lost usage during the period of lost connectivity.

3.3.5 Market sizing methodology

The total addressable market (TAM) for 5G timing is driven by the rate of rollout and extent of the 5G deployment. Equipment revenues, for example, are directly proportional to the number of 5G base stations. The impact of loss of time on sub use cases of 5G[76], are not considered as part of the

[75] Ofcom data tech tracker 2022. Available at: https://www.ofcom.org.uk/__data/assets/pdf_file/0022/239431/Tech-Tracker-2022-Main-Data-Tables.pdf

[76] This refers to users of 5G in a range of industries that would be impacted by a loss of time.

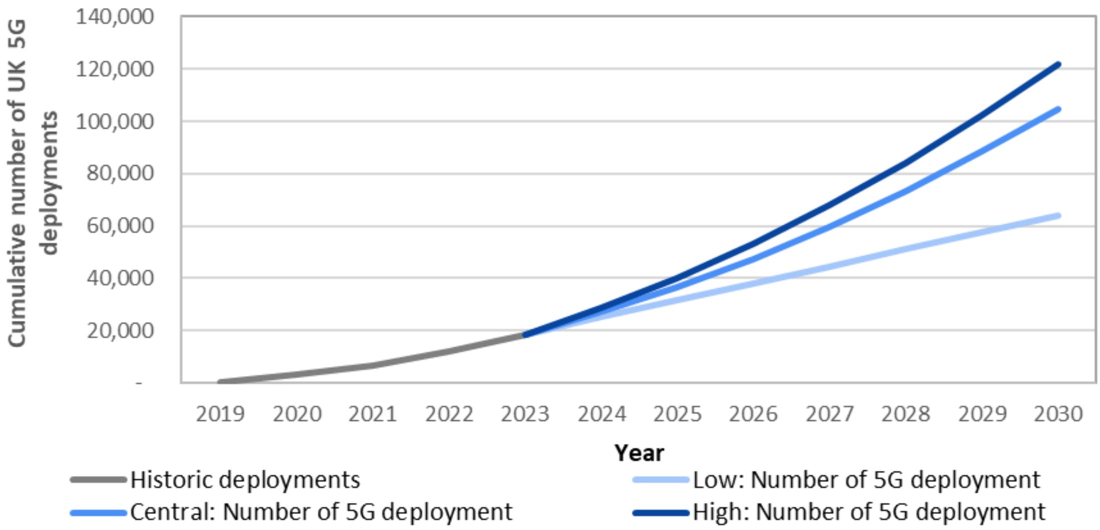
assessment for this use case (although these would be expected to be large). The methodology used to size the TAM is as follows:

Figure 29 Market sizing methodology

Forecast number of deployments

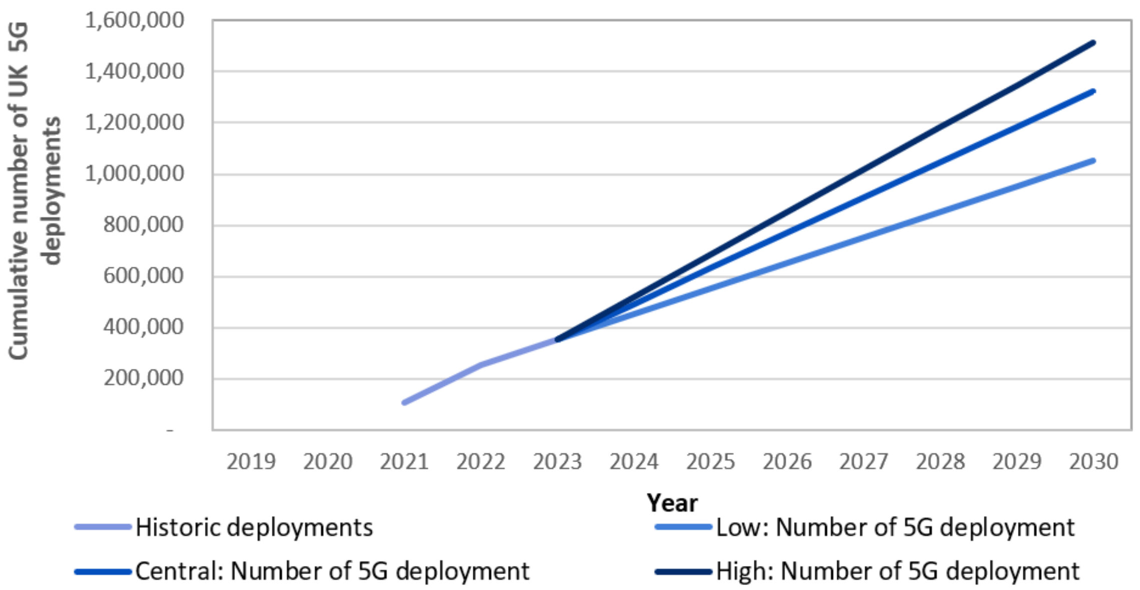
To forecast the number of 5G deployments historic data was gathered from Ofcom on the number of 5G deployments in the UK and 5G observatory for EU27. The data was then fitted using polynomial and linear regressions to construct a central scenario for the number of deployments out to the year 2030 for UK and EU27 respectively. The low scenario in the UK assumed that the same number of deployments in 2023 (6,500/yr. for UK and 99,600K/yr. for EU27) is continued out until 2030 and the high scenario that the number of units in each year was 20% higher than the central case. Note that the implied total CAPEX across all MNOs in the low, central, and high scenarios was £177m, £449m and £538m, respectively, in the year 2030. Under these scenarios it is assumed that 5G rollout in the UK and EU27 continues into the 2030s.

Figure 30 Cumulative number of UK 5G deployments



Source: LE analysis of annual Ofcom Connected Nations reports. Available at: https://www.ofcom.org.uk/phones-and-broadband/coverage-and-speeds/infrastructure-research

Figure 31 Cumulative number of EU27 5G deployments



Source: European 5G Observatory (n.d.) Detailed Country Breakdown. Available at: https://5gobservatory.eu/detailed-country-breakdown/

Estimation of timing related CAPEX and OPEX data from a 2018 DCMS report[77] was used as the primary reference to estimate the total CAPEX and OPEX associated with 5G base stations. The report outlines the total number of 5G cell base stations of all types for full rollout and their associated levels of CAPEX and OPEX – see Table 22. An average weighted score based on their total cell number was then taken to derive single CAPEX and OPEX figures, assuming MNO rollout networks by only reducing the number of small cells.

These were then adjusted for inflation from 2018 into 2024. Following this, the percentage of the "OPEX Licensing and maintenance" and "CAPEX (£/site)" licensing and the CAPEX that can be attributed to the timing market was then estimated to be 7.5%, 10% and 12.5% respectively for the low, central, and high cases respectively. The same values were assumed for 5G deployments across the EU27.

Table 22 OPEX and CAPEX assumptions

Band	700MHz large cell	3.4-3.8GHz large cell	3.4-3.8GHz small cell	Weighted average of all cells	Inflation adjustment to 2024
CAPEX (£/site)	35,073	36,450	16,023	21,829	27,256
OPEX (£/site/year)	2,625	2,925	5,384	4,605	5,750
OPEX Licensing and maintenance (£/site/year)	914	1,019	1,875	1,604	2,002
Number of sites for total coverage for one network	18,000	13,000	302,804		

Note: Bank of England inflation calculator was used. Available at: https://www.bankofengland.co.uk/monetary-policy/inflation/inflation-calculator

[77] DCMS report, UK mobile market dynamics, July 2018: Available at: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/728816/Frontier_report_on_Mobile_Market_Dynamics.pdf

3.3.6 Market sizing results

The results of the market sizing forecast out to 2030 are shown on the following pages:

Figure 32 UK TAM forecast related to 5G timing

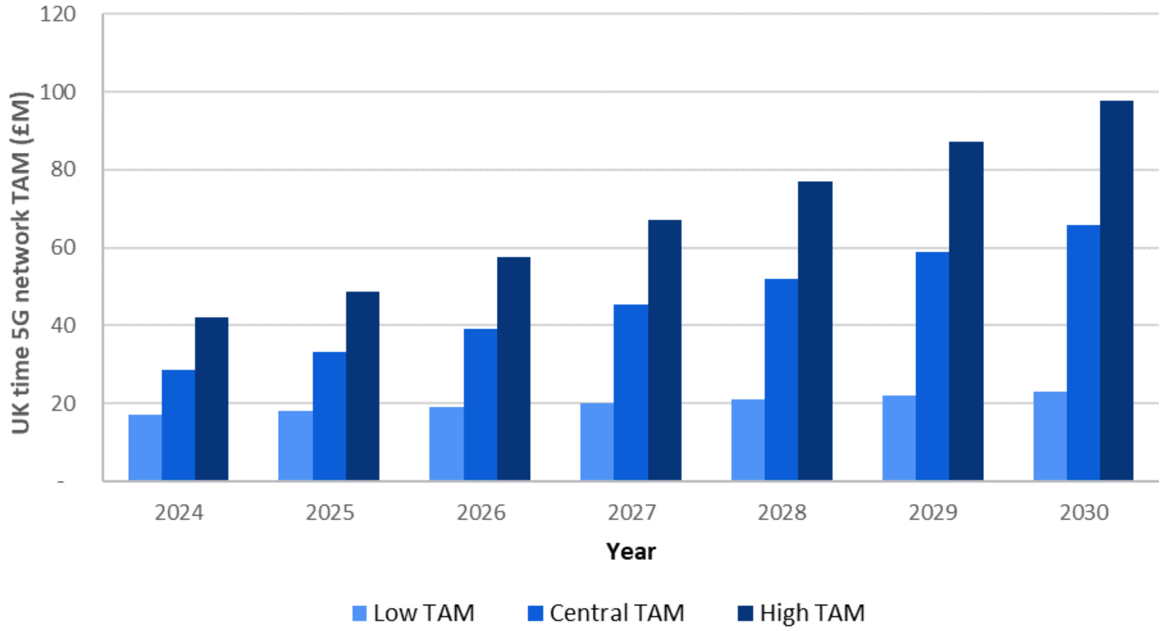
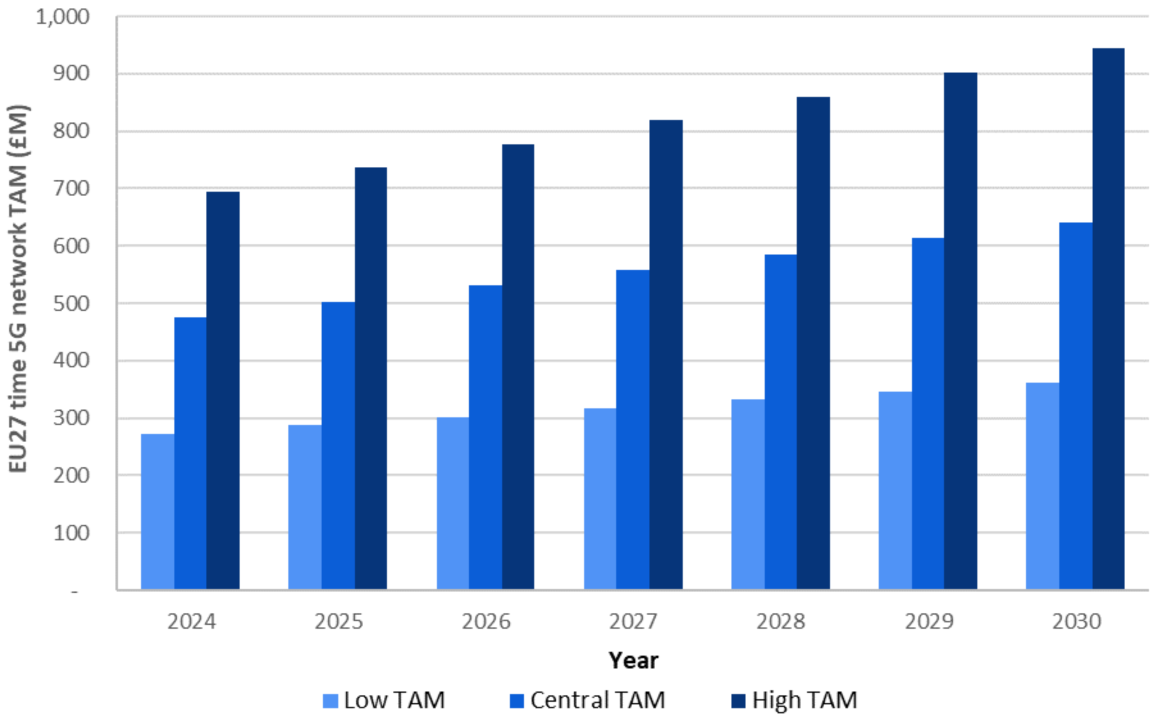


Figure 33 EU27 TAM forecast related to 5G timing



Results of the central scenario broken down by CAPEX and OPEX, noting the relative importance of OPEX as the install base of 5G increases overtime.

Figure 34 UK Central scenario CAPEX and OPEX related TAM

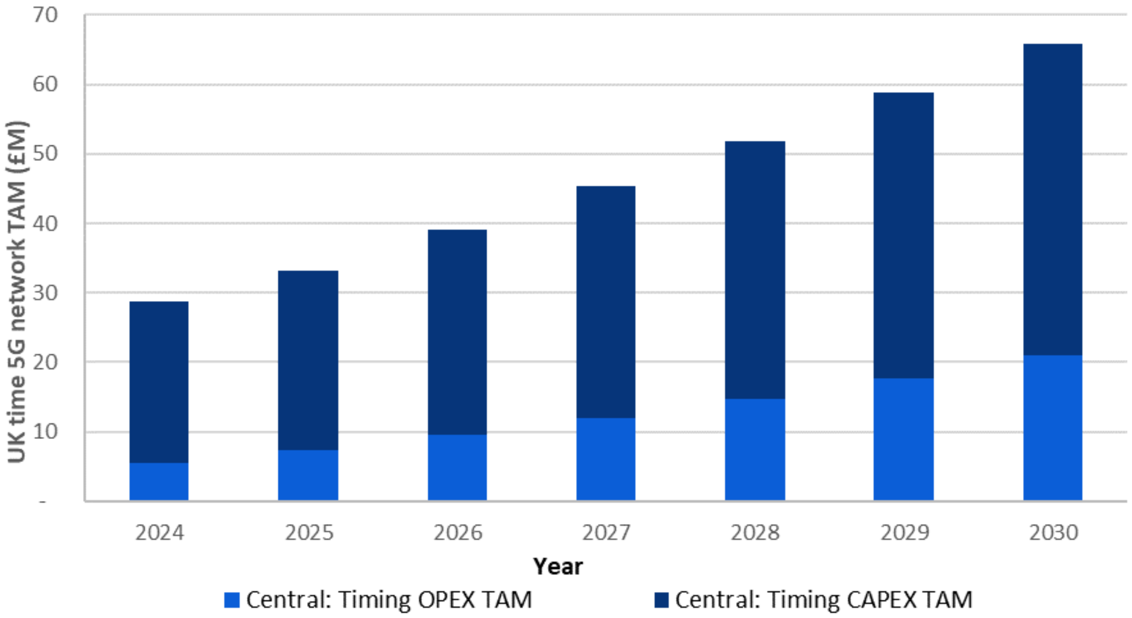
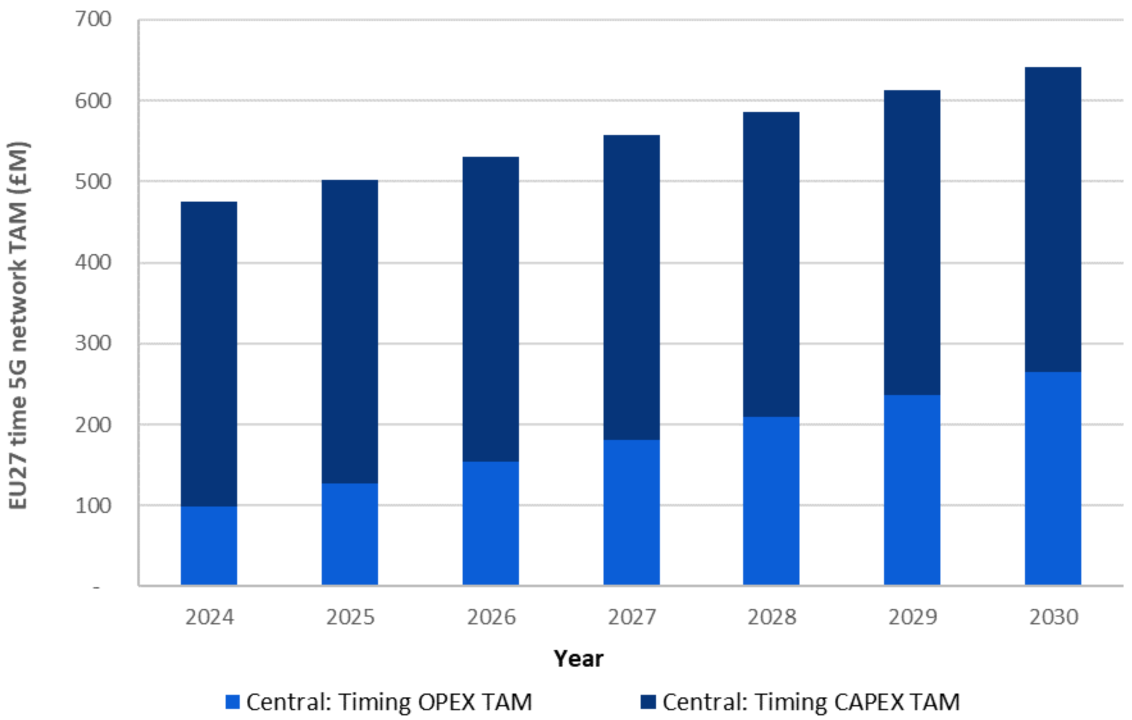


Figure 35 EU27 Central scenario CAPEX and OPEX related TAM



3.3.7 Conclusions

- **Timing is critical to the proper functioning of 5G networks**, particularly the radio access network (RAN) elements to manage interference. Specifications on the accuracy requirements are outlined under 3GPP.

- The 5G use case is highly technical and active in driving forward the state of the art of timing. The telecom requirements for PNT are well known and have been incorporated into standards (3GPP)
- **Mobile network operators (MNO) are the principal customers for 5G timing** given the limited number of private 5G networks. There are currently 4 MNOs in the UK.
- However, **Mobile network operator business models, especially in the UK are under pressure from falling revenues per user**. As a result, the rollout of 5G will be more limited to lower 700MHz especially in rural areas. This reduces the total addressable market opportunity for timing for 5G.
- Equally, the **UK lacks compulsory compensation scheme for the loss of mobile networks** as it has with landline or home broadband services. This, along with the dominance of pay monthly contracts reduces the incentive for MNOs to ensure a reliable network.
- There are however **strong incentives for MNOs to ensure their networks have reliable and secure timing**:
  - Competition between MNOs to maintain and secure either direct subscription revenues customers or wholesale service agreements with Mobile Virtual Network operators (MVNOs)
  - The UK government has targeted for "all populated areas" in the UK, including rural communities, to have standalone 5G coverage by 2030
- The analysis of this use case does **not** consider the impacts of loss of time on the sub use cases of 5G, which would be expected to be very large.
- **The central estimate for the total addressable market for 5G timing is expected to be £29M/yr. rising to £65M/yr. by 2030 in the UK**. Note that this compares with around £240M/yr. of total CAPEX investment in 2022 across all MNOs for 5G mobile access.
- **The central estimate for the total addressable market for 5G timing is expected to be £475M/yr. rising to £640M/yr. by 2030 across the EU27**.

3.4 UC4: Next generation telecommunications (6G)

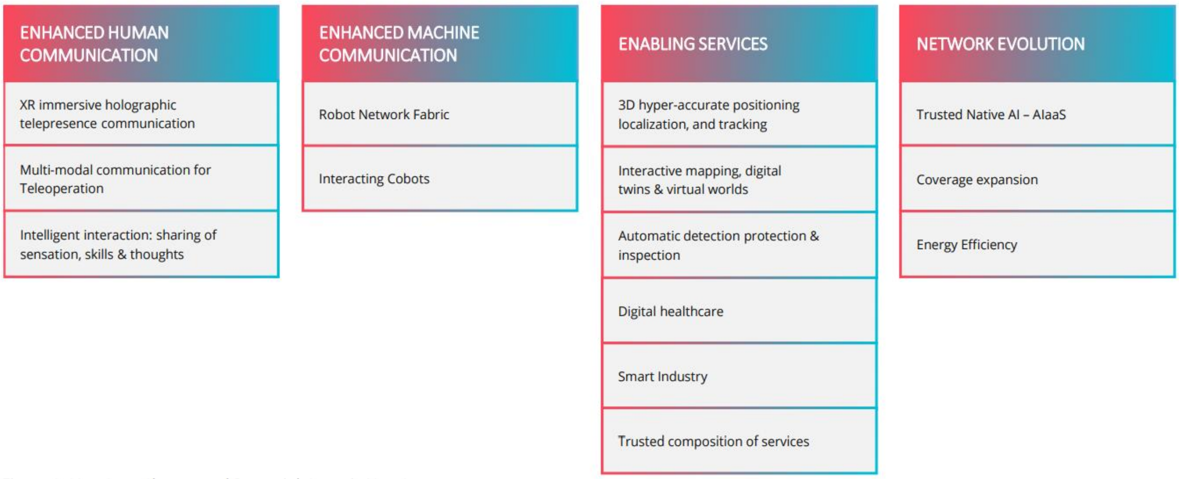
6G is the next generation of mobile communications networks, which aims to provide faster, smarter, more efficient, and more secure services than 5G. It hopes to achieve a seamless integration of terrestrial, aerial, and satellite networks, as well as interconnectivity of humans, machines, and devices. 6G aims to enable new applications and experiences, such as holographic communication, immersive reality, artificial intelligence, and quantum computing.

The definition of future 6G is still at an early stage of development. It is expected that the 6G will need to be aligned and evolve with market demand and relevance before it is defined formally in requirements standards towards the end of this decade.

The uses of 6G are wide ranging. The Next Generation Mobile Networks Alliance an association of mobile operators, vendors, manufacturers and research institutes who provide guidance on continuing to support 5G and defining 6G[78] have carried out an assessment of the use cases of 6G grouped into four areas – see Figure 36:

[78] NGMN Alliance (NGMN). Available at: https://www.ngmn.org/about-us.html

Figure 36 6G use cases



Source: NGMN Alliance (NGMN) 6G requirements. Available at: https://www.ngmn.org/wp-content/uploads/NGMN_6G_Requirements_and_Design_Considerations.pdf

3.4.1 Use of time

The main challenge for the development and deployment of 6G networks is limited availability of spectrum, particularly below 6GHz. As such, it is expected that 6G will have to rely on higher frequencies that have shorter ranges and worse propagation characteristics. The anticipation therefore will be that 6G will focus (at least initially) more on the densification of the network infrastructure, and smaller cells. As a result, the rollout would begin with congested urban locations where there is limited network capacity and the economics for new infrastructure is most accommodative. However, as cells get more numerous, each cell would have to lower its costs (5G small cells are around half the cost of large cells[79]). It is also highly unlikely that a rapid rollout of 6G would coincide with a large increase in performance given the implied increase in CAPEX.

The specific timing requirements will depend on the choices and trade-offs that the telecoms industry chooses including:

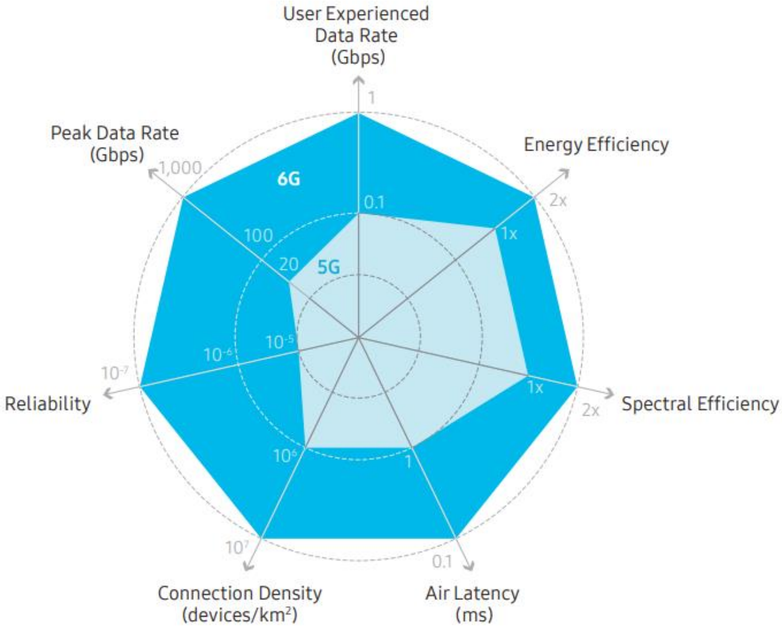
- The type and topology of the network architecture, such as centralized or distributed radio access networks (RANs), and the use of virtualization and cloud technologies. These choices affect the level of coordination and synchronization needed between different network elements and the trade-off between processing power and backhaul capacity.
- The choice and availability of spectrum bands, such as low, mid or high frequencies, and the degree of spectrum sharing or aggregation. These factors influence the cell size, the interference management and the spectral efficiency of the network, as well as the potential for frequency and phase alignment errors.
- The modulation and coding schemes, such as orthogonal frequency division multiplexing, (OFDM), time division duplex (TDD), filter bank multicarrier (FBMC), and the multiple access techniques, such as time division multiple access (TDMA) or non-orthogonal multiple access (NOMA). These methods determine the data rate, the bandwidth efficiency, and the robustness of the signal transmission, as well as the sensitivity to timing errors and distortions.

[79] Frontier report on the cost of 5G rollout. Available at: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/728816/Frontier_report_on_Mobile_Market_Dynamics.pdf

3.4.2 User requirements

As stated, the 6G specification is still under development and has not yet been finalized. Ericsson expects that the 6G specifications will be ready by the end of 2028, which would enable the launch of the first commercial 6G systems by 2030[80]. However, this timeline is subject to change depending on various factors, such as the availability of new spectrum, the evolution of 5G, and the market demand for 6G services. Discussion with a UK MNO provided no further insight into these timing requirements. Therefore, it is not possible to state with certainty what the requirements for 6G will be today. High level summaries are shown in Figure 37, Table 23, and Figure 38 on the expected performance requirements:

Figure 37 Comparison of key performance requirements between 5G and 6G



Source: Samsung 6G vision. Available at: https://cdn.codeground.org/nsr/downloads/researchareas/6G%20Vision.pdf

Table 23 Comparison of different technology generations

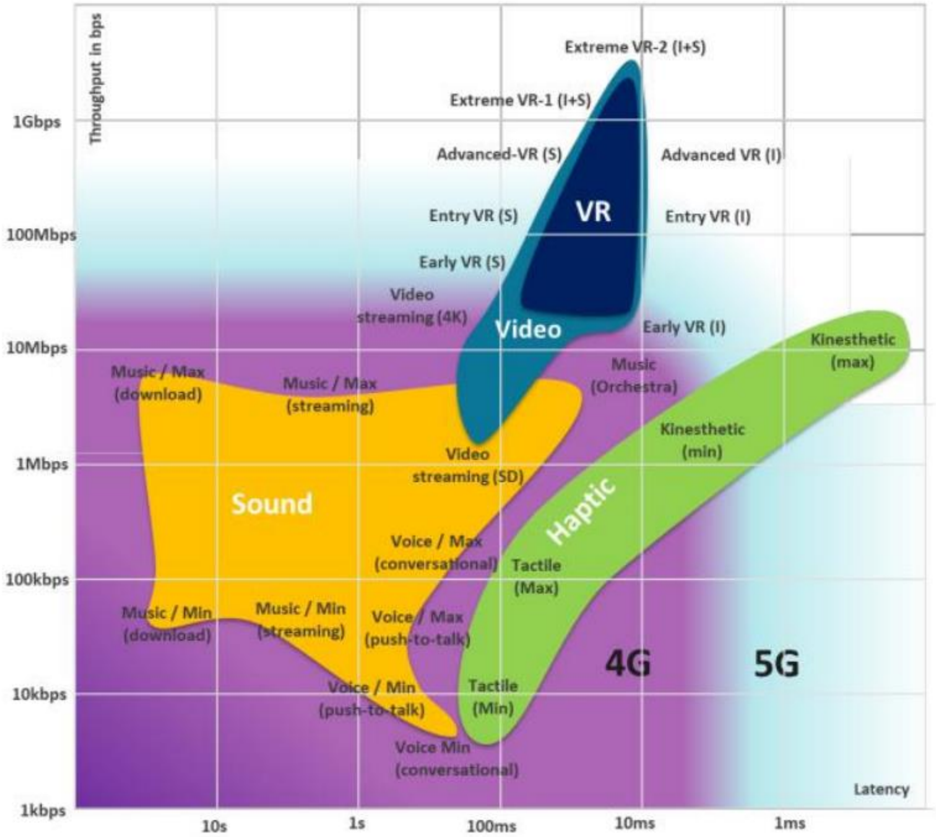
	2G	3G (HSPA+)	4G	5G	6G (Est.)
Year	1990	2000	2010	2020	2030
Max DL Speed (theoretical)	473.6 Kbps	42 Mbps	3 Gbps	20 Gbps	1 Tbps
Avg DL Speed (practical)	50 Kbps	8 Mbps	100 Mbps	300 Mbps	1 Gbps
Max UL Speed (theoretical)	473.6 Kbps	11.5 Mbps	1.5 Gbps	10 Gbps	10 Gbps
Avg UL Speed (practical)	50 Kbps	2 Mbps	50 Mbps	100 Mbps	1 Gbps
E2E Latency (practical)	600 ms	120 ms	30 ms	10 ms	1 ms
Reliability	99%	99.9%	99.99%	99.999%	99.99999%
Connection Density	N/a	N/a	10^5 devices/km2	10^6 devices/km2	10^7 devices/km2
Mobility	150 km/h	300 km/h	350 km/h	500 km/h	1000 km/h

Source: 6G Mobile Wireless Communications Vision, Roadmap, Technologies & Use Cases. Available at: https://3g4g.co.uk/6G/6GTraining/Free6Gtraining_2021_Part_05_6G_Requirements.pdf

Note: Reliability is defined as 1 - downtime per year/number of minutes in the year.

[80] Ericsson 6G standardisation timeline. Available at: https://www.ericsson.com/en/blog/2024/3/6g-standardization-timeline-and-technology-principles

Figure 38 Estimate of minimum throughput and reciprocal latency requirements for delivery of each form of sensory communications



Note: See Ofcom's Technology Futures report for more detail. Haptic refers to the communication of movement and touch. (S) refers to 'streaming' and (I) refers to 'interactive'.

Source: Ofcom (2022). Mobile networks and spectrum: meeting future demand for mobile data. Available at: [*https://www.ofcom.org.uk/__data/assets/pdf_file/0017/232082/mobile-spectrum-demand-discussion-paper.pdf*](https://www.ofcom.org.uk/__data/assets/pdf_file/0017/232082/mobile-spectrum-demand-discussion-paper.pdf)

To achieve this performance, 6G will need to address various technological and economic challenge targets, which have implications for 6Gs timing requirements. Ultimately this will depend on the requirements of the underlying use cases. Some use case such as autonomous vehicles are nascent, and therefore there is significant uncertainty on what the requirements for 6G will be:

Synergies with 5G

There needs to be a managed transition from 5G. 5G is still being rolled out across many countries and 6G must therefore not invalidate investments made in the 5G network. At this stage in 6Gs development it is possible for 6G to retain the core network, the RAN, or both from 5G[81]. Should a new 6G-Radio Access Technology (6G-RAT) displace 5G it will need to demonstrate significant benefits over and above an evolved 5G-RAT in the most significant metrics such as spectral and/or energy efficiency. However, if the 6G-RAT is shared with 5G along with the same duplex techniques, then it is likely that the timing requirements for 6G could be equivalent to 5G. In this scenario, the timing solutions would be copied across from 5G into 6G.

[81] NGMN Alliance e.V. (2023). 6G requirements and Design Considerations https://www.ngmn.org/wp-content/uploads/NGMN_6G_Requirements_and_Design_Considerations.pdf

Peak and user data rates and spectrum

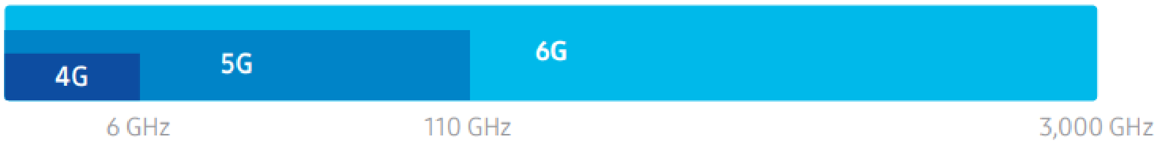
The minimum technical performance requirement for 5G under IMT2020 included peak rates of 20Gbps on the downlink and 10Gbps on the uplink, with target user experienced data rates of 100Mbps on the downlink and 50Mbps on the uplink[82]. However, in practice this has been difficult to achieve given real-world spectral efficiency, limitations on transmitter power and path loses.

One possible target for 6G networks is to increase the peak and user experienced data rates by an order of magnitude compared to 5G, i.e., to achieve 200Gbps on the downlink and 100Gbps on the uplink, and 1Gbps on the downlink and 500Mbps on the uplink, respectively. This would enable new applications and services that require ultra-high bandwidth and low latency, such as holographic communications, immersive virtual and augmented reality, and high-precision remote sensing.

The allocation of new IMT spectrum has been a more cost-effective means of improving the performance of mobile networks[83]. The use of additional spectrum can lower site densities and reduce overall power consumption of transmission which would by extension reduce the cost of building out and operating 6G networks. However, spectrum is a scarce resource with competition from other use cases such as air traffic control radars, legacy 2G and 3G networks and broadcast TV. At this stage it is not known what, if any additional spectrum will be allocated to 6G.

One of the biggest areas of focus to alleviate this issue for 6G is the use of Terahertz spectrum. In March 2019, the Federal Communications Commission (FCC) opened the spectrum between 95 GHz and 3,000 GHz for experimental use and unlicensed applications to encourage the development of new wireless communication technologies[84]. The THz band includes large amount of available bandwidth, which can enable extremely wideband channels with tens of GHz-wide bandwidth. This could potentially provide a means to meet the 6G requirement of Tbps data rates.

Figure 39 Comparison of bandwidth requirements for 4G, 5G and 6G



Source: Samsung 6G vision. Available at: https://cdn.codeground.org/nsr/downloads/researchareas/6G%20Vision.pdf

An added benefit is that THz frequencies could provide high-precision positioning capability because: 1) The links between transmitter and receiver will most likely be line of sight (LoS), 2) the use of narrower beams will improve angular resolution and triangulation accuracy of 3D position estimation and 3) the wideband waveforms would enable more accurate ranging[85].

However, there are reasons that THz communications has yet to be used and large technical challenges need to be overcome:

1) **Severe path-loss and atmospheric absorption**: Free-space path-losses and atmospheric absorption is higher in the THz band. This could be overcome by using larger antenna arrays at base stations, but this would be costly.

[82] Specification # 37.910 (3gpp.org)
[83] GSMA estimating mid band spectrum needs. Available at: https://www.gsma.com/spectrum/wp-content/uploads/2021/07/Estimating-Mid-Band-Spectrum-Needs.pdf
[84] CDN. 6G vision. Available at: https://cdn.codeground.org/nsr/downloads/researchareas/6G%20Vision.pdf
[85] Hadi Sarieddeen et al., "Next Generation Terahertz Communications: A Rendezvous of Sensing, Imaging, and Localization," Available: https://arxiv.org/pdf/1909.10462. pdf

2) **RF front-end, photonics and data conversion**: There is a lack of devices, which can generate and detect signals in THz band. In these bands, the device dimensions are significantly larger relative to the wavelength, and it results in high power loss and low efficiency.
3) **Antenna, lens, and beamforming architecture**: Massive antenna arrays would be necessary to compensate for the increased path-loss of THz frequencies. Designing such arrays that will operate with high efficiency at THz frequency poses many challenges to designing the feed network and the antenna elements to support GHz-wide bandwidth. Moreover, the use of ultra-massive arrays results in very focused beams. As a result, communication links at these frequencies will depend on LoS and focused-reflected paths, not on scattering and diffracting paths.

The impact of using THz spectrum for 6G is that it could be to increase the timing requirements. Since THz signals have very narrow beams and depend on line-of-sight, the network would need to constantly track the location and movement of users and devices to maintain the connection. This would require fast and accurate beamforming algorithms and hardware, as well as sophisticated channel estimation and synchronization techniques. Moreover, the use of ultra-wide bandwidths at THz frequencies would also impose stringent constraints on the sampling rate and resolution of analog-to-digital and digital-to-analog converters.

Network area capacity

A significant challenge for MNOs is to economically meet the growing demand for mobile services, especially in dense urban environments with many users. According to Ofcom, in the UK, the average consumption per data user on mobile increased by 24% in 2022 to 8.0 GB per month[86].

For MNOs to meet this demand, a combination of network densification (deploying more cell sites), increased spectrum bandwidth and increased spectrum efficiency usage will be required. How MNOs approach these factors will determine what timing requirements are ultimately required. Increasing the number of cell sites would increase the volume and locations requiring secure time while increasing the amount of spectrum and spectrum efficiency could increase the need for accurate timing synchronisation across the network. Therefore, the demand for secure time and frequency distribution to cell sites is likely to grow in parallel with the growth of mobile data traffic.

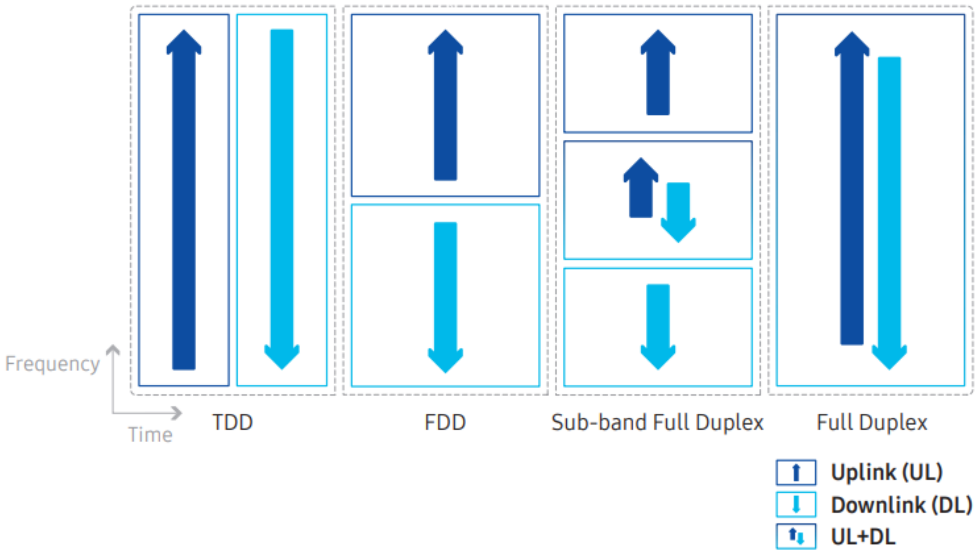
Adoption of new duplex technology

A key driving requirement for timing in 5G networks today is the use of dynamic time division duplex (TDD)[87]. It was introduced to improve the network flexibility making it possible to adjust the ratio between downlink and uplink time slots depending on traffic demand. If 6G networks could remove the restriction i.e. that downlink and uplink must use mutually exclusive time-frequency resources, then system capacity could in theory increase by a factor of two.

However, this has not been done before due to the issues of self-interference and cross-link interference. There has been research on self-interference cancellation (SIC) techniques, which typically require both analog and digital domain cancellation[88]. Should the industry adopt these techniques for 6G then the requirements on timing could be significantly different to that with 5G.

[86] Ofcom. Communications market report 2023. Available at: https://www.ofcom.org.uk/__data/assets/pdf_file/0034/264778/Communications-Market-Report-2023.pdf
[87] 5G synchronisation requirements. Available at: https://www.ericsson.com/en/reports-and-papers/ericsson-technology-review/articles/5g-synchronization-requirements-and-solutions
[88] Meng Ma et al., "A Prototype of Co-Frequency Co-Time Full Duplex Networking," IEEE Wireless Communications, vol. 27, no. 1, pp. 132-139, Feb. 2020.

Figure 40 Dynamic operation of duplex modes



Source: Samsung 6G vision. Available at: https://cdn.codeground.org/nsr/downloads/researchareas/6G%20Vision.pdf

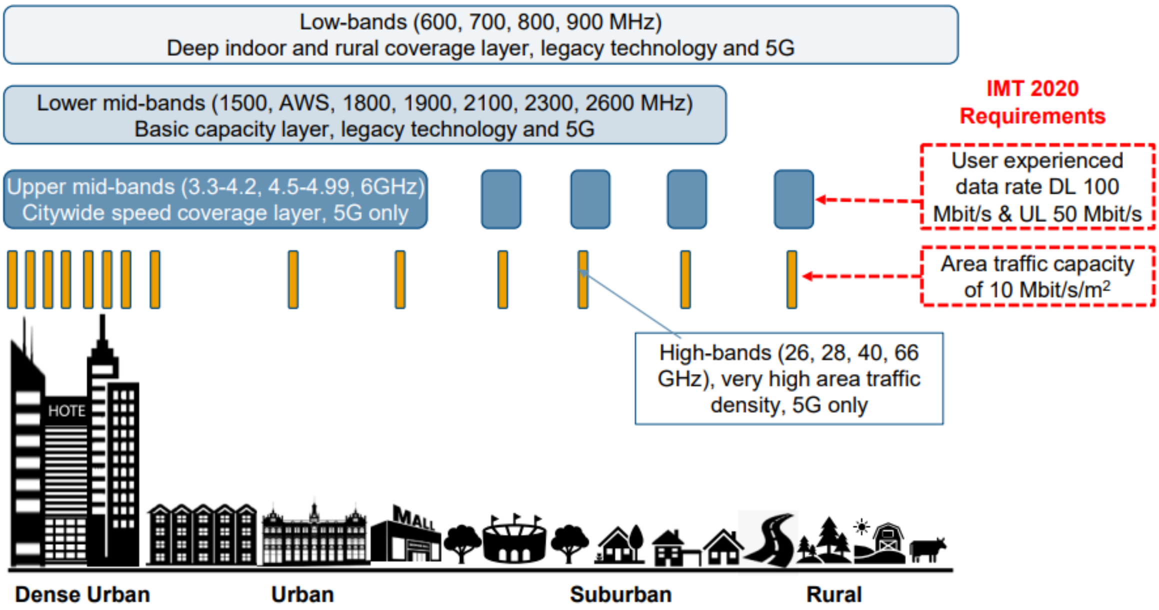
Maximising network coverage

It is desirable for mobile coverage to be achieved across all areas especially rural areas, where it can be difficult to deliver economic service with existing infrastructure solutions. This has already been a challenge with the rollout of 5G. Therefore, 6G needs to consider how to bring similar performance while also being economical to deploy in sparsely populated regions.

To balance the density demands of urban environments and the low demand of rural, the expectation is that the current divergence in spectrum and technologies used in urban and rural environments would continue, as shown in Figure 41.

This factor could significantly affect the aggregate demand for resilient timing services with the potential for tight timing requirements being required in urban locations while rural locations have less stringent requirements.

Figure 41 Mix of spectrum for 5G



Source: Coleago Consulting (2021) GSMA estimating mid band spectrum needs. Available at: https://www.gsma.com/spectrum/wp-content/uploads/2021/07/Estimating-Mid-Band-Spectrum-Needs.pdf

3.4.3 Drivers and enablers for adopting resiliently disseminated time

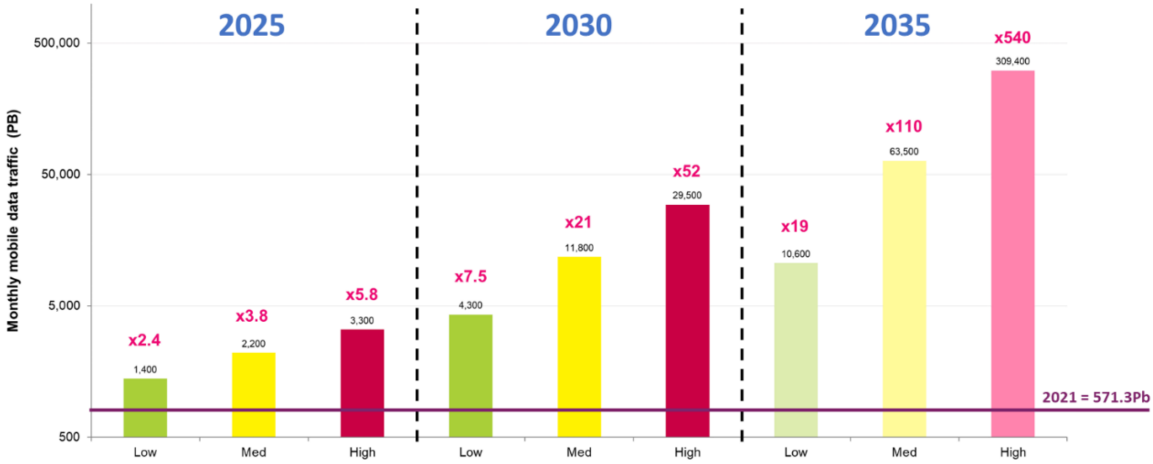
Increasing demand for data

For 6G to be required, demand for data and performance must increase beyond what can be achieved with 5G networks. However, this demand and the use cases which support this demand are uncertain.

In 2021, Ofcom modelled what total mobile data traffic could look like in 2025, 2030 and 2035[89] (shown in Figure 42 and Figure 43). Since this report, Ofcom reported that in 2022 to 2023, total monthly traffic has risen from 724 Petabytes (PB) to 905 PB, an annual growth of around 25%. Should growth of 25% continue, this would broadly align with lower scenario depicted with 1,414 and 4,315 and 13,169 PB in 2025, 2030 and 2035 respectively. However, the range of uncertainty is substantial and the implications for when 6G is required for mobile networks varies quite substantially on the eventual growth that arises. Should the growth data demand slow it would delay the need for 6G in the UK. For reference, in 2022 the UK had an average monthly mobile data usage per mobile broadband subscription of 8.1Gb, below the OCED average of 33 countries of 14.2 GB[90].

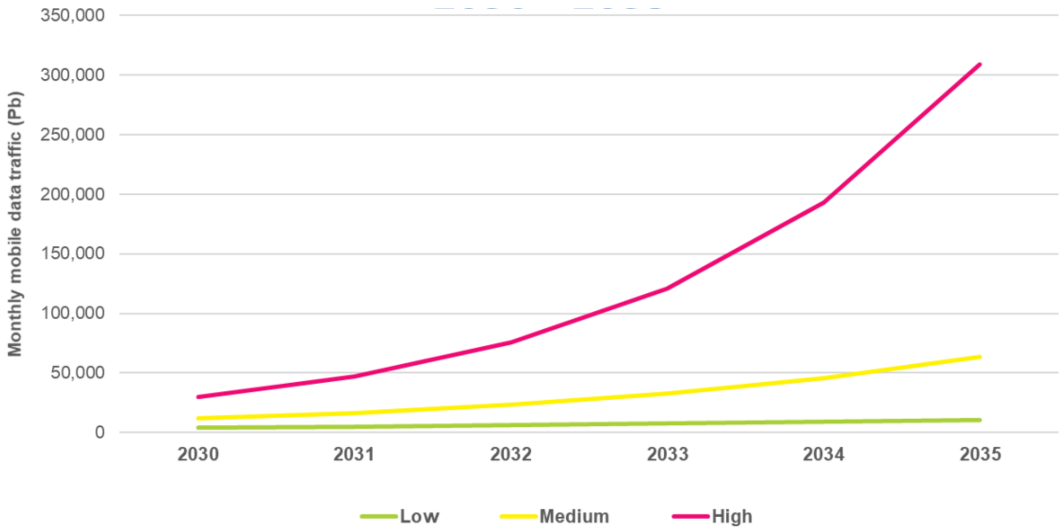
[89] Ofcom (2022). Mobile networks and spectrum: meeting future demand for mobile data. Available at: https://www.ofcom.org.uk/__data/assets/pdf_file/0017/232082/mobile-spectrum-demand-discussion-paper.pdf
[90] OECD. Going digital. Available at: https://goingdigital.oecd.org/dimension/use

Figure 42 Illustration of data traffic growth over time in our low, medium and high scenarios



Source: Ofcom (2022). Mobile networks and spectrum: meeting future demand for mobile data. Available at: [***https://www.ofcom.org.uk/__data/assets/pdf_file/0017/232082/mobile-spectrum-demand-discussion-paper.pdf***](https://www.ofcom.org.uk/__data/assets/pdf_file/0017/232082/mobile-spectrum-demand-discussion-paper.pdf)

Figure 43 Illustration of how data traffic growth diverges over time across our low, medium and high growth scenarios



Source: Ofcom (2022). Mobile networks and spectrum: meeting future demand for mobile data. Available at: [***https://www.ofcom.org.uk/__data/assets/pdf_file/0017/232082/mobile-spectrum-demand-discussion-paper.pdf***](https://www.ofcom.org.uk/__data/assets/pdf_file/0017/232082/mobile-spectrum-demand-discussion-paper.pdf)

Figure 44 Factors which may drive low and high growth demand scenarios for 5G

Low Growth	High Growth
Where possible, many consumers choose to stick with 4G. Those with 5G typically use modest amounts of data.	5G rollout continues at a high pace. Consumer uptake grows rapidly, with many making use of large amounts of data.
New data-intensive applications typically fail to hit the mainstream and remain niche, used by a subset of early adopters. Few unforeseen applications arise. Use of wireless data by machines, sensors and devices does not grow substantially.	A range of new, data-intensive applications hit the mainstream and are used day-to-day, supported by advanced new devices. This includes various applications that had not been previously considered. Use of wireless data by machines, sensors and devices grows rapidly.
The most popular applications use limited mobile data. For example, many do not require mobility beyond the home and offer good functionality even when offline. Machines, sensors and devices do not typically require mobile connectivity, instead using alternatives e.g. wired connections.	The most popular applications are highly mobile data intensive and require a high degree of mobility. For example, cloud gaming over 5G becomes the norm for mobile gaming. Machines, sensors and devices increasingly connect via mobile.
Wi-Fi speeds grow at a fast rate, supported by growing gigabit capable and full-fibre fixed availability and adoption. Wi-Fi remains the default for indoor connectivity, and greater hotspot coverage and quality increases Wi-Fi usage on the move.	Mobile remains the default for on the move connectivity due to faster speeds and ease of connectivity. Indoor mobile coverage improves meaning 5G is perceived as better than Wi-Fi in some locations. Consumers often opt to connect to mobile even when Wi-Fi is available.
Industry increasingly uses non-mobile connectivity technologies or selects standalone private mobile networks instead of relying on MNO networks.	Industry increasingly uses MNO networks or MNO provided network slices to support connectivity. Standalone private mobile networks remain niche.
Alternative connectivity technologies support an increasing range of applications. For example, low-power wide-area networks are the default for IoT, and satellite supports an increasing range of applications.	Mobile technology supports an increasing range of applications. For example, 5G becomes the default for IoT connectivity and satellite typically supports applications only in remote areas lacking mobile connectivity.

Source: Ofcom (2022). Mobile networks and spectrum: meeting future demand for mobile data. Available at: *https://www.ofcom.org.uk/__data/assets/pdf_file/0017/232082/mobile-spectrum-demand-discussion-paper.pdf*

3.4.4 Blockers for adopting resiliently disseminated time

MNO financial and business model pressure

See section 3.3.4 and Figure 25 for discussion of how UK MNOs' business models are under increasing pressure. The relevance of these points for 6G are that MNOs will be keen to reduce their CAPEX and to extend the operational lifetime of their 5G investments. Much of this depends on the specification of 6G: if 6G is incremental and cheap to rollout (as was the case with non-standalone 5G) then these effects could be mitigated but if 6G is expensive expect a slower rollout of 6G concentrated in highly populated urban environments.

3.4.5 Market sizing methodology

To size the TAM for 6G resilient time and manage the uncertainty surrounding the 6G specifications, three scenarios were constructed. To enable comparisons to be made, each scenario is defined relative to 5G:

- **Scenario 1 – Evolution of 5G:** 6G seeks to achieve incremental improvements over 5G. 6G retains the 5G core and 5G RAN. Timing requirements remain the same as 5G networks.

Rollout focuses on densification of networks using very small cells which are cheaper on per unit basis than large 5G cells.

- **Scenario 2 - New RAN:** 6G adopts new RAN with new duplexing approaches that are more demanding. Spectrum is freed up to avoid use of higher frequencies as far as possible. As a result, timing requirements remain low to avoid cost of rollout. Rollout focuses on densification of networks using small cells which are cheaper on per unit basis than large 5G cells.
- **Scenario 3 - Revolutionary technology:** Brand new 6G RAN is adopted with heavy use of new spectrum. Strong emphasis on spectral efficiency requiring advanced modulation techniques requiring very tight timing requirements. Heavy use of high frequencies increases the expected density networks required increasing locations for where time is required. Rollout is slowed due to large technical challenges.

To derive a TAM, estimates were made for each scenario's costs leveraging a Frontier report on 5G investment costs for the UK, see Table 24.

Note that the TAM estimate here focuses on the time equipment CAPEX and OPEX for 6G networks and does not include revenues associated with research and development or product development of 6G timing technologies.

Table 24 6G scenario CAPEX and OPEX estimates

	Scenario 1: Densification of 5G	Scenario 2: New RAN	Scenario 3: Revolutionary technology
% of 6G CAPEX and OPEX per base station compared to 5G costs	25%	50%	50%
Total 6G base station CAPEX (£)	6,814	13,628	13,628
% of 6G CAPEX and OPEX related to timing	10%	15%	20%
Timing CAPEX per base station	681	2044	2726
Timing OPEX per 6G base station	50	150	200
Rate of rollout compared to 5G	300%	200%	100%

Note: 6G costs compared to average 5G base station costs of £27,256 derived from LE analysis correcting for inflation and % of small and large cells of Frontier report on the cost of 5G rollout for small cells; LE estimation of % of base stations costs that could be related to timing equipment; OPEX defined as licensing and maintenance only, estimated to be £2,002 per cell per year; Historic rate of 5G rollout as reported by Ofcom is based on period of 2019 – 2023, see Figure 23

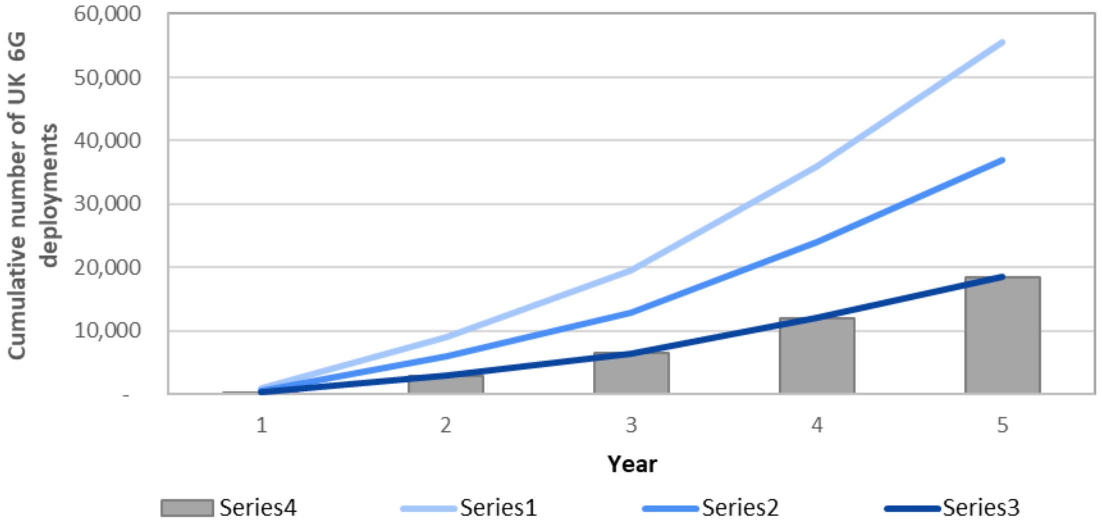
Source: Frontier report on the cost of 5G rollout for small cells. Available at: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/728816/Frontier_report_on_Mobile_Market_Dynamics.pdf

It must be emphasized that the values stated in the above are highly speculative. However, in general, four factors are expected of the 6G rollout 1) focus on densification and hence higher rollout rate than 5G on a base station volume basis; 2) the adoption of new technologies such as duplex methods and higher frequencies will increase the criticality of timing; 3) as cells get smaller and more numerous they will need to be cheaper to remain economically viable for MNOs 4) the greater the technological shift from 5G the slower and more concentrated in urban environments the rollout rate is likely to be. How these factors play out will define the TAM for 6G time.

The estimated rollout rates and market sizes for the UK for the three scenarios defined by the above table are shown in Figure 45, and Figure 46[91]:

[91] Figure 45 and Figure 46 assume a 2030 start date for the UK rollout, this is by no means assured

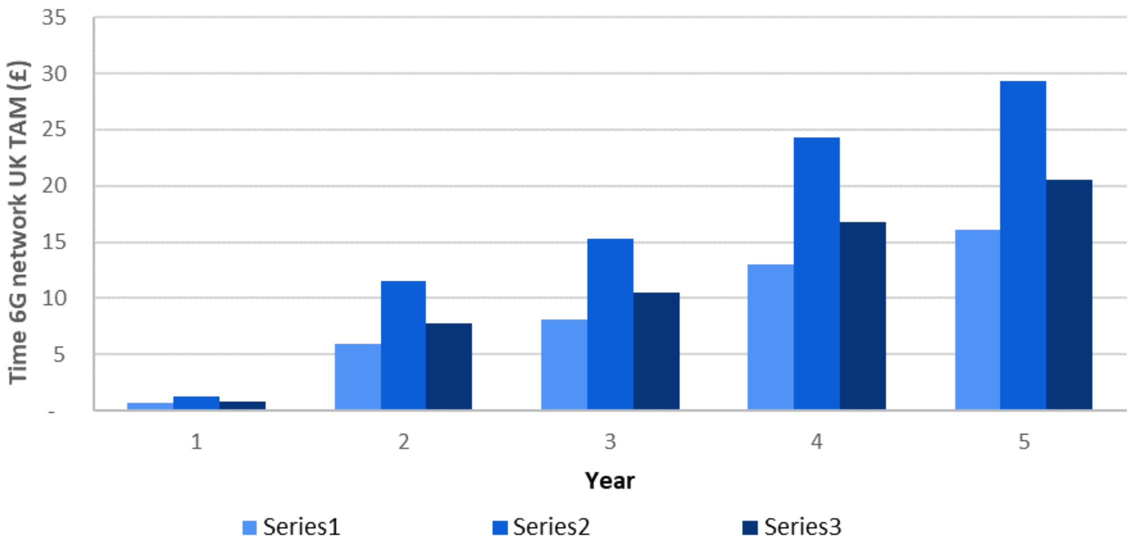
Figure 45 6G scenario roll out rates



Source: LE analysis using annual Ofcom Connected Nations reports. Available at: https://www.ofcom.org.uk/phones-and-broadband/coverage-and-speeds/infrastructure-research

3.4.6 Market sizing results

Figure 46 6G TAM market sizing results



3.4.7 Conclusions

- 5G networks are expected to be able to meet the vast majority of demand in the UK for the foreseeable future based on currently known use cases;
- The **growth rate in demand for mobile data will drive the urgency of the 6G rollout** which depends on a variety of socio-economic factors and the rate of adoption of the underlying use cases for data. The UK is trending towards the lower end of an Ofcom data usage forecast made in 2020;
- It would not be expected for the UK to lead in the rollout of 6G networks as the UK is lagging with respect to average data usage across the OECD;

- The **specifications for 6G have yet to be ratified,** which is expected to occur in 2028. 6G is not expected to begin its rollout until 2030 at the earliest for some countries;
- The requirements for resilient timing cannot be determined at this point given that the specification for 6G have not been agreed;
- Scenarios how 6G could be rolled out have been explored through three scenarios with 5G being used as the basis for the forecast;
- **Annual TAM for timing in 2034 for 6G was estimated to be in the region of £16m - £29m**, which is believed to be optimistic given data usage trends in the UK and potential start date of 6G rollout;
- Should the ratio of market sizes between UK and EU27 remain for 6G as it was for 5G this would imply a **TAM in 2034 for 6G timing in the EU27 to be £156m - £287m**;
- The **TAM stated here should be treated as indicative given the uncertainty on 6G timing requirements**;
- The **TAM does not include revenues associated with research and development or product development of 6G timing technologies** and is based on timing equipment CAPEX and OPEX only;
- It should be noted that **more stringent timing requirements do not necessarily mean a larger TAM for resilient timing**. Two factors can drive this 1) Smaller cell puts an even greater emphasis on reducing per cell costs as they get more numerous and 2) should 6G adopt higher frequencies (e.g. THz) their worse propagation characteristics would likely limit 6G adoption to dense urban environments.

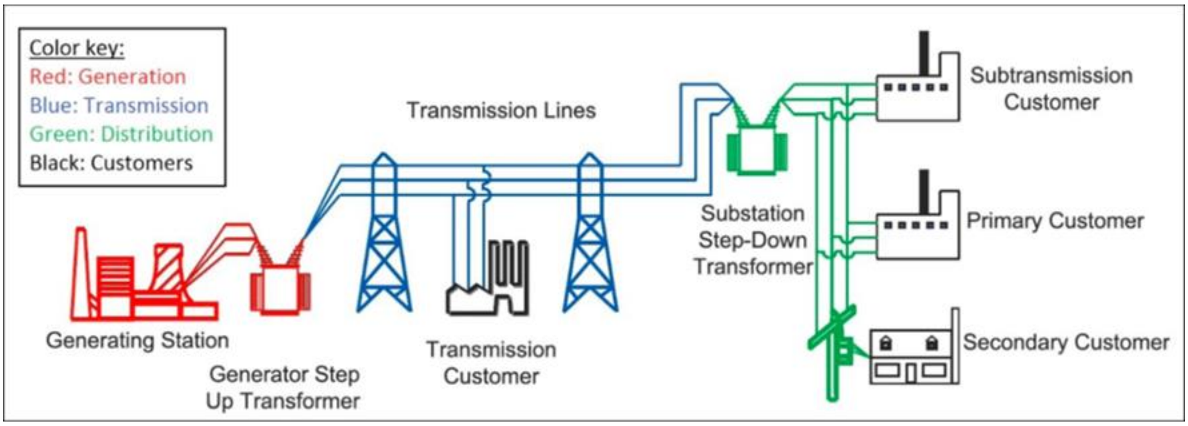
3.5 UC5: Energy monitoring, measurement, and analysis

This use case focuses on the utilisation of time by Distribution Network Operators (DNOs) and Independent Distribution Network Operators (IDNOs) within their networks.

Distribution Network Operators

DNOs are entities responsible for managing the distribution of electricity from high-voltage transmission networks to end-users, including homes and businesses. They own and operate the infrastructure, such as substations, transformers, and power lines, necessary for delivering electricity to consumers within their geographical regions. The figure below illustrates the downstream position in which Distribution Network Operators (DNOs) operate.

Figure 47 Typical electricity system



Source: Department of Energy, "Quadrennial Technology Review Chapter 3," September 2015. [Online]. Available: https://www.energy.gov/sites/prod/files/2017/03/f34/qtr-2015-chapter3.pdf . [Accessed April 2024]

Figure 48 UK map of Distribution Network Operators

In the UK, there are 7 major DNOs:

1. Scottish and Southern Energy
2. SP Energy Networks
3. Northern Power Grid
4. Electricity North West
5. National Grid Electricity Distribution
6. UK Power Networks
7. Northern Ireland Electricity

Source: UK Power Networks [Online]. Available: https://www.ukpowernetworks.co.uk/our-company/areas-we-cover [Accessed June 2024]

Independent Distribution Network Operators

To foster competition in the electricity distribution sector, Ofgem now grants licenses to Independent Distribution Network Operators. IDNOs, similar to DNOs, are organisations tasked with distributing electricity to end-users. They establish connections either to the local distribution network or directly to the transmission network to distribute electricity to new residential and commercial developments. IDNOs bear the responsibility for operating the networks they establish, encompassing all maintenance and fault repair. Examples of IDNOs include:

- Eclipse Power Limited
- Energy Assets Networks Limited
- Energetics Electricity Limited
- ESP Electricity Limited
- Fulcrum Electricity Assets Limited

Both DNOs and IDNOs operating in the UK are subject to regulation by Ofgem.

3.5.1 Use of time

The primary uses of time for DNOs and transmission operators (TOs) are largely similar. While both DNOs and TOs employ time for common purposes in network operations, there exist nuances in their specific applications and requirements which vary based on the scale, complexity, and function of each network segment.

3.5.2 User requirements

Table 25 User requirements for use case

Application	Timing accuracy	Availability %	Integrity	Continuity	Time to alert	Indoors (Y/N)
Power distribution network health and usage monitoring	1ms	99.999	N	7d	<7s	N
Line protection scheme	100µs	99.999	N	7d	<7s	N
Sampled Value data streams (IEC 61850-9-2-LE / IEC 61869-9)	1µs	99.999	N	7d	<7s	N
Power system measurements/ power quality measurements	1ms	99.999	N	7d	<7s	N
Fault recording and location	1µs	99.999	N	7d	<7s	N
Phasor Measurement Units (Wide Area Monitoring system)	1µs	99.999	N	7d	<7s	N

Source: Internal UK Government PNT use case review, submitted to IEEE P1952 committee (2022)

3.5.3 Drivers and enablers for adopting resiliently disseminated time

Regulatory enforcement

In the UK, both DNOs and IDNOs operate under the regulatory framework established by Ofgem. These entities bear the responsibility of upholding grid reliability and addressing power outages by ensuring uninterrupted electricity supply to consumers. Under these regulations, DNOs and IDNOs are obligated to provide compensation to customers affected by prolonged power outages. The compensation scheme outlines specific amounts that household and business customers are entitled to claim, depending on the duration of the outage[92]. Customers may claim a fixed amount for every 12-hour period they are without electricity, up to a maximum total compensation amount of £300. In order to mitigate financial losses incurred through compensation payouts, network operators are motivated to acquire services that bolster the grid's resilience in the event of a potential service disruption.

Network investment due to increasing demand

The increasing demand for electricity is being primarily driven by two factors: the electrification of homes, particularly through the adoption of heat pumps, and the rising popularity of Electric Vehicles (EVs). Projections indicate that by 2035, a substantial portion of the transportation and residential sectors could be transitioning towards electricity as their primary energy source. Specifically, it is estimated that 80% of vehicles on the road could be electric by this time, while 41% of households could be utilising electricity for heating purposes[93]. Furthermore, in alignment with ambitious net-zero targets, there is a pressing need to integrate a diverse array of new energy generation sources into the grid. While a major source of investment, and requiring synchronisation, integrating new power generation sources into the grid are not expected to be a driver of demand for resiliently disseminated time given the low volume of individual power plants compared to substations and other grid infrastructure that require synchronisation. Addressing growing demand for energy requires substantial investment in new and upgraded infrastructure from DNOs.

[92] www.ofgem.gov.uk. (n.d.). *Compensation for energy supply issues | Ofgem*. [online] Available at: https://www.ofgem.gov.uk/information-consumers/energy-advice-households/check-compensation-rules-power-cut-or-supply-problem[Accessed 5 Apr. 2024].

[93] Regen, (n.d.). Building a GB electricity network ready for net zero. [online] Available at: https://www.regen.co.uk/wp-content/uploads/Building-a-GB-electricity-network-ready-for-net-zero.pdf [Accessed 11 Apr. 2024].

Estimates suggest that DNOs may need to invest between £70-90 billion[94] between now and 2050 to adequately meet this increased demand.

Anticipating future electricity demand growth is driving increased investment in infrastructure, reflecting a proactive response to evolving energy needs. Maximising existing network capacity is essential to accommodate this growth, requiring improved network monitoring and flexibility. Facilitated by the RIIO-ED2 price controls, DNOs have been allocated £166 million of IT & Telecoms (IT&T) funding[95] to invest in improved network monitoring. Time plays a crucial role in this monitoring process, ensuring network synchronisation and accurate time stamping. The allocation of this funding indicates a willingness to invest in initiatives that enhance energy distribution operations. Therefore, it may serve as a catalyst for the adoption of a resiliently disseminated time service. For telecommunications functions in the energy sector, DNOs strategically depend on public mobile networks when operationally viable but rely on private networks (such as the National Grid Telecoms Network) for critical functions requiring high reliability and low latency. The part A study does not cover this second-order dependency, which will be explored in the part B study.

3.5.4 Blockers for adopting resiliently disseminated time

High costs to modernise the grid

The modernisation of DNO operations to meet the growing demands of energy consumption requires significant capital investment. DNOs are confronted with various capital and operational expenditure needs, including upgrading ageing infrastructure, implementing smart grid technologies, and improving cybersecurity measures. The RIIO-ED2 price control established by Ofgem determines the funding allocated to DNOs to meet customer demand during the period spanning from 2023 to 2028. The overall funding allocated to DNOs during this timeframe totals £22.207 billion, representing a shortfall of 11.8% compared to the funding request made by the DNOs (£25.176 billion)[96]. This deficit underscores the limited availability of financial resources. Given the finite nature of these resources, DNOs are compelled to prioritise competing demands as they work to modernise their networks. Resilient disseminated time services may be deprioritised to initiatives perceived as more pressing or crucial to overall modernisation efforts. DNOs may choose to allocate resources to initiatives offering immediate or tangible benefits, such as infrastructure upgrades or system enhancements that directly tackle known operational challenges.

Existing time resiliency measures

DNOs typically already have established systems and protocols (such as GNSS receivers, PTP grandmasters, and PTP boundary clocks) in place to ensure the synchronisation and accuracy of timing across their networks. These existing measures may include backup timing sources, synchronisation technologies, and protocols that have been in use for years and have proven to be reliable. One challenge is the reluctance to deviate from these established systems, particularly if they have been in place for a long time without major issues. DNOs may be hesitant to invest in new timing services if they perceive their current measures as sufficient for meeting operational needs and regulatory requirements.

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94 Appendix I: Electricity Networks Modelling. (2022). Available at: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1096248/electricity-networks-strategic-framework-appendix-1-electricity-networks-modelling.pdf.

95 Open letter on future reform to the electricity connections process. (2023). Available at: https://www.ofgem.gov.uk/sites/default/files/2023-05/Open%20Letter%20Connections%20%28Final%2016.5.23%29.pdf [Accessed 8 Apr. 2024].

96 Ofgem. (n.d.). *Ofgem confirms local electricity networks price control for 2023 to 2028*. [online] Available at: https://www.ofgem.gov.uk/publications/ofgem-confirms-local-electricity-networks-price-control-2023-2028.

3.5.5 Market sizing methodology

TAM assessment approach

This assessment evaluates DNOs potential financial exposure due to Global Navigation Satellite Systems (GNSS) outages, and thus their willingness to pay for a resiliently disseminated time service.

The liability of DNOs is assessed by estimating the capital at risk in the event of a service interruption caused by a GNSS outage. In the UK, customers are entitled to compensation under Ofgem regulation if they experience a power outage lasting more than 12 hours[97]:

- Household customers can claim £90.
- Business customers can claim £175.
- Both household and business customers are entitled to an additional £40 for every subsequent 12-hour period without power, up to a maximum of £300.
- For this analysis, the compensation per customer is calculated assuming a 48-hour outage and assumed to be constant over the forecast period (i.e. not adjusted for inflation).

It is important to note that DNOs in the EU are subject to national regulations which vary across each member state. Due to lack of available data from EU member states on the specific fines imposed by national regulators, the compensation for EU customers in case of a power outage is estimated by utilising the UK compensation and adjusting it based on GDP per capita[98].

In estimating the potential financial impact on DNOs, compensation per customer is multiplied by the total number of household and business customers, respectively. This provides an estimate of the total penalty that may be levied on each DNO in the event of a service interruption.

The likelihood of such service disruptions occurring is considered by utilising figures from the National Risk Register to determine the annual probability of experiencing a loss of Global Navigation Satellite Systems (GNSS). These probabilities are based on a reasonable worst-case scenario of a severe technical failure, due to either hardware failure or human error. It should be noted that the assessment does not seem to account for other risks to GNSS[99], such as the threat from space debris or nation-state attacks, which could escalate probabilities past the stated range.

The willingness to pay for each DNO is approximated by multiplying the annualised probability of a loss of GNSS by the financial penalty they face during a power outage. Taking the average DNO willingness to pay and multiplying by the number of DNOs yields the TAM.

[97] Ofgem. *Check the compensation rules for a power cut or supply problem*. [online] Available at: https://www.ofgem.gov.uk/information-consumers/energy-advice-households/check-compensation-rules-power-cut-or-supply-problem.

[98] OECD. *GDP and Spending - Gross Domestic Product (GDP) - OECD Data*. [online] OECD. Available at: https://data.oecd.org/gdp/gross-domestic-product-gdp.htm#indicator-chart.

[99] Editor (2023) *PNT loss on UK National Risk Register - Bad assumptions on purpose? - RNTF*. https://rntfnd.org/2023/08/08/pnt-loss-on-uk-national-risk-register-bad-assumptions-on-purpose/.

Figure 49 Market sizing approach

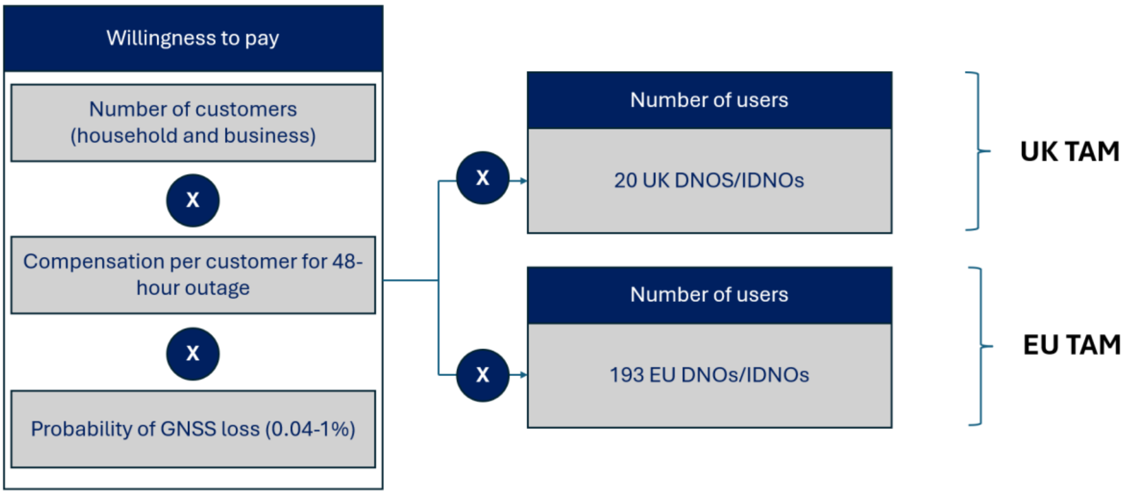


Table 26 Market sizing parameters

Parameter	Description	Source
(1) Number of customers	Number of household and business customers for DNOs/IDNOs in UK and EU.	DNO public data and LE analysis
(2) Compensation per customer for 48-hour outage	Compensation entitled per customer for a 48-hour outage (£210 for household customers, £295 for business customers).	Ofgem
(3) Probability of GNSS loss	Probability of loss of GNSS services (0.04-1%).	National Risk Register
(4) Number of distribution network operators and independent distribution network operators	The number of DNOs and IDNOs in the UK and EU.	LE analysis

Note: These parameters are incorporated in the market sizing exercise. They are the inputs to the methodology that are used to estimate the TAM. In addition, the National Risk Register assessed likelihood of loss of GNSS over 5 years, so the published probabilities in the register were divided by five to calculate the annual risk.

Source: DNO customers – SSE Networks [Online] Available at: https://ssenfuture.co.uk/about-ssen/, SP Energy Networks [Online] Available at: https://www.spenergynetworks.co.uk/pages/what_we_do.aspx , Northern Power Grid [Online] Available at: https://www.northernpowergrid.com/about-us, Electricity North West [Online] Available at: https://www.enwl.co.uk/globalassets/about-us/regulatory-information/documents/business-plan-annexes/individual-sections/section2-companyoverview.pdf, National Grid Electricity Distribution [Online] Available at: https://www.nationalgrid.com/electricity-transmission/document/150811/download, UK Power Networks [Online] Available at: https://www.thedrum.com/news/2023/11/30/how-uk-power-networks-created-more-engaging-online-experiences, Northern Ireland Electricity [Online] Available at: https://www.nienetworks.co.uk/documents/annual-reports/nien-2023-credit-rating-full-report-011123.aspx, Compensation per customer [Online] Available at: https://www.ofgem.gov.uk/compensation-energy-supply-issues, Number of DNOs and IDNOs UK – Nationwide Utilities [Online] Available at: https://www.nationwideutilities.com/service/dno-idno/, Number of DNOs and IDNOs EU – Eurelectric [Online] Available at: https://cdn.eurelectric.org/media/5089/dso-facts-and-figures-11122020-compressed-2020-030-0721-01-e-h-6BF237D8.pdf

Distribution network operator number of household and business customers

Data from the UK government on smart meter roll out progress[100] is utilised to determine the total number of meters installed in households, assumed to reflect the number of household customers nationwide. The total number of business customers in the UK is represented by the number of business locations[101], with the assumption that each location has a meter installed.

The number of household and business customers per DNO is estimated by applying the ratio of total UK households to businesses to the public customer data provided by the DNOs on their websites. Household customer growth is scaled based on population growth trends, while business customer growth is determined by applying the average growth rate in the number of businesses in the UK per year since 2010.

EU household customers are estimated by applying the UK's household customer to population ratio to the EU population count. Given the average household size of 2.36 in the UK[102] and 2.3 in the EU[103], this method is considered reasonable. The number of EU businesses are calculated using the same methodology as UK businesses – obtaining historical data on the number of businesses and using the average growth over the period to forecast growth up to 2030.

Equipment volume

The TAM assessment for a resiliently disseminated time service focuses on the service revenue generated, considering factors such as the number of users and their willingness to pay for the service. As the scope of the study does not consider any particular technology for time dissemination, the TAM does not include equipment costs, as pricing equipment would not be feasible in a technology-agnostic approach.

However, it is essential to recognise that to utilise this service, users will require equipment. Therefore, a comprehensive evaluation extends beyond service revenue alone and includes an analysis of the equipment volume necessary for service implementation, acknowledging the interconnected nature of service provision and the requisite infrastructure. The equipment volume figures serve as a useful metric in understanding the quantum of investment required from transmission operators to adopt a resiliently disseminated time service.

In assessing the equipment needs, the analysis considered both the quantity of substations per operator[104] [105] and the average count of timing devices situated at each individual substation site[106]. The technologies used in transmission substations often include sophisticated synchronisation systems to manage the precise timing needed for high-voltage operations. DNO substations, on the

[100] Responsible statistician: Mita Kerai Smart Meter Statistics in Great Britain: Quarterly Report to end. (2023). Available at: https://assets.publishing.service.gov.uk/media/646f7ff47dd6e70012a9b3f6/Q1_2023_Smart_Meters_Statistics_Report.pdf.

[101] www.ons.gov.uk. *UK business; activity, size and location - Office for National Statistics*. [online] Available at: https://www.ons.gov.uk/businessindustryandtrade/business/activitysizeandlocation/bulletins/ukbusinessactivitysizeandlocation/2023

[102] www.ons.gov.uk. (2023). *Families and households in the UK - Office for National Statistics*. [online] Available at: https://www.ons.gov.uk/peoplepopulationandcommunity/birthsdeathsandmarriages/families/bulletins/familiesandhousehold

[103] European Commission *Housing in Europe - Size of housing*. [online] Available at: https://ec.europa.eu/eurostat/cache/digpub/housing/bloc-1b.html [Accessed 25 Apr. 2024].

[104] Centre, E.I.D. (2023). *Locations and characteristics of electricity substations (33 kV or larger), Great Britain, 2018*. [online] www.data.gov.uk. Available at: https://www.data.gov.uk/dataset/1192779d-be8e-4a24-9436-2d1391809cc9/locations-and-characteristics-of-electricity-substations-33-kv-or-larger-great-britain-2018 [Accessed 25 Apr. 2024].

[105] Northern Ireland Electricity. *Connect a new home, business or property to our network | Northern Ireland Electricity Networks*. [online] Available at: https://www.nienetworks.co.uk/connections/capacity-map.

[106] London Economics (2017). The economic impact on the UK of a disruption to GNSS Full Report Redacted. (2017). Available at: https://londoneconomics.co.uk/wp-content/uploads/2017/10/LE-IUK-Economic-impact-to-UK-of-a-disruption-to-GNSS-FULLredacted-PUBLISH-S2C190517.pdf.

other hand, typically operate at lower voltages, utilising technologies that are designed for local distribution and do not require such stringent synchronisation, making their timing requirements inherently less demanding.

Equipment volume assessment approach

The increase in the number of substations displayed a correlation with the electricity consumption observed in the National Grid CNI Network and Systems use case. Consequently, this correlation was leveraged in the Energy Monitoring, Measurement, and Analysis Solutions use case. Historical data regarding the quantity of substations managed by Distribution Network Operators (DNOs) was extrapolated based on projections for electricity consumption. This extrapolation enabled the estimation of the anticipated growth in the number of substations up to the year 2030.

An assumption was made that, on average, each substation would be equipped with eight timing devices[107,108]. Multiplying this average by the respective number of substations provided estimates for the volume of equipment required within the UK and EU markets.

3.5.6 Market sizing results

Total addressable market

The forecasted total addressable market (TAM) for both the UK and EU is projected across low, central, and high scenarios, incorporating the annualised probability of GNSS loss from the National Risk Register as a sensitivity variable (0.04%, 0.2%, and 1%, respectively). Due to its direct impact on willingness to pay, this results in a large difference in market size between each scenario.

In the central scenario, the TAM for UK distribution network operators is currently valued at approximately £34.3 million, and is anticipated to reach £36.1 million in 2030, with a compound annual growth rate (CAGR) of 1% from 2025-2030.

The RIIO-ED2 price control framework, covering 2023 to 2028, guides DNOs' financial planning and resource allocation, impacting their investment decisions. The £22 billion allocated through RIIO-ED2 for investment spending aims to support the transition to net zero, enhance network resilience, foster innovation, and deliver consumer value. While this investment may include spending on resilient timing services, specific allocations are not detailed. The annualised RIIO-ED2 investment is approximately £4.4 billion per year, with the average TAM for resilient timing services at around £35 million per year for the same period, representing just under 1% (0.8%) of the annual investment. This is considered to be a reasonable proportion of overall investment spending.

Table 27 Range of TAM estimates for UK market (2024-2030)

Scenario	2024	2025	2026	2027	2028	2029	2030
Low	£7.92m	£8.00m	£8.08m	£8.15m	£8.21m	£8.28m	£8.34m
Central	£34.28m	£34.63m	£34.99m	£35.28m	£35.56m	£35.85m	£36.10m
High	£171.39m	£173.17m	£174.96m	£176.38m	£177.80m	£179.24m	£180.50m

[107] London Economics (2017) The economic impact on the UK of a disruption to GNSS. https://londoneconomics.co.uk/wp-content/uploads/2017/10/LE-IUK-Economic-impact-to-UK-of-a-disruption-to-GNSS-FULLredacted-PUBLISH-S2C190517.pdf (Accessed: March 28, 2024).
[108] This assumption does not influence the TAM.

Figure 50 Growth of UK TAM under low scenario

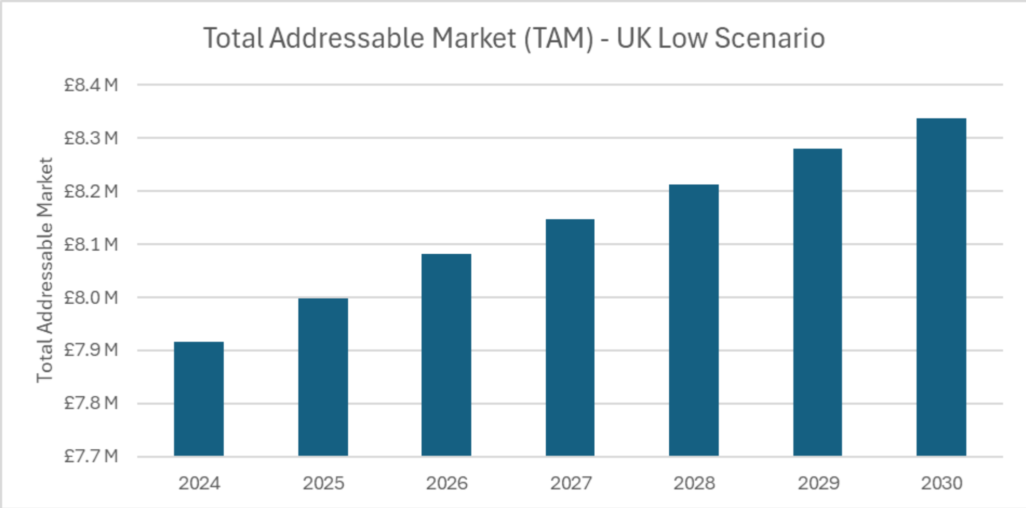


Figure 51 Growth of UK TAM under central scenario

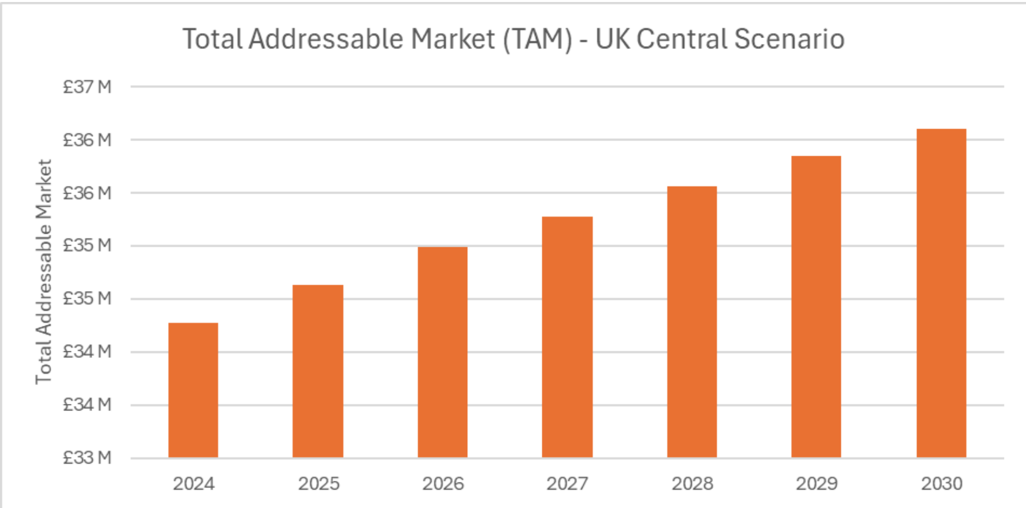
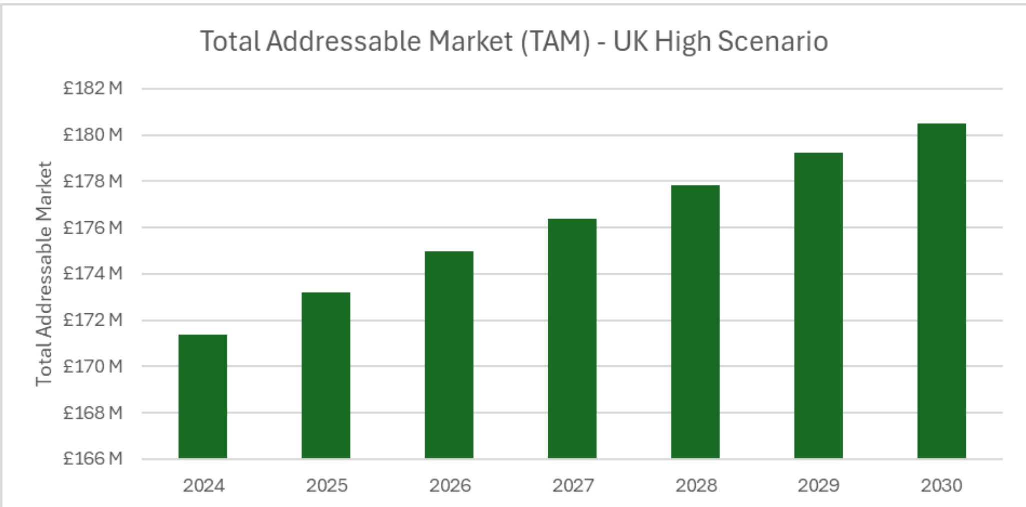


Figure 52 Growth of UK TAM under high scenario



In the central scenario, the TAM for EU distribution network operators is currently valued at approximately £120.5 million and is anticipated to reach £122.1 million in 2030, with a compound annual growth rate (CAGR) of 0.2% from 2025-2030. This slow growth rate can be attributed to a forecasted decline in the EU's population up to 2030[109], which is a significant factor influencing the growth of household customers and the total compensation metric, affecting willingness to pay and thus market size.

Table 28 Range of TAM estimates for EU market (2024-2030)

Scenario	2024	2025	2026	2027	2028	2029	2030
Low	£24.09m	£24.19m	£24.23m	£24.28m	£24.33m	£24.38m	£24.43m
Central	£120.47m	£120.93m	£121.16m	£121.40m	£121.64m	£121.89m	£122.14m
High	£602.35m	£604.64m	£605.81m	£607.01m	£608.22m	£609.46m	£610.71m

Figure 53 Growth of EU TAM under low scenario

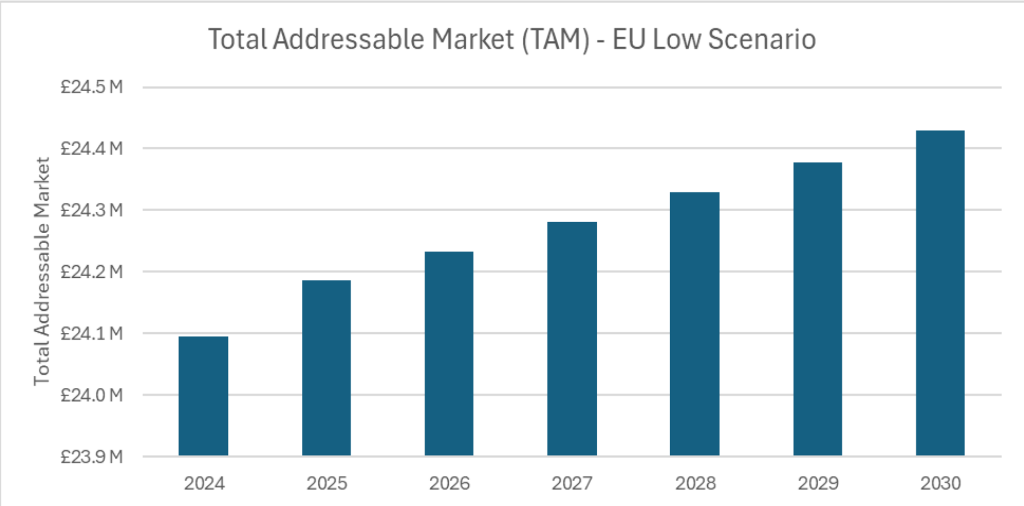
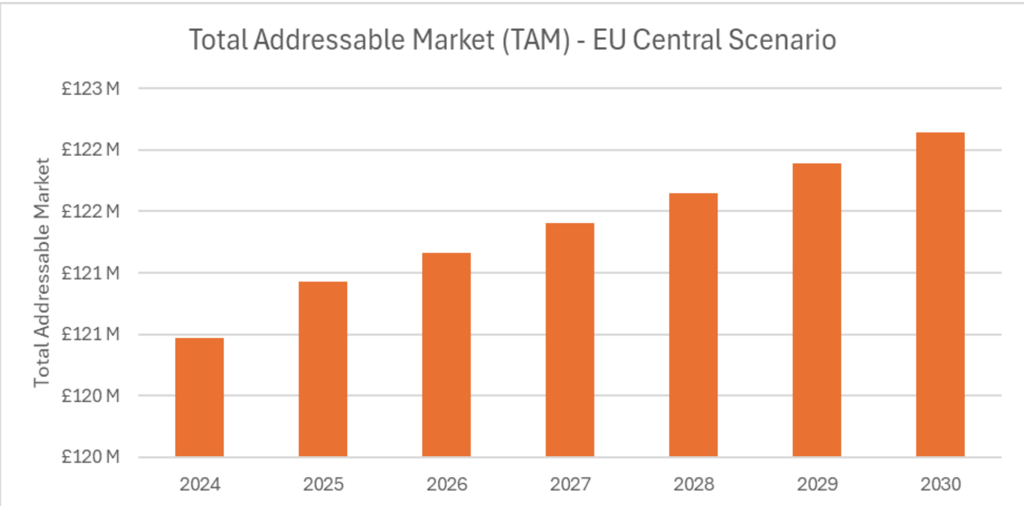
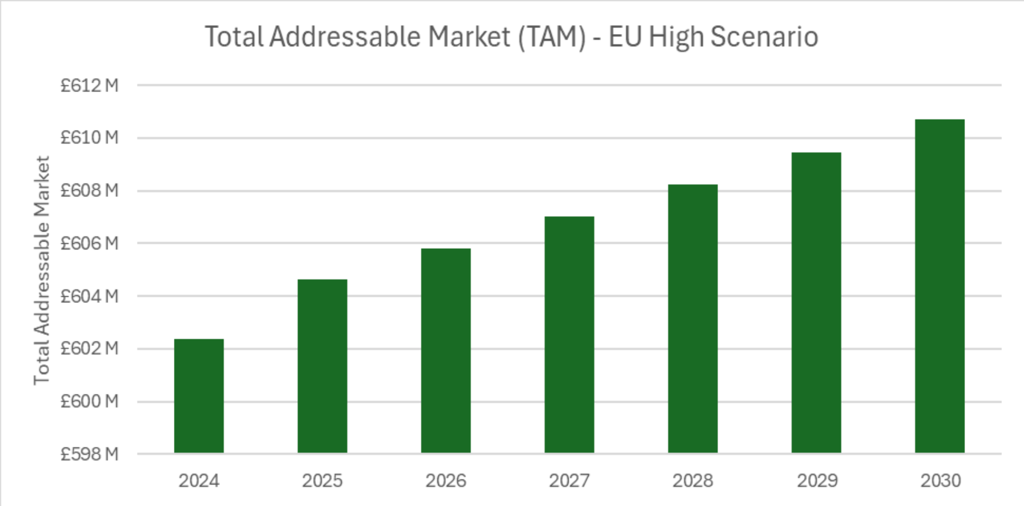


Figure 54 Growth of EU TAM under central scenario



[109] European Commission - European Commission. (n.d.). *Press corner*. [online] Available at: https://ec.europa.eu/commission/presscorner/detail/fr/MEMO_05_96.

Figure 55 Growth of EU TAM under high scenario



Equipment volume

The volume of equipment required is tied to the expansion of substations, a growth trend assumed to remain consistent across the different scenarios. This growth is predominantly driven by the rise in electricity consumption, reflecting the increasing demands placed on the electrical grid infrastructure. It is important to note that these equipment volume figures are distinct from the TAM estimates. This separation stems from the approach of maintaining technology neutrality throughout the assessment, which precludes the assignment of specific prices to the equipment. The table presented below illustrates the number of timing devices and their projected increase throughout the forecasted period.

Table 29 Forecast of number of timing devices for UK and EU markets

Region	2024	2025	2026	2027	2028	2029	2030
UK	48,296	48,792	50,152	51,888	53,680	55,392	57,360
EU	453,776	475,776	497,704	519,704	541,768	563,768	585,864

It should be noted that in this assessment, the count of timing devices associated with Independent Network Operators (IDNOs) is not included due to insufficient available data regarding the number of substations operated by them.

3.5.7 Conclusions

- DNOs must invest in infrastructure upgrades to meet **increasing energy demands**, driven by the electrification of homes and transportation, while also achieving net-zero goals.
- **Upgrading networks** and **building resilience** are imperative for DNOs to maintain robust operations, of which accurate and secure timing information is crucial, thus ensuring continuous supply to customers.
- Large fines for widespread outages will **incentivise DNOs to prioritise resiliency** measures to mitigate liabilities.
- The large liability faced due to regulatory fines stems from a substantial customer base comprising households and businesses, each eligible for compensation in the event of a power outage.

- Given that willingness to pay is incentivised by these fines, there exists a **considerable market potential** for resiliently disseminated time in terms of size.
- However, since market growth is tied to the expansion of the customer base, which is experiencing limited growth due to factors such as modest household and business growth, and in the case of the EU, a declining population, the market is projected to experience **minimal growth** during the forecast period.
- Regulatory oversight from Ofgem imposes RIIO-ED2 price controls and allocates funding, necessitating strategic **prioritisation of spending**.
- Shortfall in funding allocation for the next five years requires DNOs to **balance competing priorities**, including capacity upgrades, connectivity, technology adoption, and grid resilience.
- Different DNOs may **perceive priorities differently** based on their current operations and perceived areas of business risk.
- This analysis indicates a **significant motivation towards ensuring resilience**, and the decision to adopt a resiliently disseminated time service will hinge on how DNOs weigh their current resilience strategies against the perceived risk of a GNSS outage.

3.6 UC6: National grid CNI network and systems

This use case is focused on the utilisation of time in the electricity transmission network of a country's infrastructure. The UK transmission network mainly consists of a vast network of high-voltage (400 kV and 275 kV) power lines, substations, transformers, and other infrastructure that span across the country.[110] They are responsible for transmitting electricity from power generation sources, such as fossil fuel power plants, nuclear plants, wind farms, and solar farms to various distribution points, including large industrial consumers and distribution network operators (DNOs). The network operates at high voltage levels to minimise power loss during transmission and ensure efficient delivery of electricity over long distances. Figure 47 from section 3.5 depicts a typical electrical system broken down into the four key functions of generation, transmission, distribution, and customers.

The transmission networks in the UK are managed by four organisations:

- **National Grid:** England and Wales
- **Scottish Power Energy Networks:** Central and southern Scotland
- **Scottish and Southern Energy Networks:** Northern Scotland
- **System Operator for Northern Ireland:** Northern Ireland

They are responsible for ensuring the safe, reliable, and efficient operation of the system in their respective regions. Their remit includes monitoring power flows, managing grid stability, coordinating maintenance activities, and responding to system disturbances or emergencies. The transmission operators work closely with other stakeholders including electricity generators, DNOs, regulators, and government agencies, to maintain the integrity of the transmission network and meet the region's energy demands.

Transmission operators deliver electricity to DNOs through a combination of high-voltage transmission lines and interconnected substations. Substations are key components of the

[110] National Grid (n.d.) Substations, pylons and overhead lines. Available at: https://www.nationalgrid.com/electricity-transmission/who-we-are/running-our-network/substations-pylons-and-overhead-lines

transmission system and serve as intermediate points for voltage transmission, switching and control. These can be found where electricity enters the network (such as near power generation sources), or where it leaves the transmission network, known as grid supply points. They play a vital role in regulating the flow of electricity, maintaining voltage levels, and isolating sections of the grid during maintenance or emergency. Substations often house the equipment used for time synchronisation such as GNSS receivers, PTP grandmasters, PTP boundary clocks and phasor measurement units (PMUs), to ensure that all grid operations are coordinated and synchronised with a common time reference.

Figure 56 Locations of 400 kV and 275 kV substations in England, Wales and Scotland

Source: Locations and characteristics of electricity substations (33 kV or larger), Great Britain, 2018, Available at: https://www.data.gov.uk/dataset/1192779d-be8e-4a24-9436-2d1391809cc9/locations-and-characteristics-of-electricity-substations-33-kv-or-larger-great-britain-2018

3.6.1 Use of time

Precise and accurate time synchronisation is crucial in electricity transmission networks to achieve grid stability, ensuring continuous and efficient operations. The accuracy and resilience requirements of this time varies across the power network. In general, resilient time is required at substations for monitoring systems and to enable the system to respond to faults. The importance of this timing signal to operators varies based on the size of the substation, with larger substations being more dependent on precise timing. Given that transmission operators typically oversee the largest substations, accurate timing is critical across the majority of their substation infrastructure. Co-ordinated Universal Time (UTC) is used in various power grid applications and can be crucial for certain functions, especially those involving data sharing between organisations or high-precision timing, it's not universally required for all aspects of power grid operation, such as human to human communications[111]. The importance of UTC varies depending on the specific application and context within the power system. Key uses of time include:

[111] Vanoli, C. (2023). Future of time: Synchronization of electric power networks. [online] ITU. Available at: https://www.itu.int/hub/2023/08/future-of-time-synchronization-of-electric-power-networks/ [Accessed 28 Jun. 2024].

Log file coordination

In electricity transmission networks, timestamps on log files serve as crucial markers, ensuring the accurate sequencing of events and establishing a chronological record of system operations and incidents. This chronological perspective is invaluable for operators and engineers, as it enables them to trace the sequence of events during grid operations or disturbances. Moreover, accurate time synchronisation across various components of the grid is essential. It allows operators to correlate events seamlessly, even across disparate devices and systems. This correlation capability greatly aids in troubleshooting efforts, fault diagnosis, and comprehensive analysis of grid performance. By accurately aligning events in time, operators can effectively identify the root causes of issues, assess their impact on grid operations, and implement targeted solutions to enhance system reliability and resilience.

Phasor measurement units (PMU)

Time is also used in electricity transmission networks to synchronise measurements from PMUs distributed across the grid. These PMUs capture critical data on grid conditions and dynamics, including voltage, current, and frequency measurements, which are essential for monitoring and managing the power system. Accurate time stamps associated with PMU measurements enable synchronised collection and analysis of phasor data, ensuring consistency and reliability in assessing grid performance. By harmonising the timing of PMU measurements, grid operators gain access to synchronised phasor data, which is indispensable for wide-area monitoring (WAM) and control of grid dynamics. Time-synchronised PMUs offer valuable insights into various aspects of grid operation, including stability, power flows, and dynamic behaviour. This information supports advanced grid management and control functions, allowing operators to make informed decisions to enhance grid reliability, efficiency, and resilience. Note that interconnector links to other countries are direct current (DC) and therefore have no need for synchronisation, but will require measurement to monitor the flow of power.

Travelling wave fault detection

In the event of a disruption, the National Grid must swiftly transfer the load from an affected power line to an operational one within 120 milliseconds[112]. This process hinges on the meshed configuration of the transmission grid. Being fully meshed allows the grid to close off any individual line and redirect power elsewhere. This capability is crucial for promptly responding to incidents such as fallen trees, as it enables the instant localisation of faults, thereby preventing fires and other collateral damage.

Time-synchronised measurements from strategically positioned sensors along transmission lines play a vital role in detecting and locating traveling wave faults. Precise time synchronisation is essential for coordinating data collection from multiple sensors, enabling detailed fault detection and characterisation. With time-stamped travelling wave data, operators can swiftly locate, isolate, and rectify faults, thus improving grid reliability and minimising downtime. Fault locations can be pinpointed with an accuracy of up to 100 meters, leading to more efficient maintenance practices.

[112] The economic impact on the UK of a disruption to GNSS Full Report Redacted. (2017). Available at: https://londoneconomics.co.uk/wp-content/uploads/2017/10/LE-IUK-Economic-impact-to-UK-of-a-disruption-to-GNSS-FULLredacted-PUBLISH-S2C190517.pdf.

3.6.2 User requirements

The timing precision stipulated in IEC68150 encompasses various levels of accuracy, with the most rigorous being measured in microseconds (µs). There are indications suggesting a potential shift towards a range of 300-1000 nanoseconds (ns) for fault location purposes[113]. It is worth noting that the energy telecommunications network demands a precision of 100ns, a requirement typically addressed within the telecommunication function.

Establishing a direct fibre connection to the time source proves unfeasible for many grid locations requiring precise timing. While primary substations could use Two Way Satellite Time Transfer (TWSTT) from a National Timing Centre (NTC) site, secondary substations find a more scalable and widely accessible solution in utilising a wireless broadcast signal. Within this industry, the adoption of a Low Frequency (LF) broadcast system like eLoran is regarded as a viable option, as explored in the NPL Time Over eLoran (NTOL) project[114].

The following table illustrates the requirements for applications within transmission operator networks that rely on time signals.

Table 30 User requirements for use case

Application	Timing accuracy	Availability	Integrity	Continuity	Time to alert	Indoors (Y/N)
Protection synchronisation (ET)	1ms	99.999	N	7d	<7s	N
SCADA (SCS) (ET)	1ms	99.999	N	7d	<7s	N
Line protection scheme	100µs	99.999	N	7d	<7s	N
Sampled Value data streams (IEC 61850-9-2-LE / IEC 61869-9)	1µs	99.999	N	7d	<7s	N
Power system measurements/ power quality measurements	1ms	99.999	N	7d	<7s	N
Fault recording and location	1µs	99.999	N	7d	<7s	N
Phasor Measurement Units (Wide Area Monitoring system)	1µs	99.999	N	7d	<7s	N
Wind power generation power transfer	1ms	99.999	N	7d	<7s	N
National Grid CNI network	1ms	99.999	N	7d	<7s	N
IEMS (integrated energy management system) (ET/ESO)	1ms	99.999	N	7d	<7s	N
BM SORT (System Operation Real Time) (ESO)	1ms	99.999	N	7d	<7s	N
EBS (Electricity Balancing System) (ESO)	1ms	99.999	N	7d	<7s	N
FATE (Frequency And Time Error) (ESO)	1ms	99.999	N	7d	<7s	N

Source: ReThinkPNT analysis

[113] Meinberg, “Time Synchronisation in Power Applications,” in International Timing and Sync Forum, Dusseldorf, 2022
[114] UKRI NTOL NPL Timing Over Loran (2024). Available at: https://gtr.ukri.org/projects?ref=10037825 [Accessed 10 Apr. 2024]

In addition, data was retrieved from the Environmental Information Data Centre[115] was utilised to develop a dashboard showcasing the geographical distribution of substations in Great Britain with operational voltages of 33kV or higher where time is required. This dataset was aggregated from public information available on transmission and distribution network operator websites. The dashboard facilitates a comprehensive analysis of the number of substations per company and their respective operating voltages, offering insights into the regional presence of distribution and transmission operators.

3.6.3 Drivers and enablers for adopting resiliently disseminated time

Regulatory enforcement

As power grids are natural monopolies, they are heavily regulated. These regulations are the principal mechanism for incentivising operators to ensure that their networks are reliable and functional. In the UK Ofgem is the energy regulator. Ofgem has legal powers to enforcement including[116]:

- **Enforcing licence conditions and other relevant requirements**: Financial penalties of up to 10% of a regulated person's turnover, make consumer redress orders and issue provisional/final orders, where appropriate, for breaches of relevant licence conditions and other relevant requirements (and certain other provisions) under the Gas Act 1986 and the Electricity Act 1989;
- **Enforcing competition law**: Impose directions and penalties (e.g. a financial penalty on the infringing party of up to 10% of a company's applicable turnover) for breaches of the prohibitions on anti-competitive agreements and abusing positions of dominance in the Competition Act 1998;
- **Enforcing consumer protection law:** Take action including applying to the courts for an order to stop breaches of certain consumer legislation, including under the: Enterprise Act 2002, Consumer Rights Act 2015 and Business Protection from Misleading Marketing Regulations 2008;
- **Market investigation references:** Powers to carry out market reviews of activities connected with the generation, transmission and supply of electricity and the transportation and supply of gas;
- **Enforcing the Network and Information Systems Regulations**: Impose Enforcement Notices and/or Penalty Notices for failures and contraventions under the Network and Information Systems Regulations 2018;
- **REMIT and wholesale market integrity**: REMIT is Regulation (EU) no. 1227/2011 on wholesale energy market integrity and transparency, as incorporated into UK law by the European Union (Withdrawal) Act 2018 as amended by the European Union (Withdrawal Agreement) Act 2020 on 1 January 2021. It is a mechanism for reporting and preventing wholesale energy market abuse, in force since 28 December 2011.

[115] Lovett, A.A.; Sünnenberg, G. (2022). Locations and characteristics of electricity substations (33 kV or larger), Great Britain, 2018. NERC EDS Environmental Information Data Centre. https://doi.org/10.5285/0eed5c99-f409-4329-a98e-47f496bb88a2
[116] Ofgem (n.d.). Compliance and enforcement. Available at: https://www.ofgem.gov.uk/energy-policy-and-regulation/compliance-and-enforcement

Overall increase in electricity consumption

The National Grid estimates that electricity consumption in the UK will increase by approximately 50% by 2036 and more than double by 2050 as electric cars and heat pumps are adopted more widely. Currently, the electricity network experiences demand of 330 TWh per annum[117]. Depending on how we reach net zero, demand is expected to increase to between 450-500 TWh by 2035 and between 570- 770 TWh by 2050. This could create capacity problems for the electricity grid, with the potential for supply distribution issues if it is not addressed.

This growth will help increase demand for secure time in three ways 1) electricity becomes even more critical to the continued functioning of the economy 2) increases the revenues and hence incentives for transmission operators to ensure continued operations and 3) opens up opportunities for newer technologies to be inserted into the grid.

Grid modernisation

The transmission network in the UK is undergoing its largest overhaul in generations, empowered by the National Grid's "Great Grid Upgrade" initiative[118]. The £16 billion initiative will see significant investment in upgrading current and building new infrastructure to support the country's future energy ambitions. Development consent has recently been granted on a £400 million network upgrade in North Yorkshire, which will see refurbishments to overhead lines, as well as the delivery of new overhead lines and substations[119].

This modernisation has implication on the needs for timing. On the supply side, National Grid expects offshore wind to experience a 4.5 to 6 times growth in capacity and solar 2.5 to 5 times in capacity[120]. However, while the shift to new energy sources is significant, they do not, in and of themselves, have new specific timing requirements, as such they are not expected to be major driver for secure time[121]. A greater area of opportunity is the digitalisation of substations which increases the adaptability and maintains system reliability while reducing material and labour costs. However, these are often only rolled out at new "green field" sites given the fiscal constraints on operators. Operators implement consistent technological solutions in substations within the same part of the grid. For this reason, green field sites lend themselves well to a blanket implementation of digital solutions. Existing substations on the other hand have residual useful life in their equipment, which may not be the same for all substations, so the pressure to extract the full value of the equipment trumps the gains from digitalisation.

3.6.4 Blockers for adopting resiliently disseminated time

High costs to adopt new technology

Transmission infrastructure is expensive. As an example, Scottish & Southern Electric Networks is undertaking a project to reinforce the existing 275kV overhead line connecting the substations at

[117]Electricity Networks Strategic Framework: Enabling a secure, net zero energy system. Available at https://assets.publishing.service.gov.uk/media/62eb9bd78fa8f503349631c5/electricity-networks-strategic-framework.pdf

[118] National Grid (n.d.) The Great Grid Upgrade. Available at: https://www.nationalgrid.com/the-great-grid-upgrade (Accessed: March 25, 2024).

[119] Construction Enquirer. (n.d.). First 'Great Grid Upgrade' job goes to MGroup and Murphy. [online] Available at: https://www.constructionenquirer.com/2024/03/15/morrison-energy-services-and-murphy-win-first-great-grid-upgrade/ [Accessed 10 Apr. 2024].

[120] Delivering for 2035: Upgrading the grid for a secure, clean and affordable energy future. (n.d.). Available at: https://www.nationalgrid.com/document/149496/download.

[121] Interview with PNDC, who focus on supporting the acceleration of novel energy and transport technologies.

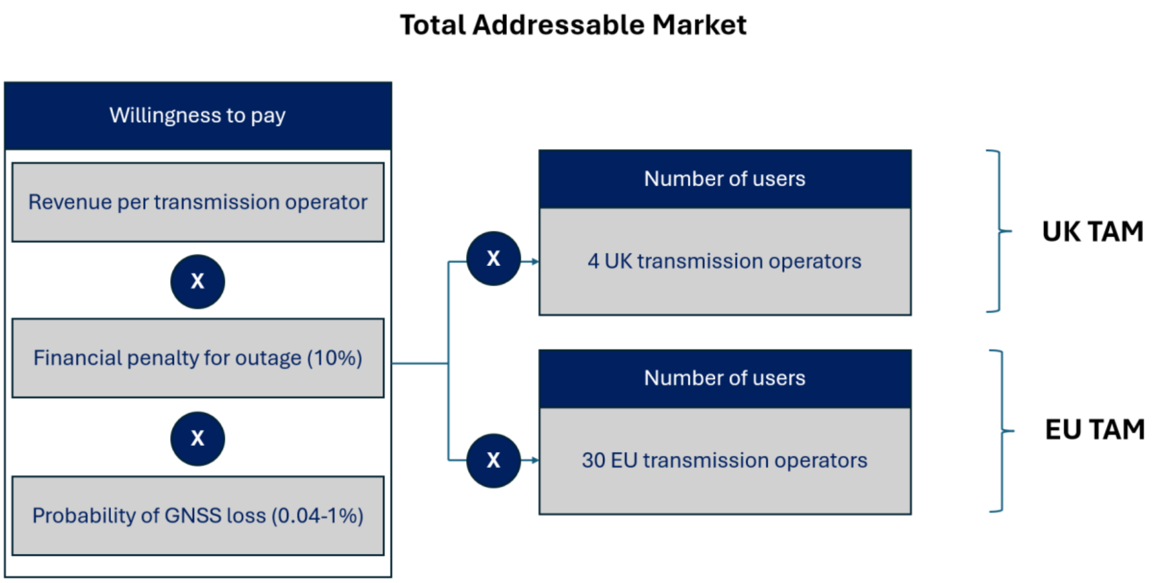
Blackhillock, Keith, Kintore and Peterhead to enable operation at an increased voltage of 400kV. The total cost for the project £212m[122]. Combined with the sector being heavily regulated, the ability for transmission network operators to be able to invest in replacing old (but working) infrastructure is limited. This is especially true for the digitalisation of substations where much of the saving is in reducing the footprint of the substation and hence the amount of copper wiring required, which is not relevant for existing substations. Additionally, transmission operators are faced with bottlenecks in connecting projects to the grid, which is limiting the ability for new projects to link to the transmission network – less than 10% of currently available sites for connection in England and Wales are available before 2030[123]. This situation may compel transmission operators to prioritise investment in constructing essential infrastructure while maintaining their existing resilience measures, indicating a reluctance to embrace new resilient services.

Existing time resiliency measures

As the transmission network is so critical, transmission operators have already taken steps to ensure that they operate efficiently and reliably. In general, redundancy and duplication of time sources within substations are driven by voltage level, which is high for all electrical transmission. Based on stakeholder consultation, at each substation there will generally be redundant timing sources for transmission networks with two grand master clocks (often highly accurate Cesium clocks which are calibrated using GNSS). As such, the incremental value for a new timing source may be marginal.

3.6.5 Market sizing methodology

Figure 57 Market sizing approach



[122] North East 400kV Upgrade Engineering Justification Paper: Available at: https://www.ssen-transmission.co.uk/globalassets/documents/engineering-justification-papers/north-east-400kv-upgrade-justification-paper.pdf
[123] Duff, R. (2023). *UK Power Grid Bottlenecks Threaten Investments, Centrica Warns*. [online] Energy Voice. Available at: https://www.energyvoice.com/renewables-energy-transition/539669/uk-power-grid-bottlenecks-threaten-investments-centrica-warns/ [Accessed 10 Apr. 2024].

Table 31 Market sizing parameters

Parameter	Description	Source
(1) Transmission operator revenue	Yearly revenues of transmission operators over 2024-2030 period.	Transmission operator financial statements and assumptions based on LE analysis.
(2) Financial penalty for outage	Fine levied on transmission operators for failure to provide the transmission facilities when required (10%).	Ofgem European Commission
(3) Probability of GNSS loss	Annualised probability of loss of GNSS services (0.04-1%)	National Risk Register
(4) Number of transmission operators	The number of electricity transmission operators in the UK and EU.	LE analysis based on Next

Source: John Simpson (2019) Company Report: SONI Ltd. Available at: https://www.belfasttelegraph.co.uk/business/northern-ireland/company-report-soni-ltd/38269810.html; Scottish Hydro Electric Transmission plc (2023). Directors Report and Financial Statements. Available at: https://www.ssen-transmission.co.uk/globalassets/information-centre-media/financial-information/statutory-financial-accounts/shet-plc-financial-statements-2023.pdf; SP Transmission Plc (2022). Annual Report and Accounts for the year ended 31 December 2022. Available at: https://www.spenergynetworks.co.uk/userfiles/file/SPT_2022_Accounts.pdf; National Grid (2023). 2022/23 Full Year Results Statement. Available at: https://www.nationalgrid.com/document/149561/download; Next (n.d.) A nearly complete list of European TSOs. Available at: https://www.next-kraftwerke.com/knowledge/european-tsos-list

TAM assessment approach

Determining the market size for a resilient timing service involves a multifaceted approach, primarily considering the potential customer base comprised of transmission operators. This assessment entailed evaluating their willingness to pay for such a service, which is tied to several factors. It incorporates an analysis of their revenues, as operators within the UK and EU face a fine of up to 10% of their turnover in the event of a failure to provide transmission services[124][125]. Additionally, the likelihood of such service disruptions occurring is factored in, utilising figures from the National Risk Register to determine the annual probability of experiencing a loss of Global Navigation Satellite Systems (GNSS). These probabilities are based on a reasonable worst-case scenario of a severe technical failure, due to either hardware failure or human error. It should be noted that the assessment does not seem to account for other risks to GNSS[126], such as the threat from space debris or nation-state attacks, which could escalate probabilities past the stated range.

Transmission operator revenue estimation

Revenue data for UK transmission operators was sourced from the latest financial statements available. Projected revenue growth up to 2030 was calculated by mapping revenue to the expected electricity usage during the forecasted period[127]. By comparing the proportion of revenue to electricity consumption among UK transmission operators, the revenues of EU transmission operators were estimated based on forecasts of electricity consumption in the European Union[128].

[124] Electricity Act 1989, c.29
[125] EU Directive 2009/72/EC – Article 37
[126] Editor (2023) *PNT loss on UK National Risk Register - Bad assumptions on purpose? - RNTF*. https://rntfnd.org/2023/08/08/pnt-loss-on-uk-national-risk-register-bad-assumptions-on-purpose/.
[127] GOV.UK. (2023). *Energy and emissions projections: 2022 to 2040*. [online] Available at: https://www.gov.uk/government/publications/energy-and-emissions-projections-2022-to-2040 .
[128] Statista. (n.d.). EU: electricity demand by sector & scenario 2030. [online] Available at: https://www.statista.com/statistics/1418493/electricity-demand-by-sector-and-scenario-european-union-2030/ [Accessed 10 Apr. 2024].

Equipment volume

The TAM assessment for the resilient timing service focuses on the service revenue generated, considering factors such as the number of users and their willingness to pay for the service. However, it is essential to recognise that to utilise this service, users will require specific equipment. Therefore, a comprehensive evaluation extends beyond service revenue alone and includes an analysis of the equipment volume necessary for service implementation, acknowledging the interconnected nature of service provision and the requisite infrastructure.

In assessing the equipment needs, the analysis took into account both the quantity of substations per operator and the average count of timing devices situated at each individual substation site.

Equipment volume assessment approach

Desk-based analysis identified the number of transmission substations currently in operation by each of the transmission operators. Projects within the National Grid were identified through research focusing on announcements regarding the establishment of new substations. It was assumed that the construction timeline for each substation spans approximately three years, from inception to operational readiness[129]. By aligning the announcement year with the projected operational year, the analysis anticipated the integration of these new projects into the transmission network. For announcements concerning the forecast period beyond 2024 (i.e. 2025-2027), a predictive methodology was used. This entailed computing a rolling average value derived from the number of new substations announced over the preceding two years, offering a reasoned approximation for future National Grid substation developments within the up to 2030.

Table 32 Announced National Grid new substation projects (2023-2024)

Announced year	2023	2024
National Grid project	■ Uprating (3 substations) ■ Bengeworth Road (1 substation)	■ Navenby (1 substation) ■ Grimsby to Walpole (4 substations) ■ North Humber to High Marnham (2 substations) ■ Yorkshire GREEN Project (2 substations) ■ Eastern Green Link 1 (1 substations) ■ Norwich to Tilbury (1 substation)
Total	**4**	**11**

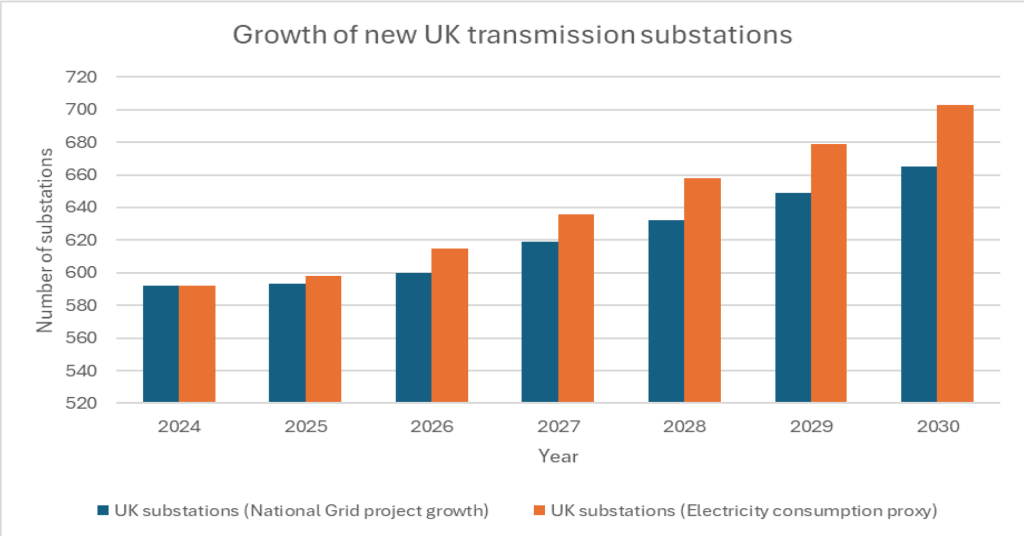
Source: Uprating – National Grid [Online] Available at: https://www.nationalgrid.com/electricity-transmission/network-and-infrastructure/infrastructure-projects/brinsworth-high-marnham-uprating, Bengeworth Road – AtkinsRealis [Online] Available at: https://careers.atkinsrealis.com/projects/2023-6/national-grid-and-linxon-breaks-ground-on-a-new-substation, Navenby – National Grid [Online] Available at: https://www.nationalgrid.com/electricity-transmission/network-and-infrastructure/infrastructure-projects/navenby-substation, Grimsby to Walpole – National Grid [Online] Available at: https://www.nationalgrid.com/electricity-transmission/network-and-infrastructure/infrastructure-projects/grimsby-to-walpole, North Humber to High Marnum – National Grid [Online] Available at: https://www.nationalgrid.com/electricity-transmission/network-and-infrastructure/infrastructure-projects/north-humber-to-high-marnham, Yorkshire GREEN Project – National Grid [Online] Available at: https://www.nationalgrid.com/electricity-transmission/network-and-infrastructure/infrastructure-projects/yorkshire-green, Eastern Green Link – New Civil Engineer [Online] Available at: https://www.newcivilengineer.com/latest/interview-national-grids-carl-trowell-on-meeting-the-challenges-of-the-great-grid-upgrade-26-02-2024/, Norwich to Tilbury - New Civil Engineer [Online] Available at: https://www.newcivilengineer.com/latest/interview-national-grids-carl-trowell-on-meeting-the-challenges-of-the-great-grid-upgrade-26-02-2024/

This methodology was implemented to forecast the growth of substations within the National Grid infrastructure, extending projections up to the year 2030. Leveraging the growth rate observed within the National Grid, a comparative analysis was conducted to estimate the trajectory of

[129] National Grid (n.d.). Frequently asked questions. Available at: https://nationalgrid.com/electricity-transmission/network-and-infrastructure/infrastructure-projects/uxbridge-moor-substation/frequently-asked-questions

substations for other transmission operators across the United Kingdom throughout the forecast period. This analysis revealed a correlation between the growth of substations and the expansion in electricity consumption within the region.

Figure 58 Correlation between using National Grid project growth and electricity consumption growth to estimate substation increase



Source: LE analysis of transmission operator substation data. National Grid and Scottish Power Transmission - Segundo Sevilla, F.R. et al. (2022) State-of-the-art of data collection, analytics, and future needs of transmission utilities worldwide to account for the continuous growth of sensing data. International Journal of Electrical Power & Energy Systems, [online] 137, p.107772.doi:https://doi.org/10.1016/j.ijepes.2021.107772. Scottish Hydro Electric – SHE Transmission [Online] Available at: https://www.ssen.co.uk/globalassets/library/connections---useful-documents/transmission/transmission-connections.pdf, System Operator for Northern Ireland – SONI [Online] Available at: https://www.soni.ltd.uk/customer-and-industry/general-customer-information/connections-and-applicati/20230808-Connections-Register-8-August-2023.pdf

Consequently, this empirical relationship was used to extrapolate the anticipated number of new substations for the European Union (EU), utilising power consumption growth as a proxy for forecasting future substation infrastructure requirements within the broader European context.

An assumption was made that, on average, each substation would be equipped with eight timing devices[130]. Multiplying this average by the respective number of substations provided estimates for the volume of equipment required within the UK and EU markets.

3.6.6 Market sizing results

Total addressable market

The forecasted total addressable market (TAM) for both the UK and EU was projected across low, central, and high scenarios, incorporating the annualised probability of GNSS loss from the National Risk Register as a sensitivity variable (0.04%, 0.2%, and 1%, respectively)[131]. Due to its direct impact on willingness to pay, this results in a large difference in market size between each scenario.

[130] Conversation with National Grid during writing of GNSS Loss Report: London Economics (2017) The economic impact on the UK of a disruption to GNSS. https://londoneconomics.co.uk/wp-content/uploads/2017/10/LE-IUK-Economic-impact-to-UK-of-a-disruption-to-GNSS-FULLredacted-PUBLISH-S2C190517.pdf (Accessed: March 28, 2024).

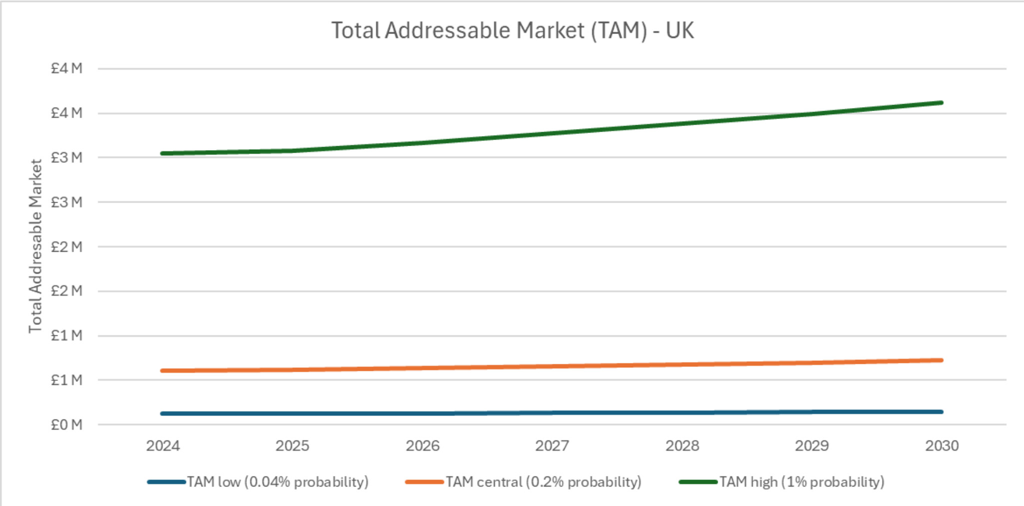
[131] The National Risk Register assessed likelihood of loss of GNSS over 5 years, so the provided probabilities in the register were divided by five to calculate the annual risk

In the central scenario, the TAM for UK transmission operators is currently valued at approximately £609k, and is anticipated to reach £724k in 2030, with a compound annual growth rate (CAGR) of 3% from 2025-2030.

Table 33 Range of TAM estimates for UK market (2024-2030)

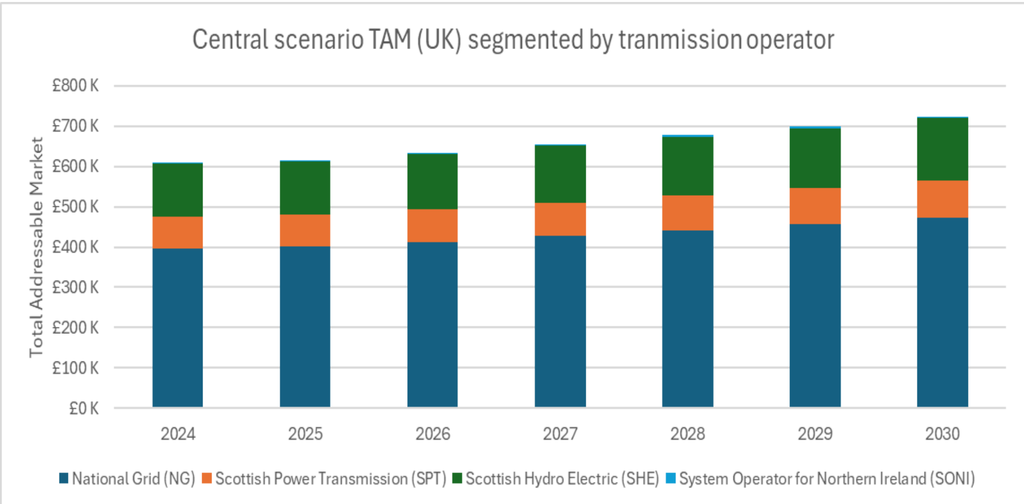
Scenario	2024	2025	2026	2027	2028	2029	2030
Low	£122k	£123k	£127k	£131k	£135k	£140k	£145k
Central	£609k	£616k	£633k	£655k	£677k	£699k	£724k
High	£3.05m	£3.08m	£3.2m	£3.3m	£3.4m	£3.5m	£3.6m

Figure 59 Growth of UK TAM under different scenarios



It is important to highlight that the majority of the TAM in the UK is attributed to National Grid, primarily because of its extensive network and revenue-generating capacity compared to the other transmission operators.

Figure 60 Central scenario UK TAM segmented by transmission operator

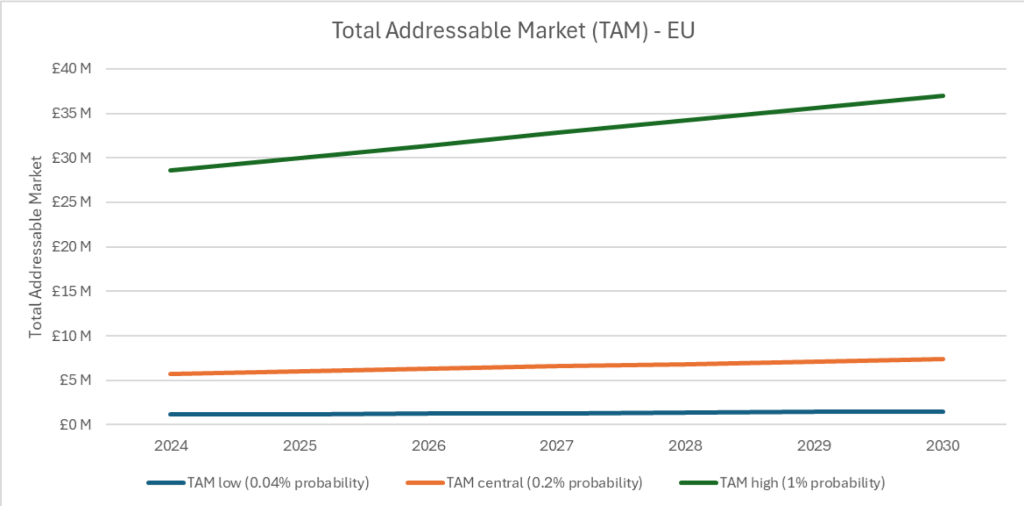


In the central scenario, the TAM for EU transmission operators is currently valued at approximately £5.72 million, and is anticipated to reach £7.39 million in 2030, with a compound annual growth rate (CAGR) of 4% from 2025-2030.

Table 34 Range of TAM estimates for EU market (2024-2030)

Scenario	2024	2025	2026	2027	2028	2029	2030
Low	£1.15m	£1.20m	£1.26m	£1.31m	£1.37m	£1.42m	£1.48m
Central	£5.72m	£6.03m	£6.28m	£6.56m	£6.84m	£7.11m	£7.39m
High	£28.6m	£30.02m	£31.41m	£32.79m	£34.18m	£35.56m	£36.95m

Figure 61 Growth of EU TAM under different scenarios



Equipment volume

The volume of equipment required is tied to the expansion of substations, a growth trend assumed to remain consistent across the different scenarios. This growth is predominantly driven by the rise in electricity consumption, reflecting the increasing demands placed on the electrical grid infrastructure. It is important to note that these equipment volume figures are distinct from the TAM estimates. This separation stems from the approach of maintaining technology neutrality throughout the assessment, which precludes the assignment of specific prices to the equipment.

However, they serve as a useful metric in understanding the quantum of investment required from transmission operators to adopt a resilient timing service. The table presented below illustrates the number of timing devices and their projected increase throughout the forecasted period.

Table 35 Forecast of number of timing devices for UK and EU markets

Region	2024	2025	2026	2027	2028	2029	2030
UK	4736	4744	4800	4952	5056	5192	5320
EU	29,307	30,727	32,146	33,565	34,984	36,403	37,823

3.6.7 Conclusions

- The **transmission grid is currently undergoing significant updates** to keep up with the evolving demands for energy.

- This ongoing development **signifies substantial investment** in the grid, highlighting the nation's **increasing reliance on its robustness** to sustain energy supply.
- The focus on grid resilience **may potentially result in greater incentives to strengthen its resiliency further**, ensuring its ability to withstand disruptions and maintain continuous operation.
- However, it's crucial to acknowledge that the cost of implementing a resilient timing service will be carefully **balanced against competing investment priorities** by transmission operators.
  - These include **addressing bottlenecks** in connecting the electric grid to new energy generation projects in addition to evaluating the **additional value** that a resilient timing service would bring compared to or in conjunction with existing resiliency measures.
- The UK market, as estimated in the central scenario, presents a **modest opportunity** characterised by a **stable growth** rate. This growth is linked to the **increasing demand for electricity**.
  - It should be noted that the increase in demand for electricity only represents growth for this market if transmission operators are able to **add capacity at the necessary rate** to meet the demand.
- Willingness to pay for a resilient timing service remains **uncertain**, primarily due to the **considerable range of likelihood** associated with GNSS loss.
  - The actual willingness to pay is contingent upon various factors, including the **perceived risk** from transmission operators, their individual **risk profile**, and their **perception of alternative solutions** available to bolster timing resilience.

3.7 UC7: ATC radar systems

Communication, Navigation and Surveillance (CNS) are the three essential functions that enable air traffic control (ATC). Safe air travel can be achieved when two of the three functions are operational. Air Traffic Control Radars (ATC-Radar) is an umbrella term for all radar devices used to secure and monitor aircraft in Air Traffic Management (ATM) and provide surveillance capabilities for ATC[132]. Radars are usually fixed systems that have a high degree of specialisation used to manage air traffic in a region of air space. Common groupings for different types of air traffic control radars include[133]:

- **En-route radar systems**[134]: Used to monitor air traffic outside the special control areas near airfields. These radars normally operate in the L-band with a maximum range of up to 240 NM (≙ 450 km). These are primary radars[135], which usually only provide a two-dimensional view of the airspace for cost reasons. However, they are always coupled with a modern Mode S capable secondary radar[136], which then provides the third spatial coordinate.
- **Air Surveillance Radar (ASR) systems:** An approach control radar used to detect and display an aircraft's position in the terminal area. These radar sets operate usually in E-band and are capable of reliably detecting and tracking aircraft at altitudes below 25,000 feet (7,620 meters) and within 40 to 60 nautical miles (75 to 110 km) of their airport.

[132] This use case is only looking a civilian air traffic management and not military which in general have much tighter requirements for time synchronization

[133] Radar tutorial (n.d.) Air Traffic Control Radar. Available at: https://www.radartutorial.eu/02.basics/ATC-Radars.en.html

[134] Defined as aircraft are operating between departure and destination terminal areas

[135] "Conventional" radar sensor that illuminates a large portion of space with an electromagnetic wave and receives back the reflected waves from targets within that space

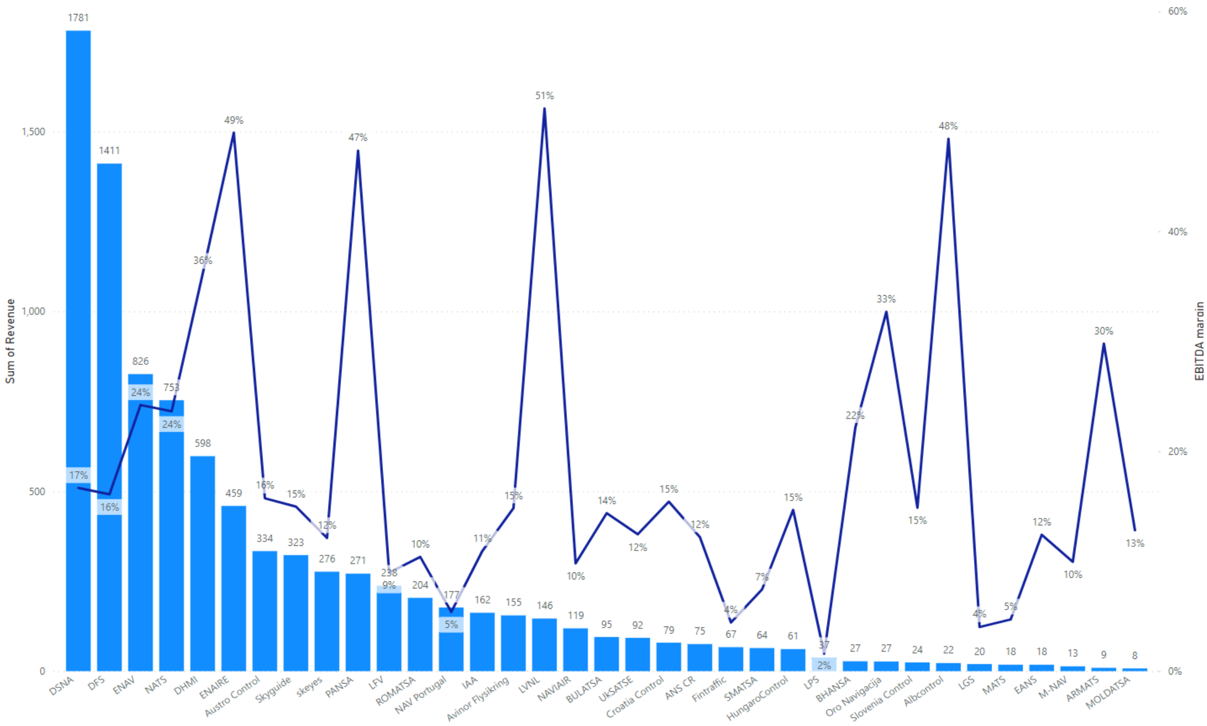
[136] Relies on targets to be equipped with a radar transponder, which responses by transmitting encoded data such as an identity code, the aircraft's altitude and further information depending on its chosen mode.

- **Precision Approach Radar (PAR) systems**: An approach control radar used to detect and display an aircraft's position in the terminal area. These radar sets operate usually in E-band and are capable of reliably detecting and tracking aircraft at altitudes below 25,000 feet (7,620 meters) and within 40 to 60 nautical miles (75 to 110 km) of their airport. However, use of PARs for civil applications is decreasing[137].
- **Surface Movement Radars (SMR)**: Radar that provides surveillance cover for the manoeuvring area, which is defined as that used for the take-off, landing, and taxiing of aircraft, excluding aprons. They usually operate in the X and K Band. Higher resolution SMR operate between 92 and 96 GHz.

Air Navigation Services (which require the use of radar systems) for en-route are provided for and managed by air navigation service providers (ANSPs) which can be public or private legal entities. In the UK, the ANSP is NATS (National Air Traffic Services) which is a public-private company in which the UK state has a 49% share. Under the Transport Act 2000 the UK government issues a licence to NATS to provide en-route air traffic services in the UK. In the UK ATC radars such as air surveillance and surface movement radars are operated by airports themselves, however, some use NATS as a service provider.

Across Europe there are 31 ANSPs who collaborate to manage the air traffic across the region. In 2021 their total revenues totalled 8,989M€ with an average EBITDA margin of 18%. The largest four operators are DNSA (France), DFS (Germany), NATS (UK) and ENAV (Italy) had a share of 53% of all revenue – see following Figures:

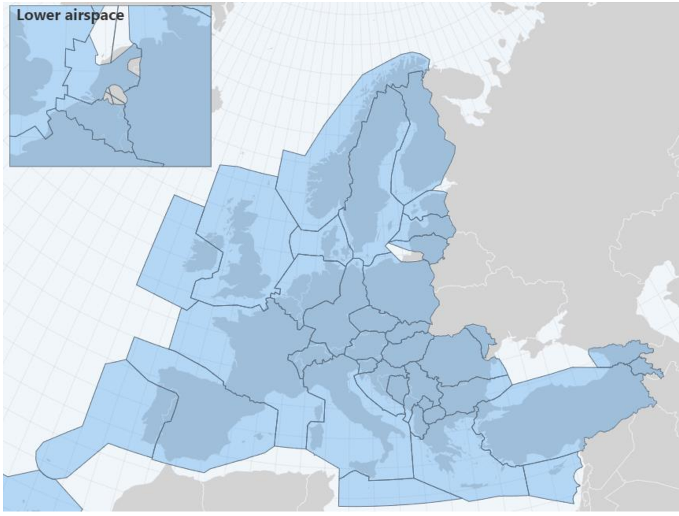
Figure 62 2021 revenues and EBITDA margins for ANSP across Europe (M€)



Source: LE analysis of Eurocontrol reports. Available here: https://ansperformance.eu/data/

[137] International Civil Aviation Organization (2002). Global Air Navigation Plan for CNS/ATM Systems. Available at: https://www.icao.int/publications/Documents/9750_2ed_en.pdf

Figure 63 ANSP regions across Europe



Source: Eurocontrol (n.d.). ATM Cost Effectiveness Dashboard. Available at: https://www.eurocontrol.int/ACE/ACE-Home.html

3.7.1 Uses of time

There are two main uses specifically for time for radars in the context of ATC:

- Pulse synchronisation (Monostatic)[138]
- ATC network synchronisation

Pulsed radar synchronisation (Monostatic)

To operate, pulsed radars need to create an RF signal which consists of a series of a controlled number of pulses. To achieve this a master timer / master oscillator / master synchronizer / local oscillator produces timing pulses to control the pulse repetition frequency (PRF) of the radar. These timing pulses are supplied synchronously to[139]:

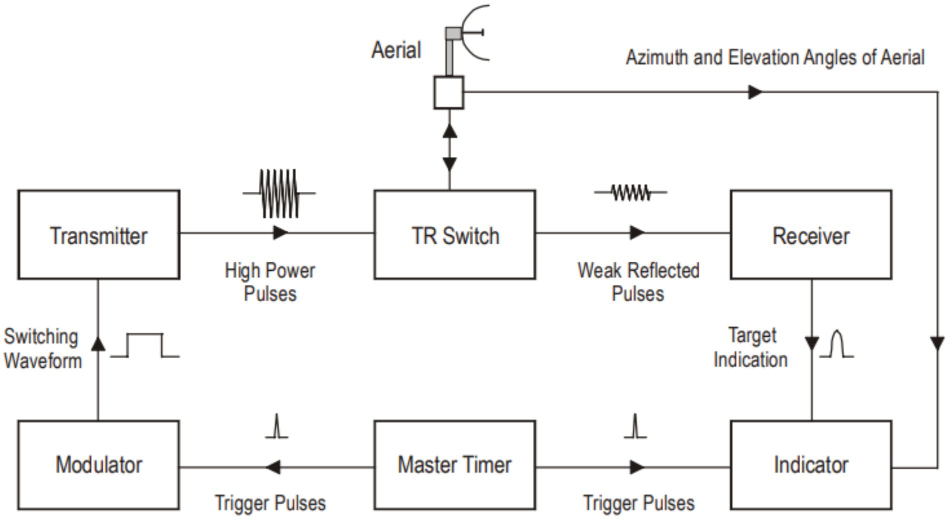
4) The modulator to trigger the transmitter operation at precise and regular instants of time;
5) The timebase generator of the indicator to synchronize the start of the trace with the operation of the transmitter.

A block diagram for a pulsed radar is shown in Figure 64:

[138] Continuous-wave (CW) radars are not typically used in modern air traffic control (ATC) systems as they lack the ability to accurately determine range

[139] The Central Flying School (CFS) Manual of Flying (2020). AP3456 – Volume 11 - Radar. Available at: https://assets.publishing.service.gov.uk/media/5e18b9a3ed915d3b15939ad9/Volume_11_Radar.pdf

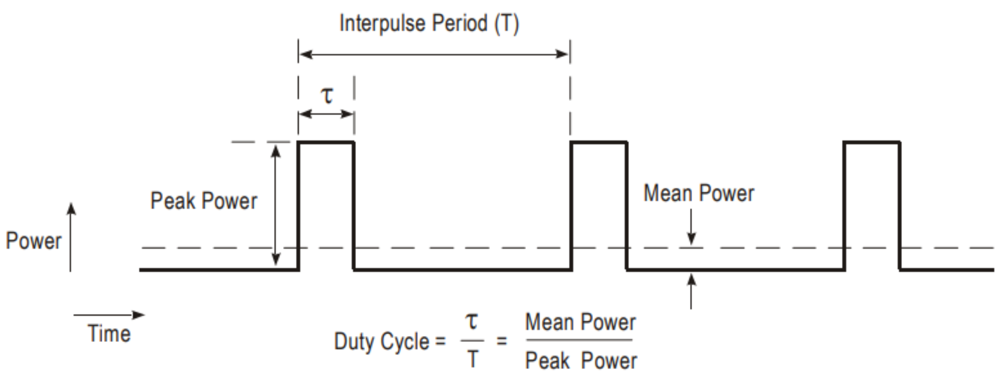
Figure 64 Block schematic of a typical pulse radar



Source: The Central Flying School (CFS) Manual of Flying (2020). AP3456 – Volume 11 - Radar. Available at: https://assets.publishing.service.gov.uk/media/5e18b9a3ed915d3b15939ad9/Volume_11_Radar.pdf

The pulses are short rectangular pulses which are produced from a master oscillator. Note that the pulses must be coherent for the radar to operate. i.e. the outputs must have the same frequency, wavelength, and a constant phase difference. However, this stability is not required for long periods, only for a single burst (a few 1000 pulses). As such, monostatic pulsed radar systems only require a local oscillator such as oven-controlled crystal oscillators (OCXO)[140]. This means that ATC radars require no external time reference in order to operate.

Figure 65 Pulse Radar Parameters



Source: The Central Flying School (CFS) Manual of Flying (2020). AP3456 – Volume 11 - Radar. Available at: https://assets.publishing.service.gov.uk/media/5e18b9a3ed915d3b15939ad9/Volume_11_Radar.pdf

ATC network synchronisation

Aircraft are typically tracked by multiple radars or other surveillance methods at the same time. For a single position to be reported and displayed to air traffic control operators, the time of each positional measurement must be recorded from a common time synchronised across the ATC network.

[140] Global Navigation Satellite Systems disciplined oscillator synchronisation of multistatic radar. Available at: https://ietresearch.onlinelibrary.wiley.com/doi/full/10.1049/rsn2.12475

3.7.2 User requirements

As mentioned above, ATC radars do not require an external time reference to operate, and only require stability of coherence over short time periods. Thus, timing requiring are met with standard local oscillators e.g. OXCO.

In cooperative surveillance systems used by the ANSP, the CAA outlines minimum Air Traffic Services Safety Requirements. This requires that the position of an aircraft be refreshed at least once every six seconds[141]. Driven by this, the requirements for synchronisation between measurements are of the order of one second[142]. This timing requirement is relatively very low and as such can be maintained for extended or indefinite periods with cheap atomic clocks.

3.7.3 Drivers and enablers for adopting resiliently disseminated time

Increasing threats affecting air traffic management

Since February 2022, there has been a notable increase in jamming and possible spoofing of GNSS, particularly affecting areas near conflict zones, as highlighted in a safety bulletin by a European Union Aviation Safety Agency (EASA)[143]. Following suit, the UK Civil Aviation Authority issued its own advisory[144], indicating a year-over-year rise in interference, especially in the same geographic regions. Both advisories outline the adverse effects that can include failure or degradation of a variety of air traffic management service and aircraft systems that use GNSS as a time reference.

A significant surge (over 2000%) in GNSS Radio Frequency Interference (RFI) incidents has been observed since 2018, as documented in a Eurocontrol report[145], with a substantial impact on European en-route traffic. RFI incidents, mostly associated with conflict zones, extend their reach to affect civil aviation within a 300km radius, posing risks to safety and operational efficiency.

Cybersecurity threats further compound aviation sector vulnerabilities, as highlighted in a report by the Department for Transport, emphasising the inevitability of cyber-attacks[146] and their potential for catastrophic commercial consequences, though the risk to human safety is considered low. Previous incidents, such as a cyber-attack on Europe's air traffic control body by Russian hackers[147], underscore the ongoing threat and the imperative for robust defence measures to safeguard aviation operations.

Investment decisions in Air Traffic Control are driven by the needs of their primary customers, the airlines. While cost-saving measures were prioritised in the past, there is now a growing emphasis

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[141] CAA. CAP670 Air Traffic Services Safety Requirements. Available at: https://www.caa.co.uk/publication/download/19302
[142] Interview with NATS
[143] ad.easa.europa.eu. (n.d.). EASA Safety Publications Tool. [online] Available at: https://ad.easa.europa.eu/ad/2022-02R2 [Accessed 29 Apr. 2024].
[144] Civil Aviation Authority SAFETY NOTICE Global Navigation Satellite System Outage Leading to Navigation/Surveillance Degradation This Safety Notice contains recommendations regarding operational safety. (n.d.). Available at: https://www.caa.co.uk/publication/download/20273 [Accessed 29 Apr. 2024].
[145] Eurocontrol (n.d.). Does Radio Frequency Interference to Satellite Navigation pose an increasing threat to Network efficiency, cost-effectiveness and ultimately safety? [online] Available at: https://www.eurocontrol.int/sites/default/files/2021-03/eurocontrol-think-paper-9-radio-frequency-intereference-satellite-navigation.pdf [Accessed 29 Apr. 2024].
[146] Field, M. (2023). 'Not if but when': How cyber attacks threaten Britain's air traffic control. The Telegraph. [online] 29 Aug. Available at: https://www.telegraph.co.uk/business/2023/08/29/how-cyber-attacks-threaten-britain-air-traffic-control/#:~:text=Air%20traffic%20control%20systems%20have.
[147] Pancevski, B. (n.d.). WSJ News Exclusive | Europe's Air-Traffic Agency Under Attack From Pro-Russian Hackers. WSJ. [online] Available at: https://www.wsj.com/articles/europes-air-traffic-agency-under-attack-from-pro-russian-hackers-54b4514d [Accessed 29 Apr. 2024].

on resilience. Airlines are becoming increasingly wary of rising Global Navigation Satellite System (GNSS) interference, prompting a shift towards prioritising resilience over cost reduction[148].

These escalating challenges in GNSS reliability and cybersecurity underscore the critical need for resilient time within the aviation sector. As GNSS-dependent systems face increasing susceptibility to jamming, spoofing, and cyber-attacks, alternative timing references become essential to maintain operational continuity and ensure the safety and efficiency of air traffic management.

Regulatory oversight and financial incentives of ANSP

In the UK, the Transport Act 2000 gives the CAA the role of economic regulator over NATS civilian en-route air traffic control[149]. The CAA exercises this role mainly through monitoring and enforcing the conditions of the licence[150]. Under the terms of the license, NATS are required to publish measures on its service standards including but not limited to: delays, service interruptions and complaints such that its quality of service can be assessed[151]. Moreover, air navigation services providers are overseen by Eurocontrol in Europe which is largely equivalent in terms of a regulatory regime[152].

The CAA incentivises NATS service performance, under the terms of the license which includes financial incentives for capacity and environment performance attributable en-route delays[153]. However, there is concern that this incentivisation is not sufficient. On the summer bank holiday (28th August) 2023, there was a major failure in the flight planning system operated by NATS. The CAA estimated that over 700,000 passengers were affected by the failure, over several days, with considerable financial and emotional impact.

An interim investigation report carried out by the CAA[154] concluded that the performance incentive framework for NATS may not be measuring the right metrics. Currently, the incentivisation of NATS performance is based solely in terms of Air Traffic Flow Management (ATFM) delay minutes[155], as opposed to the inclusion of passenger impact caused by cancellations as well as by knock-on delays. While NATS performs well on ATFM delay minutes measure compared to other providers – see Figure below, the report states that the review panel will consider the incentive structure for NATS in more detail in its final report.

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148 Stakeholder interview with NATS En-Route Limited (NERL)

149 NATS is split into two main service provision companies: NATS En-Route PLC (NERL) and NATS Services Ltd (NSL). NERL is the sole provider of civilian en-route air traffic control over the UK and is regulated by the CAA

150 NATS En Route plc NERL Licence. Available at: https://www.caa.co.uk/commercial-industry/airspace/air-traffic-management-and-air-navigational-services/air-navigation-services/nats-en-route-plc-nerl-licence/

151 UK Civil Aviation Authority (2023). Air Traffic Services License for NATS (En Route) PLC. Page 55 Available at: https://www.caa.co.uk/publication/download/21346

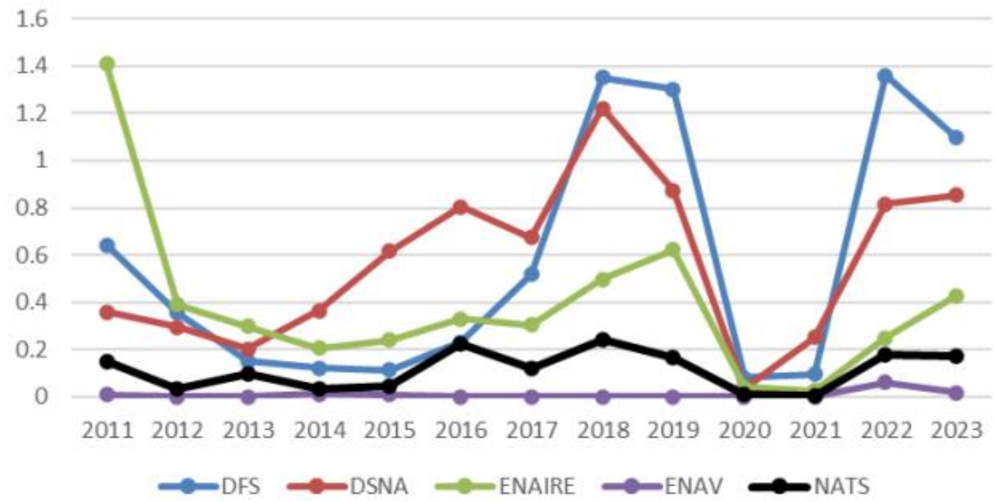
152 Eurocontrol (n.d.). Air Navigation Services Performance Review. Available at: https://www.eurocontrol.int/air-navigation-services-performance-review

153 en route air traffic flow management (ATFM) delay calculated by Eurocontrol and expressed as the difference between the take-off time requested by the aircraft operator in the last submitted flight plan and the calculated take-off time allocated by Eurocontrol

154 Independent Review of NATS (En Route) Plc’s Flight Planning System Failure on 28 August 2023: Available at: https://www.caa.co.uk/publication/download/21478

155 Defined as the duration between the last Estimated Take-Off Time (ETOT) and the Calculated Take-Off Time (CTOT) allocated by the Network Manager

Figure 66 Air Navigation Service Provider (ANSP) attributable delay minutes per flight



Source: CAA analysis of En-route ATFM delay data in http://ansperformance.eu/data/. NERL comparators: DFS (Germany) DSNA (France); ENAV (Italy); ENAIRE (Spain). 2023 – Jan to Nov

In addition, it is important to note that under CAA regulations passengers can claim compensation if a flight is delayed or cancelled for more than three hours[156]. However, for a passenger to claim compensation the cause of the flight delay or cancellation must be the airline's fault. Examples classed as within the airline's control include the pilot being sick and not being replaced or technical problems on the aircraft. However, air traffic control issues are not the fault of airlines, and, as such, are not covered under this compensation scheme if a flight has been cancelled or delayed as a direct result of these problems[157]. For context, Eurocontrol estimates a network average cost per flight of €100 per ATFM delay minute, a cost of €1,000-7,000 per diversion of regional flights, and a system-wide average cancellation cost per flight of €20,930.[158]

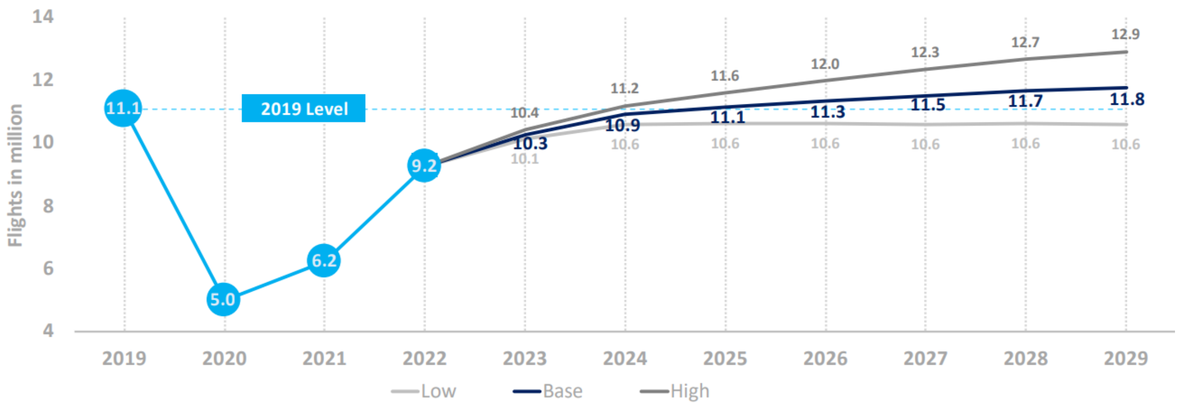
In summary, while there are incentives in place under the existing CAA license to NATS to ensure a high level of service provision (and by extension the willingness to procure to resilient source of time). These incentives may be increased in the future, and should they be increased further, would increase the willingness to pay for resilient time.

Increasing demand for flights following pandemic

The pandemic had a major impact on the aviation industry. Instrument flight rules (IFR) movements across Europe is approaching pre-pandemic levels, reaching 91% of 2019 volumes in 2023 with the 2019 number of flights (11.1 million) expected to be reached in 2025[159].

[156] UK Civil Aviation Authority (n.d.). Delays: Your rights when a flight is delayed. Available at: https://www.caa.co.uk/passengers/resolving-travel-problems/delays-and-cancellations/delays/
[157] Money saving expert, flight disruption. Available at: https://www.moneysavingexpert.com/news/2023/08/flight-delays-air-traffic-control-failure-your-rights/
[158] Values are 2022 prices from: Eurocontrol (2024). 'Eurocontrol Standard Inputs for Economic Analysis'. Available at: https://www.eurocontrol.int/sites/default/files/2024-05/eurocontrol-standard-inputs-economic-analyses-ed-10.pdf
[159] Eurocontrol (2023). 7 year forecast. https://www.eurocontrol.int/sites/default/files/2023-03/eurocontrol-seven-year-forecast-2023-2029-spring-2023.pdf

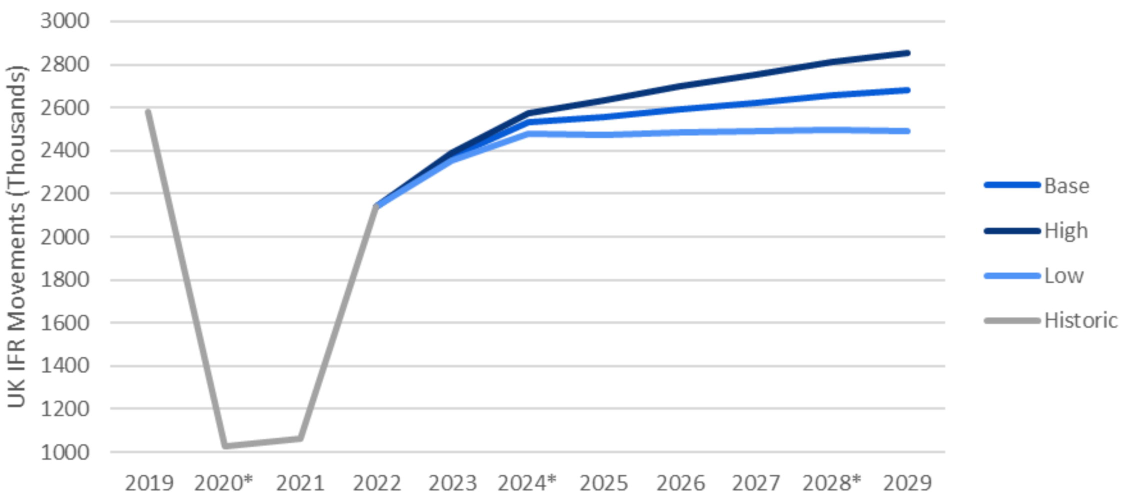
Figure 67 Eurocontrol 7-year forecast for Europe* 2023-2029 (spring 2023)



Note: *Europe = ECAC 44 Member States.

Source: Eurocontrol (2023). 7-year Forecast 2023-2029, Spring 2023. Available at: Eurocontrol (2023). 7 year forecast. https://www.eurocontrol.int/sites/default/files/2023-03/eurocontrol-seven-year-forecast-2023-2029-spring-2023.pdf

Figure 68 Eurocontrol autumn 2023 forecast for UK instrument flight movements



Source: Eurocontrol (2023) 7 year forecast 2023-2029, Autumn 2023. Available at: https://www.eurocontrol.int/publication/eurocontrol-forecast-update-2023-2029-autumn-2023

Increases in the volume of air travel in turn increases demand on radar systems to provide accurate data to manage the traffic. However, this effect driver is not expected to be a significant driver of demand given the low absolute levels of demand and the modest growth rate.

3.7.4 Barriers to adopting resiliently disseminated time

Resilience of the system-of-systems approach to ATC

Air traffic control (ATC) has evolved over many decades. In the process, various approaches to navigate, communicate and survey aircraft have been developed including but not limited to: primary radars, secondary radars, wide area multilateration (WAM), automatic dependent surveillance-broadcast (ADS-B), SELCAL, and procedural control. Moreover, ATC radars, have overlapping coverage providing redundancy in the event that one radar system should fail.

Each of these approaches has different strengths, weaknesses, vulnerabilities, dependencies, and uses of time. As such, each approach is complementary and mitigates each other's risks, creating a resilient systems-of-systems approach to ATC. For example, if the primary radar fails, the secondary radar or WAM can still provide surveillance. If the transponder malfunctions, the primary radar or ADS-B can still track the aircraft. If the GNSS signal is lost, the procedural control can still guide the aircraft.

Moreover, many of the systems used in ATC remain highly manual and procedural processes. Aircraft today are still primarily controlled via direct voice communications between air traffic control and the pilot. While these systems are in the medium to long-term going to be automated, mainly for cost reasons, these manual processes do provide robustness and resilience to time disruption. In addition, it is worth noting that the introduction of fully autonomous drones is expected to eliminate the requirement of voice communication for ATC. However, they are not expected to be adopted widely before 2030. In addition, it would be unlikely that the adoption of drones would necessitate a large increase in the number of ATC radar systems which are highly capital-intensive to build and maintain.

As a result, of this system-of-systems approach there is a reduced willingness to pay for resilient time, because the vulnerability of the loss of time has to some extent already been mitigated.

Lack of adoption of multistatic radars in ATC

ATC radars in the UK are not operated in multistatic or bistatic configurations[160]. This results in radars having substantially lower timing requirements than they otherwise would.

Multistatic radar systems (MSRS) are types of radar systems where there are multiple transmitters and receivers that form a network, and the target's position is determined by the geometric intersection of the bistatic ranges from each pair of transmitter and receiver. MSRS have advantages over monostatic radars, such as increased coverage, reduced vulnerability to stealth and jamming, and improved target classification and identification.

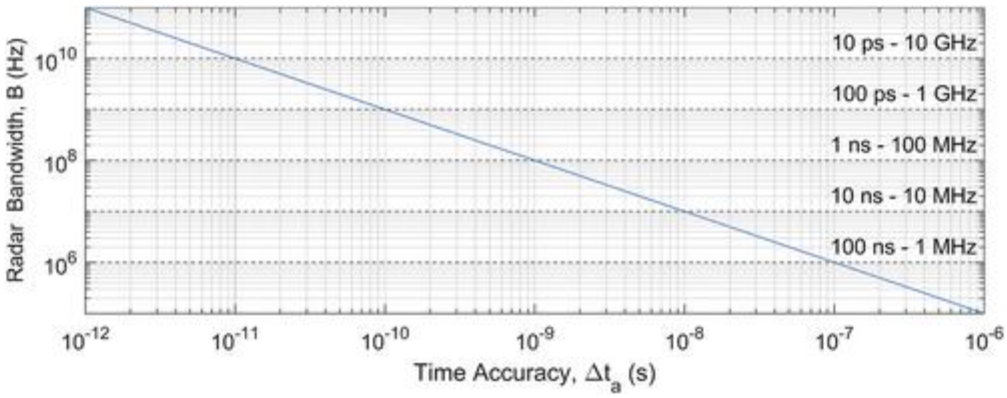
MSRS can be further split into three classes depending on the spatial coherence of the system[161]:

- **Spatially non-coherent**: Individual radars only receive signals emitted by their own dedicated transmitters. Systems of this type can be considered as a network of monostatic radars and or netted radar.
- **Fully spatially coherent**: Full radar or node-to-node phase synchronisation. The system sensitivity can theoretically increase with the square of the number of nodes, instead of linearly for non-coherent systems;
- **Short-term spatially coherent:** System can effectively be synchronized coherently over a short time frame.

The highest sensitivity for detection can be derived from a fully coherent MSRS. However, this form of MSRS is the most complex and costly strategy to implement. For this reason, these systems are usually limited to defence applications as opposed to air traffic control use cases. Timing accuracy requirements in coherent MSRS are typically derived from the bandwidth of transmitted waveform, where accuracies are in the order of a fraction of the radars compressed pulse width are required.

[160] Interview with NATS
[161] Beasley, P. J., Peters, N., Horne, C., Ritchie, M. A. (2023). 'Global Navigation Satellite Systems disciplined oscillator synchronisation of multistatic radar', IET Radar, Sonar & Navigation, vol. 18(1), (September) pp. 23-40.

Figure 69 Timing accuracy requirements for the synchronisation of fully and short-term spatially coherent multistatic radar systems (MSRS) as a function of radar bandwidth



Source: Beasley, P. J., Peters, N., Horne, C., Ritchie, M. A. (2023). 'Global Navigation Satellite Systems disciplined oscillator synchronisation of multistatic radar', IET Radar, Sonar & Navigation, vol. 18(1), (September) pp. 23-40 https://doi.org/10.1049/rsn2.12475

Spatially non-coherent or netted radar systems have lower node-to-node time synchronisation requirements than coherent radar systems.

High cost and asset lifetimes of radar systems

Radar systems, and especially primary radar systems are expensive, driven by their high power and large antennas to generate and receive faint radar signals. These requirements increase the complexity, size, weight, and cost of the primary radar equipment, as well as the energy consumption and maintenance needs especially when compared to secondary radars.

The high cost of primary radar systems limits their availability and affordability, especially for small airports or remote locations. reliable surveillance of the airspace, ensuring the safety and efficiency of air traffic control. In 2013, NATS completed a 10 year £164m infrastructure renewal project involved upgrading or replacing all of the UK's main 23 radar stations[162]. The upgraded radars were expected to have around a 15-year lifespan. These high CAPEX costs, low volume and long asset lifetimes mean that the market opportunity for secure time is smaller than it otherwise would be.

3.7.5 Market sizing methodology

The approach taken to size the market opportunity began with undertaking a survey of ATC radars across the UK operated by both NATS and airport operators. The following assumptions and references were used in the analysis[163,164,165,166]. Identified radars were categorised into:

- **Primary**: Primary en-route radar
- **Secondary**: Secondary en-route radar

[162] NATS (2013). Programme to replace UK radar network complete. Available at: https://www.nats.aero/news/programme-to-replace-uk-radar-network-complete/

[163] NATS (2024). eAIS Package United Kingdom. Available at: https://www.aurora.nats.co.uk/htmlAIP/Publications/2024-05-16-AIRAC/html/index-en-GB.html

[164] Ofcom (2023). Protected Radar list. Available at: https://www.ofcom.org.uk/__data/assets/pdf_file/0020/44921/protected_radar-May-2023.pdf

[165] F17 Ltd (n.d.). Radar heads. Available at: https://labs.f17.co.uk/apps/radar-heads/

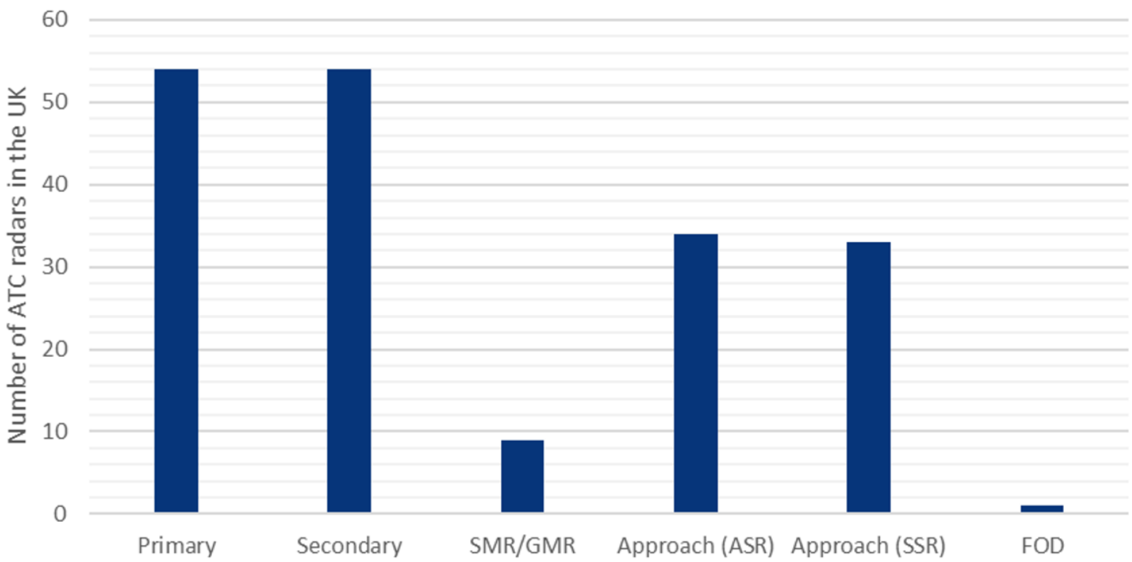
[166] Eurocontrol (2022). LSSIP 2022 United Kingdom Local Single Sky Implementation. Available at: https://www.eurocontrol.int/sites/default/files/2023-04/eurocontrol-lssip-2022-uk-released.pdf

- **SMR/GMR**: Surface/Ground movement radar
- **Approach (ASR)**: Air Surveillance Radar (primary radar) used for airport approach.
- **Approach (SSR)**: Secondary surveillance radar used for airport approach.
- **FOD**: Foreign Object Debris radar for detecting objects on the runway surface.

For the analysis several assumptions were made. First, it was assumed that all en-route ATC radars consisted of both primary and secondary radars since these are typically coupled[167]. Second, it was assumed that all airports identified to have SMR/GMR have only one radar for this purpose, as no evidence was found of airports incorporating multiple SMRs (however this should be considered a lower bound). Third, for all airports with an approach radar identified, it is assumed that both ASR and SSR are present as it is standard for these to be coupled[168] (with only one exception identified where it was explicitly stated that only primary radar (ASR) is available at Gloucestershire airport[169]). It is also assumed that these airports have only one of each of these radars as no evidence was found of UK airports featuring more (however this should also be considered a lower bound). Heathrow airport is also the only airport in the UK identified to have an FOD radar.[170] No defence or military operated radars were included in this analysis.

3.7.6 Market sizing results

Figure 70 Number of radars in the UK by type



In total, 185 radars were identified. It was then assumed that each radar would have an average time related CAPEX. The CAPEX was then amortised over 15 years, the expected lifetime of the radar asset, and added to this was an OPEX estimated to be 10% of the CAPEX each year. The results are shown in the table below:

[167] Radar tutorial. 'En-Route Radar', accessible at: https://www.radartutorial.eu/02.basics/rp32.en.html
[168] Radar tutorial. 'Airport Surveillance Radar', accessible at: https://www.radartutorial.eu/02.basics/rp31.en.html
[169] NATS (n.d.) EGBJ – Gloucestershire. Available at : https://nats-uk.ead-it.com/cms-nats/opencms/en/Publications/AIP/Current-AIRAC/html/eAIP/EG-AD-2.EGBJ-en-GB.html
[170] David Learmount (2008). London Heathrow airport unveils Tarsier FOD detection system. Available at : https://www.flightglobal.com/london-heathrow-airport-unveils-tarsier-fod-detection-system/80915.article

Table 36 UK ATC radar market estimation

Parameter	Value
Total number of identified radars in the UK	185
Assumed average timing related CAPEX per radar (£)[171]	10,000
Amortization period for CAPEX (Year)	15
% estimate of CAPEX as annual OPEX	10%
Amortized annualised CAPEX related to timing	123,333
Annualised OPEX related to timing	185,000
UK annualised total addressable market timing related ATC radar	**308,333**

The UK annualised total addressable market timing related ATC radar is estimated to be £308K/yr**.** Extrapolating on revenue figures of ANSP service providers from Figure 62 using NATS as a UK reference would imply an EU27 TAM of £3.7m. This estimate is based on the premise that holdover clocks are all that are required to meet the timing needs for ATC.

Moreover, the number of radars or the requirements of time are not expected to change, in the UK over the 2024 – 2030 period, implying negligible growth potential for time related to ATC radars.

3.7.7 Conclusions

- ATC radars require local oscillators to be able to make precise range measurements. The oscillator is only required to be stable for short periods of time (few thousand pulses) and long-term stability is not a requirement;
- ATC radars (unlike many military radars) currently only operate in monostatic configurations, this results in radars having substantially lower timing requirements than they otherwise would as they do not require tight synchronisation across radars;
- Synchronisation requirements are still required across the ATC network and between radars are very low (around one second). This is driven by the requirement for ATC radar screens to only update aircraft positions once every six seconds;
- There are strong incentives to ensure that ANSP and airports remain operational, with the potential for further regulatory incentives being introduced for NATS, the UK ANSP. The invasion of Ukraine has also increased airlines' willingness to support measures to increase ATC resilience;
- There is already a system-of-system approach to ATC with many systems (e.g. radar, WAM, ADS-B) providing redundancy and complementarity to ensure that flights can be flown safely and efficiently. This resilience results in a reduced willingness to pay for resilient time as its can be mitigated by other systems not dependent on time – the precise impact to a loss of time varies depending on which systems are being employed in a given region;
- A survey has been undertaken to understand how many ATC radars are installed across the UK. It is estimated that 185 radars are operated in the UK excluding military and defence;
- The UK Annualised total addressable market timing related ATC radar is estimated to be £308K/yr**.** Extrapolating on revenue figures of ANSP service providers from Figure 62 using NATS as a UK reference would imply an EU27 TAM of £3.7m.

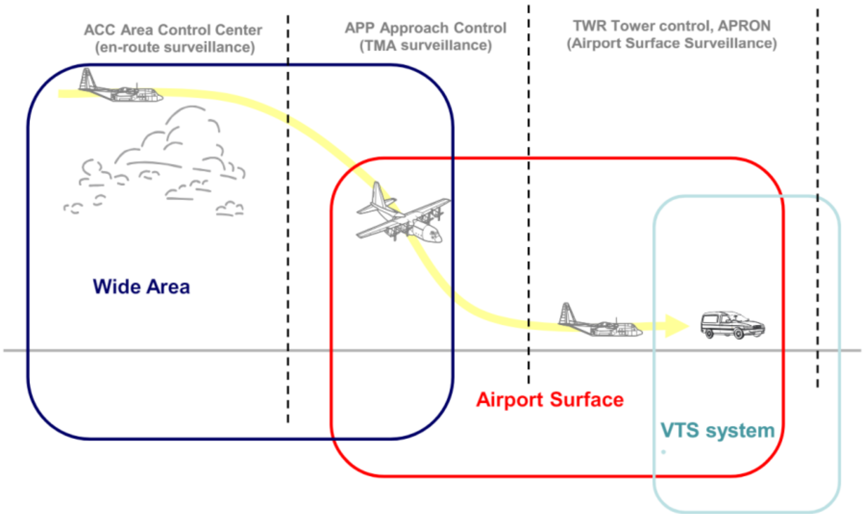
[171] Assumption being that timing related equipment are of this order of magnitude for typical high quality holdover clocks. While uncertainty exists around this figure and will vary across radar types, it is not reasonable to expect values much higher than this for time related equipment

- Negligible nominal growth is expected in 2024-2030 period – the total number of ATC radars are not expected to increase, nor are the requirements expected to increase;
- Driven by low timing requirements, which can largely be met by holdover clocks and local oscillators and systems-of-systems approach, ATC radars are not expected to be a significant market for resilient time.

3.8 UC8: ATC WAM systems

Wide Area Multilateration (WAM) systems are surveillance systems using non-rotating antennas employed in air traffic control to monitor and track aircraft within a large geographic area, such as en-route or approach areas. En-route areas delineate airspace allocated for aircraft traveling between departure and arrival points, typically following established airways. Conversely, approach areas encompass the vicinity of airports where aircraft undergo guidance during the concluding phases of landing or the initial phases of take-off. These zones play a vital role in maintaining both the safety and efficiency of air traffic management.

Figure 71 Airspace coverage by WAM systems



Source: ERA presentation on multilateration and ADS-B surveillance solutions [online] Available at: https://www.icao.int/APAC/Meetings/2011_ADS_B_SITF10/SP11%20-%20ERA%20-%20ADS-B%20WAM.pdf [Accessed 24 Apr. 2024].

WAM systems are often deployed alongside traditional radar systems for air traffic surveillance. They supplement radar systems by providing a number of benefits[172] [173] [174]:

- **Increased coverage:** Enhances cooperative surveillance where necessary, augmenting existing radar coverage.
- **Increased flexibility:** WAM antennas can be installed in regions with rugged terrain, facilitating surveillance in areas where secondary radar deployment is constrained.

[172] Federal Aviation Administration. ADS-B Wide Area Multilateration (WAM) | Federal Aviation Administration. [online] Available at: https://www.faa.gov/air_traffic/technology/adsb/atc/wam.
[173] Multilateration era Corporation. (n.d.). Available at: https://www.multilateration.info/downloads/MLAT-ADS-B-Reference-Guide.pdf.
[174] Futureairport.com. (2017). Comsoft Solutions - The future of multilateration - Future Airport. [online] Available at: https://www.futureairport.com/contractors/air-traffic-management-and-control-systems-(atm--atc)/comsoft-solutions/ [Accessed 1 May 2024].

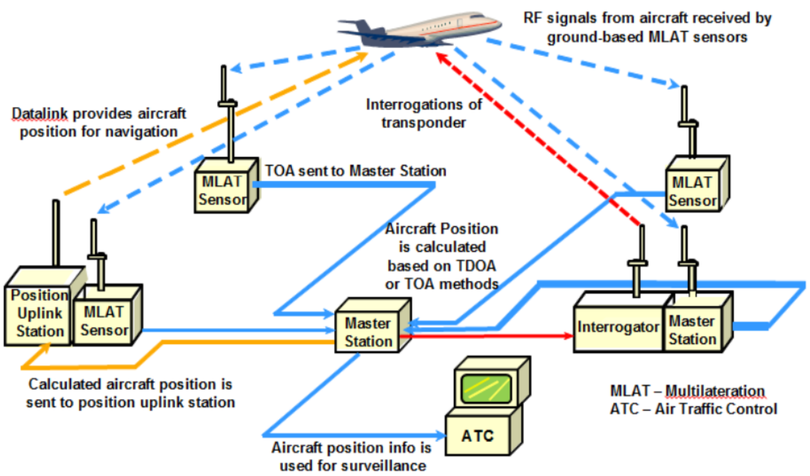
- **Lower cost:** WAM systems often present a more economical option for deployment and maintenance in comparison to radar systems.
- **Lower power:** A radar typically uses approximately 200 times more power than a WAM ground station (12 kilowatts compared to 50 watts).

WAM systems employ an array of ground-based receivers to detect and measure the time difference of arrival (TDOA) of signals emitted by aircraft. Through processing of these measurements, WAM systems ascertain the exact location of aircraft in real-time. Multilateration (MLAT), a core principle utilised in WAM systems, entails the deployment of numerous ground stations strategically positioned around an airport, its local terminal area, or a broader airspace region. These units listen for "replies," typically in response to interrogation signals transmitted from a local Secondary Surveillance Radar (SSR) or a multilateration station. Since individual aircraft may vary in their distances from each ground station, their replies are received at slightly different times by each station. Leveraging computer processing techniques, these minute time differences enable precise calculation of an aircraft's position.

Multilateration operates without the need for additional avionics equipment, utilising replies from Mode A, C, and S transponders, as well as military Identification Friend or Foe (IFF). Multilateration systems can also use the broadcast signals Automatic Dependent Surveillance-Broadcast (ADS-B) transponders to calculate aircraft position. A multilateration system comprises multiple antennas receiving signals from an aircraft, along with a central processing unit that calculates the aircraft's position based on the TDOA of the signal at the different antennas. With signals detected by at least four antennas, the system can estimate the aircraft's three-dimensional position by determining the intersection of resulting hyperbolas.

WAM systems can be categorised as either active or passive. Passive WAM systems comprise solely of receivers, while an active system integrates one or more transmitting antennas to initiate an interrogation of an aircraft’s transponder. The primary benefit of an active system is its independence from external sources to prompt a transmission from an aircraft. A WAM system primarily consists of passive stations, supplemented by a few active stations dedicated to interrogating Air Traffic Control Radar Beacon System (ATCRBS) aircraft.

Figure 72 MLAT surveillance and navigation system depicting active and passive stations



Source: Niles, F., Conker, R., Bakry El-Arini, M., Daniel, M.-C., O'laughlin, G. and Baraban, D. (n.d.). Wide Area Multilateration for Alternate Position, Navigation, and Timing (APNT). [online] Available at: https://www.faa.gov/sites/faa.gov/files/about/office_org/headquarters_offices/ato/WAM_WhitePaperFINAL_MITRE_v2.pdf [Accessed 24 Apr. 2024].

These WAM systems are operated by Air Navigation Service Providers (ANSP), who are responsible for providing air traffic control services, including airspace management, navigation assistance, and communication support, within a specific region or country. All organisations seeking to offer air navigation services must possess a certificate issued by the Civil Aviation Authority (CAA) in compliance with UK Regulation (EU) 550/2004[175], also known as the Service Provision Regulation, Article 7. Airports may maintain their own dedicated Air Traffic Control (ATC) facilities and staff, overseeing these operations internally, ensuring adherence to regulations and safety protocols. Alternatively, some airports opt to outsource their ATC services to specialised firms, such as NATS Services Limited (NSL) or Air Navigation Solutions. These contractors deliver air traffic control services on behalf of the airport, utilising either on-site personnel or remote facilities.

3.8.1 Use of time

Synchronisation for time difference of arrival calculation

To calculate the position of an aircraft, WAM systems rely on analysing the time differences between signals received by multiple antennas strategically positioned across a designated area. These antennas capture the signals transmitted by aircraft, allowing the WAM system to measure the time it takes for each signal to reach each antenna. By comparing these time differences, the system can triangulate the aircraft's position in three-dimensional space.

In the operation of these WAM antennas, synchronisation is crucial. It is important to highlight that whilst synchronisation among the antennas is essential (otherwise the signals at different sites will be referenced to separate clocks, rendering them non-comparable), they do not require synchronisation with coordinated universal time (UTC)[176].

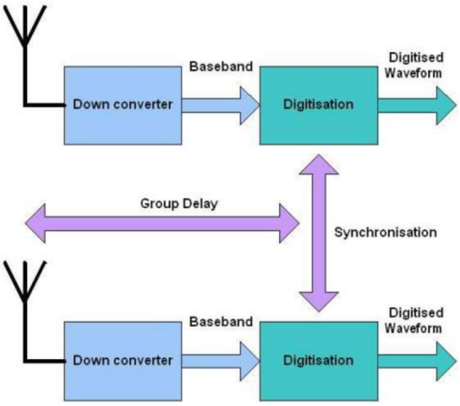
WAM systems can be categorised by the synchronisation method used in the calculation of aircraft position. Synchronisation is the method by which the digitation processes of the signals at each site are tied together[177]. In order to calculate the TDOA, the signal from the aircraft needs to be timestamped, which is carried out during the digitisation process. During this processing phase, there is a delay introduced, occurring because of the group delay associated with the down conversion process, which is the conversion of the signal from a higher frequency to a lower intermediate frequency that is suitable for digital processing. In practical terms, group delay quantifies how different frequencies within a signal are delayed relative to each other as they pass through a device or system, such as a filter, amplifier, or communication channel. This delay must be known and taken into account in order to accurately calculate the TDOA and hence the position of the aircraft. The diagram in Figure 73 displays the group delay between the RF components in a WAM system.

[175] UK Government. Regulation (EC) No 550/2004 of the European Parliament and of the Council of 10 March 2004 on the provision of air navigation services in the single European sky (the service provision Regulation) (Text with EEA relevance). [online] Available at: https://www.legislation.gov.uk/eur/2004/550/contents [Accessed 7 May 2024].

[176] Niles, F., Conker, R., Bakry El-Arini, M., Daniel, M.-C., O'laughlin, G. and Baraban, D. (n.d.). Wide Area Multilateration for Alternate Position, Navigation, and Timing (APNT). [online] Available at: https://www.faa.gov/sites/faa.gov/files/about/office_org/headquarters_offices/ato/WAM_WhitePaperFINAL_MITRE_v2.pdf.

[177] National Aerospace Laboratory (NLR) (2005) Wide Area Multilateration Report [online] Available at: https://www.eurocontrol.int/sites/default/files/2019-05/surveilllance-report-wide-area-multilateration-200508.pdf

Figure 73 Group delay and synchronisation diagram



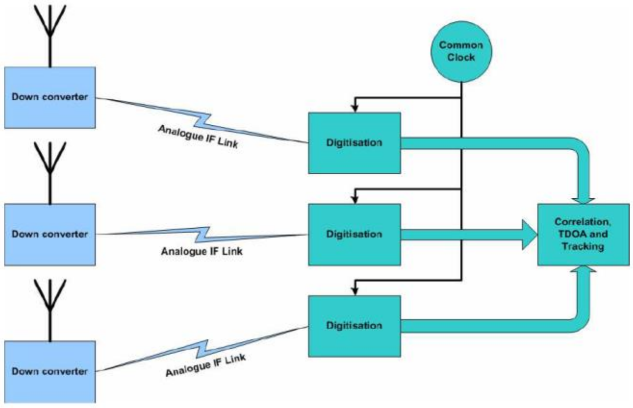
Source: National Aerospace Laboratory (NLR) (2005) Wide Area Multilateration Report [online] Available at: https://www.eurocontrol.int/sites/default/files/2019-05/surveilllance-report-wide-area-multilateration-200508.pdf

Wide Area Multilateration (WAM) systems employ various synchronisation methods to ensure accurate coordination among antennas.

Common clock systems:

- Use a simple receiver design, with most complexity centralised at the processing site.
- No need to synchronise at the receiver, as digitisation occurs at the central processing site.
- However, a large group delay is introduced over the analogue IF link between receivers and the processing site.
- Increasing link distance increases the delay, making it harder to achieve a given accuracy, resulting in stringent requirements on the type and range of the link.
- To transmit signals back to the processing site, either fibre optic cables or microwave links are used.

Figure 74 Common clock architecture



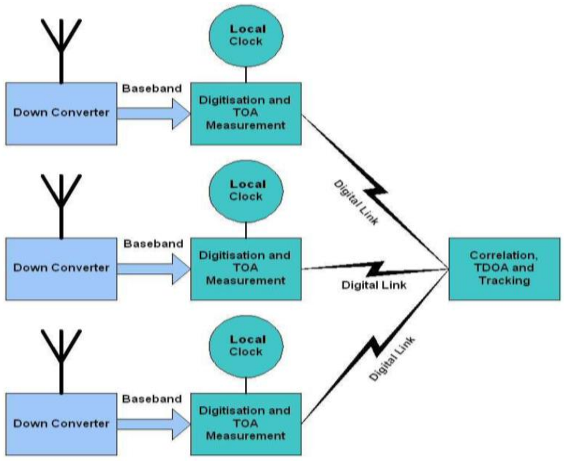
Source: National Aerospace Laboratory (NLR) (2005) Wide Area Multilateration Report [online] Available at: https://www.eurocontrol.int/sites/default/files/2019-05/surveilllance-report-wide-area-multilateration-200508.pdf

Distributed clock systems:

- Use a more complex receiver, where digitisation, code extraction, timestamping, and TOA measurement are all done at the receiver.

- This gives greater flexibility and reduces demand on the data link as only the SSR code value and the TOA need to be transmitted to the processing site.
- It also means that the link latency is not critical.
- As digitisation and timestamping occurs at the receiver, local clocks at the receiver site must be synchronised.
- This approach is the most commonly used.

Figure 75 Distributed clock architecture



Source: National Aerospace Laboratory (NLR) (2005) Wide Area Multilateration Report [online] Available at: https://www.eurocontrol.int/sites/default/files/2019-05/surveilllance-report-wide-area-multilateration-200508.pdf

Distributed clocks may be synchronised in a number of ways:

- **Transponder synchronisation**
  - Transponder-synchronised systems utilise signals transmitted from a designated reference transponder to synchronise the clocks across all receiver sites.
  - This requires the synchronisation transponder to maintain a direct line of sight (LOS) with each of the receivers.
  - Consequently, in the case of a Wide Area Multilateration (WAM) system, tall masts or towers are typically necessary to ensure unobstructed communication between the synchronisation transponder and the receivers.
- **Standard GNSS synchronisation**
  - GNSS can serve as a common timing reference for the receivers.
  - In standard GNSS synchronisation, each receiver independently acquires and tracks signals from multiple satellites.
  - The receiver's internal clock is adjusted based on the timing information provided by the GNSS satellites it is tracking.
  - Systems synchronised with GNSS are simpler to set up compared to those relying on common clocks and transponders, as they eliminate the need for tall towers for synchronisation and can utilise any digital data link available.
- **Common view GNSS synchronisation**
  - In scenarios where standalone GNSS synchronisation among receivers lacks sufficient accuracy, a common-view synchronisation method can be employed instead.
  - Common-view GNSS synchronisation involves multiple receivers simultaneously observing the same set of satellites.

- Instead of relying solely on their individual observations, the receivers compare their measurements of the same satellites' signals.
- By comparing the time delays in the signals received from common satellites, the receivers can calculate and compensate for any differences in their clock offsets.
- This enables the elimination of many error sources shared among signals, resulting in a substantially more precise synchronisation solution.

GNSS time synchronisation serves as the fundamental method for aligning time across MLAT systems, while both wired and wireless synchronisation methods are utilised as supplementary means of synchronisation[178].

Target report time stamping

A target report is a message output by a surveillance system containing information about a possible object[179]. A target report can be generated by a sensor or a tracker. When an aircraft is detected by a WAM system, its position, along with other relevant information, is recorded in a database or transmitted to air traffic controllers for further processing. This recorded information includes the target's position, velocity, and identification, as well as a timestamp, synchronised to UTC, indicating the time at which the target report was generated. This can serve as a temporal reference for air traffic controllers, allowing them to track the movement of aircraft over time, enables correlation of aircraft positions with other data sources, and facilitates historical analysis of air traffic movements.

3.8.2 User requirements

Table 37 User requirements for use case

Application	Timing accuracy	Availability	Integrity	Continuity	Time to alert	Indoors (Y/N)
Time difference of arrival calculations	50 ns	99.99%	Y	2 × 10–4 per flight hour	Terminal: 10 seconds, Enroute: 15 seconds	N
Target report time stamp	100ms	99.99%	Y	2 × 10–4 per flight hour	Terminal: 10 secs, Enroute: 15 secs	N

Source: Jan, S.-S., Jheng, S.-L., Chen, Y.-H. and Lo, S. (n.d.). Evaluation of Positioning Algorithms for Wide Area Multilateration based Alternative Positioning Navigation and Timing (APNT) using 1090 MHz ADS-B Signals. [online] Available at: https://web.stanford.edu/group/scpnt/gpslab/pubs/papers/JanLo_IONGNSS_2014_ADSB_APNT_clean_WAM.pdf [Accessed 10 May 2024]; Niles, F., Conker, R., Bakry El-Arini, M., Daniel, M.-C., O'laughlin, G. and Baraban, D. (n.d.). Wide Area Multilateration for Alternate Position, Navigation, and Timing (APNT). [online] Available at: https://www.faa.gov/sites/faa.gov/files/about/office_org/headquarters_offices/ato/WAM_WhitePaperFINAL_MITRE_v2.pdf; EUROCAE (2010) ED-142 Technical Specification for Wide Area Multilateration (WAM) Systems; European Union Aviation Safety Agency (EASA) Acceptable Means of Compliance and Guidance Material to Commission Implementing Regulation (EU) No 1207/2011 Available at: https://www.easa.europa.eu/en/downloads/117152/en

[178] Yoo, S.-H., Oh, J.-H., Koh, Y.-M., Kim, S.-H. and Sung, T.-K. (2016). Performance Analysis of MLAT System Receiver for Aircraft Flight Control System. Journal of Positioning, Navigation, and Timing, 5(1), pp.29–36. doi:https://doi.org/10.11003/jpnt.2016.5.1.029.
[179] EUROCONTROL Specification for ATM Surveillance System Performance (Volume 1). (n.d.). Available at: https://www.eurocontrol.int/sites/default/files/2023-06/eurocontrol-spec-esassp-vol-1.pdf [Accessed 10 May 2024].

3.8.3 Drivers and enablers for adopting resiliently disseminated time

Regulatory oversight and financial incentives

The Civil Aviation Authority (CAA) oversees all UK airports to ensure compliance with international and UK safety standards. However, the CAA's regulatory scope extends beyond safety to include service standards and maximum airline charges at airports wielding significant market power[180].

Under the Civil Aviation Act 2012, the CAA holds authority to license airport operators after evaluating their market dominance. This evaluation comprises three criteria: first, whether the operator possesses or is likely to gain substantial market power; second, whether competition law adequately guards against potential abuse of this power; and third, whether regulating the operator through licensing would outweigh any negative impacts for air transport users. Presently, this regulatory framework applies only to London Heathrow and London Gatwick airport.

At Heathrow, the Measures, Targets, and Incentives (MTI) Scheme[181], initiated by the CAA in May 2023 under the H7 framework, replaces the previous Service Quality Rebates and Bonuses scheme from Q6. Embedded within Heathrow's licensing framework, the MTI Scheme aligns with the CAA's Outcomes Based Regulation (OBR) framework, incentivising the airport to meet predefined service quality standards crucial for passengers and airlines. Performance on these metrics triggers either financial or reputational incentives, with rebate payments issued to airlines monthly for underperformance against targets.

Conversely, Gatwick undergoes ongoing service monitoring by the CAA, which includes audits of departure and arrival punctuality[182]. Gatwick Airport Limited (GAL) provides rebates to airlines if service quality falls below specified standards.

For airports not meeting the CAA's market power criteria, economic regulation and licensing requirements do not apply. Consequently, financial arrangements, including rebate schemes or incentives, are determined through individual service level agreements (SLAs) between the airport operator and airlines[183]. These contracts may feature provisions for rebates or incentives in cases of service disruptions or other issues, ensuring a tailored approach to economic regulation across the airport landscape.

To prevent the occurrence of delays and violations of performance metric SLAs, which could result in financial rebates being paid to airlines, airport operators will be motivated to prioritise resilient operations. Utilising a resiliently disseminated timing service can offer a potential safeguard solution.

[180] Civil Aviation Authority. Airport market power assessment | Civil Aviation Authority. [online] Available at: https://www.caa.co.uk/commercial-industry/airports/economic-regulation/licensing-and-price-control/airport-market-power-assessment/.

[181] Heathrow Airport. *Measures, Targets and Incentives | Heathrow*. [online] Available at: https://www.heathrow.com/company/about-heathrow/performance/airport-operations/measures-targets-and-incentives[Accessed 7 May 2024].

[182] Civil Aviation Authority. *Economic licensing of Gatwick Airport | Civil Aviation Authority*. [online] Available at: https://www.caa.co.uk/commercial-industry/airports/economic-regulation/licensing-and-price-control/economic-licensing-of-gatwick-airport/.

[183] International Air Transport Association (IATA). Airport Service Level Agreement (SLA) -Best Practice. [online] Available at: https://www.iata.org/contentassets/fa95ede4dee24322939d396382f2f82d/airport-service-level-agreement.pdf.

Airspace modernisation programmes to enhance capacity

The International Civil Aviation Organisation's (ICAO) Global Air Navigation Plan (GANP)[184] outlines the international roadmap for modernisation, which the UK has agreed to implement. The GANP represents a rolling, 15-year strategic approach which leverages existing technologies and anticipates future developments based on State/industry agreed operational objectives. At its core are Aviation System Block Upgrades (ASBUs), organising modernisation efforts into threads under three headings:

1) Information
2) Operational
3) Communications, navigation, and surveillance (CNS) technology and services

The CAA has outlined the UK's strategy for modernising its airspace management operations and aligning them with the ICAO's GANP through the Airspace Modernisation Strategy[185] (2023-2040). This initiative aims to address the future demands of the aviation industry while also meeting international obligations and ensuring alignment with neighbouring traffic management areas. A primary driver for modernisation is the imperative to expand airspace capacity due to the growing levels of air traffic, which lead to the emergence of airspace bottlenecks.

From 2010, the UK witnessed robust growth in commercial air transport demand, peaking in 2019 with around 2.6 million flights operating in its airspace. At this volume, the existing airspace system began to struggle to meet demand, exceeding capacity in some cases, resulting in congestion and increased delays[186]. Analysis by NATS En Route Limited (NERL) indicated that without airspace capacity upgrades, passenger delays would sharply rise as traffic levels continued to increase. The analysis predicts rapid increases in passenger delays up to 2040, disproportionately to traffic level growth post-Covid-19 recovery. The forecasted increase in delays as a consequence of a lack of airspace capacity could accumulate to around 4.1 million minutes of delay in 2040 (growing from 1.6 million in 2019) and over £1.1 billion in costs to airlines and passengers between 2021 and 2040.

Capacity constraints, and thus lack of flexibility, in the existing system have reduced resilience against adverse weather and unforeseen events, limiting the ability to handle traffic surges or airspace closures. Additional capacity would enhance resilience, allowing for strategic planning and better demand management to mitigate disruptions. WAM systems provide a means to increase airspace capacity, offering a higher update rate and greater positional accuracy compared to traditional radar and other cooperative methods[187]. It also does so in a more cost-effective manner - WAM is anticipated to decrease the life cycle cost of acquiring ground-based infrastructure systems by 20-35% or more[188]. A growing dependence on WAM infrastructure to bolster airspace capacity would make their reliable operation of critical importance, increasing the need for resiliently disseminated timing services.

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184 International Civil Aviation Authority, Global Air Navigation Plan 2016-2030 [online] Available at: https://www.icao.int/publications/Documents/9750_5ed_en.pdf [Accessed 29 Apr. 2024].

185 Civil Aviation Authority (CAA) Airspace Modernisation Strategy (2023-2040) Available at: https://www.caa.co.uk/publication/download/17167 [Accessed 29 Apr. 2024].

186 Airspace Change Organising Gorup (ACOG) (2022), UK Airspace Change Masterplan Iteration 2 Available at: https://www.caa.co.uk/publication/download/19383 [Accessed 29 Apr. 2024]

187 Aviation Pros. (2011). Saab Sensis' Wide Area Multilateration and Precision Runway Monitoring Now Operational at Sydney Airport. [online] Available at: https://www.aviationpros.com/home/news/10563993/saab-sensis-wide-area-multilateration-and-precision-runway-monitoring-now-operational-at-sydney-airport [Accessed 7 May 2024].

188 Multilateration era Corporation. (n.d.). Available at: https://www.multilateration.info/downloads/MLAT-ADS-B-Reference-Guide.pdf.

Increasing threats affecting air traffic management

This use case faces the same threats affecting air traffic management as described in Section 3.7.3 of UC7.

3.8.4 Blockers for adopting resiliently disseminated time

Resilience of the system-of-systems approach to ATC

Air Traffic Control (ATC) has evolved over many decades. In the process, various approaches to track, identify, and control aircraft have been developed including: primary radars, secondary radars, wide area multilateration (WAM), automatic dependent surveillance-broadcast (ADS-B), and procedural control.

Each of these approaches have different strengths, weaknesses, vulnerabilities, dependencies, and uses of time. As such, each approach is complementary and mitigates each other's risks, creating a resilient systems-of-systems approach to ATC. For example, if the primary radar fails, the secondary radar or WAM can still provide surveillance. If the transponder malfunctions, the primary radar or ADS-B can still track the aircraft.

As a result, this system-of-systems approach reduces the willingness to pay for resilient time, because the vulnerability of the loss of time has to some extent already been mitigated.

Aviation safety critical factor

Safety is paramount in ATC, and any new technology or service must meet rigorous standards to ensure it does not compromise aviation safety. As such, strict acceptance criteria are needed to ensure that the safety levels provided by a resiliently disseminated time services are comparable to the aviation industry's existing safety record. The critical factor of aviation safety means that the pace and uptake of innovation within ATC can be slower than desired[189]. Any potential disruption or risk to the smooth operation of air traffic management systems is carefully evaluated, leading to cautious approaches to adopting new technologies.

Furthermore, the complex and interconnected nature of ATC systems means that any changes or upgrades must undergo thorough testing and validation to ensure they do not introduce unintended consequences or vulnerabilities. This rigorous testing process, coupled with the need to meet strict safety standards, can affect the adoption sentiment and prolong the timeline for new time services in the ATC sector.

Overall, while resiliently disseminated time services offer the potential to enhance the reliability and resilience of ATC operations, their adoption may be hampered by the need to meet stringent safety requirements and ensure compatibility with existing systems. Addressing these safety concerns and demonstrating the reliability and effectiveness of new time services will be essential to overcoming this barrier and facilitating their adoption within the ATC sector.

[189] Civil Aviation Authority (CAA) Airspace Modernisation Strategy (2023-2040) Available at: https://www.caa.co.uk/publication/download/17167 [Accessed 29 Apr. 2024].

3.8.5 Market sizing methodology

Number of WAM sensors

In approximating the TAM, the number of WAM sensors operational in the UK are identified using publicly available data from Eurocontrol[190], who produce monitoring reports on the implementation of airspace modernisation efforts. It is important to note that not all airports in the UK are currently equipped with WAM systems.

An analysis of the air transport movements of airports (number of take-offs and landings) in the UK from the CAA[191] reveals a correlation between number of airport WAM sensors and air transport movements, indicating higher traffic density necessitates more precise separation calculations, thereby requiring a greater number of sensors. Based on correlation findings, the ratio of WAM sensors to air transport movements is calculated and averaged, serving as a metric for estimating the required number of sensors to effectively cover the air traffic at each UK airport.

The lower boundary of the TAM is established by considering the current number of airports equipped with WAM sensors, based on Eurocontrol data. This analysis rests on the assumption that airports currently utilising WAM systems possess adequate sensor capacity, as evidenced by their ability to accommodate pre-pandemic levels of air traffic. Given that air travel has yet to fully rebound from pandemic-induced downturns[192] and projections remain modest, forecasted to average single digit growth up to 2030, the TAM estimation is based off existing installations and sensor growth is assumed to be negligible.

To determine the upper boundary of the TAM, a calculation is made under the assumption that all UK airports surveyed by the CAA will adopt WAM systems between 2024 and 2030. By taking the average ratio of WAM sensors to air transport movements and applying it to the air transport movements of airports yet to adopt a WAM system, an estimate of the required number of WAM sensors to cover the airspace is derived. It is assumed that a minimum of 6 WAM sensors is required as part of an airports WAM system[193]. This includes a minimum of 4 sensors necessary for multilateration calculations and additional sensors for redundancy and operational flexibility. It is also assumed that the subsequent growth of WAM sensors at each airport following the initial installations will be negligible, largely due to the expectation that the initial installations will adequately cater to the demand until 2030. This assumption is grounded in the belief that the initial capacity deployments will be strategically planned to effectively manage airspace and air traffic control requirements up to at least the 2030 timeframe.

Information regarding WAM sensors across the European Union (EU) is sourced from Eurocontrol figures within their ASBU Implementation Monitoring Report[194]. For the lower boundary scenario of the TAM, it is assumed that the count of WAM sensors in Europe remains constant, as per the data

[190] Eurocontrol (2023). United Kingdom Local Single Sky Implementation (LSSIP) document – 2022 | EUROCONTROL. [online] Available at: https://www.eurocontrol.int/publication/united-kingdom-local-single-sky-implementation-lssip-document-2022 [Accessed 8 May 2024].

[191] Civil Aviation Authority (2023) *UK airport data | Civil Aviation Authority*. [online] Available at: https://www.caa.co.uk/data-and-analysis/uk-aviation-market/airports/uk-airport-data/.

[192] Supporting European Aviation EUROCONTROL. Available at: https://www.eurocontrol.int/sites/default/files/2024-02/eurocontrol-seven-year-forecast-2024-2030-february-2024.pdf.

[193] ADS-B and other means of surveillance implementation status. (2018). Available at: https://transport.ec.europa.eu/system/files/2018-06/20180515-sesar-ads-b-report.pdf [Accessed 8 May 2024].

[194] ICAO EUR States ASBU Implementation Monitoring Report. Available at: https://www.icao.int/EURNAT/Documents/ASBU/eurocontrol-icao-asbu-implementation-monitoring-report-2022.pdf [Accessed 9 May 2024].

provided in this report. This assumption establishes a conservative estimate of the TAM, considering the current status of WAM sensor deployments across the region.

To determine the upper boundary of the TAM for the EU, the methodology assumes that the upper boundary estimate for the UK market's number of WAM sensors is sufficient to cover the country's area. This assumption is then used to establish a relationship between the area of the country and the number of WAM sensors necessary for full WAM coverage. By applying this ratio, the total area of each of the EU member states[195] is multiplied to estimate the number of WAM sensors required for the country. This approach provides a systematic way to extrapolate from the known market scenario of the UK to assess the potential market size for the broader EU context

Cost of WAM sensor acquisition and maintenance

When considering the capital expenditure (CAPEX) and operational expenditure (OPEX) associated with WAM sensors, approximately 10% of both CAPEX and OPEX are assumed to be attributed to the functioning of their timing infrastructure. This allocation accounts for costs associated with maintaining and ensuring the accurate timing of the sensor systems, which is crucial for their effective operation and synchronisation within the wider air traffic management framework. This is applied to the number of sensors to estimate the TAM.

Table 38 Timing related CAPEX for WAM sensors

Parameter	Value
CAPEX per sensor (£)	90,000
Lifetime of sensor (years)	15
Amortised annualised CAPEX (£)	6,000
% estimate of timing related CAPEX	10%
Amortised annualised CAPEX related to timing (£)	600

Source: Calculated using figures from: ATC Network (2019). The World's Largest Wide Area Multilateration System to be Deployed in Russia. [online] www.atc-network.com. Available at: https://www.atc-network.com/atc-news/the-worlds-largest-wide-area-multilateration-system-to-be-deployed-in-russia [Accessed 9 May 2024]; European Commission. ADS-B and other means of surveillance implementation status. (2018). Available at: https://transport.ec.europa.eu/system/files/2018-06/20180515-sesar-ads-b-report.pdf.

Table 39 Timing related OPEX for WAM sensors

Parameter	Value
Annual OPEX per sensor as proportion of CAPEX	4%
Annual OPEX per sensor (£)	3,600
% estimate of timing related OPEX	10%
Annual OPEX per sensor related to timing (£)	360

Source: Calculated using figures from: Multilateration era Corporation. (2009). Available at: https://www.multilateration.info/downloads/MLAT-ADS-B-Reference-Guide.pdf.

3.8.6 Market sizing results

In the lower boundary scenario, 192 WAM sensors in the UK are identified, leading to a total addressable market of £184k per year. In the upper boundary scenario, 488 WAM sensors in the UK are estimated, resulting in a total addressable market of £468k per year.

[195] World Bank. World Bank Open Data. [online] Available at: https://data.worldbank.org/indicator/AG.SRF.TOTL.K2?locations=EU [Accessed 10 May 2024].

In the EU, the present count of WAM sensors stands at 1,316, which corresponds to a total addressable market of £1.2 million annually under the lower boundary scenario. Considering the implementation of WAM sensors to cover the area of each EU member state, the projected number of required sensors is 8,528. This calculation yields a total addressable market of £8.2 million per year under the upper boundary scenario.

3.8.7 Conclusions

- The calculation of aircraft positions using WAM systems relies heavily on the precision of time difference of arrival (TDOA) methods, necessitating stringent synchronisation and signal timestamping. To achieve this, GNSS serves as a common synchronisation method, utilising GNSS disciplined oscillators at each sensor site to synchronise the WAM system with nanosecond accuracy.
- As GNSS interference becomes increasingly prevalent in aviation, there's a growing demand for resilient timing sources to safeguard the robustness of ATC infrastructure. Although the impact of GNSS interference in the UK has remained relatively low, primarily affecting areas near conflict zones, airlines are becoming increasingly attuned to these challenges. Consequently, they are advocating for enhanced resilience measures, shifting the focus from cost reduction to ensuring operational resilience.
- The imperative for operational continuity is further emphasised for airports, driven by incentive schemes outlined by the Civil Aviation Authority (CAA) or through Service Level Agreements (SLAs) established with airlines. This ensures that ATC operations remain uninterrupted - avoiding any rebate payments to airlines.
- However, in the realm of ATC, a robust systems-of-systems approach is adopted, with various systems such as radar, WAM, and ADS-B providing redundancy and complementarity. This may reduce willingness to pay for a resiliently disseminated time service, although this is dependent on the systems deployed in a particular region.
- Advantages inherent in WAM systems over traditional radar approaches, both economically and in terms of implementation flexibility, could drive increased installations, replacing aging radar infrastructure at their end of life. Increased dependency on WAM systems, and their reliance on time may stimulate demand for a resiliently disseminated time service to safeguard their continued operations.
- The affordability of WAM systems implies that operators may exhibit a reduced willingness to allocate resources towards ensuring the resilience of the time source, particularly if the risk of GNSS interruption is perceived to be low.
  - This reluctance stems from a perception that only a fraction of the system's total value should be devoted to bolstering the resilience of its time synchronisation.
- The total addressable market for resiliently disseminated time in the UK and EU is estimated to be:
  - **UK** - £184k per year in the lower boundary scenario and up to £468k per year in the upper boundary scenario.
  - **EU** - £1.2m per year in the lower boundary scenario and up to £8.2m per year in the upper boundary scenario.

3.9 UC9: Timing systems for airborne applications

Time signals play a crucial role in airborne applications, ensuring the safe and uninterrupted operations of airspace users. These users encompass operators of both manned and unmanned air vehicles, each requiring timing and synchronisation to maintain operational integrity and safety.

Airspace users within the UK can be classified into several broad categories[196], as depicted in the diagram below.

Figure 76 Airspace user categorisation

- **Airlines:** Airlines are commercial air transport operators that use airspace to provide scheduled and charter passenger and cargo services. They rely heavily on controlled airspace for efficient and safe operations, adhering to strict regulations and flight paths managed by air traffic control.
- **General aviation:** General aviation encompasses all civil aviation activities other than scheduled commercial air transport. This includes private flying, business aviation, flight training, agricultural aviation, and aerial work. General aviation users operate in both controlled and uncontrolled airspace, often requiring flexible routing and access to smaller airports.
- **Ministry of Defence:** The Ministry of Defence (MoD) represents military airspace users, including the Royal Air Force, Navy, and Army aviation units. They utilise airspace for training, operational missions, and other defence-related activities. Military operations may require restricted or segregated airspace to ensure safety and security.
- **Emergency services:** Emergency services, such as police, air ambulances, and search and rescue operations, use airspace to respond quickly to incidents and emergencies. They require priority access to airspace and the ability to operate in various weather conditions and at all times of day to provide critical services.
- **Drones:** Drones, or Unmanned Aerial Vehicles (UAVs), are increasingly prominent airspace users for both recreational and commercial purposes. They operate at various altitudes and require integration into the airspace system to ensure safe coexistence with manned aircraft. Regulations are evolving to address their unique operational needs and safety requirements.

3.9.1 Use of time

Civil Aircraft

Flight management system synchronisation

The flight management system (FMS) of an aircraft is a computerised system that automates a wide range of in-flight tasks, including navigation, performance management, and guidance[197]. It integrates data from multiple sources to provide pilots with real-time information and optimise the aircraft's flight path. The FMS often serves as the master clock in modern aircraft and is synchronised

[196] Adapted from: NATS (2024). NATS OpenAir: consultation Phase 1 – Industry engagement [Online]. Available at: https://www.nats.aero/wp-content/uploads/2024/02/NATS-OpenAir-consultation-document-Feb-2024.pdf [Accessed 15 May 2024]
[197] SKYbrary (2021). Flight Management System. [online] SKYbrary Aviation Safety. Available at: https://skybrary.aero/articles/flight-management-system.

to UTC as part of pre-flight procedures[198] and can be updated based on received signals from GNSS. Accurate time synchronisation of the FMS is important for several reasons:

- **Longitudinal navigation:**
  - Time-based longitudinal separations between aircraft following the same route or intersecting routes are evaluated based on the differences in their estimated times of arrival (ETA) or actual times of arrival (ATA) at shared waypoints.
  - Errors in aircraft clocks can cause inaccuracies in reported waypoint ATAs, which may reduce the actual longitudinal separations between aircraft, potentially affecting safety.
- **Avionic system co-ordination and data exchange:**
  - Onboard avionics networks facilitate the interconnection of various aircraft subsystems, including sensors, power systems, navigational equipment, and flight controls.
  - To ensure effective coordination among these diverse subsystems during flight and to manage safety-critical operations, precise synchronisation of application timing across the network is essential[199].
  - The FMS is able to disseminate time information over the aircraft's data bus using the ARINC-429 technical specification, which defines the standard requirements and protocols for the transportation of digital data between avionic systems in commercial aircraft[200].

Data link communications

Controller-Pilot Data Link Communications (CPDLC) facilitates communication between controllers and pilots by allowing direct exchange of standardised messages, offering a viable alternative to traditional voice communications. Operating through data links, CPDLC ensures efficient Air Traffic Control (ATC) communications, enabling smoother coordination and reducing radio frequency congestion. However, CPDLC's effectiveness hinges on timing synchronisation. Accurate timing is essential to ensure messages are transmitted and received in the correct sequence and within expected time frames, mitigating the risk of communication errors and enhancing response times. Without accurate timing, delays, message misordering, and synchronisation issues may arise, potentially compromising communication efficiency and safety. To meet safety objectives outlined in ED-120/DO-290201, CPDLC implementations mandate access to accurate clocks, typically synchronised to within one second of Coordinated Universal Time (UTC). This timing requirement ensures message integrity, accurate timestamping, and rejection of outdated messages, bolstering the reliability and effectiveness of CPDLC in enhancing air traffic management and aviation safety.

[198] International Civil Aviation Authority (ICAO) (2023). North Atlantic Operations and Airspace Manual V.2023-1. Available at: https://www.icao.int/EURNAT/EUR%20and%20NAT%20Documents/NAT%20Documents/NAT%20Documents/NAT%20Doc%20007/NAT%20Doc%20007%20Ed%20V.2023-1_eff%20Jan2023.pdf

[199] Rockwell Collins. TIME SYNCHRONIZATION OVER REDUNDANT AND DETERMINISTIC SWITCH-BASED AVIONICS NETWORKS. Available at: https://data.epo.org/publication-server/rest/v1.0/publication-dates/20210428/patents/EP3812875NWA1/document.pdf [Accessed 15 May 2024].

[200] United Electronic Industries. ARINC-429 Tutorial and Reference - Aerospace DAQ, Test, HIL - UEI. [online] Available at: https://www.ueidaq.com/arinc-429-tutorial-reference-guide [Accessed 15 May 2024].

[201] EUROCAE Document ED-120 / RTCA DO-290 - Safety and Performance Requirements Standard for Air Traffic Data Link Services In Continental Airspace (SPR IC), May 2004, including Change 1 (April 2007) and Change 2 (October 2007)

4D navigation

4D navigation introduces the concept of incorporating time as a fourth dimension alongside the traditional three spatial dimensions (latitude, longitude, and altitude). This approach enables aircraft to plan and execute routes not only based on their geographical position but also considering the time dimension.

In 4D navigation, time plays a crucial role in determining the precise timing of waypoints, route segments, and overall flight trajectory. By integrating time into navigation calculations, pilots can optimise flight paths to account for various factors, including wind conditions, airspace constraints, traffic flow management, and arrival slot times at congested airports. This capability allows for more efficient route planning, reduced fuel consumption, and improved overall flight performance202.

Time synchronisation is critical in 4D navigation for ensuring that aircraft follow planned trajectories accurately and adhere to designated arrival and departure times. Any discrepancies in timing can lead to deviations from planned routes, missed arrival slots, and potential disruptions to air traffic flow.

Military aircraft

Airborne reconnaissance operations

Surveillance aircraft are equipped with sensor systems that rely on precise frequency synchronisation to accurately receive and process sensor data[203]. By maintaining receiver frequency synchronisation, aircraft can capture signals from various sources such as radar, communications, and electronic emissions. Any deviation in frequency synchronisation can result in signal degradation or loss, compromising the quality of intelligence gathered.

Recorded sensor data must be precisely time-stamped to facilitate synchronisation across the military network. Time-stamping ensures that data collected during reconnaissance missions is accurately sequenced and aligned with other operational activities and intelligence sources. This chronological synchronisation enables analysts and decision-makers to correlate events, identify patterns, and derive actionable insights from the collected data.

Emergency services

Air to ground communications synchronisation and timestamping

In emergency services aviation units, Time Division Duplex (TDD) is a crucial method for managing communications efficiently and reliably. TDD allows the same frequency channel to be used for both transmission and reception by dividing communication into time slots. This ensures that different units can transmit and receive data without interference. Aviation units use precise time signals, often derived from GPS, to synchronise their internal clocks. Each unit (e.g. aircraft, ground control, rescue teams) is allocated specific time slots for transmission and reception. Accurate time signals ensure that each unit transmits and receives data at the correct times, avoiding overlap and ensuring orderly communication. TDD optimises the use of available communication bandwidth by dividing it into discrete time slots allocated for uplink and downlink transmissions. This allows the same

[202] Schuurman, R. (2023). Lufthansa to introduce 4D navigation technology in 2024 |. [online] Available at: https://airinsight.com/lufthansa-to-introduce-4d-navigation-technology-in-2024/ [Accessed 15 May 2024].
[203] Bark, P. (2019). Precision Timing for Airborne Reconnaissance. [online] Safran - Navigation & Timing. Available at: https://safran-navigation-timing.com/precision-timing-for-airborne-reconnaissance/ [Accessed 16 May 2024].

frequency channel to be used more efficiently, maximising the effectiveness of the communication system. The requirement for this timing is understood to be similar to that in the 3GPP mobile broadband standards[204]. In 3GPP cell phase synchronization is specified as 3µs. i.e. the requirement on cell phase synchronization is ultimately specified in terms of maximum deviation in relation to a common absolute timing requirement and dividing the requirement by half (±1.5µs).

Time signals ensure that data is transmitted in an orderly sequence. Each unit knows exactly when to transmit and when to listen, preventing collisions and ensuring that messages are sent and received in the correct order. Accurate timing reduces the risk of data corruption and loss during these communications, ensuring that critical information is transmitted reliably.

Time signals are also used to timestamp all communications, providing a precise log of when each message was sent and received. This is crucial for post-mission analysis, legal documentation, and improving future response strategies. These timestamps help track the sequence of events during a mission, allowing for a detailed reconstruction of actions taken and decisions made.

Drones

Capacity optimisation and time division multiple access (TDMA) functions

In drone operations, the merging of data from different sensors is essential for comprehensive situational awareness and effective mission execution. To optimise the data transmission process, efficient packet scheduling techniques are necessary. One such technique is Time Division Multiple Access (TDMA), which categorises data packets based on their urgency for transmission and assigns specific timeslots to each node. These timeslots are cyclically repeated, ensuring that each node has designated "windows of opportunity" to transmit information in every cycle. To mitigate the risk of broadcast overlap, which can lead to delays, the timespan slots are tightly constrained to a few milliseconds, with a guard time included to account for synchronisation errors. Higher synchronisation accuracy allows for narrower guard times, reducing the interference probability and enabling more timeslots to fit into one cycle[205]. As a result, the capacity of the channel is increased, enhancing overall data transmission efficiency and system performance in drone operations.

Power management

Accurate synchronisation processes are important for effective power management in drone operations[206]. Establishing a communication link involves a series of steps, including radio transmission, sensing, and data processing, all of which consume varying amounts of power resources. Duty cycling is a technique used to reduce power consumption in wireless sensor networks[207]. It involves cycles of activity and rest for nodes, where they switch between low-power states and active states as needed. For example, nodes may enter a low-power sleep mode until they need to perform a task or receive information. This approach ensures that nodes are ready to receive data precisely when other nodes are about to transmit it, maximising energy efficiency and prolonging the network's battery life. Therefore, precise timing and synchronisation between nodes

[204] 3GPP – The Mobile Broadband Standard: Available at: https://portal.3gpp.org/desktopmodules/Specifications/SpecificationDetails.aspx?specificationId=3204

[205] Puttnies, H., Danielis, P., Sharif, A.R. and Timmermann, D. (2020). Estimators for Time Synchronization—Survey, Analysis, and Outlook. IoT, 1(2), pp.398–435. doi:https://doi.org/10.3390/iot1020023.

[206] Schmid, Thomas & Friedman, Jonathan & Charbiwala, Zainul & Srivastava, Mani. (2010). On the Interaction of Clocks and Power in Embedded Sensor Nodes.

[207] Nikolic, Goran & Stojcev, Mile & Stamenkovic, Zoran & Panic, Goran & Petrovic, Branislav. (2014). Wireless Sensor Node with Low-Power Sensing. FACTA UNIVERSITATIS Series Electronics and Energetics. 27. 435-453. 10.2298/FUEE1403435N.

are essential for the system to operate efficiently, maximising power utilisation and prolonging flight endurance in drone missions.

3.9.2 Drivers and enablers for adopting resiliently disseminated time

Increasing GNSS interference

The escalating incidents of GNSS interference underscore the urgent need for resiliency in airborne applications. Airbus Flight Data Monitoring reported a staggering increase, with almost 50,000 incidents of GNSS outage in 2022, a significant rise from approximately 11,000 incidents recorded in the previous year[208]. This surge in disruptions highlights the growing vulnerability of aircraft systems to external interference. Contributing to this challenge is the increasing availability of jamming and spoofing devices and other technologies capable of disrupting GNSS signals. Such devices are becoming more widely accessible, posing a heightened risk, particularly in conflict zones and regions where geopolitical tensions prevail[209]. For airlines operating in these areas, GNSS interference has become a pressing concern, potentially compromising flight safety and operational integrity. Disruption of GNSS signals can lead to disorientation, causing aircraft to deviate from their intended flight paths. This disruption could result in aircraft becoming lost, running out of fuel, or inadvertently entering prohibited airspace, posing significant risks to both passengers and crew[210]. A resiliently disseminated time service can provide an alternative to GNSS-based timing by ensuring in the event of GNSS disruption the aircraft's systems remain accurately synchronised.

Increasing levels of air traffic

As air traffic gradually rebounds from the impact of the pandemic, industry forecasts predict a full recovery by 2025, with continued growth projected into the next decade[211]. With airspace density increasing, airlines and air traffic management systems will be under greater pressure to optimise flight paths and minimise delays. 4D navigation, which incorporates time as the fourth dimension alongside latitude, longitude, and altitude, has emerged as a critical strategy for optimising flight trajectories, reducing fuel burn, ATC charges, and improving airspace efficiency[212].

The implementation of Automatic Dependent Surveillance-Contract (ADS-C) Extended Projected Profile (EPP) is set to further enhance air traffic management capabilities, with the European Union mandating its adoption on newly delivered aircraft and ground control systems by 2028[213]. ADS-C is a surveillance technology where an aircraft automatically transmits its position, velocity, and other relevant data to air traffic control (ATC) at predetermined intervals or based on specific events. The Extended Projected Profile (EPP) is an enhancement to ADS-C that includes additional information about the aircraft's predicted future trajectory, needed for effective 4D navigation. ADS-C EPP relies heavily on precise timing information to facilitate efficient communication and coordination

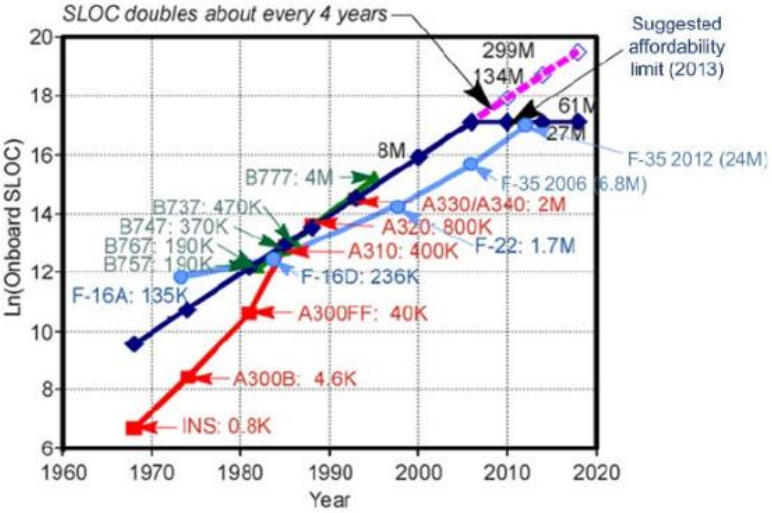
[208] Garcia, M. (2024). FAA Tells Pilots To Go Analogue As GNSS 'Spoofing' Incidents Increase. [online] Forbes. Available at: https://www.forbes.com/sites/marisagarcia/2024/02/03/faa-tells-pilots-to-go-analogue-as-gnss-spoofing-incidents-increase/ [Accessed 16 May 2024].
[209] Financial Times (2024). How GPS warfare is playing havoc with civilian life. [online] Available at: https://www.ft.com/content/be9393db-cd63-4141-a4c8-c16b4fe1b6b0 [Accessed 16 May 2024].
[210] GPS World. (2023). Increasing GNSS interference: UK and EU warn aviation. [online] Available at: https://www.gpsworld.com/increasing-gnss-interference-uk-and-eu-warn-aviation/.
[211] EUROCONTROL. (2024). Forecast Update 2024-2030 Available at: https://www.eurocontrol.int/sites/default/files/2024-02/eurocontrol-seven-year-forecast-2024-2030-february-2024.pdf.
[212] Rosenow, J., Fricke, H., Luchkova, T. and Schultz, M. (2019). Impact of optimised trajectories on air traffic flow management. The Aeronautical Journal, [online] 123(1260), pp.157–173. doi:https://doi.org/10.1017/aer.2018.155.
[213] EUROCONTROL STAKEHOLDER FORUM Q&A SESSION TECHNICAL WEBINAR ON THE USE OF AUTOMATIC DEPENDENT SURVEILLANCE-CONTRACT (ADS-C). Available at: https://www.eurocontrol.int/sites/default/files/2022-11/esf-ads-c-q-and-a.pdf [Accessed 16 May 2024].

between aircraft and ground control, underscoring the growing reliance on accurate timing in modern aviation operations. This may drive demand for a resiliently disseminated time service.

Increasing levels of complexity in airborne technologies

The aviation industry has consistently shown an increasing demand for enhanced onboard functionalities. This demand is driven by the need for safety enhancements, performance improvements, and addressing security issues. Observing cockpit panels across different generations of aircraft reveals a significant increase in resources available to pilots. Today, the true extent of this complexity is largely hidden within the onboard computers. Modern aircraft systems are increasingly reliant on software and interconnected systems. The figure below illustrates this trend in aviation, with the y-axis displaying the natural logarithm of software lines of code (SLOC) for various aircraft[214]. It includes data for Boeing and Airbus planes, as well as US military fighters, dating back to 1965.

Figure 77 Growth in software complexity onboard aircraft



Source: Butt, Nathan. (2018). Development and Thermal Management of A Dynamically Efficient, Transient High Energy Pulse System Model. 10.13140/RG.2.2.30814.13123.

Driven by digitisation and increased automation, the newest generation of aircraft collect exponentially more data, with each flight generating over 30 times the amount of data the previous generation of aircraft produced[215]. High-bandwidth and low latency communications are necessary to handle the vast amounts of data generated by modern avionics, sensors, communications, and entertainment systems, all of which rely on on-board networks for data transfer. As avionics systems become more complex, the demand for supporting networks capable of handling increasing data bandwidth will also rise[216]. Avionics network protocols rely on time synchronisation for various functions, such as data correlation from multiple sensors and event sequencing, ensuring the efficient and accurate functioning of onboard systems. A resiliently disseminated time service would

[214] Butt, Nathan. (2018). Development and Thermal Management of A Dynamically Efficient, Transient High Energy Pulse System Model. 10.13140/RG.2.2.30814.13123.

[215] Bouchard, J. and Murray, G. Connected Aircraft. [online] www.oliverwyman.com. Available at: https://www.oliverwyman.com/our-expertise/insights/2017/jun/aviation-s-data-science-revolution.html.

[216] Avionics Interface Technologies — A Teradyne Company. On-board / Flight Test Applications. [online] Available at: https://aviftech.com/onboard-and-flight-test-2/ [Accessed 17 May 2024].

provide value in ensuring that these systems can maintain synchronisation and operate reliably even in the presence of GNSS disruptions.

3.9.3 Blockers for adopting resiliently disseminated time

Redundancy of onboard navigation systems

Modern aircraft are equipped with multiple layers of backup systems to ensure continuous and reliable operation. These systems are designed to take over in the event of primary system failures, providing pilots with the necessary tools to maintain control and safely navigate the aircraft to a landing. This inherent redundancy ensures that even with a disruption of GNSS signals, aircraft can still maintain a safe level of control and navigation, which could reduce the immediate need for external time services.

Airborne navigation devices such as Inertial Navigation Systems (INS) use accelerometers and gyroscopes to calculate the aircraft’s position, orientation, and velocity without the need for external references. The INS is initially provided position and velocity information from other sources, such as a GNSS receiver, and thereafter computes its own updated position and velocity. However, purely relying on inertial position information may not provide sufficient accuracy to meet the required navigation performance (RNP) standards over extended periods.

Additionally, there are other layered safety nets that facilitate navigation independent of GNSS, in the form of navigation aids such as Very High Frequency Omnidirectional Range (VOR), Distance Measuring Equipment (DME) and Instrument Landing System (ILS). However this is dependent on the infrastructure available at airports.

Airlines and operators may weigh the cost of implementing an additional resilient time service against the already high reliability of existing redundant systems and may find it difficult to justify the additional expense.

Limitations of a “timing only” service in airborne applications

In scenarios where Global Navigation Satellite System (GNSS) signals are lost or compromised, access to time signals from alternative sources can indeed be valuable. However, it's important to recognise that these alternative signals do not offer a complete substitution for GNSS. While they can provide timing information, they may not offer comprehensive situational awareness, particularly in terms of external position data.

Relying solely on alternative time signals may not provide the level of situational awareness necessary for safe navigation, especially in complex airspace environments. An ideal solution to address GNSS disruptions is an Alternative Positioning, Navigation, and Timing (A-PNT) system. A-PNT solutions encompass all aspects of PNT, offering not only accurate timing signals but also reliable positioning data and navigation guidance.

Given the critical importance of comprehensive PNT solutions for safe and effective navigation, the willingness to pay for a resiliently disseminated timing solution is expected to be limited. Air vehicle operators may prioritise investing in A-PNT solutions that offer a more holistic approach to addressing GNSS disruptions and ensuring operational resilience.

Aviation safety critical factor

Ensuring safety remains the foremost priority within airborne systems, necessitating rigorous adherence to established standards when introducing new technologies or services. Stringent acceptance criteria are thus essential to guarantee that resiliently disseminated time services uphold the aviation industry's robust safety standards. This steadfast commitment to safety often translates to a cautious approach in integrating innovations within airborne systems, leading to a gradual uptake of new technologies[217].

Given the complex and interconnected nature of airborne systems, any modifications or enhancements undergo thorough testing and validation processes to pre-empt any potential unintended consequences or vulnerabilities. This meticulous validation process, coupled with the imperative to meet stringent safety benchmarks, can considerably lengthen the timeframe for the integration of new time services into airborne systems.

While a resiliently disseminated time service holds promise for bolstering the reliability and resilience of airborne operations, its adoption may encounter hurdles due to the stringent safety requisites and the imperative for compatibility with existing systems.

3.9.4 Market sizing methodology

As discussed, there are five segments of airspace users: airlines, general aviation, defence, emergency services and drones. Each segment has different requirements and by extension, varying willingness to pay for resilient time. From research and stakeholder engagement, the segment with the greatest potential was determined to be emergency services. The rationale for this selection was:

1) **High criticality and urgency of the use case**: The impact of the emergency services not flying these missions would be high which would extend to a higher willingness to pay for time.
2) **High dependency on time**: Emergency services use time to support their air-ground communications – with the current solution being highly dependent on GNSS.

The other segments were ruled out for varying reasons. First, due to the timeframe under consideration (until 2030) the drone segment is not expected to represent a significant market by that time whose need for time is yet to be validated. Second, with operational service life of over 30 years for most aircraft, the limited value of just time services and stringent regulations on new technology, it is assumed that airlines and general aviation would have negligible willingness to pay. Finally, defence use cases are out of scope of this study.

Market sizing methodology

Within the emergency services subsegment, there are three types of emergency services users: air ambulance, coastguard, and police (the UK fire brigade does not have its own aerial firefighting capabilities[218]). The methodology for assessing the air ambulance and coastguard user markets is similar, whereas the method for sizing the police user market differs due to variations in modelling the value of a resiliently disseminated timing service. To derive a TAM for the emergency services market, these three user markets are summated. User requirements for the emergency services

[217] Connectskies. (2020). Innovation Versus Safety – A Necessary Conflict? [online] Available at: https://connectskies.com/innovation-versus-safety-a-necessary-conflict/ [Accessed 17 May 2024].
[218] Royal Aeronautical Society. A burning issue - does the UK need aerial firefighting aircraft? [online] Available at: https://www.aerosociety.com/news/a-burning-issue-does-the-uk-need-aerial-firefighting-aircraft/.

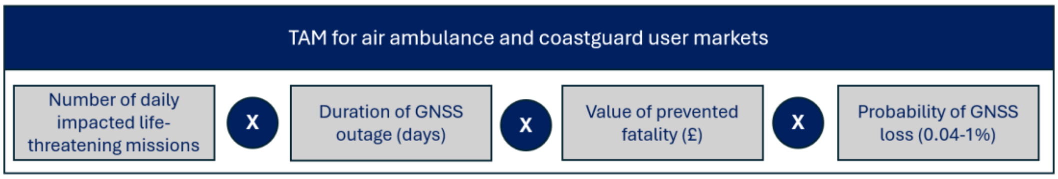
market are assumed to be equivalent to carry out time division duplex (TDD) for ground to air communications, without which the ability to carry out missions would be degraded.

Air ambulance and coastguard

The number of missions flown per year by air ambulance and coastguard aviation units is identified through online sources[219,220], and converted into an average daily value. It is assumed that a proportion of these missions respond to incidents where the patient's life is at immediate risk, estimated at 50%, based on data provided by an air ambulance unit[221]. A subset of these life-threatening missions is presumed to be significantly affected by GNSS outages, rendering the aviation units unable to reach the designated mission sites. This percentage is factored into low, central, and high scenarios to accommodate varying levels of uncertainty, with estimates set at 20%, 50%, and 80% respectively.

The number of missions affected by GNSS outages per day is multiplied by the duration of the outage, assumed to be two days for this analysis. This figure is then combined with the £1.8 million value of a prevented fatality in the UK and the annualised probability of GNSS outage in low (0.04%), central (0.2%), and high (1%) scenarios from the national risk register to calculate a range for the TAM.

Figure 78 TAM approach for air ambulance and coastguard user markets



Forward projections for the TAM are forecast by estimating the growth in the number of missions, using population growth as a benchmark, estimated at 9%[222].

Police

The TAM for police aviation units is determined by assessing both operational expenses (OPEX) and annualised capital expenditures (CAPEX) allocated to their aviation operations. Information regarding police budget allocations is taken directly from the National Police Air Service (NPAS) financial statements[223]. Additionally, data on the number of helicopters and fixed-wing aircraft in their fleet[224], their respective costs[225], and average lifetimes are identified to calculate the annualised CAPEX. A proportion of the summated OPEX and CAPEX costs are assumed to be assigned

219 Air Ambulances UK. The UK's Air Ambulance Charities. [online] Available at: https://www.airambulancesuk.org/the-uks-air-ambulance-charities

220 Office of National Statistics. Search and Rescue Helicopter Statistics: Year ending March 2023. [online] Available at: https://www.gov.uk/government/statistics/search-and-rescue-helicopter-annual-statistics-year-ending-march-2023/search-and-rescue-helicopter-statistics-year-ending-march-2023

221 Biddle, R. (2024). Record Breaking 2023 Mission Statistics Revealed for Devon Air Ambulance. [online] Air Ambulances UK. Available at: https://www.airambulancesuk.org/2023-mission-statistics-for-daa/

222 Cangiano, A. (2023). The Impact of Migration on UK Population Growth - Migration Observatory. [online] Migration Observatory. Available at: https://migrationobservatory.ox.ac.uk/resources/briefings/the-impact-of-migration-on-uk-population-growth/.

223 National Police Air Service. Financial statements | National Police Air Service. [online] Available at: https://www.npas.police.uk/about-us/financial-statements

224 National Police Air Service. Annual Report 2022/23 | National Police Air Service. [online] Available at: https://www.npas.police.uk/about-us/annual-report-202223.

225 Police helicopter contract to be extended in options study. (2014). BBC News. [online] 26 Feb. Available at: https://www.bbc.co.uk/news/uk-scotland-26360018.

to timing related expenditures in a low, central, and high scenario to determine the TAM for a resiliently disseminated timing service in the police user segment. The forecast of each scenario up to 2030 is modelled using population growth (9%) as a proxy.

Table 40 UK police aviation units financial summary

Market modelling parameter	Value
National Police Air Service annual budget	£43.9m
Number of police helicopters	19
Number of police fixed wing aircraft	4
Cost per helicopter (2024 value)	£8.4m
Cost per fixed wing (2024 value)	£2.7m
Average lifetime helicopter	15
Average lifetime fixed wing	30
Annualised CAPEX per helicopter	£563k
Annualised CAPEX per fixed wing	£89k
Total annual spend (OPEX and CAPEX)	£55m
Proportion spent on maintaining time onboard (low/central/high)	0.5%/1%/1.5%

***Source:** National Police Air Service. Financial statements | National Police Air Service. [online] Available at: https://www.npas.police.uk/about-us/financial-statements; National Police Air Service. Annual Report 2022/23 | National Police Air Service. [online] Available at: https://www.npas.police.uk/about-us/annual-report-202223; Police helicopter contract to be extended in options study. (2014). BBC News. [online] 26 Feb. Available at: https://www.bbc.co.uk/news/uk-scotland-26360018.*

EU market sizing

The TAM results for the UK emergency services are mapped to the EU using population figures as a scaler.

3.9.5 Market sizing results

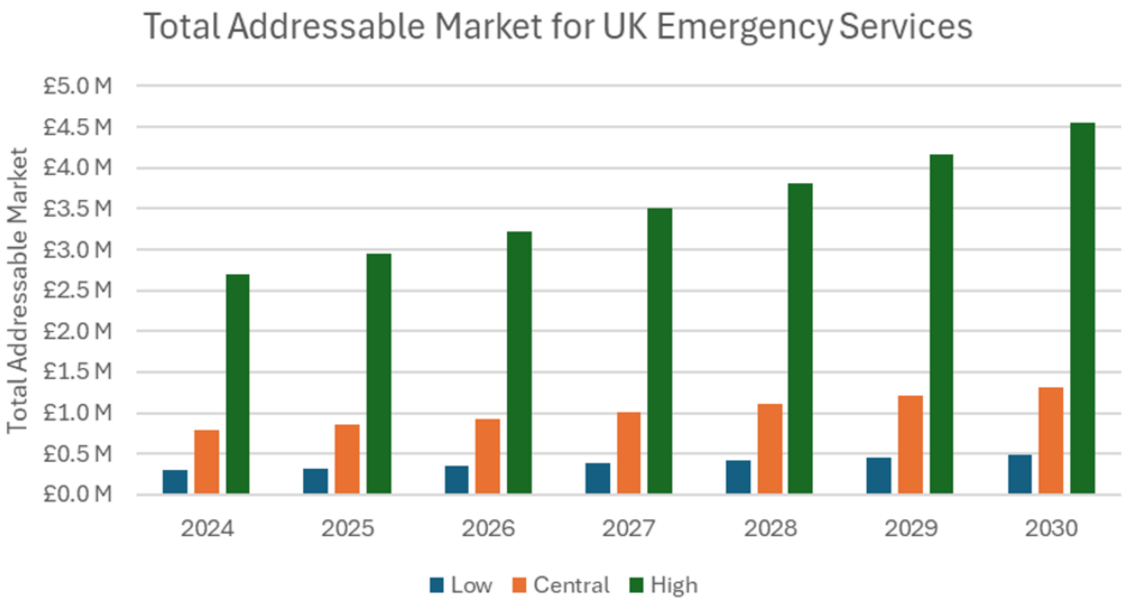
UK market

In the central scenario, the TAM for emergency services in the UK is currently valued at approximately £783 thousand and is projected to reach £1.3 million in 2030.

Table 41 Range of TAM estimates for emergency services market in UK (2024-2030)

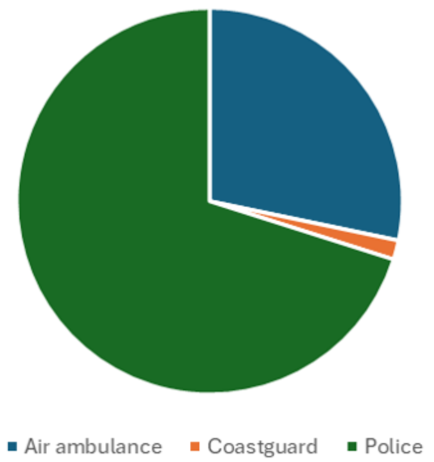
Scenario	2024	2025	2026	2027	2028	2029	2030
Low	£293k	£320k	£349k	£380k	£414k	£451k	£492k
Central	£783k	£854k	£932k	£1,015k	£1,106k	£1,207k	£1,317k
High	£2,696k	£2,943k	£3,211k	£3,501k	£3,813k	£4,162k	£4,550k

Figure 79 Total addressable market for in the UK for emergency services over different scenarios



The chart below illustrates the distribution of annual revenue among the emergency services end users. The police user market constitutes approximately 70% of the annual revenue, while the air ambulance accounts for 28%, and the coastguard for 2%.

Figure 80 TAM market split by emergency service user



This disparity can be attributed to several factors:

- **Budget differences:** The annual police budget for operations is larger than that of the air ambulance, with an annual funding of £44 million compared to £33 million[226] . This larger budget provides the police with more disposable capital to invest in a resiliently disseminated timing service.

[226] Charity Commission. THE AIR AMBULANCE SERVICE - Charity 1098874. [online] Available at: https://register-of-charities.charitycommission.gov.uk/charity-search/-/charity-details/4000782/charity-overview

- **Mission complexity:** Police aviation missions may involve sophisticated tasks, such as thermal imaging and surveillance operations, which require advanced technology and specialised personnel. This increases the value placed on accurate timing services to ensure mission success and operational efficiency.
- **Frequency of missions:** The number of missions flown annually by the coastguard is substantially lower (2,580 missions) compared to both the air ambulance (45,000 missions) and police (15,000 missions). Consequently, the coastguard has a reduced need and willingness to pay for a resilient timing service due to their lower operational tempo.

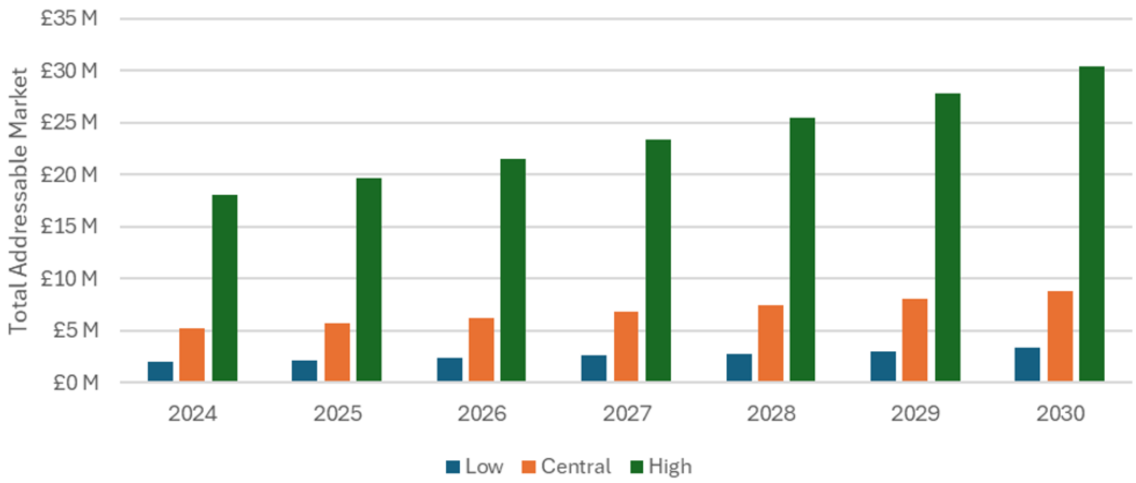
EU market

In the central scenario, the TAM for emergency services in the EU is currently valued at approximately £5.2 million and is projected to reach £8.8 million in 2030.

Table 42 Range of TAM estimates for emergency services market in the EU (2024-2030)

Scenario	2024	2025	2026	2027	2028	2029	2030
Low	£293k	£320k	£349k	£380k	£414k	£451k	£492k
Central	£783k	£854k	£932k	£1,015k	£1,106k	£1,207k	£1,317k
High	£2,696k	£2,943k	£3,211k	£3,501k	£3,813k	£4,162k	£4,550k

Figure 81 Total addressable market in the EU for emergency services over different scenarios



3.9.6 Conclusions

- Accurate timing is **integral across various applications** within the aviation sector, from navigation and communication to operational efficiency and safety protocols. It supports synchronisation of systems, flight planning, and air traffic management.
- The aviation sector faces **escalating threats from GNSS interference**, which can disrupt navigation and communication systems. Additionally, **growing levels of air traffic** increase the demand for precise timing to ensure safe and efficient airspace management. Accurate timing becomes even more crucial to mitigate these challenges and maintain operational integrity.
- Despite the importance of accurate timing, aviation actors may choose to prioritise technologies that offer **comprehensive Positioning, Navigation, and Timing (PNT)** capabilities. This preference stems from the need for integrated solutions that enhance overall situational awareness and flight safety, rather than investing in standalone timing services.

- Given the **timelines under consideration** in this study, the market sizing exercise focused specifically on the emergency services segment of the aviation sector. This segment includes air ambulance, coastguard, and police aviation units.
- Timing is critical to ensure **that emergency services communications systems are synchronised**, enabling the transfer of critical mission data while ensuring reliable and efficient operations.
- The estimated size of the TAM for resiliently disseminated time in the UK emergency services sector is currently valued at approximately **£783k** and is projected to reach **£1.3m** in 2030.
- The estimated size of the TAM for resiliently disseminated time in the EU emergency services sector is currently valued at approximately **£5.2 million** and is projected to reach **£8.8 million** in 2030.

3.10 UC10: Data centres (Ecommerce)

Data centres can be defined as physical facilities that organisations use to house their critical applications and data. Its primary purpose is to store, process, manage, and disseminate large amounts of data and information for organisations and businesses.[227] Data centres are designed to handle high volumes of data and traffic with minimum latency. A data centre typically houses computing systems and components such as servers, storage systems, networking equipment, which provide:

- *Network infrastructure* to connect servers (physical and virtualised), data centre services, storage, and external connectivity to end-user locations,
- *Storage infrastructure* to hold valuable data and information, and
- *Computing resources* to provide the processing, memory, local storage, and network connectivity that drive applications.

The main types of data centres are:

- **Enterprise/on-premises data centres**: These are built, owned, and operated by companies for their own internal use and are often housed on the corporate campus. These data centres give organisations more control over their infrastructure but require higher initial investments and ongoing maintenance.
- **Managed services data centres**: These data centres are managed by a third party ("managed services provider") on behalf of a company. The company leases the equipment and infrastructure instead of buying it.
- **Colocation data centres**: In colocation ("colo") data centres, a company rents space within a data centre owned by others and located off company premises. The colocation data centre hosts the infrastructure: building, cooling, bandwidth, security, etc., while the company provides and manages the components, including servers, storage, and firewalls.
- **Cloud data centres:** In this off-premises form of data centre, data and applications are hosted by a cloud services provider such as Amazon Web Services (AWS), Microsoft (Azure), or IBM Cloud. Cloud data centres offer scalable resources and services on a pay-as-you-go model.
- **Edge Data Centres**: A smaller data centre that is as close to the end user as possible. Instead of having one massive data centre, businesses may have multiple smaller ones to minimize

[227] Cisco (n.d.) What is a Data Centre. [Accessed online: https://www.cisco.com/c/en_uk/solutions/data-center-virtualization/what-is-a-data-center.html#~infrastructure-evolution]

latency and lag. These are more common with IoT devices and low-latency data demands are high.

3.10.1 Use of time

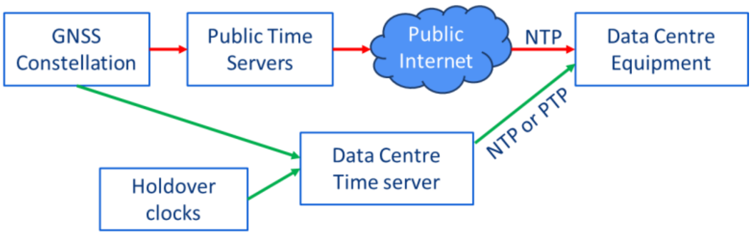
Accurate time synchronisation is key for log keeping, event sequencing, and ensuring consistent operations across distributed systems. The role of time in data centres has greatly evolved over the years, driven by the rise of distributed systems, edge computing, financial transactions, and real-time applications, all requiring precise timing for optimal operation.

How do data centres get time?

Data centres rely on external time sources and synchronisation mechanisms to ensure accurate timekeeping across their systems and devices. Common external time sources used by data centres to acquire Coordinated Universal Time (UTC) are via the internet using publicly available Network Time Protocol (NTP) time servers and via satellite using GPS or other GNSS networks. Time servers in data centres receive UTC from one of these external time sources, and are then responsible for propagating that time through the data centre network. This is typically done using network-based standards such as Network Time Protocol (NTP) and Precision Time Protocol (PTP). These protocols ensure that time is synchronised between all servers within a network.

While timing through public NTP timeservers over the internet was common during early deployment of distributed databases, inherent performance, traceability, and security issues have created the push to move away from this solution.[228] These public time servers are typically maintained by volunteers, and as such provide no guarantee of availability or accuracy. It is generally recommended that organisations requiring an accurate and reliable source of time, should consider installing a local time reference that relies on GNSS.[229]

Figure 82 How do data centres source time?



Source: LE Analysis

Because GNSS signals are vulnerable to events such as solar storms and jamming, backup clocks are deployed in individual data centres to preserve synchronization when the transmitted time is not available. Caesium and Rubidium-based clocks are commonly used as backup clocks. Caesium atomic clocks are widely used due to their stability and accuracy while rubidium clocks are smaller and less expensive but have a shorter holdover duration.

[228] GPS World (2022) The role of atomic clocks in data centres. Available at: https://www.gpsworld.com/the-role-of-atomic-clocks-in-data-centers/

[229] NTP Pool Project (2024) How do I use pool.ntp.org? Available at: https://www.ntppool.org/en/use.html

Why is time important?

Time is used for correlating and ordering simultaneous events between millions of servers.[230] Time differences of even just a couple of milliseconds can cause serious issues. Accurate time within data centres produces the following benefits:

- **Reduced Packet Loss**: Packet loss occurs when one or more packets of data travelling across a computer network fail to reach their destination. In real-time applications like video and audio streaming, packet loss can affect user experience. By providing a more accurate reference time, devices in the network can synchronise more effectively, leading to fewer errors and packet loss.[231]
- **Improved Network Performance**: Accurate and precise time synchronisation is crucial for applications that rely on the coordination of data and processes across devices and systems (such as industrial IoT networks). With better synchronisation and reduced packet loss, the overall performance of the network can improve. This can lead to faster and more reliable data transfer rates, lower latency, and higher network reliability.[232]
- **Reduce the number of data replicas**: When tasks are distributed across geographically distant nodes, each task or data exchange between nodes requires communication over networks, and the physical distance between nodes introduces latency in these communications. To overcome latency challenges, strategies such as database replication near users are employed. By creating local replicas of the database, users can interact with data without the need for cross-country communication for every transaction. Periodically, the replications are compared and reconciled to ensure consistency. During the reconciliation process, the transaction timestamps are used to determine the actual sequence of transactions, and records are sometimes rolled back when there is an irreconcilable difference such as when the transaction time-envelopes overlap. Reducing clock uncertainty reduces the number of irreconcilable differences in replicated instances, as more time-envelopes reduce the probability of overlaps. This results in higher efficiencies and lower probabilities of data corruptions.[233]
- **Security**: Clock synchronisation is critical for implementing secure communication protocols. In 2014 the bitcoin exchange Mt Gox was attacked, resulting in $450 million worth of bitcoins being stolen. The attackers used a range of techniques including NTP hijacking to gain control of NTP servers to send malicious time information allowing them to manipulate the trading system.[234] Accurate timestamping of events can provide a mechanism for detecting and mitigating cyber-attacks.[235, 236]
- **Increased visibility and troubleshooting**: Latency measurement, facilitated by precise timing, helps identify bottlenecks in a system. This information can be used to optimise performance

[230] ITU (2023) Time synchronization in data centres. [accessed online: https://www.itu.int/hub/2023/06/time-synchronization-in-data-centres/]
[231] Faster Capital (n.d.) The Benefits Of Precision Timestamping In Ptp Networks. [Accessed online: https://fastercapital.com/topics/the-benefits-of-precision-timestamping-in-ptp-networks.html]
[232] Balakrishnan, K., Dhanalakshmi, R., Sinha, B. B., & Gopalakrishnan, R. (2023). Clock synchronization in industrial Internet of Things and potential works in precision time protocol: Review, challenges and future directions. International Journal of Cognitive Computing in Engineering.
[233] GPS World (2022) The role of atomic clocks in data centres. Available at: https://www.gpsworld.com/the-role-of-atomic-clocks-in-data-centers/
[234] Dhami, I. (2024) Inception's Timely Reminder of Cyber Resilience. [Available at: https://www.thedigitaltransformationpeople.com/channels/cyber-security/inceptions-timely-reminder-of-cyber-resilience/]
[235] Balakrishnan, K., Dhanalakshmi, R., Sinha, B. B., & Gopalakrishnan, R. (2023). Clock synchronization in industrial Internet of Things and potential works in precision time protocol: Review, challenges and future directions. International Journal of Cognitive Computing in Engineering
[236] Cloudflare (2019) Introducing time.cloudflare.com [accessed online: https://blog.cloudflare.com/secure-time/]

and improve overall system responsiveness. Precise time also enables accurate sequencing of events, which is crucial for troubleshooting, auditing, and ensuring the correctness of system operations.

- **Compliance**: Many industries and applications require compliance with specific regulations and standards. For example, **SMPTE ST 2059-2** standard for Professional Broadcast Applications requires synchronisation of 1 microsecond[237], and **MiFID II** requires 1 millisecond for automated trading and 100 microseconds for high frequency trading in financial services.

3.10.2 User requirements

If a data centre is not synchronised, it could severely impact the ability of companies to carry out operations. **Operations failure** occurs when automated events, like data backups or order processing, break or fail to occur due to improper sequencing. **Data loss** happens when system software erroneously saves outdated versions of files. **Security holes** emerge, both directly and indirectly, from poor timekeeping, such as vulnerabilities introduced by NTP or inaccurate log files that hinder security monitoring. **Legal liability** issues arise because it is impossible to verify the timing of transactions or the authenticity of digital signatures, leading to disputes. Finally, **loss of credibility** results when the inability to maintain synchronised operations undermines confidence in the organisation's overall business processes and audit integrity.

Data centres typically provide computer storage and processing functions for various applications such as managing databases, optimising search functions, delivering real-time content and providing faster responses to users. However, to enable the applications to perform the required functions, the accuracy of synchronisation needed between data centres is in the **order of milliseconds**. This means that while synchronisation is important for optimal performance, the primary focus for most industries is on the reliability of data transfer rather than strict timing constraints. The exceptions to this are data centres for industries such as Telecommunications and Financial industry which are covered in Use Cases 1, 2, 3, and 4.

3.10.3 Drivers and enablers for adopting resiliently disseminated time

Regulation/standards requirements

Industries and applications are increasingly requiring companies to comply with specific timing regulations and standards. For example, the **SMPTE ST 2059-2** standard for Professional Broadcast Applications requires synchronisation of 1 microsecond[238], and **MiFID II** requires 1 millisecond for automated trading and 100 microseconds for high frequency trading in financial services.[239]

Rise in AI, distributed systems

Latency is the delay between the moment data is sent and the moment it is received. It is a critical factor in the performance of applications requiring real-time or near-real-time processing and response. Latency can be minimised by reducing the distance that data has to travel to end users. This is one of the reasons why many global enterprises are increasingly turning to distributed digital

[237] Calnex (2019) SMPTE ST 2059-2: Synchronizing Professional Broadcast Networks. Available at: https://theiabm.org/wp-content/uploads/2019/12/Calnex-Whitepaper-Synchronizing-Professional-Broadcast-Networks.pdf

[238] Calnex (2019) SMPTE ST 2059-2: Synchronizing Professional Broadcast Networks. Available at: https://theiabm.org/wp-content/uploads/2019/12/Calnex-Whitepaper-Synchronizing-Professional-Broadcast-Networks.pdf

[239] Safran (2023) time synchronization: time is at the heart of MiFID regulation. Available at: https://safran-navigation-timing.com/time-synchronization-time-is-at-the-heart-of-mifid-regulation/.

infrastructure.[240] By replacing their traditional infrastructure, where all data traffic has to pass through a centralised data centre, organisations can decrease the distance their data has to travel, while also taking advantage of the performance benefits of interconnection (see Figure 83). However, this requires all data centres to have access to an accurate time source in order for them to be synchronised.

Figure 83 Reducing latency through distributed systems

Source: Equinix (2023) What is Latency, and How Can You Address It? https://blog.equinix.com/blog/2023/03/01/what-is-latency-and-how-can-you-address-it/

AI applications involve the execution of numerous parallel tasks or jobs running simultaneously. Precise timing and time synchronisation is essential to manage and coordinate these parallel processes effectively, and becomes even more critical as the scale and complexity of AI models continue to expand.[241]

By 2027, it is projected that global capital expenditures (CAPEX) on data centres specifically for supporting AI workloads will reach an estimated $500 billion.[242] This massive investment reflects the increasing demand for computational resources, storage capacity, and infrastructure optimisation to accommodate AI-driven workloads. Major technology companies are allocating a significant portion of their digital infrastructure investment towards AI-related initiatives. For example, in 2023, Microsoft dedicated 13.3% of its total digital infrastructure CAPEX towards AI projects.

Real consequences of loss in time

Timing failures in data centres can have significant real-world consequences, impacting operations, data integrity, and even financial stability. For instance, when GPS signals experience disruptions or outages, data centres may struggle to maintain accurate time across their systems. This can lead to synchronisation errors, data inconsistencies, and disruptions to critical operations such as financial transactions, network communications, and system logging. Similarly, failure to account for leap seconds, which adjust Coordinated Universal Time (UTC) to account for irregularities in the Earth's rotation, can result in time drifts that affect the timing of events and the reliability of timestamped data. Such timing failures not only compromise the integrity and reliability of data centre operations but can also have broader implications for industries reliant on precise timekeeping, including finance, telecommunications, and transportation. Therefore, ensuring resilient time synchronisation mechanisms and strategies is essential for mitigating the risks associated with

[240] Equinix (2023) What is Latency, and How Can You Address It? https://blog.equinix.com/blog/2023/03/01/what-is-latency-and-how-can-you-address-it/
[241] Forbes (2024) The Role Of Precision Timing In The AI Revolution. Available at: https://www.forbes.com/sites/forbestechcouncil/2024/01/11/the-role-of-precision-timing-in-the-ai-revolution/
[242] Spirent Connect Forum (30 April 2024)

timing failures in data centres. Figure 84 provides two examples of where timing errors such as these made headlines.

The first article describes a 12 hour outage for a telecoms company after 15 GPS satellites broadcasted the wrong time. The GPS time signals were **13 microseconds** out. According to the Resilient Navigation and Timing Foundation (RNTFnd), this issue had only minor impacts on infrastructure sectors. Much larger impacts may be felt by industries when timing is out by relatively longer time periods. The article on the right describes how Reddit experienced a few hours of downtime after failing to anticipate a leap second in 2012.

Figure 84 Inaccurate timing can lead to serious consequences for companies


GPS error caused '12 hours of problems' for companies
4 February 2016

Source: BBC (2016) GPS error caused '12 hours of problems' for companies. ***https://www.bbc.co.uk/news/technology-35491962***


Leap second and storm disrupt weekend web services
2 July 2012
What is a leap second? The BBC's Rebecca Morelle went to Greenwich's Royal Observatory to find out

Source: BBC (2012) Leap second and storm disrupt weekend web services. ***https://www.bbc.co.uk/news/technology-18672173***

3.10.4 Blockers for adopting resiliently disseminated time

Resilient timing solutions already in market

Accurate timing and synchronisation is already addressed within many data centres through backup atomic clocks. This could be a significant blocker to adopting more resilient time dissemination strategies. In particular, data centres with critical time-sensitive operations may have multiple backup atomic clocks in place to ensure redundancy. These solutions typically cost under $5,000 and can support a network consisting of thousands of computers.[243]

For example, *OSA 3350 ePRC+* and *OSA 3350 SePRTC* are commercial optical caesium clocks developed by Oscilloquartz.[244] These clocks have been designed to ensure 100ns accuracy even over long holdovers of up to 25 days and 45 days respectively.

In 2021, Meta addressed synchronisation dependencies in distributed data centres by creating the Time Appliance, a specialised hardware device that includes a GNSS receiver and a miniaturised atomic clock (MAC) to maintain accurate time even without continuous satellite connectivity.[245] The holdover of a MAC is within 1 microsecond for 24 hours, meaning that after 24 hours, the time accuracy is nondeterministic but accurate within 1 microsecond.

[243] Microsemi (2014) Five Dangers of Poor Network Timekeeping. White paper
[244] Oscilloquartz (n.d.) OSA 3350 ePRC+ and SePRC. Available at: https://www.oscilloquartz.com/en/products-and-services/cesium-clocks/osa-3350
[245] Engineering at Meta (2021) Open-sourcing a more precise time appliance. Available at: https://engineering.fb.com/2021/08/11/open-source/time-appliance/

Additionally, they developed the Time Card, a PCIe card that can convert any standard server into a time appliance, enabling precise and reliable time synchronisation across existing infrastructure. This innovation ensures that all data centres can maintain synchronised operations, crucial for efficient data processing and interconnection. By developing these technologies, Meta removed dependencies on continuous GNSS connectivity and created a robust and flexible solution for time synchronisation in distributed digital infrastructures.

3.10.5 Market sizing methodology

It is not always clear who bears the responsibility of providing accurate time within a data centre, in particular colocation data centres.[246] Many colocation data centres will offer space and connectivity for companies to connect their own GNSS antennas, while others may include precise timing within their service offering. This makes it difficult to measure the Total Addressable Market (TAM) as it is unclear who the ultimate client for a resilient timing service may be.

This section aims to understand the Total Addressable Market (TAM) by estimating the total cost to data centres in the UK if GNSS was lost for a 2 day period and data centres no longer have access to a precise time source. It should be noted that the availability of inexpensive clocks that provide holdover over multiple days means that the impact of GNSS disruption is unlikely to have a large (if any) impact.

This case study estimates two ways in which business could be impacted by a loss of accurate timing from GNSS sources. Firstly, without access to an accurate time source internal server clocks will begin to drift apart leading to slower synchronisation and reduced efficiency of the data centre, thereby increasing energy costs. Secondly, when data centres are less synchronised, latency increases, creating a worse user-experience.

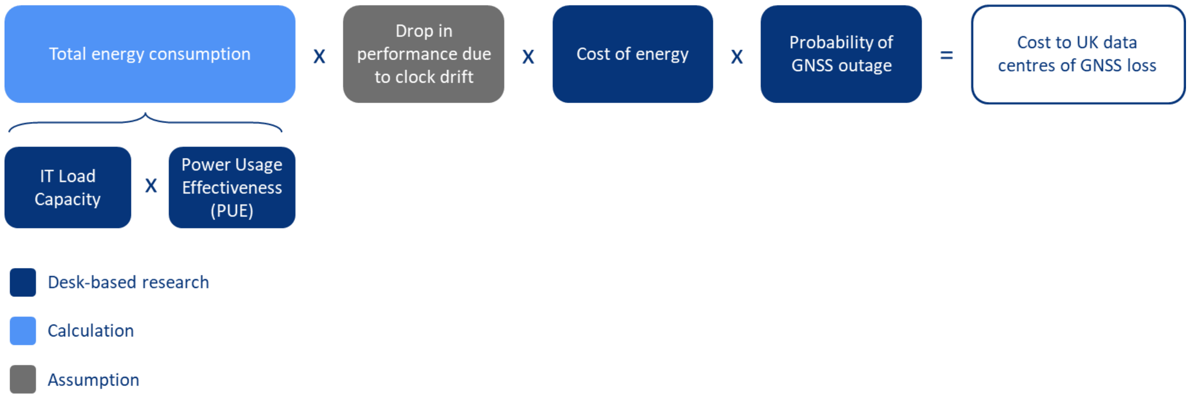
This methodology assumes (i) that a typical data centre has a holdover clock, and (ii) that holdover clocks start to drift enough to impact performance within 2 days. These assumptions have not yet been verified with industry stakeholders.

Energy consumption

After some time of GNSS loss, holdover clocks will begin to drift, and data centres will no longer be synchronised. This leads to loss of efficiency due to the inability to accurately timestamp events, which can disrupt operations, cause data inconsistencies, and impact system performance. This results in higher resource utilisation and higher energy costs. Figure 85 describes a method to calculate the cost that this decrease in system performance may have for data centres in the UK.

[246] Based on Stakeholder interview

Figure 85 Cost to UK data centres in the event of GNSS loss



Key assumption:

- A loss of GNSS would result in a drop in performance of 2% after 1 day and 5% after 2 days. This assumption will be further tested with stakeholders in Part B.

Table 43 Components of performance calculation for UK

Indicator	Value	Source
Total IT load capacity in the UK	2,190 MW	Mordor Intelligence (2024) United Kingdom Data Centre Market. Available at: https://www.mordorintelligence.com/industry-reports/united-kingdom-data-center-market
Power Usage Effectiveness	1.59	Statista (2024) What is the average annual power usage effectiveness (PUE) for your largest data centre? Available at: https://www.statista.com/statistics/1229367/data-center-average-annual-pue-worldwide/
Energy Prices	0.44 USD/kWh	Statista (2024) Household electricity prices worldwide in September 2023, by select country. Available at: https://www.statista.com/statistics/263492/electricity-prices-in-selected-countries/
Annualised probability of GNSS loss is	Low: 0.04%, Central: 0.2% High: 1%	National Risk Register (2023)
Drop in performance due to clock drift	After 1 day: 2% After 2 days: 5%	*Assumption*

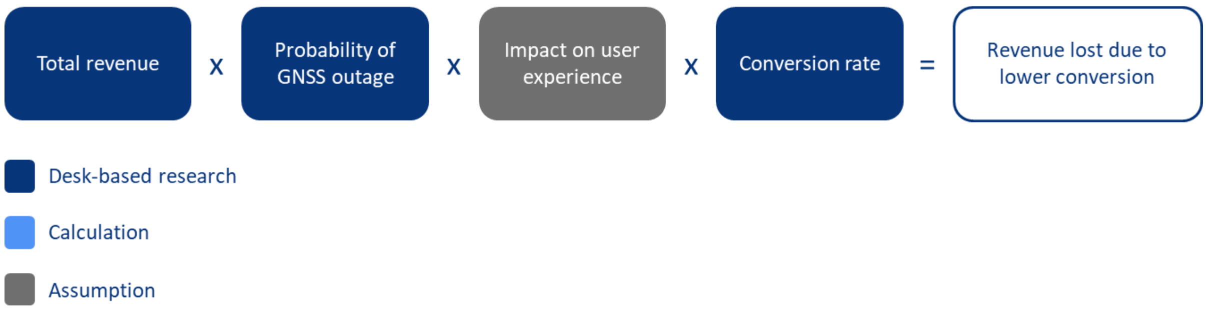
User experience in e-commerce industry

Applications are getting faster every day, and transactions that used to take a few seconds now happen within milliseconds or even microseconds. In streaming media, customer experience is defined by fast, smooth playback with flawless audio-video sync for viewers in dispersed locations. In the gaming industry, multiplayer games involving thousands of players around the world rely on coordinated, time-synced transactions for fair play.

Improving end-user experiences begins with lowering latency by ensuring the continuity and accuracy of data centre timing. In data centres, latency refers to the delay in processing and transmitting data within the data centre infrastructure. Latency directly affects the quality of user experiences, and tiny amounts of latency spread across a large user base can have significant impacts on conversion rates, and by extension on firms' revenue. Even barely perceptible interruptions to page load times (from the user perspective) result in substantial revenue losses. For example, Amazon found that every 100ms in added page load time cost them 1% in sales, and in 2006, Google found an extra 0.5 seconds in search page generation time dropped traffic by 20%.[247] Latency has even larger consequences for user experience in video watching behaviour. Data from Mux, a company that builds infrastructure for clients to stream videos, shows that just one buffering event decreases the amount of video watched by 39%.[248]

Figure 86 describes a method to calculate the revenue loss from reduced user-experience for companies in the UK.

Figure 86 Lost revenue due to reduced user-experience from GNSS loss



This calculation provides an example of how a loss of GNSS may impact the e-commerce industry in the UK. It only takes into account user-experience in e-commerce, however, user-experience in industries such as online gaming and media streaming may also be severely impacted.

Over 30% of all retail sales in the UK are e-commerce sales, and this percentage is expected to increase to almost 40% by 2025. A study by Portent (2022) which analysed e-commerce and conversion data from 20 websites and over 27,000 landing pages found that customer conversion rates drop substantially as website load pages increase. A site that loads in 1 second was found to have a conversion rate 3x higher than a site that loads in 5 seconds, and 5x higher than a site that loads in 10 seconds.[249] The study also found that over 85% of pages load in under 5 seconds, with the majority loading between 1-2 seconds.

Key assumption:

- A loss of GNSS would result in website loading times increasing by 2 seconds after 1 day and 5 seconds after 2 days, resulting in conversion rates dropping by 0.6% (0.3%*2) and 1.5% (0.3%*5) respectively.
- On average e-commerce sites load within 1-2 seconds resulting in a conversion rate of 3.05%.

[247] Linden, G. (2006) Marissa Mayer at Web 2.0. [Accessed online: https://glinden.blogspot.com/2006/11/marissa-mayer-at-web-20.html]
[248] Mux (2016) Buffering reduces video watch time by ~40%, according to research. [Accessed online: https://www.mux.com/blog/buffering-reduces-video-watch-time-by-40-according-to-research]
[249] This ratio is oddly lower than for 5 seconds, however, this is likely to be due to small sample size of websites with such low loading times.

Table 44 Components for user-experience calculation for the UK

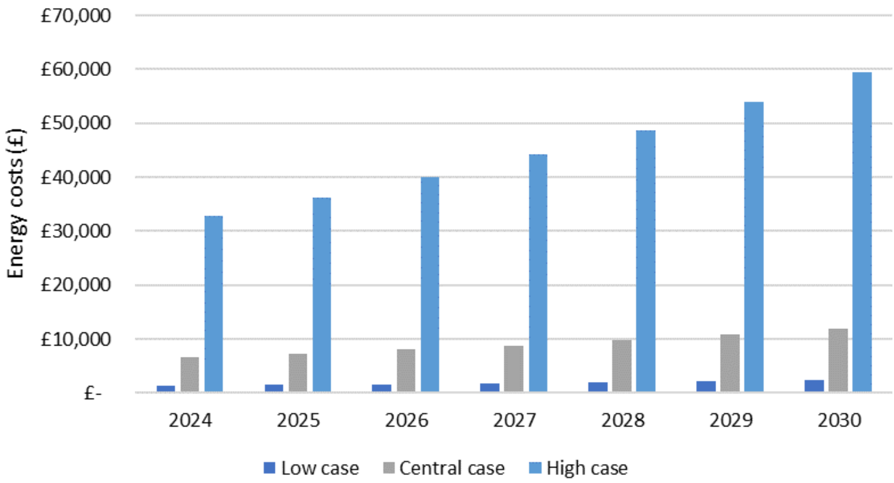
Indicator	Value	Source
e-commerce conversion rate decrease per second of lag	0.3%	Portent (2022) Site Speed is (Still) Impacting Your Conversion Rate. Available at: https://www.portent.com/blog/analytics/research-site-speed-hurting-everyones-revenue.htm
Typical conversion rate for online retailers	3.05%	Ibid.
Average daily revenue from e-commerce in the UK	£ 79.1 million	ONS (2024) Internet retail sales, £ millions. All retailing. Available at: https://www.ons.gov.uk/businessindustryandtrade/retailindustry/timeseries/je2j
Retail e-commerce sales CAGR	7%	Statista (2024) Retail e-commerce sales compound annual growth rate (CAGR) from 2024 to 2028, by country Available at: https://www.statista.com/forecasts/220177/b2c-e-commerce-sales-cagr-forecast-for-selected-countries
Impact on website load times due to clock drift	2 second increase (day 1) 5 second increase (day 2)	*Assumption*
Annualised probability of GNSS loss is	Low: 0.04%, Central: 0.2% High: 1%	National Risk Register (2023)

3.10.6 Market sizing results

Energy consumption

Over the first two days following a GNSS outage, higher energy costs lead to losses of £3.27 million. Based on the annualised probabilities of GNSS loss occurring, this results in negligible expected losses in the UK of only £1,300 in the low case, £6,500 in the central case and £32,700 in the high case. Based on the forecasted Compound Annual Growth Rate (CAGR) of data centres in the UK, this will rise to £2,400, £11,900, and £60,000 by 2030 in the low, central, and high cases respectively.

Figure 87 Energy costs in the UK as a result of reduced performance



Using similar methodology, based on energy consumption in data centres in each of the Five Eyes countries (UK, US, Canada, Australia, New Zealand), the total addressable market in these countries is estimated at a limited £10k, £52k, and £258k in the low, medium, and high cases, respectively.

Table 45 Energy costs in 5 Eyes countries due to GNSS loss

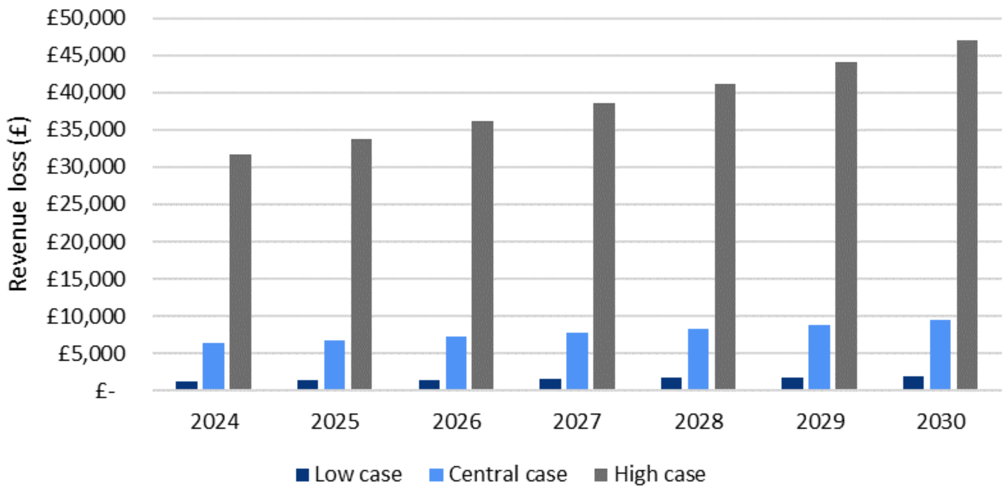
Country	Case	2024	2030
UK	Low case	£ 1,310	£ 2,383
	Central case	£ 6,548	£ 11,914
	High case	£ 32,740	£ 59,568
USA	Low case	£ 3,422	£ 6,202
	Central case	£ 17,108	£ 31,010
	High case	£ 85,542	£ 155,048
Canada	Low case	£ 112	£ 188
	Central case	£ 561	£ 939
	High case	£ 2,803	£ 4,693
Australia	Low case	£ 1,016	£ 1,433
	Central case	£ 5,080	£ 7,166
	High case	£ 25,401	£ 35,828
New Zealand	Low case	£ 43	£ 107
	Central case	£ 213	£ 533
	High case	£ 1,065	£ 2,667

Source: LE Analysis

User experience in e-commerce industry

Over the first two days following a GNSS outage, reduced conversion rates lead to e-commerce losses of £3.17 million. Based on the annualised probabilities of GNSS loss occurring, this results in expected losses in the UK of approximately £1,300 in the low case, £6,300 in the central case and £31,700 in the high case. Based on the forecasted compound annual growth rate (CAGR) of e-commerce in the UK, this will rise to £1,900, £9,400, and £47,000 by 2030 in the low, central, and high cases respectively.

Figure 88 Lost revenue in the UK e-commerce sector as a result of lower user experience



Using similar methodology, based on e-commerce in each of the Five Eyes countries (UK, US, Canada, Australia, New Zealand), the total addressable market in these countries is estimated at a limited £133k, £664k, and £3,322k in the low, medium, and high cases, respectively.

Table 46 Lost Revenue in e-commerce sector in 5 Eyes Countries

Country	Case	2024	2030
UK	Low case	£ 1,268	£ 1,884
	Central case	£ 6,339	£ 9,422
	High case	£ 31,693	£ 47,112
USA	Low case	£ 62,787	£ 122,739
	Central case	£ 313,933	£ 613,697
	High case	£ 1,569,666	£ 3,068,486
Canada	Low case	£ 1,878	£ 3,035
	Central case	£ 9,390	£ 15,176
	High case	£ 46,950	£ 75,880
Australia	Low case	£ 254	£ 468
	Central case	£ 1,271	£ 2,339
	High case	£ 6,354	£ 11,694
New Zealand	Low case	£ 2,918	£ 4,739
	Central case	£ 14,588	£ 23,696
	High case	£ 72,942	£ 118,478

Source: LE Analysis

3.10.7 Conclusions

- Accurate time synchronization is crucial for log keeping, event sequencing, and ensuring consistent operations across distributed systems.
- The importance of precise time synchronization is increasing due to the rise of distributed systems, edge computing, financial transactions, and real-time applications, all of which require exact timing for optimal performance.
- A lack of synchronization in data centres can have significant consequences for businesses, potentially leading to system failures in extreme cases.

- Given the fundamental necessity of precise timing for modern data centres, many off-the-shelf solutions are available that provide sufficient holdover during a 2-day GNSS loss. These solutions have become more cost-effective and accessible for data centre operators, offering precise timing over extended holdover periods.
- The estimated size of the TAM for resiliently disseminated time in the UK data centres sector is currently valued at approximately **£13k** and is projected to reach **£21k** in 2030.
- The estimated size of the TAM for resiliently disseminated time in Five Eyes data centre sector is currently valued at approximately **£362k** and is projected to reach **£695k** in 2030.
- The estimated size of the TAM should not imply that timing is unimportant for data centres. On the contrary, timing is so fundamental that market players have already implemented measures to prevent de-synchronization. Consequently, a 2-day GNSS outage would not significantly impact data centres, as they are prepared to handle such disruptions.

4 Use case technology mapping

This section provides a detailed analysis of the various technologies that can be utilised to meet user timing needs. Understanding the current and emerging technologies is essential to determine how a new resilient time dissemination service can be effectively positioned against existing solutions. It is therefore necessary to:

- **Identify current technologies:** Evaluate the technologies currently available in the market, their capabilities, and limitations;
- **Explore emerging technologies:** Horizon scanning of technologies under development that may offer attractive timing solutions in the future;
- **Benchmark against competing solutions:** Analyse how a new service would compare with existing solutions to identify unique selling points and value propositions.

In addition to primary technologies used to disseminate time, it is important to consider substitute solutions such as holdover clocks. These alternatives are critical in potential users' decision-making processes when determining how to meet their timing requirements who will, in general, select solutions that are the most economically affordable to meet their requirements.

The table below provides a description of the various timing solutions, their technology readiness level (TRL), along with some examples of each.

Table 47 Timing solutions

Solution category	Solution	Description	TRL	Examples
Wired time signals	Time over fibre	Time over Fibre (ToF) refers to the transmission of precise time and frequency signals over optical fibre networks. In this technology, accurate time information, often derived from atomic clocks, is encoded into optical signals and transmitted over fibre-optic cables. Time over Fibre is particularly useful in scenarios where maintaining precise synchronization between distant locations is essential. By leveraging the speed of light in optical fibres, ToF ensures minimal signal delay and enables synchronised timekeeping across distributed systems, contributing to the reliability and efficiency of applications that rely on accurate time information.	9	NTP PTP Optical Fibre (frequency transfer not data)
	White Rabbit	EEE-1588-2019 High Accuracy (HA) profile, known as White Rabbit protocol is a time & frequency distribution protocol, developed by CERN, which combines PTP packets with the frequency base of Synchronous Ethernet (SyncE) to provide sub-nanosecond time transfer accuracy. This technology is developed by commercial companies, that offer hardware and software as a Time-as-a-Service (TaaS) solution. They also offer monitoring and resilience capacity, with a focus on the seamless switchover between time sources in case of failure and the detection and raising of alarm if a time source goes out of specification, allowing for the switchover to a valid time source.	9	White Rabbit
Wireless PNT signals	eLoran	eLoran, or Enhanced Long Range Navigation, is a ground-based radio navigation system designed as a robust and resilient alternative or complement to satellite-based positioning systems like GPS. eLoran transmits pulsed ground wave signals with a central frequency of 100kHz. Signals are transmitted with high power and low frequency making the signals robust. Building upon the original Loran-C system, eLoran incorporates technological advancements to enhance signal modulation and receiver capabilities, offering improved accuracy and reliability.	9	eLoran
	Longwave time	Longwave time signals refer to radio signals transmitted at low frequencies, specifically in the longwave radio frequency band. These signals are primarily used for time synchronisation purposes, disseminating precise time information to a wide geographic area.	9	DCF77 in Germany, MSF in United Kingdom, ALS162 in France, WWVB US

Solution category	Solution	Description	TRL	Examples
	LEO-provided PNT	A dedicated navigation signal sent from LEO satellites which also provides time synchronisation. Currently, only Iridium provides such a service (STL). STL is a time of arrival multilateration system offering 3D positioning and timing using dedicated satellite signals designed by Satelles for the Iridium Satcom system. The STL signals are broadcast in the frequency band 1621.35–1626.5 MHz (uplink and downlink).	9	Satelles STL
	Pseudolites	Pseudolites are a terrestrial positioning technology that uses a network of ground-based transmitters providing a robust radio-positioning signal within a specific area. The network is synchronised on the nano-second level to provide position and time. There are two solutions – the use of precise oscillators (such as atomic clocks) or internal synchronisation (using frequency alignment).	9	Ultrawideband RF Beacons Pseudo GNSS Satellites Locata NextNav MBS
	Satellite-based augmentation systems (SBAS)	SBAS systems provide augmentation services to improve the accuracy and provide integrity to the GNSS signals. SBAS systems can also broadcast GNSS ranging signals from their Space Segment. The accuracy is enhanced through the transmission of wide-area corrections to the GNSS range errors while the integrity is ensured by quickly detecting satellite signal and ionosphere errors and sending alerts to users. SBAS systems consist of a Space Segment (geostationary satellites), Ground Segment (reference stations, master stations and uplink stations), a User Segment (user receivers processing the SBAS signals), and a Support Segment (to support the provision of the SBAS services).	9	EGNOS (EU), WAAS (US), MSAS (Japan), KASS (Korea)
Signals of opportunity	5G and mobile networks	5G and mobile networks, designed for fast and efficient communication, can be utilised as a reliable source of time. These networks use advanced technologies like millimetre-wave frequencies and synchronized architecture, allowing for the transmission of time signals with high precision.	7	UK Mobile networks
	802.1az	The new IEEE 802.11ax protocol release includes structures and protocols for positioning and timing determination, including the ability to transfer time either relative or absolute.	7	
Holdover technology	Atomic clock	Clocks incorporating caesium or rubidium oscillators, to ensure accurate timekeeping without constant synchronisation. An atomic clock measures time by monitoring the frequency of radiation of atoms. Atom's electron states have different energy levels, and in transitions between such states, they produce a very specific frequency of electromagnetic radiation. Measuring those allows for precise time and frequency readings.	9	Various manufacturers: Microsemi, Adtran, FEI, Oscilloquartz, Hopf, Meinberg, Safran, Leonardo, Exelitas, Schnieder, Brandywine, Drumgrange
	Miniature chip scale atomic clock (CSAC)	Compact, low-power consumption devices using microelectromechanical systems (MEMS) and incorporating a low-power semiconductor laser as the light source. Unlike traditional atomic clocks, CSACs are designed to fit on a chip, making them suitable for portable applications where space and weight are critical factors.	9	Microsemi CSAC Teledyne CSAC MINAC (Teledyne UK)
	Oven controlled crystal oscillator (OCXO)	The key feature of an OCXO is its internal temperature control mechanism, typically in the form of a small oven that surrounds the crystal oscillator. This oven maintains a constant temperature, mitigating the frequency variations caused by external temperature fluctuations. The crystal oscillator, usually a quartz crystal, serves as the frequency reference, and the controlled temperature environment helps minimise thermal-induced frequency drift, resulting in a highly stable and precise output signal.	9	Product line from RAKON
	Quantum clock	Quantum superposition and entanglement enable these clocks to measure time with extraordinary precision, potentially surpassing the capabilities of current atomic clocks. Quantum clocks often operate at optical frequencies, which are much higher than microwave frequencies. This higher frequency allows for more precise time measurements, meaning they may be considered as replacements for caesium atomic clocks in many terrestrial applications.	6	Tiqker MINAC NPL AFRL QuantX
	Pulsar PNT	A Pulsar is a highly magnetised and fast rotating neutron star, that emits beams of electromagnetic radiation out of its magnetic poles. As Neutron stars are very compact objects with short, regular rotational periods, the interval between pulses is very precise and ranges from milliseconds to seconds for an individual pulsar. The electromagnetic signal (in particular in the radio, optical and X bands) emitted by the pulsars can be detected by the specialised equipment and to be a source time but can also be used for navigation. The main interest of pulsars' navigation is for deep space systems and interplanetary travel.	2	N/A

Source: London Economics and Rethink PNT analysis of the European Radio Navigation Plan (2023) and various other public sources

Each solution is evaluated for its advantages and disadvantages. While it is out of scope of this project to carry out a deep technical assessment, a high-level assessment can offer an understanding of its appropriateness for various applications which are crucial factors for potential users when choosing the timing solution that best fits their specific needs.

Table 48 Timing solutions pros and cons

Solution category	Solution	Pros	Cons
Wired time signals	Time over fibre	• Immune from RF interference • Supports time transfer over significant distances • Can be used for indoor and underground applications where GPS or RF signals are unavailable • Fibre optic provides future proof foundation that can accommodate higher performance demands and evolving standards	• Any changes to fibre (length) requires the system to be recalibrated • Has to be combined with an alternative timing source (distribution only technology) • Cost of installing fibre limits distribution of network • Limited availability in remote areas
	White Rabbit	• Technology is mature and has been demonstrated over 100s of kms • Better than one ns accuracy, often several times better • Open standard, fostering interoperability among different vendor equipment • Provides enhanced accuracy over distances compared to normal PTP	• Requires a dedicated source of time independent of GPS • Requires fibre connection to distribute time
Wireless PNT signals	eLoran	• Resistant to jamming given strong signal strengths • Low frequency enables signal to penetrate building and urban canyons and to propagate without suffering from the line-of-sight limitations • Maintains user anonymity	• Requires the use of dedicated / new receiver to GPS (Current costs of receivers are in range of thousands of dollars, although it is expected that marginal cost of adding eLoran to a GNSS device will disappear with scale) • Infrastructure is vulnerable to ground-based natural and adversarial threats • Hyper local interference can be a problem if not addressed
	Longwave time	• Large coverage area (ranges of 2000km) • Ability to penetrate inside buildings and in difficult environments • High level of availability • Maintains user anonymity • Antennas can be small enough for devices as small as wristwatches • Relatively low-cost receivers	• Low level of timing accuracy signal is maintained to within > 5 microseconds • Vulnerable to interference
	LEO-provided PNT	• L-band signals are 30dB higher in LEO than MEO at the same transmitter power, enabling indoor reception and greater resistance to jamming • Maintains user anonymity	• Large number of signals further SoO approaches can be developed • Large numbers of satellites needed to support service • Satellite's relative speed to the ground is much higher. • Lower timing accuracy 100 - 150 ns
	Pseudolites	• No capacity limitations • Maintains user anonymity • Provides signal indoors where space-based signals are not available • Much higher signal strength than normal GNSS signals and thus much greater resistance to jamming	• Limited operation range, by the near horizon, near-far effect, and existing spectrum regulations (5 – 15 km) • A network must be deployed around vicinity of desired service area
	Satellite-based augmentation systems (SBAS)	• Maintains user anonymity • Systems comply to global standard and are therefore compatible (don't interfere with each other) and interoperable (standard receiver can be used)	• Still ultimately dependant on GNSS signals and systems • Time distribution can be complex depending on implementation

Signals of opportunity	5G and mobile networks	• Low SWaP-C of user terminals to receive timing signal (most devices already compatible requiring no additional investment) • Higher power compared with GPS and therefore more difficult to jam / spoof	• Limitations in regards to signal coverage • Relatively low accuracy - able to maintain time to nearly ±1.5 microsec of UTC, as long as the base stations maintain time to this accuracy
	802.1az	• Indoor operation • Large application opportunity • Low SWaP-C • For time, can deliver <5μs to sub-ns time transfer	• Localised with limited range • Requires wifi infrastructure to be configured and deployed
Holdover clocks	Atomic clock	• Accuracy - Atomic clocks are accurate to 1 ns per year. • Long term stability, timekeeping accuracy remains consistent over extended periods	• Although price has fallen, atomic clocks cost thousands of dollars
	Miniature chip scale atomic clock (CSAC)	• Lower SWaP-C than atomic clocks	• Lower levels of technological maturity • Not as stable as existing atomic clocks (depending on the measurement period)
	Oven controlled crystal oscillator (OCXO)	• SWAP-C much reduced over atomic technologies, although use case is different. • Can have excellent short-term stability (over the period of ms to s)	• Higher power consumption • Requires significant warm up time before reaching specified frequency stability • Lower accuracy and stability compared to atomic clocks • Temperature sensitive even when in the oven (requires temperature controls internally and externally)
	Quantum clock	• Long term stability with no external input • Likely to be aligned with the optical caesium grade of products, therefore high end initially • Unaffected by external RF interference	• SWaP-C of current designs • Low technological maturity • May be impacted by vibration and/or environmental aspects
	Pulsar PNT	• Completely independent source of time available everywhere in the world and in space	• Require precise holdover clock and precisely aligned antennas for each tracked pulsar (each direction). To maintain a lock on a pulsar signal, the antenna must continuously adjust its pointing direction • Hardware is still to be miniaturised and the signal processing calculations are still computationally intensive • Large antenna size required

Source: London Economics and Rethink PNT analysis of various public sources

The performance characteristics of various timing solutions are analysed and mapped to each use case to assess their suitability. Accuracy is the primary measure of suitability as it is the most well defined and critical factor across all use cases. Other key performance metrics include availability, continuity, holdover, and integrity, which, although essential, are less clearly defined for specific use cases and less understood by operators and users. This gap presents an opportunity of further work and user education to be explored in the future.

For instance, Vodafone is trialling network time over fibre, traced back to National Physical Laboratory (NPL) time at a data centre[250]. This initiative addresses the unreliable availability of GNSS at some base station locations due to issues like satellite visibility, multipath, or interference. However, Vodafone has not yet shared specific metrics for availability and continuity from these trials. Integrity, or trustworthiness of the time source, is a relatively new consideration in the timing sector. Currently, specific integrity metrics are mainly defined in critical applications such as power systems.

The first table below outlines the most stringent timing accuracy requirements for each use case. The subsequent table provides a visual mapping of how the accuracy performance of different

[250] Stakeholder consultation with Vodafone

timing solutions aligns with these requirements across the use cases. In this mapping, a green cell indicates that the timing solution's accuracy meets or exceeds the requirement for the corresponding use case, while a red cell signifies that the timing solution's accuracy falls short of the required level.

Table 49 Most stringent timing accuracy requirements per use case

Use case number	Use case	Most stringent accuracy requirement
1	Exchange and trading systems	1ms
2	Future trading	100µs
3	Mobile communications network (5G)	1.5µs
4	Next generation telecom (6G)	<1.5µs*
5	Energy monitoring, measurement, and analysis solutions	1µs**
6	National grid CNI network and systems	1µs**
7	Air traffic control radar systems	1s
8	Air traffic control WAM systems	50ns
9	Timing systems for airborne applications	1.5µs
10	Data centre (Ecommerce)	1ms

6G timing accuracy requirement assumed to be at least as stringent as 5G, however the actual timing requirements are still uncertain and may demand greater accuracy
***** There are indications of a potential shift towards sub-microsecond requirements for fault location purposes. This is commented on in the energy sector use case write up.***

Table 50 Timing solution accuracy performance mapping to use case requirement

Solution	Accuracy	UC1	UC2	UC3	UC4	UC5	UC6	UC7	UC8	UC9	UC10
Legacy GPS	<20ns										
GNSS DFMC[251]	<20ns										
eLORAN	<1µs, 100ns with differential correction										
Satelles STL	100ns										
NextNav MBS	<100ns										
Locata	<5ns										
802.1az	<5µs										
5G cellular	1.5µs at 24 hours										
DGNSS/other[252]	100ns										
Longwave time	100µs										
NTP	1ms										
PTP	1µs										
White Rabbit	<1ns										
Atomic clock	1µs at 24 hours										

Source: RAND Corporation (2021). Analyzing a More Resilient National Positioning, Navigation, and Timing Capability. [online] Available at: https://www.rand.org/content/dam/rand/pubs/research_reports/RR2900/RR2970/RAND_RR2970.pdf; In addition, RethinkPNT analysis of public and private sources including past conference proceedings of the ITSF conference and the MaRINav study

[251] Global Navigation Satellite System Dual-Frequency Multi-Constellation – Receiver technology that is capable of using signals from multiple GNSS constellations and across multiple frequencies simultaneously. Combining these signals allows for higher accuracy, better availability, and enhances resilience by providing redundancy.

[252] Differential Global Navigation Satellite System and other signals – Normally used to transmit correction and integrity information for GNSS in ranging mode, possibly alongside other existing Signals of Opportunity (SoOPs) such as AIS broadcasts. It works by comparing the positions obtained from a reference station with known coordinates (typically a base station with a precisely known location) to correct errors caused by factors such as atmospheric interference, satellite clock inaccuracies, and ionospheric delays.

An evaluation of the associated costs for each timing solution is also conducted as part of the analysis. To facilitate a direct comparison among the various timing solutions, the analysis focuses on the estimated costs of user access, such as subscription fees, licensing charges, and upfront equipment expenses including implementation cost. While the infrastructure costs incurred by the solution providers are acknowledged, they will not be factored into this assessment. By concentrating solely on the costs borne by the end-users, the analysis aims to provide a like for like approach for evaluating the financial implications of adopting each timing solution from an end user's perspective.

Table 51 Timing solutions cost of user access

Solution	Cost of user access
Legacy GPS	<£500
GNSS DFMC	<£500
eLORAN	<£500
Satelles STL	<£1,500
NextNav MBS	<£1,500
Locata	<£1,500
802.11	<£500
5G cellular	<£500
DGNSS/other	<£500
WWVB	<£500
DCF77	<£500
NTP	<£500
PTP	<£10,000
White Rabbit	<£10,000
Atomic clock	Rubidium (Rb) - <£1500 Caesium (Cs) - <£100,000 Optical/Quantum - >£100,000

Note: White Rabbit technology provides sub-nanosecond synchronisation over Ethernet networks with timing and data transfers among its different elements. The solution is part of the White Rabbit (WR) Project which is led by CERN and follows an "Open Hardware" strategy. White Rabbit is based on existing standard but extends them for high accuracy use cases. It is used as the High Accuracy profile of the IEEE-1588-2019 Precision Time Protocol.

Source: RethinkPNT analysis of public and private sources

When selecting the most appropriate timing solution, accuracy and cost will undoubtedly be one of the primary considerations for users. However, it is crucial to recognise that other characteristics (e.g. availability, continuity, integrity, etc.) and factors will also play a significant role in the decision-making process. These additional considerations include:

- **Existing infrastructure:** Availability of existing infrastructure to service network nodes can significantly impact the cost of adoption and speed/ease of implementation.
- **Vendor and ecosystem support:** Solutions with strong vendor support and a well-established ecosystem may be preferential for their reliability, ensuring long term sustainability of a user's timing solution.
- **Scalability:** The scalability of a timing solution is essential for accommodating growth in user demand or expanding coverage areas. Timing solutions with inherent scalability or the ability to scale cost-effectively provide flexibility and adaptability.
- **Future proofing:** The ability of a timing solution to adapt to future technological advancements and evolving requirements is crucial for long-term viability. Solutions with a roadmap for future enhancements and compatibility with emerging technologies can be advantageous for their future-proofing capabilities.

- **Vulnerabilities and threats:** The vulnerability of a timing solution to various threats, both intentional and non-intentional, is a critical consideration for ensuring the security and resilience of the system. Timing technologies that offer robust security measures and resilience against known vulnerabilities are considered of greater value for specific use cases.

5 Conclusions

This project identified the top ten most critical use cases for time in the UK to evaluate the current and future market potential for resilient time dissemination. The uses and requirements of time in each use case were assessed alongside the enablers and blockers for the adoption and growth of resilient time dissemination. Finally, the Total Addressable Market (TAM) for resilient time dissemination in the UK and internationally was estimated and projected until 2030.

For each use case, a bespoke market sizing methodology was designed and implemented, incorporating information and assumptions validated through stakeholder consultations, and an understanding of the uses and requirements of time for use cases individually. Market trends, drivers and blockers were also taken into consideration in this analysis. Data was collected to provide quantitative evaluation of the TAM for the UK for each use case, which was then scaled to estimate an international TAM (predominantly for EU27).

The estimated TAM for the ten analysed use cases are combined in Table 52, and visualised in Figure 89 and Figure 90.

Table 52 Use case total addressable market summary

Sector	Use case	Cumulative TAM (£K) (2024 - 2030)	Average TAM/yr. (£K)	Average TAM/yr. (EU27) (£K)
Finance	Exchange and trading systems	420,000	60,000	61,700
	Future trading	400,000	57,000	221,000
Telecoms	Mobile communications network (5G)	320,000	46,000	558,000
	Next generation telecom (6G)	N/A	12,000	141,000
Energy	Energy, monitoring, measurement and analysis solutions	250,000	35,000	121,000
	National grid CNI network and systems	4,600	660	6,560
Aviation	ATC radar systems	2,200	310	3,700
	ATC WAM systems	2,300	330	4,730
	Timing systems for airborne applications	7,200	1,000	6,900
Information Technology	Internet data centre (Ecommerce)	120	17	513

Note: Value reported for 6G corresponds to the average TAM over 2030 – 2034 period as 6G is not expected to being its rollout until 2030; International value stated for data centres refers to 5 eyes countries excluding the UK (USA, Canada, Australia and New Zealand) instead of EU27

Figure 89 Total addressable market for ten identified time dissemination use cases

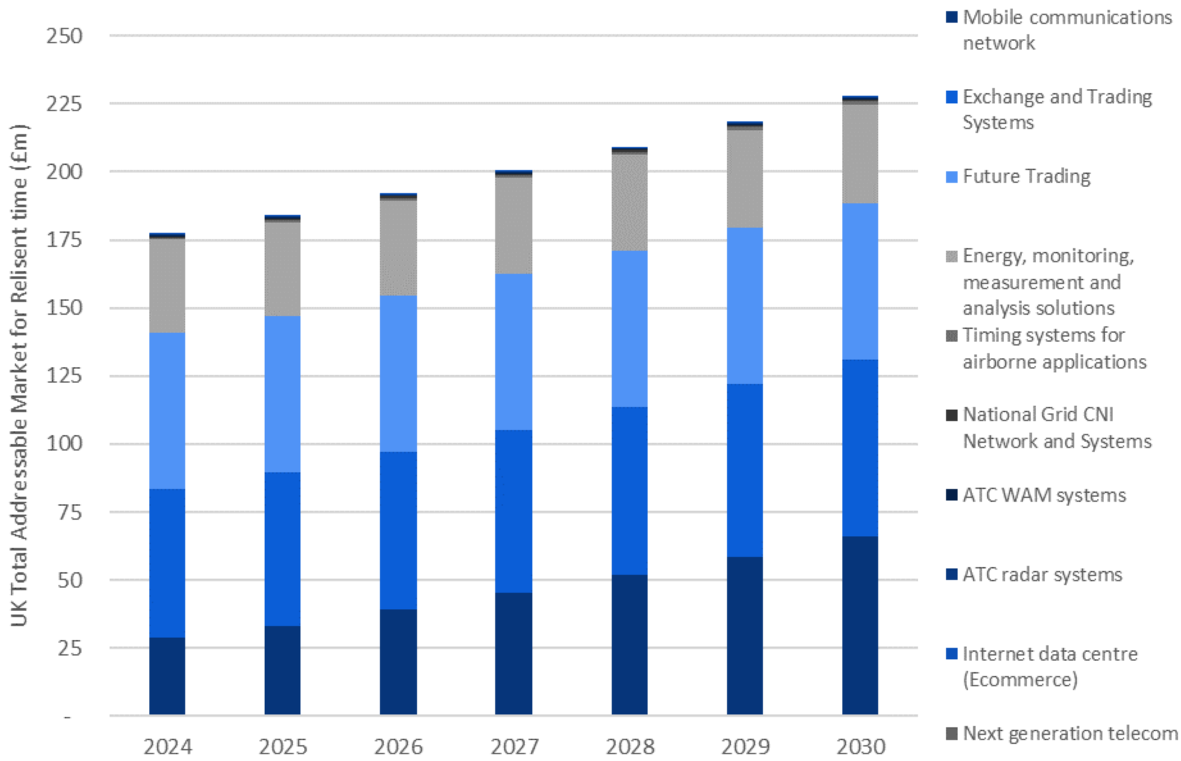
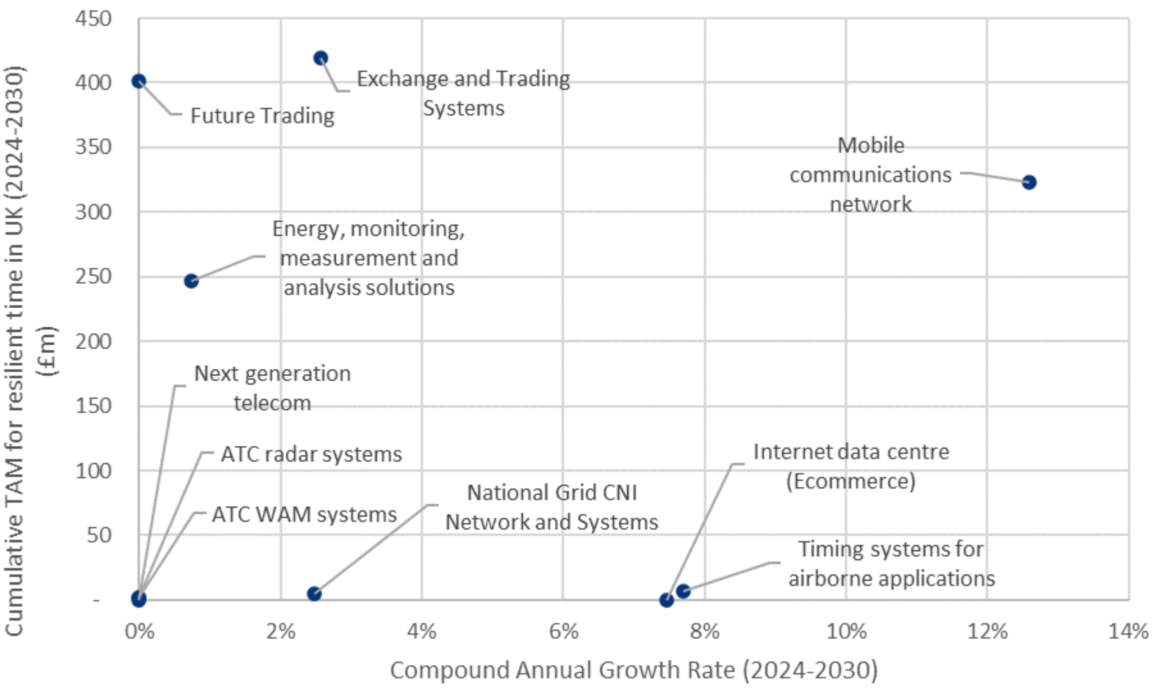


Figure 90 Central estimate for UK total Addressable Market (TAM) for Resilient time (£m)



Note: Rollout for 'Next generation telecom' does not begin until end of 2030. The cumulative TAM and CAGR for this use case from 2030-2034 are £58.5m and 89% respectively.

All use cases identified used GNSS to some extent to provide time dissemination given its low cost and broad availability. However, in general these use cases already have timing solutions robust enough to manage disruptions lasting less than two to five days but not weeks. The most common of these was local atomic clocks, with type varying according to the accuracy requirements of the use case. The price of these clocks in general set a ceiling on the willingness to pay for time resilience from the user. Given this report assumed a disruption of two days, these solutions therefore strongly influence the estimated market size.

The TAM for resilient time in the UK over the 2024 - 2030 period is estimated to be worth £1.4bn or £201m/year. The major use cases contributing were found to be: Mobile communications network; Exchange and Trading Systems; Future Trading; and Energy, monitoring, measurement. A combination of two factors were key contributors to the size of these markets. First, the demanding resilient time accuracy requirements seen in these use cases require a degree of sophistication from the time infrastructure. Second, these use cases feature large numbers of geographically separated locations that require synchronized time. Market size increases at least proportionally with the number of locations, leading to larger markets for these use cases.

These results reflect estimations within the parameters of this study. This includes limiting the assessment to only two days of disruption, and using probabilities of disruption taken from the National Risk Register. The expected probability and duration of time disruption has a major impact on the market size for resilient time dissemination. Should the national threat environment increase, the market for time dissemination would increase as a minimum proportionally but potentially exponentially if new technological solutions must be adopted. Observing ongoing jamming campaigns in the Baltic, jamming could be a future risk factor for UK access to GNSS. The use cases examined in this report are all vulnerable to time disruptions given their reliance on easily accessible and cost effective GNSS signals. Risk assessments of these vulnerabilities should drive decision making for mitigating disruptions by providing resiliently disseminated time in these sectors.

5.1 Importance of externalities

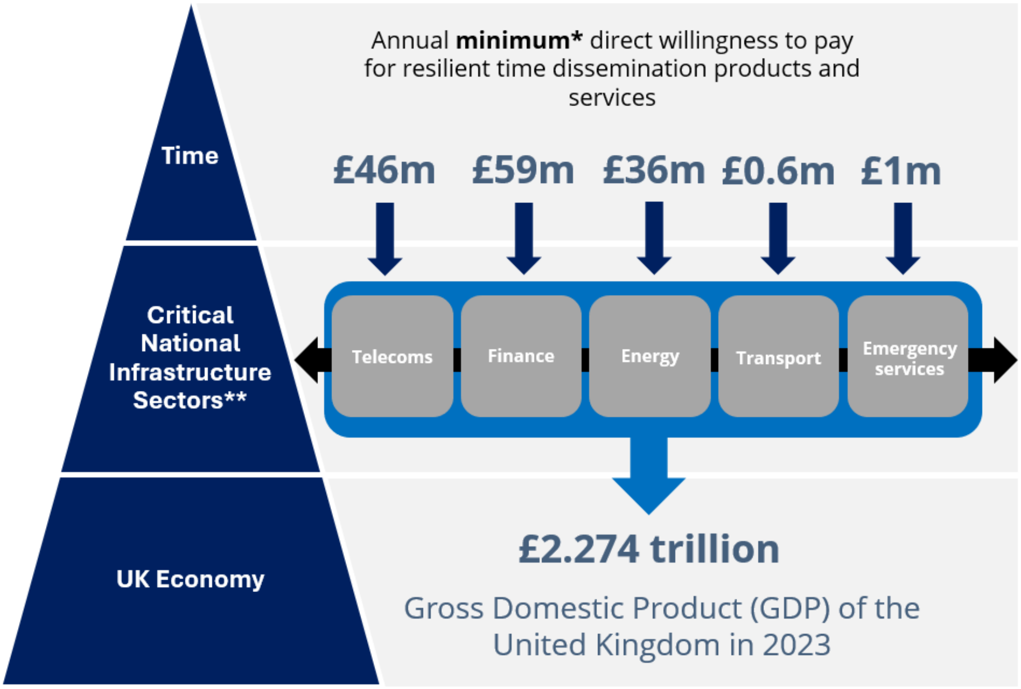
Time plays a crucial role in the proper functioning of critical national infrastructures (CNI). This importance is often underestimated, yet its impact on various sectors is far-reaching. CNI encompasses essential elements of infrastructure, including assets, facilities, systems, networks, processes, and the workers who operate and facilitate them[253]. The significance of these elements is determined by the potential impact of their loss or compromise, which could result in:

a) "Major detrimental impact on the availability, integrity or delivery of essential services - including those services whose integrity, if compromised, could result in significant loss of life or casualties - taking into account significant economic or social impacts; and/or
b) Significant impact on national security, national defence, or the functioning of the state."

Only the direct willingness to pay for to mitigate the risks of the time loss has been evaluated for each of the ten use cases in this report, nine of which reside within one of the UKs 13 national infrastructure sectors - see Figure 91:

[253] National Protective Security Authority (2023). Critical National Infrastructure | NPSA. [online] www.npsa.gov.uk. Available at: https://www.npsa.gov.uk/critical-national-infrastructure-0.

Figure 91 Importance of time for CNI



**Only a subset of use cases for each CNI sector time have been assessed*

***CNI sectors not assessed include: Chemicals, Civil Nuclear, Defence, Food, Government, Health, Space, and Water*

However, this approach underestimates the total economic impact of time loss in each sector for two reasons. First, there is limited exposure to the procuring economic agent for the external impacts arising from a loss of time. In other words, the entity responsible for paying for timing services will not bear the full economic impact (externalities) of a time-related failure, which is especially true for CNI use cases. For example, in the Wide Area Multilateration (WAM) use case airports that rely on WAM antennas for airspace management are critically dependent on time signals. If a loss of time occurs, these WAM systems would fail, disrupting airspace management and leading to flight delays or cancellations, impacting passengers and cargo transport operations. However, air traffic control (ATC) agencies do not face fines for flight delays, unlike airlines. Therefore, their direct incentive is to ensure the proper operation of the timing systems, rather than being directly motivated by the financial penalties associated with delays. The magnitude of this misalignment varied from use case to use case. Second, there are dependencies for time across national infrastructure sectors such that a time failure in one sector can impact another, which can be true if they rely on the same timing infrastructure or not. For example, a telecoms outage would impact the transport sector's ability to operate effectively even if the timing infrastructure were independent systems.

Together these can lead to under investment in providing robust crucial infrastructure, such as in resilient timing systems. The key challenge lies with regulatory bodies in aligning the willingness to pay of the paying entities with the true economic and societal impact of potential failures. This issue will be examined in detail during the Part B phase of this study.

Index of Tables, Figures and Boxes

Tables

Figures

ANNEXES

Annex 1 Glossary

Table 53 Glossary

Term	Definition	Use cases
10% drop report	A report or notification issued when the value of an investment portfolio or asset drops by 10% or more within a specified period, often used to inform investors of significant changes in value.	UC1
2G	Second-generation cellular network technology standard.	UC4
3G	Third-generation cellular network technology standard.	UC4
3GPP	3rd Generation Partnership Project, provides specifications for mobile telecommunications.	UC3, UC9
4G	Fourth-generation cellular network technology standard.	UC3, UC4
5G	Fifth-generation cellular network technology standard.	UC3, UC4
5G nodes	Small cell towers for transmitting and receiving 5G data in densely populated areas.	UC3
6G	Sixth-generation cellular network technology standard.	UC4
AC	Alternating Current	UC3
ADS-B	Automatic Dependent Surveillance-Broadcast, transmits information such as position and identity to air traffic control and other aircraft.	UC7, UC8
ADS-C	Automatic Dependent Surveillance-Contract, system for automatic transmission of information such as position from an aircraft to one or more specific ground stations.	UC9
AI	Artificial Intelligence, computer systems capable of completing tasks usually associated with human levels of intelligence.	UC2, UC10
Air Navigation Solutions	A company that provides air traffic control and engineering services to airports.	UC8
Airspace Modernisation Strategy	A CAA document that details the strategic objectives for the modernisation of the UK airspace.	UC8
ANSP	Air Navigation Service Providers, organisations that provide services such as air traffic management.	UC7, UC8
A-PNT	Alternative Position, Navigation and Timing, technologies that provide PNT independently of GNSS.	UC9
Arbitrage	The buying and selling of the same asset in different markets, exploiting price difference to make a profit.	UC2
ARINC-429	A technical standard for digital data transportation between avionic systems of commercial aircraft.	UC9
ASBU	Aviation System Block Upgrades, provide a harmonised approach for enhancing global air navigation capabilities by coordinating necessary objectives and advancements.	UC8
ATA	Actual Time of Arrival, the true time that an aircraft arrived at a given destination.	UC9
ATC	Air Traffic Control, a ground-based service for guiding aircraft to aid in collision prevention, ensure efficient flow of air traffic, and provide support for pilots.	UC7, UC8, UC9
ATCRBS	Air Traffic Control Radar Beacon System, assists air traffic control radars by acquiring additional information from monitored aircraft. This makes use of secondary surveillance radars on the ground and transponders on-board aircraft.	UC8

Term	Definition	Use cases
ATFM	Air Traffic Flow Management, regulation of air traffic control capacity to ensure efficient use of air traffic control capacity without exceeding this capacity or the capacity of airports.	UC7
ATM	Air Traffic Management, a group of services including air traffic control for ensuring safe and efficient flow of air traffic.	UC7
Atmospheric absorption	The gases in the Earth's atmosphere absorb electromagnetic radiation of different wavelengths to different degrees.	UC4
Backhaul capacity	The maximum information transfer rate between the core networks and smaller subnetworks.	UC4
Base station	A transceiver in a fixed location enabling communication between user equipment and the wireless network.	UC3
Beamforming	Signal processing technique utilising interference in antenna arrays to create spatial selectivity or directionality. This can be done when transmitting or receiving.	UC4
Benchmark regulation	Regulations governing the use and administration of financial benchmarks, such as interest rate benchmarks or commodity price indices, to ensure their accuracy, integrity, and reliability.	UC1
Best execution	A legal requirement that compels brokers to pursue the most advantageous methods for executing their clients' orders within the current market conditions.	UC1
BM SORT	Balancing Mechanism System Operation Real Time,	UC6
Bonds	Bonds are debt securities issued by governments, corporations, or other entities to raise capital. When an investor buys a bond, they are essentially lending money to the issuer in exchange for periodic interest payments and the return of the bond's face value at maturity.	UC1
CAA	Civil Aviation Authority, regulator of private and commercial (non-military) aviation in the UK.	UC7, UC8
CAGR	Compound Annual Growth Rate, the mean annual growth rate over periods longer than one year.	UC1, UC5, UC6, UC10
Carrier aggregation	Used to increase the rate of data transfer by assigning multiple carrier frequency blocks to a single user.	UC3
Cell phase synchronization	A requirement on the synchronization of time between cells in a network.	UC3
CFI	Classification of Financial Instruments, a coding system used to classify financial instruments based on their characteristics, such as asset class, currency, or maturity.	UC1
CNI	Critical National Infrastructure, these are the systems, facilities and other elements of infrastructure that are necessary for the functioning of society and the economy, where significant economic, social or security impacts would be expected if they were compromised.	UC6
CNS	Communication, Navigation and Surveillance, the core functions of air traffic management.	UC7, UC8
Conversion rate	A measure in Ecommerce calculated by dividing the number of sales on a site by the number of visitors to the site.	UC10
Cooperative surveillance	Equipment on aircraft are interrogated by signals from ground systems, then information such as identity and position are transmitted from the aircraft back to ground-based sensors.	UC8
Costs and charges	The fees and expenses associated with investment products or financial services. This includes any costs incurred by investors when buying, selling, or holding assets, as well as fees charged by investment managers, brokers, or other service providers.	UC1

Term	Definition	Use cases
Counterparty	In financial transactions, a counterparty refers to the other party involved. It can be an individual, institution, or entity with whom one enters into a financial contract or agreement.	UC1
CPDLC	Controller-Pilot Data Link Communication, method of air-ground communication between air traffic control and pilots that uses data-link to transmit non-urgent messages as an alternative to voice communication.	UC9
CPU	Central Processing Unit, the primary functional component of a computer composed of electronic circuitry for executing instructions.	UC2
Cross-link interference	This occurs when one base station is receiving in the same frequency band that another is transmitting, and the transmitted signal interferes with signals received from user equipment.	UC4
Custody statement	A document provided by a custodian to the owner of financial assets, detailing the holdings, transactions, and other activities related to those assets.	UC1
Dark pool	Private trading venues or platforms where institutional investors can execute large orders without revealing details to the public until after the trade is completed.	UC1
Dark trading	Trading activity that occurs off-exchange or in dark pools, where buy and sell orders are matched privately, often leading to less transparency in price discovery.	UC1
DC	Direct Current.	UC6
DCMS	Department for Culture, Media and Sport.	UC3
Derivatives	Derivatives are financial instruments whose value is derived from the value of an underlying asset, index, or reference rate. Examples include options, futures, swaps, and forwards.	UC1
DFS	Deutsche Flugsicherung, air navigation service provider in Germany.	UC7
DMA	Direct Market Access, allows investors to trade directly on the order books of exchanges.	UC2
DME	Distance Measuring Equipment, a combination of ground and airborne equipment for measuring the distance of an aircraft relative to a ground-based beacon.	UC9
DNO	Distribution Network Operator, responsible for the distribution of electricity from the national transmission network to homes and businesses.	UC5, UC6
DNSA	Direction des Services de la navigation aérienne, air navigation service provider in France.	UC7
Downlink	The transmission of data from a network to user equipment.	UC4, UC9
Dual connectivity	Enables a single device to connect to both LTE (long term evolution) and 5G signals simultaneously for improved coverage and data rate.	UC3
Duplex techniques	Methods for enabling bidirectional communication between devices.	UC4
DVC	Double volume cap - A regulatory mechanism under MiFID II that imposes limits on the amount of trading that can occur in dark pools or other venues in order to promote transparency in trading.	UC1
EASA	European Union Aviation Safety Agency, body responsible for safety and environmental protection of air transport in Europe.	UC7
EBITDA	Earnings Before Interest, Taxes, Depreciation, and Amortization.	UC3, UC4, UC7
EBS	Electricity Balancing System, Implemented by the National Grid, this is a system that ensures electricity consumption matches electricity generation in the grid.	UC6
ED-120/DO-290	Set of performance requirements for air traffic control data-link services.	UC9
EEA	European Economic Area.	UC1

Term	Definition	Use cases
eLoran	Enhanced Long-Range Navigation, a terrestrial-based hyperbolic radio navigation system developed as an alternative positioning, navigation and timing system to GPS.	UC6
EMIR	European Market Infrastructure Regulation, a set of regulations governing over-the-counter (OTC) derivatives markets within the European Union, aimed at increasing transparency and reducing risks.	UC1
ENAV	Ente Nazionale Assistenza al Volo, air navigation service provider in Italy.	UC7
EPP	Extended Projected Profile, an enhancement of the Automatic Dependent Surveillance-Contract that incorporates information about flight intent and projected trajectory.	UC9
ESMA	The European Securities and Markets Authority, is an independent EU authority that regulates securities markets, ensuring the integrity, transparency, and stability of financial markets in the European Union.	UC1, UC2
ESO	Electricity System Operator, balances the supply and demand of electricity among other responsibilities such as market development and advising on network investment.	UC6
ET	Electricity Transmission, the process of delivering electricity from generation sites to the distribution grid.	UC6
ETA	Estimated Time of Arrival, the predicted time an aircraft will reach its destination.	UC9
Ex-post reporting requirements	Involves providing information to investors after a transaction or investment has occurred. This information typically includes details about the costs, charges, and performance of the investment over a specific period.	UC1
FAA	Federal Aviation Administration, agency in charge of regulating civil aviation in the US.	UC8
FATE	Frequency and Time Error, the monitoring and reporting of deviations in the power system frequency and time error compared to established standards and requirements. Frequency error refers to deviations of the actual power system frequency from the nominal or target frequency value. Time error refers to the difference between the system's actual time and the reference or standard time.	UC6
Fault recording and location	Systems used to identify and locate faults or disruptions in electrical networks. Time alignment of information can be essential to determine the location of a specific fault or event or may be significant in the forensic determination of events leading to a specific incident.	UC5, UC6
FBMC	Filter Bank Multicarrier, a form of modulation similar to OFDM where a prototype filter is used to construct a group of filters that filter each subcarrier waveform.	UC4
FCA	The Financial Conduct Authority (FCA) is the regulatory body responsible for overseeing financial firms and markets in the United Kingdom. It aims to protect consumers, ensure market integrity, and promote competition in the financial services industry.	UC1, UC2
FCC	Federal Communications Commission, regulator of interstate and international communications in the U.S.	UC2, UC4
Feed network	The interconnection between the elements that make up an antenna array.	UC4
Fibre optics	A method of data transmission by passing light through thin transparent fibres.	UC2, UC3, UC8
FINRA	Financial Industry Regulation Authority, independent regulatory body for securities firms in the US.	UC2
Fixed income	A type of investment that pays a fixed interest or dividend income until its maturity date, including bonds, certificates of deposit (CDs), and treasury bills.	UC1
Fixed-line	The use of cables or wires for transmission in telecommunications systems.	UC3

Term	Definition	Use cases
FMS	Flight Management System, a computer system on-board aircraft for coordinating aircraft systems for precise and efficient operation.	UC9
FPGA	Field Programmable Gate Array, a type of configurable integrated circuit or programmable logic device. They can be reprogrammed for desired applications post manufacturing.	UC2
Front-running	Front-running refers to the unethical practice of a broker or trader executing orders on a security for their own benefit before executing orders for their clients. It involves using advance knowledge of pending trades to profit from subsequent market movements.	UC1
GAL	Gatwick Airport Limited, the owner and operator of Gatwick Airport.	UC8
GANP	Global Air Navigation Plan, a strategic document for air navigation, and a plan for the evolution of the global air navigation system.	UC8
GNSS	Global Navigation Satellite System, a satellite constellation that provides worldwide position, navigation and timing services.	UC1, UC2, UC3, UC5, UC6, UC7, UC8, UC9, UC10
GPS	Global Positioning System, US-owned radio-based satellite navigation system.	UC6, UC8, UC9, UC10
Great Grid Upgrade	A major infrastructure project to overhaul the electricity grid in England and Wales, to help reduce the UK's reliance on fossil fuels by connecting more renewable energy to electricity users.	UC6
Green field sites	Land that has never been developed on.	UC6
Hedging	Hedging is a risk management strategy used to offset potential losses from adverse price movements in financial markets. It involves taking an offsetting position to reduce or eliminate the risk of adverse price fluctuations.	UC1
HFT	High Frequency Trading, algorithmic trading leveraging powerful computer programs to perform large volumes of trades at high speeds.	UC2
Holographic communication	Real-time communication via renderings of 3D representations in space.	UC4
ICAO	International Civil Aviation Organisation, a United Nations agency in charge of coordinating international aviation standards and policies.	UC8
IDNO	Independent Distribution Network Operators (IDNOs) connect to the local distribution network or to the transmission network to supply new housing and commercial developments with electricity.	UC5
IEC68150	International standards for communication protocols in smart grids.	UC6
IEMS	Integrated energy management system, an operational tool that combines and presents data from different substations.	UC6
IF link	Intermediate frequency link, the transmission of signals at an intermediate frequency between different stages in a communication system. Incoming signals are first converted from the original high frequency to a lower intermediate frequency before further processing. This simplifies the design and improves performance of filters and amplifiers. An IF link is the connection that carries these intermediate frequency signals from the receivers to the processing site where the signals are further demodulated, decoded, or otherwise processed.	UC8
IFF	Identification Friend or Foe, a type of transponder interrogation system that can identify aircraft as friendly or otherwise.	UC8
IFR	Instrument Flight Rules, a set of regulations for flying using guidance from instruments on the flight deck. This is the alternative to visual flight rules	UC7

Term	Definition	Use cases
	(VFR) where pilots fly using visual references when weather conditions are sufficiently clear.	
ILS	Instrument Landing System, a precision radio navigation aid for runway approach. Provides both vertical and horizontal guidance on approach to landing.	UC9
Immersive reality	A form of virtual or augmented reality, with high levels of sensory input and user interaction to increase engagement and immersion in the environment.	UC4
IMT	International Mobile Telecommunications, a generic term for broadband mobile systems.	UC4
IMT2020	International Mobile Telecommunications-2020, defines the requirements for 5G networks, devices and services.	UC4
INS	Inertial Navigation System, uses a combination of sensors that measure the change in motion of an object to determine its position, orientation and velocity relative to a starting point, i.e. via dead reckoning. This does not require external references.	UC9
Investor reporting	The communication of relevant financial information to investors or potential investors. This typically includes disclosures on performance, fees, risks, and other pertinent details about investment products or services.	UC1
IoT	Internet of Things, a network of physical devices embedded with sensors that collect and share data through network connectivity.	UC10
ISIN	International Securities Identification Numbers, unique codes assigned to individual securities, such as stocks, bonds, and options, to facilitate trading and identification.	UC1
Jamming	Interference of GNSS signals leading to degraded or lost signals.	UC7, UC9, UC10
Latency	The time delay in the transfer of data from one location to another.	UC1, UC2, UC3, UC4, UC8, UC9, UC10
LEI	Legal Entity Identifiers, unique codes assigned to legal entities engaged in financial transactions, used to enhance transparency and traceability in financial markets.	UC1
Line protection scheme	A set of measures or devices designed to protect power lines from various types of faults or disturbances. Power measurements are continuously sampled by line protection devices at both ends of a line. Each sampled measurement is stored temporarily at its respective end and sent to the remote end as a data message via a communications circuit.	UC5, UC6
Link performance	Measure of the signal quality and coverage of a communication link between transmitter and receiver encompassing a range of factors such as path loss, received signal strength and interference.	UC3
Liquidity	Liquidity refers to the degree to which an asset or security can be quickly bought or sold in the market without significantly affecting its price. High liquidity means an asset can be easily traded, while low liquidity implies difficulty in buying or selling without impacting the market price.	UC1
Listing Authority	Regulatory body responsible for the listing of shares on the stock exchange.	UC1
Lit market	The portion of the financial market where trades are executed on public exchanges or visible trading platforms, providing transparency in price discovery.	UC1
LoS	Line of Sight.	UC4, UC8
MAC	Miniaturised Atomic Clock, atomic clocks are oscillators with very high frequency stability derived from the resonant frequencies of specific atoms. Miniaturised versions have reduced size, weight and power.	UC10

Term	Definition	Use cases
Make-whole clause	A provision in a financial contract that compensates the holder for any potential losses incurred due to early repayment or redemption of the instrument.	UC1
MAR	Market Abuse Regulation, a set of European Union regulations designed to prevent and prohibit market manipulation and insider trading within financial markets.	UC1
Market infrastructure provider	A market infrastructure provider is an entity that provides the technological and operational infrastructure necessary for the functioning of financial markets.	UC1
Massive antenna arrays	A very large group of antenna elements that work together as a single antenna.	UC4
MiFID	The Markets in Financial Instruments Directive (MiFID) is a European Union regulation that regulates investment services and trading venues within the EU. It aims to harmonise financial markets, increase transparency, and enhance investor protection.	UC1, UC2, UC10
MiFIR	Markets in Financial Instruments Regulation, a European Union regulation that supplements MiFID II and regulates trading venues, transparency, and market structure within the EU financial markets.	UC1
ML	Machine Learning, a subset of artificial intelligence focusing on algorithms that use data to improve performance on tasks involving generalising to unseen data.	UC2
MLAT	Multilateration, technology for accurate positioning and surveillance using TDOA of signals at different ground sites.	UC8
MNO	Mobile Network Operator, a company that sells access to cellular networks for wireless communications.	UC3, UC4
MoD	Ministry of Defence, department of the UK government responsible for armed forces and implementing the Defence policy.	UC9
Mode A, C and S transponders	Transponders are equipped on aircraft that send signals in response to requests (interrogations) from ground stations. The different modes determine the different means of communication, and the information that is conveyed by the transponder.	UC8
Monostatic radar	Radar with co-located transmitter and receiver.	UC7
MRTD	Maximum Receive Timing Difference, an upper bound on the relative timing difference that user equipment must be capable of handling.	UC3
MSRS	Multistatic Radar System, a system of spatially separated radars that provide coverage over the same geographical area.	UC7
MTF	Multilateral Trading Facility (MTF) is a trading venue that brings together multiple buyers and sellers to trade financial instruments.	UC1
MTI Scheme	Measures, Targets and Incentives Scheme, specifies a set of service standards guaranteed by Heathrow Airport as part of regulatory charges issued.	UC8
MVNO	Mobile Virtual Network Operators, companies that lease wireless network capacity from MNOs that own the network infrastructure.	UC3
NATS	National Air Traffic Services, leading air navigation service provider in the UK.	UC7, UC8
NCA	National Competent Authority (NCA) refers to the regulatory authority responsible for overseeing compliance with financial regulations within a specific country or jurisdiction.	UC1
NERL	NATS En Route Limited, en-route air traffic control service provider in the UK.	UC8
NIC	Network Interface Card, hardware component providing connection between a computer and a computer network.	UC2

Term	Definition	Use cases
NOMA	Non-Orthogonal Multiple Access, transmission method where multiple users share time and frequency resources to increase efficient use of spectrum.	UC4
Non-equity	Non-equity securities are financial instruments that do not represent ownership in a company. Examples include bonds, debt securities, options, and derivatives.	UC1
NPAS	National Police Air Service, centralised service for providing air support to all the police forces of England and Wales.	UC9
NPL	National Physics Laboratory, research institute that develops and maintains national primary measurement standards.	UC2, UC6
NSL	NATS Services Limited, provides air traffic control and related services to airports in the UK and overseas.	UC8
NTC	National Timing Centre, one of several locations with direct access to accurate time and frequency for dissemination to different sectors.	UC6
NTOL-project	National Physics Laboratory (NPL) Time Over eLoran project, a project to demonstrate the broadcast of the NPL managed national time-base across the UK using eLoran.	UC6
NTP	Network Time Protocol, protocol for computer clock synchronisation in a network with millisecond-level accuracy.	UC10
OBR framework	Outcomes Based Regulation framework, a strategy employed by the CAA for regulating Heathrow Airport based on outcomes, measures, targets and incentives.	UC8
OCXO	Oven-Controlled Crystal Oscillators, a type of clock that regulates temperature to maintain a stable resonance frequency of the oscillator crystal to provide precise timing.	UC7
Ofcom	Office of communications, the regulator of the communications sectors in the UK.	UC3, UC4
OFDM	Orthogonal Frequency Division Multiplexing, a method of transmitting data where multiple bits are transmitted in parallel using perpendicular subcarrier signals.	UC4
Ofgem	Office of Gas and Electricity Markets, the regulator for the electricity and gas markets in Great Britain.	UC5, UC6
OTF	Organised Trading Facility, is a trading venue for non-equity instruments established under MiFID II. OTFs facilitate trading in bonds, derivatives, structured finance products, and emission allowances.	UC1
Path loss	The attenuation of electromagnetic waves as they travel through space.	UC4
Pay monthly	A type of mobile data contract where consumers pay a fixed monthly fee for a fixed amount of data.	UC3
Pay-as-you-go	A type of mobile data contract where consumers pay for the data they use at a given rate.	UC3, UC10
PCIe	Peripheral Component Interconnect Express, a high-bandwidth expansion standard for computers.	UC10
Phasor Measurement Units (Wide Area Monitoring system)	Devices that measure the magnitude and phase angle of electrical quantities in power systems, used for wide-area monitoring and control. PMUs estimate this magnitude and phase in the grid using a common, distributed time source for synchronisation. The data is transmitted on a wide area monitoring system (WAMS) to a central location.	UC5
PMU	Phasor Measurement Unit, Devices that measure the magnitude and phase angle of electrical quantities in power systems, used for wide-area monitoring and control. PMUs estimate this magnitude and phase in the grid using a common, distributed time source for synchronisation.	UC6
PNT	Position, Navigation and Timing, technologies, systems and processes used to determining location, orientation and time.	UC3, UC9

Term	Definition	Use cases
Power distribution network health and usage monitoring	Systems for monitoring the condition and usage of power distribution networks to ensure reliability and efficiency.	UC5
Power system measurements/ power quality measurements	Measurements of various electrical parameters within power systems to assess their performance and quality.	UC5, UC6
PPS	Pulse Per Second, an electrical signal with width less than one second that accurately repeats once per second.	UC2
Pre- and post-trade transparency regime	Focus on making information about trading activity publicly available to market participants. Pre-trade transparency refers to the requirement to publish information about bids and offers before a trade occurs, allowing market participants to see available liquidity and market depth. Post-trade transparency involves the publication of trade details after they have been executed, providing transparency into actual trade prices and volumes.	UC1
PRF	Pulse Repetition Frequency, the number of radar pulses transmitted per second.	UC7
Primary radar	Use echolocation to detect reflections of pulses from targets to determine horizontal locations. These do not require aircraft to be equipped with transponders.	UC7
Private 5G network	Allows restricted access, and use of licensed as well as unlicensed spectrum.	UC3
Procedural control	An air traffic control methods employed when surveillance (e.g. radar coverage) is not available. These methods rely on the use of predetermined routes, and ground-based navigation aids.	UC7
PROD	Product governance - Refers to the systems and controls firms have in place to design, approve, market and manage products throughout the products' lifecycle to ensure they meet legal and regulatory requirements.	UC1
Propagation characteristics	Properties of electromagnetic radiation that are dependent on the frequency and influence how they travel in the Earth’s atmosphere.	UC4
Protection synchronisation	Differential protection schemes and relays used in electrical power systems to ensure safe and proper synchronisation conditions are met before connecting or synchronising two energised systems or sources. These protection schemes monitor parameters like voltage, frequency, and phase angle to prevent issues like out-of-phase synchronisation, which could damage equipment or cause system instability.	UC6
PTP	Precision Time Protocol, method used for clock synchronisation throughout a network.	UC6, UC10
PTP boundary clocks	Clocks that ensure synchronisation throughout a network by receiving timing information from grandmaster clocks and distributing this to other devices.	UC6
PTP grandmasters	Clocks that generate and disseminate reference time to clocks throughout a network.	UC6
PUE	Power Usage Effectiveness, a measure of the energy efficiency of data centres. It is the ratio of total energy used by the data centre facility to the total energy delivered to the data centre computing equipment.	UC10
Quantum computing	Specialized technology is used to take advantage of quantum mechanics to solve more complex problems, and to solve problems faster, than regular computing or supercomputers.	UC4
Quick fix derivative	A legislative directive issued by the European Commission to swiftly address urgent issues or make immediate changes to existing regulations.	UC1
Radio cell	The geographical area covered by a specific base station as part of a cellular network	UC3

Term	Definition	Use cases
RAN	Radio Access Network, provides a connection between individual devices and the core network of a telecommunications system via a radio link.	UC3, UC4
RAT	Radio Access Technology, the underlying technology and protocols used for connecting user devices and cellular network infrastructure.	UC4
Reference Price Waiver	A waiver under MiFID II that allows trading venues to execute transactions outside the current bid and ask prices under certain conditions.	UC1
Relative time error	The difference between the time of two different time sources.	UC3
REMIT	Regulation on Wholesale Energy Market Integrity and Transparency, a regulatory framework for defining and prohibiting market abuse.	UC6
Remote sensing	Acquisition of information of an object or area from a distance.	UC4
RF	Radio Frequency, low frequencies of the electromagnetic spectrum commonly used for communication.	UC3, UC4
RFI	Radio Frequency Interference, transmissions in the radio frequency bands of the electromagnetic spectrum that disrupt or degrade GNSS signals at receivers.	UC7, UC8
RIIO ED-2	The second Electricity Distribution Price Control Review, a regulatory framework for electricity distribution companies in the UK.	UC5
RM	Regulated markets (RM) are financial markets or trading venues governed by regulatory authorities to ensure fair, transparent, and orderly trading activities. These markets operate under specific rules and regulations established by regulatory bodies to protect investors, maintain market integrity, and promote efficient price discovery.	UC1
RNP	Required Navigation Performance, accuracy and resilience requirements for positioning for specific procedures or airspaces.	UC9
ROCE	Return on Capital Employed, a financial ratio measuring the profitability of a company in terms of its capital.	UC3, UC4
RTS 25	Regulatory Technical Standard 25, a set of technical standards under MiFID on clock synchronisation.	UC1, UC2
RTS 27	Regulatory Technical Standard 27, a set of technical standards under MiFID II governing the publication of execution quality reports by execution venues.	UC1
RTS 28	Regulatory Technical Standard 28, a set of technical standards under MiFID II governing the disclosure of execution venues and brokers used by investment firms for client orders.	UC1
Sampled Value data streams (IEC 61850-9-2-LE / IEC 61869-9)	Sampled Values are defined in the standard IEC 61850 and IEC 61869-9. These are standards for exchanging sampled value data in electrical substations, used for communication between devices in power systems. They enable the transmission of analogue measurements (e.g. voltage and current) as digital data streams. Unlike analogue signals, which may be vulnerable to noise and distortion, Sampled Value (SV) technology guarantees high-fidelity representation of electrical parameters. This data is essential for applications such as Phasor Measurement Units (PMUs), which demand accurate synchronisation for grid monitoring.	UC5, UC6
SCADA	Supervisory Control and Data Acquisition, enables remote operational management and control of power-flow in the transmission system of the national grid.	UC6
SCS	Substation Control System, collection of hardware and software enabling the management, control and monitoring of a power substation.	UC6
Secondary radar	Sends interrogation signals to aircraft transponders. Receives responses from transponders with information such as aircraft identity and altitude.	UC7
Securities	Securities are financial instruments representing ownership or debt obligations issued by corporations, governments, or other entities. Examples include stocks, bonds, options, and derivatives.	UC1, UC2

Term	Definition	Use cases
SELCAL	Selective Calling radio system that allows aircraft crew to be alerted of incoming communications from ground stations even when their radio is muted.	UC7
Self-interference	This occurs when signals from a transmitter leak into the signals at a co-located receiver, causing interference.	UC4
Short sale indicator	A signal or identifier used to indicate that a trade involves the short-selling of a financial instrument, where an investor sells a security they do not own, with the expectation of buying it back at a lower price.	UC1
SI	Systematic Internaliser (SI) is an investment firm that executes client orders in financial instruments on its own account. SIs are required to provide liquidity and execute orders in a fair and transparent manner.	UC1
SIC	Self-interference cancellation, a signal processing technique using modelling to accurately cancel out interference between co-located transmitters and receivers.	UC4
SLA	Service Level Agreement, contract between a service provider and a customer outlining the scope and standards of services provided.	UC2, UC8
SLOC	Software Lines of Code, a measure of the size of a software program that counts the total number of lines of text in the source code.	UC9
Small cell sites	Used to boost network capacity in densely populated, and indoor areas.	UC3
Smart agriculture	The incorporation of artificial intelligence and other advanced technologies into agriculture to improve sustainability and optimisation.	UC3
Smart grid	Electricity distribution that utilises two-way communication. Advanced technologies are used to monitor electricity usage and manage transport to improve efficiency and reliability.	UC3
SMC	Shortwave Modernisation Coalition, an ad hoc group representing the interests of high-frequency traders petitioning to allow data communication in the 2-25MHz range.	UC2
SMPTE ST 2059-2	A standard from the Society of Motion Picture and Television Engineers describing parameters for synchronisation of video equipment for professional broadcasting.	UC10
Spectral efficiency	A measure of the rate of information transfer achieved over a given bandwidth for a specified communication system.	UC4
Spectrum	The range of radio frequencies used for telecommunications purposes.	UC3, UC4
Spoofing (finance)	Spoofing is a form of market manipulation where traders place orders with the intent to cancel them before execution to create false market signals and deceive other market participants.	UC1
Spoofing (GNSS)	A type of GNSS interference where a transmitter transmits false information causing receivers to believe they are in a different location.	UC7, UC8, UC9
SSR	Secondary Surveillance Radar, sends interrogation signals to aircraft transponders. Receives responses from transponders with information such as aircraft identity and altitude.	UC7, UC8
Standalone 5G	5G network that only uses 5G technology as opposed to non-standalone that incorporates a mix of 4G and 5G.	UC3
Stealth	Technology used to reduce the ability of aircraft to be detected by radar and other detection methods.	UC7
STO	Standard Trading Obligation, a requirement under MiFID that certain classes of financial instruments must be traded on regulated trading venues.	UC1
Stock	Stock refers to ownership shares in a corporation. Investors who own stock in a company are entitled to a portion of its profits and have voting rights at shareholder meetings.	UC1
Synchro-phasors	Time-synchronised measurements of electrical quantities (measuring magnitude and phase).	UC3

Term	Definition	Use cases
TDD	Time Division Duplex, a method for bidirectional communication over the same frequency band that separates signals in each direction using time slots.	UC3, UC4, UC9
TDMA	Time Division Multiple Access, a technique for allowing multiple users to access the same frequency channel by using time slots. Each user transmits in different time slots in rapid succession.	UC4, UC9
TDOA	Time Difference of Arrival, a method used for determining accurate positions by measuring the difference between the arrival times of signals at different receivers.	UC8
Time Appliance	Dedicated hardware developed by Meta for accurate time keeping in the event of GNSS loss.	UC10
Time card	An expansion card that can turn a commodity server into a Time Appliance.	UC10
Time domain isolation	A method for preventing interference between adjacent cells.	UC3
TO	Transmission operator, responsible for the operation and maintenance of electricity transmission assets, including high-voltage power lines and substations.	UC5
TOA	Time of arrival, absolute time that a radio signal is received.	UC8
TOTV	The act of executing financial transactions within a regulated trading venue, such as a stock exchange or electronic trading platform.	UC1
Trade misalignment	Trade misalignment occurs when there is a discrepancy or inconsistency between trade execution prices and the prevailing market prices at the time of execution. It may result from errors, delays, or manipulation in trade execution processes.	UC1
Transaction reporting	Involves the real-time or near-real-time reporting of specific details about individual financial transactions to regulatory authorities. It focuses on capturing and transmitting key data elements related to trades, orders, and other transactions executed within financial markets.	UC1
Transmission operator	Responsible for the operation and maintenance of electricity transmission assets, including high-voltage power lines and substations.	UC6
Transport act 2000	A law in the UK for regulating transport, including air traffic services.	UC7
TRxP	Transmission Reception Point, antenna array at a specific location that transmits and receives data as part of a communications network.	UC3
TSN	Time-Sensitive Network, use time synchronisation between network components for time-critical real-time communication via ethernet.	UC3
TWSTT	Two Way Satellite Time Transfer, involves long distance transfer of signals between a pair of clocks via a common satellite, used for distribution of time and frequency standards.	UC6
UAV	Unmanned Aerial Vehicle, also referred to as drones, these are aircraft that fly without human pilot, crew or passengers on-board.	UC9
UE device positioning	User equipment device positioning, determining location of 5G devices.	UC3
UK Statutory Instrument	A form of delegated legislation in the United Kingdom, made under the authority of an Act of Parliament. Statutory Instruments are used to fill in the details or make technical changes to primary legislation.	UC1
Uplink	The transmission of data from user equipment to a network.	UC4, UC9
UTC	Coordinated Universal Time, The primary time standard use as a reference globally to regulate and synchronize clocks around the world.	UC1, UC2, UC8, UC9, UC10
VOR	Very High Frequency Omnidirectional Range, a short-range radio navigation aid for pilots in en-route navigation and approach procedures.	UC9

Term	Definition	Use cases
WAM (electrical grids)	Wide-area monitoring, a system utilising information from distributed PMUs for monitoring and management of electrical grids.	UC6
WAM (aviation)	Wide Area Multilateration, A cooperative surveillance technique where signals received from an aircraft at several ground stations as used to determine the aircraft's location.	UC7, UC8
Wholesale Markets Review	A regulatory review conducted by the UK Financial Conduct Authority (FCA) to assess and propose changes to the transparency regime, trading rules, and functioning of wholesale financial markets in the UK.	UC1
Wind power generation power transfer	The process of transmitting the electrical energy generated by wind turbines from the generation site onto the electrical grid. The power generated by the wind turbines must be synchronised with the grid in terms of voltage, frequency, and phase.	UC6

Annex 2 Stakeholder engagement

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Stakeholder consultations were conducted to update and validate information and assumptions used for analysis. This was important as not all information required for detailed TAM analysis was available in the public domain. The stakeholders interviewed and the relevant use cases for each stakeholder are outlined in Table 54.

Table 54 Stakeholder engagement

Organisation name	Company description and (stakeholder)	Use case(s)
Capita	International business process outsourcing and professional services company (business leads)	UC3, UC5, UC6, UC10
Power Networks Demonstration Centre	Energy systems research, test and demonstration facility (Energy network SME)	UC5, UC6
National Air Traffic Services (NATS)	Provides en-route air traffic control services to flights within the UK flight information regions (Air traffic SME)	UC7, UC8, UC9
Telespazio	European spaceflight services company (PNT SME)	UC7, UC8, UC9
Strontium 87	Timing network consultancy, (Finance and Data Centre subject matter expert)	UC1, UC2, UC10
Hoptroff	Provider of distributed timing services (Company leadership)	UC10
Vodafone	Telecommunications, Mobile Network Operator (Network SME)	UC3, UC4
Home Office	Emergency Services (Various)	UC9
Bach Consulting	Technical consultancy (Finance and Data Centre SME)	UC1, UC2, UC10
Viasat	Maritime and telecoms service provider, (Technical SME)	All
Strategic Synergies LLC	Technical and Management Consulting, (Aviation SME)	UC7, UC8, UC9
Chronos Technology	Global authority on synchronisation and timing solutions (Timing product SME)	All
Thales (ex-employee)	Defence and security company (Radar SME)	UC7

Note: SME = Small and Medium-sized Enterprise. PNT = Position, Navigation and Timing

Annex 3 Use case shortlisting methodology

The selection of use cases for this project was governed by a set of specific parameters that defined its scope. Primarily, the project concentrated on the timing market, deliberately excluding positioning and navigation use cases. The focus was placed on identifying use cases with significant growth potential for the timing and dissemination market, rather than those requiring more robust solutions to address vulnerabilities.

The process began with the development of an extensive list of timing applications, leveraging existing knowledge databases from London Economics and the Royal Institute of Navigation (RIN), supplemented by additional desk-based research. This comprehensive list encompassed 96 applications of timing, which were then aggregated into 59 distinct markets (use cases) across 17 sectors. The aggregation process considered factors such as the end user responsible for procuring timing solutions, the specific locations where timing signals would be utilized, and the similarity in requirements across applications. For instance, the National Grid requires precise time for various applications within substations. These applications were aggregated into a single use case because providing timing for one application would inherently provide timing for all applications within the substation.

Each use case was evaluated and ranked based on the perceived impact of a timing disruption and the likelihood of such a disruption occurring.

A3.1 Likelihood scoring

Two factors were considered in estimating a score for the likelihood of timing disruption for each use case. These were the incentive to disrupt time, and the resiliency of timing solutions employed in that market.

The incentive to disrupt was considered along three dimensions: Economic; strategic; and ideological. Economic incentives include direct financial gains from disruption such as fraudulent activities and ransom attacks, as well as from manipulation of market prices, trading volumes or other critical parameters. Strategic incentives refer to advantages gained through disruption of times of rival firms, or the use of disruption to evade regulations. Finally, ideological incentives covers whether the market is susceptible to terrorist attacks, state threats, or agenda driven motives.

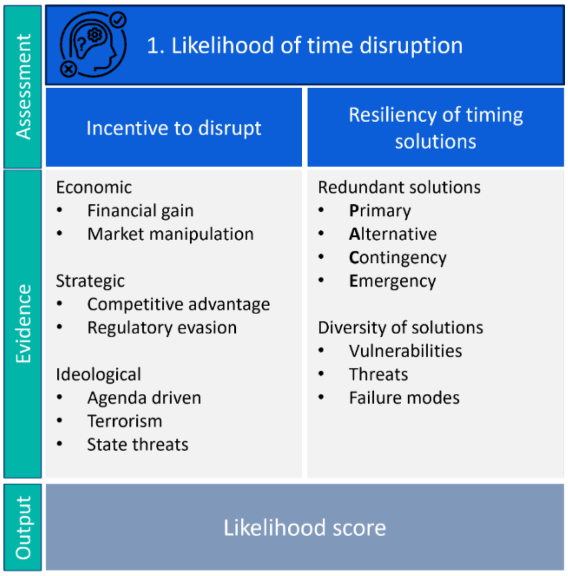
Resiliency was assessed along two dimensions: The redundant solutions that are in place; and the diversity of solutions in place. The redundancy chain of backup timing solutions for each use case was assessed using the PACE framework (Primary, Alternative, Contingency, Emergency). This framework is used in communications and resilience planning. A red, amber, yellow, or green was then assigned to each use case according to set criteria:

- **Red:** Does not meet the performance criteria and is thus unable to deliver the service. Or meets the performance criteria; however, it is wholly dependent on the primary source of PNT.
- **Amber:** Meets the minimum performance criteria to deliver the service; however, will immediately impact on cost, efficiency, etc
- **Yellow:** Meets the performance criteria without any initial impact to service delivery; however, degrades over time.

- **Green:** Will continue to meet the performance criteria without any significant impact to service delivery over time.

The diversity of backups was also evaluated, considering common vulnerabilities, threats and failure modes.

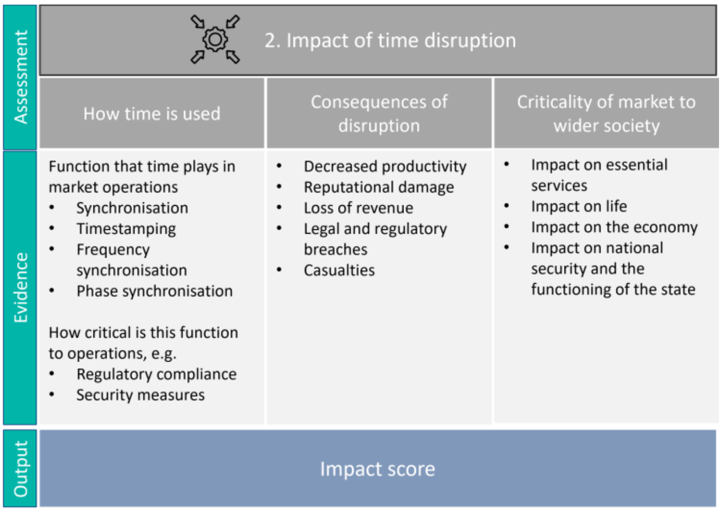
Figure 92 Methodology for likelihood scoring



A3.2 Impact scoring

The impact of time disruption was scored on a 1-5 scale in three separate categories: How is time used?; Consequences of disruption; Criticality of market to wider society. The first category evaluates the significance of time in the efficient operation and overall functionality of the use case. The second assesses the scale of the likely consequences of a disruption, and the third examines the implications of disruption to the use case on the function of wider society. The assigned scores are combined across the three categories to produce a single overall score.

Figure 93 Impact scoring methodology



Scoring was guided by the definitions provided in Table 55 and Figure 94.

Table 55 Impact scoring ranking definitions

Dimension	Ranking				
	1	2	3	4	5
How time is used	**Minimal function:** Time plays a negligible role in market operations, and its disruption has minimal impact on functionality.	**Peripheral function:** Time is a secondary consideration, with disruption introducing inefficiencies, but not halting operations.	**Supporting functions:** Time is relevant but not pivotal, disruptions would hinder core operations but not entirely impede them.	**Integral function:** Market operations are significantly influenced by time; disruptions could lead to notable operational challenges.	**Critical function:** Time is an essential aspect of the market's operation; disruptions would have severe and immediate effects on operations.
Disruption consequence	**Minimal consequence:** Disruptions result in minor delays or inefficiencies with negligible lasting consequences.	**Moderate consequence:** Disruptions lead to setbacks that result in a loss of productivity but are manageable.	**Significant consequence:** Disruptions cause notable challenges, impacting productivity and/or competitive advantage over rivals	**Material consequence:** Disruptions result in substantial operational setbacks, financial implications, reputational damage, and/or regulatory breaches	**Severe consequence:** Disruptions trigger critical failures, resulting in significant financial losses, reputational damage, regulatory breaches and loss of life and/or casualties
Criticality*	**Limited**	**Minor**	**Moderate**	**Significant**	**Catastrophic**

Note: *Criticality is assessed using definitions from the National Risk Register, found in Figure 94

Figure 94 Criticality scoring definitions

	IMPACT ON ESSENTIAL SERVICES	IMPACT ON LIFE	IMPACT ON THE ECONOMY	IMPACT ON NATIONAL SECURITY AND THE FUNCTIONING OF THE STATE
	The impact that the loss/compromise of an asset has on the delivery and integrity of the essential services that many of the critical sectors provide, as well as the resultant social impact (including disruption to normal patterns of daily lives of the UK public). Essential services are those that the public rely on a daily, or near daily, basis and are often provided by the private sector.	The impact arising from loss/compromise of an asset, as well as its aftermath (e.g. loss of water or health care, exposure to chemical or radiological materials), in terms of fatalities and casualties. It therefore includes both no notice and excess fatalities.	The direct cost of damage and cost of economic output lost as a result of the loss/compromise of an asset. This includes the cost of any damage to the asset itself, as well as the impact on the wider UK economy.	The impact that the loss/compromise of an asset has on the integrity of primary state functions and the integrity and delivery of critical state services. The primary functions of the state are defined, for the purpose of criticality assessments, as the maintenance of: a) national security and defence; b) ability to prepare for, respond to and recover from civil emergencies; c) ability to deliver critical state services to the public; and d) stability of Government.
CATEGORY 5 (Catastrophic)	Catastrophic loss of or disruption to essential services (e.g. national and long-term)	Catastrophic loss of life and/ or casualties (1,000+ fatalities/ 10s of 1,000s of casualties)	Catastrophic damage to the UK economy of c £10s of billions	Catastrophic loss of or disruption to the primary functions of the State
CATEGORY 4 (Significant)	Significant loss of or disruption to essential services (e.g. national short-term, or affecting millions of citizens)	Significant loss of life and/or casualties (101-1,000 fatalities/ 1,000s of casualties)	Significant damage to the UK economy of c £billions	Significant loss of or disruption to the primary functions of the State
CATEGORY 3 (Moderate)	Moderate loss of or disruption to essential services (e.g. regional or affecting hundreds of thousands of people)	Moderate loss of life and/or casualties (51-100 fatalities/ 100s of casualties)	Moderate damage to the UK economy of c £100s of millions	Moderate loss of or disruption to the primary functions of the State
CATEGORY 2 (Minor)	Minor loss of or disruption to essential services (e.g. affecting tens of thousands of people)	Minor loss of life and/or casualties (10-50 fatalities/10s of casualties)	Minor damage to the UK economy of c £10s of millions	Minor loss of or disruption to the primary functions of the State
CATEGORY 1 (Limited)	Limited loss of or disruption to essential services (e.g. affecting thousands of people)	Limited loss of life and/or casualties (<10 fatalities / less than 10 casualties)	Limited damage to the UK economy of c £millions	Limited loss of or disruption to the primary functions of the State

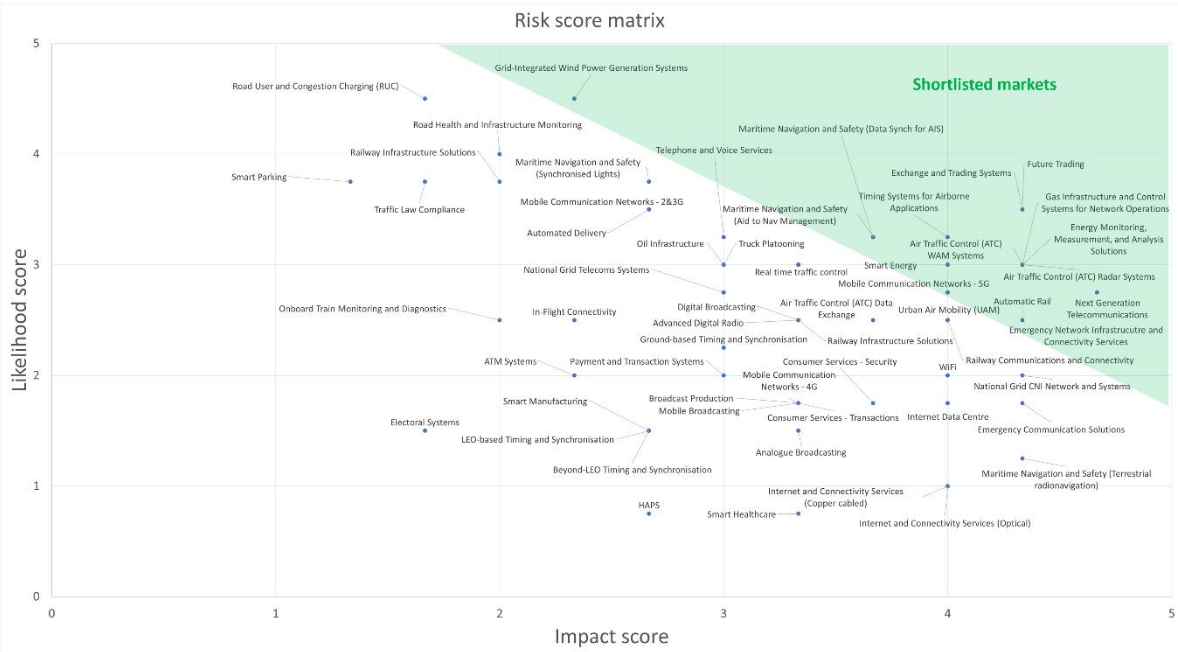
Note: Criticality was scored in each of these four categories, and the maximum value was used.

Source: UKSA PNT study.

A3.3 Shortlisted use cases

The 15 use cases with the highest willingness to pay were selected for shortlisting. The comparative scores of all use cases are shown in the matrix in Figure 95.

Figure 95 Matrix for shortlisting use cases



Source: LE analysis

A3.3.1 Prioritisation of use cases

The final 10 use cases selected for detailed analysis were chosen using a workshop with the client and Study Steering Group. This workshop centred around assessing use cases according to five desirable market criteria:

- **High willingness to pay:** Users within the market perceive resilient time to have a high value and are willing to spend money on a product or service.
- **Large market size:** Total potential demand for a resilient timing product or service.
- **High growth potential:** The likelihood or capacity of the market to experience expansion in the future.
- **Low barriers to entry:** The absence or minimal presence of challenges that may hinder new entries from capturing users within the market.
- **Broad customer base:** Diverse range of users within market who would purchase a resilient timing solution, controlling the bargaining power of buyers.

For each criteria, participants selected the top five and bottom five use cases, and these choices were used to narrow down the list to the top 10. In addition, it was ensured that a diverse range of market verticals were covered so the analysis was not restricted to a single area of opportunity, to investigate a broader scope of commercial potential.

Annex 4 Longlist of timing use cases

Table 56 Longlist of use cases

Use case	Description
Advanced Digital Radio	Digital Audio Broadcasting - Single Frequency Network (DAB-SFN) is a variant of the Digital Audio Broadcasting (DAB) standard designed to enhance the coverage, reliability, and efficiency of digital radio broadcasting services over terrestrial networks by employing synchronised transmission across multiple transmitters operating on the same frequency.
Air Traffic Control (ATC) Data Exchange	The sharing of data either: across the ground infrastructure that supports ATC operations - point-to-point node synchronisation OR air-to-ground comms. ATC relies on Master Clock System, which uses NTP linked to GNSS.
Air Traffic Control (ATC) Radar Systems	Comprises Primary Surveillance Radar (passive or non-cooperative) and Secondary Surveillance Radar (active or cooperative), which relies on aircraft having a transponder (Mode A/C/S).
Air Traffic Control (ATC) WAM Systems	Wide Area Monitoring (WAM) systems that make use of signals transmitted by an aircraft to calculate the aircraft's position. It is a distributed surveillance technology that works by deploying multiple sensors throughout an area to provide coverage of the desired airspace. WAM can be used as a replacement for secondary radar or complementary to ADS-B.
Analogue Broadcasting	The transmission of audio signals over terrestrial broadcasting networks using analog modulation techniques.
ATM Systems	Automated Teller Machine (ATM) Systems designed to provide automated and accessible banking services.
Automated Delivery	Refers to the application of automation and robot technology to support last mile deliveries in cities and delivery in remote areas.
Automatic Rail	Breadth of timing dependent applications that may be considered as part of a journey towards automatic train operation.
Beyond-LEO Timing and Synchronisation	Focuses on the in-orbit segment of BLEO spacecraft operations, i.e. activities associated with the operation, management, and control of satellites, once they have reached orbit.
Broadcast Production	Facilities or locations dedicated to the production, processing, and management of content for digital terrestrial broadcasting networks.
Consumer Services - Security	Security Digital Certificates, are cryptographic credentials used to authenticate the identity of users, devices, applications, or entities in digital communications, transactions, or interactions over networks, such as the internet.
Consumer Services - Transactions	Billing services encompass the processes and systems related to the generation, processing, or settlement of financial transactions for goods, services, subscriptions, or usage within consumer-oriented industries.
Digital Broadcasting	Digital Video Broadcasting - Terrestrial (DVB-T). DVB-T is a widely adopted and established standard for transmitting digital television signals over terrestrial networks, providing improved efficiency, quality, and versatility compared to traditional analogue broadcasting methods.
Electoral Systems	The process of casting votes in an election through electronic means, typically using computers, mobile devices, or specialised voting machines.
Emergency Communication Solutions	Emergency communications solutions provide reliable and reisilent communication technologies or systems tailored for emergency response or public safety applications.
Emergency Network Infrastructure and Connectivity Services	Specialised segment of telecommunications, focusing on the management of resilient communication solutions designed to support emergency response and public safety.

Use case	Description
Energy Monitoring, Measurement, and Analysis Solutions	Systems designed to monitor, analyse, and manage energy consumption, usage patterns, performance metrics, or operational parameters including the integration of alternative energy sources into the grid.
Exchange and Trading Systems	Regulatory compliance to facilitate and execute trading activities involving various financial instruments within organised marketplaces or exchanges.
Future Trading	Future of trading in financial markets, the advancements of technologies and trading techniques, particularly high frequency trading.
Gas Infrastructure and Control Systems for Network Operations	The physical assets and systems used in the management, monitoring, and operation of gas transmission, distribution, and storage networks.
Grid-Integrated Wind Power Generation Systems	Process of transferring the electrical power generated by wind turbines to the interconnected electricity grid or local distribution networks for distribution. Current turbines are completely autonomous from each other and all the balancing is managed by the grid at the sub-station.
Ground-based Timing and Synchronisation	Focuses on the ground segment of spacecraft operations, i.e. the terrestrial infrastructure, systems, facilities, and operations that support and facilitate the management, control, communication, operation, and monitoring of space missions, satellite operations, spacecraft, or other space assets from the ground.
HAPS	HAPS are defined as aircraft that fly at altitudes greater than 60,000ft. HAPS vehicles are typically unmanned and may be fixed-wing airplanes, airships or balloons.
In-Flight Connectivity	The integrated suite of entertainment and connectivity solutions deployed within commercial aircraft to enhance the passenger experience.
Internet and Connectivity Services (Copper cabled)	Broadband internet access technology that utilises existing telephone lines (copper twisted pair) to transmit data at high speeds over a short distance.
Internet and Connectivity Services (Optical)	Broadband internet access technology and infrastructure that utilises fibre-optic cables to transmit data using light signals.
Internet Data Centre	Data centres for Ecommerce which are designed to house and maintain networked computer servers, and infrastructure that support and facilitate the storage, processing, retrieval, and dissemination of digital data over the internet or other interconnected networks.
LEO-based Timing and Synchronisation	Focuses on the in-orbit segment of LEO spacecraft operations, i.e. activities associated with the operation, management, and control of satellites, once they have reached orbit.
Maritime Navigation and Safety (Aid to Nav Management)	AIS (Automatic Identification System) can serve as an Aid to Navigation (AtoN) by providing vessels, maritime authorities, or navigational stakeholders with real-time information or operational data regarding the location, characteristics, status, or conditions of various aids to navigation deployed within a specific maritime area, waterway, or navigational jurisdiction.
Maritime Navigation and Safety (Data Synch for AIS)	Automatic Identification System (AIS) is a key maritime communication system used by vessels to broadcast and exchange essential information, such as vessel identity, position, course, speed, navigational status, and other relevant data, to enhance navigational safety, collision avoidance, and operational coordination within the maritime domain. If a vessel's AIS receiver has no direct access to the GNSS time reference, it will either synchronise to another device or to the AIS base station with the largest number of incoming connections (known as a semaphore).

Use case	Description
Maritime Navigation and Safety (Synchronised Lights)	Synchronised lights leading into and out of shipping channels and waterways synchronised to GPS Time by GPS.
Maritime Navigation and Safety (Terrestrial radionavigation)	Navigation system that utilises ground-based transmitters to provide position, velocity, and timing information to marine based users or receivers within its coverage area.
Mobile Broadcasting	Production and transmission of live audiovisual content, events, or programs from remote locations using digital terrestrial broadcasting technologies and infrastructure.
Mobile Communication Networks - 2&3G	Second-generation (2G) and third-generation (3G) mobile communication technologies and standards that enable voice and data services over cellular networks using digital transmission techniques. These technologies represent significant advancements over earlier analog cellular systems, offering enhanced capabilities, features, and performance for mobile communications.
Mobile Communication Networks - 4G	Fourth-generation Long-Term Evolution (LTE) mobile communication technology and standard that offers enhanced capabilities, performance, and efficiency for voice and data services over cellular networks.
Mobile Communication Networks – 5G	5G mobile communication technology and standard that represents the latest evolution, advancement, and innovation in cellular network technology.
National Grid CNI Network and Systems	Network of power stations, powerlines and electricity infrastructure that allows electricity to be generated, transported and used across the country and its systems and procedures that facilitate its operation.
National Grid Telecoms Systems	To support its critical systems, National Grid has deployed a private telecommunications network for operational systems. This network utilises Synchronous Digital Hierarchy (SDH) technology in order to provide reliable and independent communications circuits with deterministic performance.
Next Generation Telecommunications	The deployment of sixth-generation (6G) wireless communication systems. Like its predecessors, 6G networks will be broadband cellular network, in which the service area is divided into small geographical areas called cells.
Oil Infrastructure	The operation of valves and pumps within oil infrastructure systems.
Onboard Train Monitoring and Diagnostics	Records data about the operation of train controls and performance in response to those controls and other train control systems. (Signals recorded may include: Wheel speed, power notch, break demand).
Payment and Transaction Systems	The integrated platforms, infrastructures, technologies, or networks designed to facilitate and manage financial transactions.
Railway Communications and Connectivity	The Global System for Mobile Communications-Railway delivers digital, secure, dependable communications between trains, signals and railway regulation control centres.
Railway Infrastructure Solutions	System of visual, audible, or electronic communication devices, and procedures used to control train movements, ensure safety, manage traffic flow, and facilitate efficient operations within a rail network or system.
Railway Infrastructure Solutions	Real time monitoring of Railways for detection of sudden defects and wears of tracks, trackbed, overhead electric and signal system. This enables infrastructures to act before there is a stop in traffic or accident.
Real time traffic control	The dynamic management and regulation of traffic flow within a transportation network using real-time data to optimise traffic conditions, enhance efficiency, ensure safety, and mitigate congestion, or delays.

Use case	Description
Road Health and Infrastructure Monitoring	Systematic assessment and evaluation of the physical condition and functionality of roads, motorways, bridges, or other transportation infrastructure assets to identify and mitigate potential issues that may impact the integrity of the transportation network.
Road User and Congestion Charging (RUC)	Implementation of fees on vehicles using specific roads, highways, bridges, tunnels, or urban areas to manage traffic congestion, reduce environmental impacts, generate revenue, or fund transportation infrastructure projects.
Smart Energy	Refers to the integration of advanced technologies within the energy sector to optimise the generation, distribution, and consumption of energy resources.
Smart Healthcare	The integration and application of advanced technologies within the healthcare sector to enhance the quality of healthcare services.
Smart Manufacturing	Smart manufacturing is a broad category of manufacturing that employs computer-integrated manufacturing, high levels of adaptability and rapid design changes, digital information technology, and more flexible technical workforce training.
Smart Parking	Smart parking applications provide real-time parking availability to drivers. Location services are then used to guide the driver to the best available space with turn-by-turn instructions.
Telephone and Voice Services	A communication system or infrastructure designed to transmit, route, and manage voice (telephone) calls using Time Division Multiplexing (TDM) technology within a telecommunications network environment. TDM is a technique used in telecommunications to share a single communication channel or transmission medium among multiple voice or data signals by allocating discrete time slots or intervals for each signal within the transmission cycle.
Timing Systems for Airborne Applications	Time required on-board and to communicate with aircraft. Aircraft require a time source to ensure the accuracy, reliability, and efficiency of various systems, operations, and functionalities onboard aircraft and to communicate with the ground.
Traffic Law Compliance	Ensures that traffic laws and regulations are being adhered to by monitoring and evaluating vehicles' compliance.
Truck Platooning	Platooning is the linking of two or more vehicles in convoy, using connectivity technology and automated driving support systems. These vehicles automatically maintain a set, close distance between each other when they are connected for certain parts of a journey, for instance on motorways.
Urban Air Mobility (UAM)	Refers to aerial vehicles that move people and cargo by air to provide on-demand transportation services within an urban area.
WiFi	The distribution of internet and web services utilising WiGi - a wireless communication standard and technology that enables devices to connect to local area networks (LANs), access the internet, and share data without the need for physical wired connections.

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