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RESEARCH ARTICLE

Techno-Economic Analysis of 5G Non-Public Network Architectures

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ABSTRACT The adoption of private 5G networks or Non-Public Networks (NPN) by industry verticals is igniting a digital transformation across various sectors and also leading to industry 4.0. This impetus comes from the integration of private wireless networks with 5G capabilities. Currently, a range of innovative applications and use cases are emerging and resulting in improved enterprise performance and solutions. The potential to boost revenue, stimulate cost reduction, and accelerate Return Of Investment (ROI) makes 5G NPN adoption attractive to industry verticals, network operators and other third-party stakeholders. However, a significant infrastructure upgrade is required, which demands understanding of the complexities of 5G NPN deployment scenarios and their economic implications. This paper addresses these needs by conducting a detailed techno-economic analysis on 5G NPN deployment. The study formulates a techno-economic model that focuses on; (i) Cost savings in support of ROI achieved by enabling Network Function Virtualization (NFV) technology and Neutral Host (NH) concept; (ii) The trade-off study between enterprise goals (cost vs deployment technologies) with a multi-objective sensitive analysis; And (iii) the trends of 5G NPN adoption worldwide. Analytical results confirm savings of up to 53% in Total Cost of Ownership (TCO) reflecting a significant reduction in Capital and Operation Expenditures (Capex and Opex). Simulation analysis identifies a ranking order of deployment parameters, which prioritise the use of Cost saving strategies and Deployment type. And finally, it offers a prediction of a starting annual average worldwide adoption rate of 82.2% with an expected height by 2026.

INDEX TERMS 5G, Capex, neutral host, network slice, NFV, NPN, Opex, private network, TCO.

I. INTRODUCTION

The Rel-16 document of the 3rd Generation Partnership Project (3GPP) has integrated 5G systems and private wireless networks. The integration is called 5G Non-Public Networks [1]. This paper will focus on the evolution, technologies, and business implications of deploying 5G NPN.

Private networks have evolved over the years, offering broadband connectivity to enterprises with inherent privacy, security, customised connection, and dedicated control of the network. Previously, various communication technologies, such as Ethernet, Fiber, Wi-Fi, WiMAX and Bluetooth, have been explored in private networks to provide connectivity for enterprise applications. Wi-Fi became the preferred technology for private networks because it delivers wireless connectivity with improved accessibility and efficiency at short range [2], [3]. Then, the arrival of 4G Long Term Evolution (LTE) technology further enhanced the development of private networks due to its superiority. Comparatively, 4G LTE delivers higher-capacity, improved coverage, superior penetration and economical for large

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scale deployments [2], [4]. However, the spectrum crunch that prevailed in the 4G LTE era hampered the growth of private wireless networks. The limited available spectrum was mostly allocated to public network operators, and often too scarce and expensive for private networks. Still, the strict spectrum regulations and the resulting capacity limits it imposes [2] against the higher performance requirements of evolving enterprise applications, often motivates industry verticals to seek more reliable and secured connectivity.

Currently, high speed, low-latency, and high bandwidth connectivity are requirements for some new applications [5]. These applications include those deployed in autonomous driving technology, interactive robot, cameras, radar and artificial intelligence (AI), smart factories, and other transformative technologies, some of which are pushing the emergence of Industry 4.0.

The arrival of 5G, creates innovative possibilities to deploy private networks. Its superior capabilities support different use cases, Enhanced Mobile Broadband (eMBB), Massive Machine-Type Communications (mMTC) and Ultra-Reliable Low-Latency Communications (URLLC) [6]. As a result, a new wave of opportunities for facilitating enterprise solutions has been triggered across a range of sectors such as manufacturing, transport, logistics, mining, entertainment, and healthcare [6].

Key 5G stakeholders in education, industry and regulation, recognize the importance of 5G NPN in meeting enterprise requirements. Some of these requirements are reliability and quality of service, security and privacy, bandwidth availability, low-latency, scalability and cost considerations [2], [7], [8]. The latest advancements in Network Function Virtualisation, Network Slicing and Edge computing technologies are emerging at a good time for 5G and private networks integration and transformation.

However, there are challenges to overcome towards achieving a successful commercial 5G NPN deployment. Firstly, the technical skills required to deploy and manage 5G NPN, stretch beyond what most enterprises can deliver. This is due to the complexities associated with 5G NPN deployment and operation. Secondly, the exponential growth in wireless network has not translated to a corresponding rise in profit margins [9]. It indicates the business and technical solutions are not evolving proportionally. Reference [10] has described the economic obstacles confronting Mobile Network Operators (MNOs) profit prospects when deploying 5G networks. The paper identified deterioration in Average Revenue Per User (ARPU) as one of the challenges.

Enterprise and network operators therefore, require a technical analysis to find the best deployment solutions for 5G NPN. In the past, technical and economic assessments have been conducted for 5G network deployment. Several publications, including [9]–[21] have examined the viability of different aspects of 5G networks deployment. These investigations range from the cost, coverage, deployment options, revenue, and technology implications. It has increased understanding of critical cost factors when deploying 5G networks. However, there exist a gap currently in the available research literature on 5G business cases [53] and especially on the techno-economic analysis of 5G NPN. This paper contribute towards filling this gap.

The study is an extension of [20], which had presented infrastructure as the most dominant cost component. The main contributions of this work are as follows:

- provision of in-depth techno-economic analysis of 5G NPN to evaluate the viability of a range of 5G NPN architectures.
- TCO calculation based on a cost saving model that integrates the traditional Capex and Opex calculations with a dynamic model for a sliced network.
- cost saving strategies for deployment with Network Function Virtualization technology and Neutral Host based use cases.
- a multi-objective sensitivity analysis of key 5G NPN parameters to determine their rank order of significance.
- forecast of the growth pattern of 5G NPN adoption over a period of 10 years across various regions of the world.

This study will benefit the 5G research community, industry verticals and 5G Enterprise Network Operators (5G ENOs). The analysis and results herein can support data-driven planning and informed decision-making.

The paper is organised as follows: Section II provides discussions on 5G NPN architectures, drivers and requirements. Section III offers technological strategies in deploying 5G NPN. Section IV performs analysis using models for cost, multi-objective sensitivity analysis, and deployment forecast then Section V presents evaluation of the various results. Finally, Section VI concludes the discussions.

II. 5G NPN ARCHITECTURES

This section provides analysis for the basic 5G NPN classifications. The advantages and disadvantages of the different deployment scenarios are also presented.

5G NPN architecture can be categorized broadly under two main headings - Standalone NPN (SNPN) and Public Network Integrated-NPN (PNI-NPN) [22]. One distinction between SNPN and PNI-NPN is how User Equipment (UE) from an NPN can access the public network. A UE from SNPN may connect to the public network through special function called the Non-3GPP Interworking Function (N3IWF). The N3IWF serves as a bridge between an untrusted Non-3GPP network (which the SNPN is in this case), and the (trusted public) 5G Core network. The UE's configuration is based on the subscriber's identifiers and credentials that are associated with a SNPN, which are also identified by the Public Land Mobile Network (PLMN) ID and Network ID. In PNI-NPNs, this is implemented by means of independent Data Network Names (DNNs) or Network Slice Instance assigned to the private network, and access could be controlled by implementing the Closed Access Group CAG (CAG) [23].

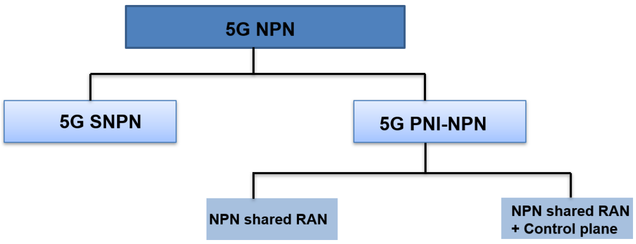


FIGURE 1. Architectural classification of 5G NPN.

Figure 1 illustrates the classification of 5G NPNs according to their architectures. In other words, the basic difference in their architectures is the isolation in the SNPN design and the extent of integration with a public network or PLMN in the PNI-NPN. This paper will focus on the configurations of three common types of NPN deployment as Figure 2 shows and compare them to the Legacy 5G network. These three architectures have been selected because their basic configurations replicates those of other NPN types.

A. 5G STANDALONE NPN

The 5G SNPN is an end-to-end isolated 5G network that is not supported by network functions provided by the public network. It is deployed with an independent NPN identity.

All network functions (User-Plane and Control-Plane), from the Radio Access Network (RAN) to Core network are deployed within a private premise and utilises a dedicated spectrum [8], [24]. As discussed above, 3GPP has a function (the N3IWF) that provides an optional link through a firewall to the public network. The operator of this NPN could be the private enterprise itself or an external third-party operator. The full control and management of the SNPN network functions lies within the capability of the NPN operator [24]. Some of the key advantages and disadvantages are summarised below. Advantages:

- Fully private, secured and isolated from external interference.
- Low latency prospects since all RAN functions are locally deployed.
- Maximum independent control and customization prospects.

Disadvantages:

- High deployment cost burden.
- Require localised highly skilled experts.
- Higher tendency for overprovisioning, leading to capacity under utilization.

B. 5G PUBLIC NETWORK INTEGRATED-NPN

Public Network Integrated NPN (PNI-NPN) is an NPN deployed in conjunction with a public network. Network infrastructure from the private and public networks are integrated, based on an agreement reached between the public network operator and enterprise. To be able to access PNI-NPN, a UE need to be subscribed to PLMN. This means that PLMN ID is a necessary requirement to be able to gain access to a particular PNI-NPN. Public Network Integrated-NPN may utilize the Closed Access Group control functionality. The CAG determines UE's access to PNI-NPN on a pre-configured basis. Details of this procedure has been provided in [25]. On the 5G Public Network Integrated-NPN, this paper will focus on the architectures of two configurations - the NPN Shared RAN and NPN Shared RAN + Control Plane. These configurations share common features with the other PNI-NPN variants.

1) NPN SHARED RAN

In this scenario, the NPN and PLMN shares common radio access network. This sharing is limited only to the RAN as all other network functions are still separated. The NPN maintains its own network identity and limits data flows from its traffic to the private network. Spectrum bands and Core network functions are also independent [8]. 3GPP specifications has defined the functionalities of Multi-Operator Core Network (MOCN) and Multi-Operator RAN (MORAN) [22]. While MOCN enables common radio frequency carriers for the public and private networks, MORAN supports an independent spectrum band for the private network different from the bands used in the public domain. Thus, MORAN allows NPN operators more flexibility to implement additional features at the cell level, such as configuration upgrade, parameter optimization, interference, and power levels for signal strength, which controls cell range [7].

These functionalities are the key enablers to achieving NPN shared RAN deployment and has proved to be a significant cost strategy for network operators. It permits operators to expand service footprint, coverage and hasten deployment. Savings can accrue from shared equipment, construction, and maintenance cost components, which falls within Capex and Opex cost components. A Neutral Host type deployment enabling sharing at the RAN side, can also support the cost reduction strategy for NPN and PLMN operators.

Some of the key advantages and disadvantages are summarised below. Advantages:

- Secured and less susceptible to interference due to licensed spectrum use.
- Moderate deployment cost.
- Functions mostly deployed locally, has low latency prospects.

Disadvantages:

- Only partially isolated from external interference.
- Limitations from external dependencies.
- Require some localised skilled personnel.

2) NPN SHARED RAN AND CONTROL-PLANE

Unlike the previous scenario, the sharing between the NPN and PLMN extend beyond the shared part of RAN. The Control Plane network functions are shared but resides in the public network, while the NPN User Plane Function (UPF) remains dedicated to data traffic in the private network. However, the data traffic associated with the

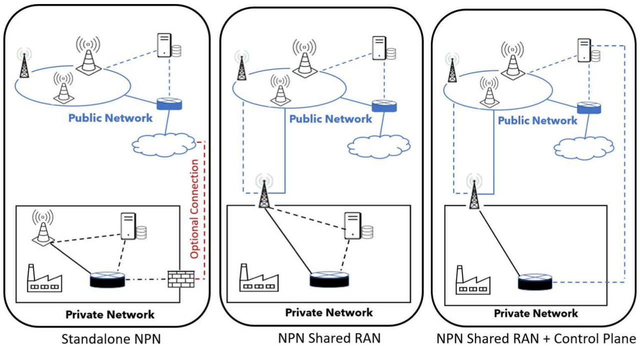


FIGURE 2. Selected architectures of 5G NPN deployment scenarios.

NPN devices utilizing the public slice may transit via the UPFs associated to the public slice managed and controlled by the PLMN, which is sited outside the NPN. This functionality is achieved via network slicing technique. For their respective implementation, the NPN and PLMN utilizes distinct slice identifiers [22]. The network functions in PNI-NPN deployment are separated either physically or logically between the private and public networks. Also, this deployment option can be implemented on a Neutral Host infrastructure and further serve as cost serving strategy for private 5G network operators. Some of the key advantages and disadvantages are summarised below. Advantages:

- Significantly reduced deployment cost.
- Service Level Agreements (SLA) are defined between public network provider and NPN operator.
- Interference free licensed spectrum.

Disadvantages:

- Susceptible to higher latency.
- Greater dependence on public network.
- Requires some localised skilled personnel.

Given the different deployment scenarios of 5G NPN, some technologies to support a deployment strategy is presented next.

III. 5G NPN DEPLOYMENT STRATEGIES

In this section, the key technologies enabling the 5G NPN model are briefly appraised. Also considered are the Neutral Host business concept and funding model in support of commercial 5G NPN deployment. Crucial to the choice of a deployment strategy are the use cases, their requirements and deployment scenarios.

For quick and cheaper private network deployment, models of pre-packaged or commercial-off-the-shelf (COTS) solutions have been suggested in some literature. While this could be a plausible temporary deployment solution, our analysis does not foresee a sustainable one-size-fit all solution for 5G NPN. The sheer differences in enterprise requirements and their diverse use cases would make a pre-packaged deployment solution unsuitable or less than-optimum for most enterprise requirements.

5G NPN use cases are already showing significant promises even as 5G network is yet to attain mainstream adoption. The potentials for enterprise application to raise revenue and set off cost reduction makes wide-scale adoption more realistic. Recent advances in Spectrum allocation, Edge computing, NFV and Network Slicing technologies are timely for the benefit of many 5G NPN use cases. For instance, to meet the strict latency and reliability demands of some use cases, a licensed spectrum, which is free for congestion and interference is considered better [8].

An important feature of the 5G NPN is the dedicated network capabilities in support of user requirements with spectrum availability. Security, scalability, reliability, high penetration, and low latency scenarios are particularly ideal for applications that support 5G NPN use cases such as mobile robots, autonomous vehicles, IoT devices, immersive reality, and other emerging applications. Manufacturing, transportation & logistics, healthcare, and energy sectors are leading industries requiring some of these uses cases.

The telecommunication company Nokia is currently implementing private network solutions, using with various use cases for airport deployment. The deployment strategy separates connectivity operations at the airport. Business and mission critical operations are offloaded to the more secured and reliable private network while freeing up public network Wi-Fi for passengers [55]. This is helping luggage and other asset tracking activities and creating better situation awareness for relevant operational areas of the airport. Turnaround time has improved resulting in reduced cost per turnaround. Brussels, Helsinki and Vienna airports have deployed these private network solutions to support their operations [56].

A. SPECTRUM APPROACH

One of the strategies for 5G NPN deployment is the choice of spectrum acquisition and utilization. The choice of spectrum usage needs to be well thought-out, since private wireless network operations are governed by legislation that determine access to operating license and other set rules.

There has been lots of concerns around private spectrum acquisition, but new trends are emerging. Previous papers on Spectrum for private 5G networks have tackled the issues surrounding private 5G spectrum licensing from diverse perspectives. Reference [24] identifies the different regulatory aspects of NPN deployment to be considered by individual countries as they adopt laws to govern private network infrastructure operation. The advantages and disadvantages of an NPN operator's dependence on MNO operating license has been considered in [6]. In addition, the UK Office of communications (Ofcom) has proposed the introduction of a new way to gain access to previously assigned spectrum that has been idle [26]. Ofcom has also promised to assist the increasing variety of wireless services and providers by way of enabling localised spectrum access [27]. These perspectives are being considered by telecommunication regulators, which [28] has categorised into four classes and can be summarised as:

- Allocation of private spectrum outside core mobile bands.

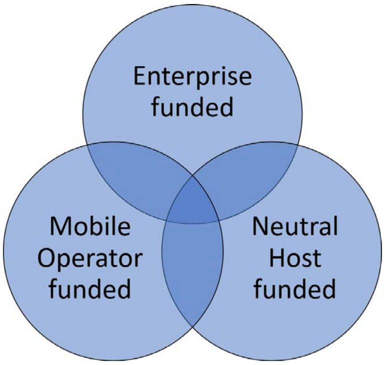


FIGURE 3. Funding model for 5G NPN.

- Customize spectrum licences according to the needs of verticals, such as spectrum subletting.
- Reserve dedicated spectrum within core mobile bands for industry verticals.
- The use of local licensing and spectrum sharing.

There are three different options for radio spectrum deployment in 5G NPN. These are the Licensed, Unlicensed and Shared Licensed Spectrum deployments [29]. The shared licensed spectrum has started to gain some prominence across many regions of the world. A popular example is the United States 150 MHz shared spectrum in the 3550 MHz to 3700 MHz band, called the Citizen Broadband Radio Service (CBRS). This has been a catalyst for the US private network market due to its low-cost acquisition. Table 1 indicates a growing interest across major national regulators in reserving spectrum to meet demands for private 5G licences.

TABLE 1. Spectrum reservations for private 5G licensing in selected countries [48].

Country	Regulatory Agency	Spectrum Reservation for Private or Local use	Spectrum Band
France	ARCEP	266 MHz	2570 MHz - 2620 MHz
Germany	BNetA	100 MHz	3700 MHz - 3800 MHz
The Netherlands	ACM	100 MHz	3400 MHz - 3450 MHz & 3750 MHz - 3800 MHz
Sweden	PTS	80 MHz	3720 MHz - 3800 MHz
United Kingdom	Ofcom	400 MHz	3.80 GHz - 4.20 GHz
United States	FCC	150 MHz	3550 MHz - 3700 MHz
Japan	MIC	100 MHz	28.2 GHz - 28.3 GHz

B. NETWORK SLICING AND NETWORK FUNCTION VIRTUALIZATION

Network slicing and Network Function Virtualization are two technologies that 5G network has further provisioned, which is timely for 5G NPN deployment.

1) NETWORK SLICING

Network slicing is especially appealing for co-existence of multiple services or applications inside the private network. It is a 5G enhancement to cloud and virtualization technology. The 3GPP has defined network slice as a ''logical network that provides specific network capabilities and network characteristics'' [30]. This translates to the provisioning of a dedicated end-to-end multiple logical networks that can operate virtually on a shared infrastructure with capability of supporting agreed service quality [24]. Every slice measure to agreed service requirements as specified in the SLA, such as latency, data rate, quality of service (QoS), and other key performance indicators. Slicing also offers the capacity for traffic isolation which is vital for performance guarantees in multiple service/application scenarios. Mobile operators and industry verticals anticipate new revenue streams from customised services because of slice capability.

2) NETWORK FUNCTION VIRTUALIZATION

NFV technology is transforming networking. Virtualized network functionalities that were previously handled by dedicated hardware now run on Commercial off-the-shelf (COTS) servers. Combined with Software Defined Network (SDN), NFV offers a huge flexibility in the management of network flows [31]. NFV helps to reduce energy consumption and hardware costs, thereby impacting on Capex and Opex.

C. FUNDING MODEL

How the private 5G Network deployment is funded constitute part of the plan towards 5G NPN implementation. Mobile Network Operators have been the main funders of mainstream wireless infrastructure, but 5G NPN is likely to witness a different funding model.

Currently, there are three concepts regarding 5G NPN funding strategy. The first is for the Enterprise, who is the infrastructure owner to deploy and operate. The second involves the use of third parties to operate and manage in an Operate and Manage (O and M) arrangement. This could consist of outsourcing through a Neutral Host model or just any third-party industry player. The third is spectrum owner management, which means spectrum owners such as MNOs operating the NPN. The degree of funding is subject to several factors based on the type of NPN architecture selected for deployment. Figure 3 illustrates the funding model considered in this study.

A brief description of Neutral Host follows next. Ahead of the Enterprise and Mobile Operator funded models, more consideration has been given to discuss the Neutral Host concept. The special attention on Neutral Host is because it constitutes a part of the cost reduction strategies used in our model. Neutral Host adoption is witnessing increased relevance within the evolving wireless industry ecosystem and paving the way for reduced physical infrastructure ownership. Neutral Host model offers the most promising solution in terms of cost management suitable for private network deployments and even in remote locations. Also, the diverse enterprise requirements need tailored solutions for each use case, which Neutral Host can support better. Another reason for Neutral Host focus is that the Mobile Operator funded model has been largely tested while the Enterprise funded model though emerging, lacks the flexibility Neutral Host offers.

1) NEUTRAL HOST

The concept of Neutral Host supports deeper levels of infrastructure sharing. This can be beneficial for private 5G network deployment, given the ROI challenges associated with wireless network deployments.

Neutral Host is a shared wireless infrastructure that offer services to end-users from different hosted operators [32]. The concept has been around since Wi-Fi and 4G technologies but has gained considerable traction with 5G emergence. It is gathering more momentum with the development towards NFV/SDN and Open RAN. Neutral Host supports the provision of differentiated services. Such deployment has the potential to deliver cost efficient coverage and capacity for wireless users in places such as enterprise facilities like warehouses, event centres, campuses, airports, and other NPN scenarios.

Network slicing, NFV technology, and Spectrum together with Neutral Host, form a useful integration for 5G NPN. Based on NFV and scalable network, slices can be implemented to support the decoupling of network function instance. This enables more Virtualized Network Functions (VNFs) and less hardware with positive Capex implications.

IV. 5G NPN COST, SENSITIVITY AND FORECAST MODELS

In this section different models are presented towards 5G NPN deployment, cost reduction solutions, sensitivity analysis of key deployment parameters and global penetration prediction. A justification in support of the choice of methods and model precedes the model formulations.

The Cost model analysis extends the earlier work in [21], which calculates the TCO of 5G networks for non-sharing infrastructure in three geo-type scenarios. This paper goes further to specifically perform cost calculations for private 5G networks in an infrastructure sharing model.

Justifications are provided in support of the model formulations. Cost calculations are performed for a dynamic sliced network in a Neutral Host based use case. The result is then integrated with Capex and Opex calculations to achieve the Total Cost of Ownership. Following these cost calculations, is a multi-objective sensitivity analysis that examines the key deployment parameters to verify their significance in 5G NPN deployment outcomes. Finally, a worldwide 5G NPN adoption prediction is provided.

A. JUSTIFICATIONS FOR MODEL

The following are some justifications for applying this model, key assumptions, and methods. The three 5G NPN architectures have been selected because their basic configurations replicate other variants of NPN architectures as described in section II.

The TCO for Legacy 5G network, simply equals the summation of the total cost of their respective Capex and Opex without consideration for the dynamic characteristics of a slice based network. As considered in this study, the higher level of granularity encompasses the different network resource types and their capacities. It therefore offers more realistic TCO calculation.

The calculations for capacity planning, Capex and Opex followed the earlier study as in [21] and has in addition formulated the model based on the following assumptions:

- 40% Energy savings from NFV usage;
- 2 Km radio Coverage area;
- 50% sharing for Neutral Host;
- 4.4% annual inflation rate;
- 5G NPN projected adoption follows wireless communication adoption for selected countries;
- Market capacity (m) follows wireless market size for selected countries.

40% energy savings from NFV has been arrived at based on research literature. The conclusions in [33] and [34] corroborates the current research opinions, which suggest that reduction in energy consumption can be on the order of 40 percent when Network Function Virtualization/Software Defined Networking technology is deployed.

The 2 km coverage area has been considered based on Coverage radius of 5G small cell, typical area of major industrial sectors and campus-based environments, such as airports, factory, warehouse, events centres, and underground transport networks, which form the primary deployment scenarios of 5G NPN.

The infrastructure sharing option is based on Neutral Host concept as described in Section III. Neutral Host has continued to gain traction following the 5G styled service based architecture (SBA) [49]. The SBA design enables Neutral Host to leverage 5G services to offer customised and differentiated services with reduces outlay.

The rate of annual inflation was set at 4.4% based on the prevailing figure for the European Union as of October 2021 [54], when computation for this study was conducted. European Union inflation figure has been selected since cost items have been listed in Euro currency. Due to global economic instability, the rate of annual inflation in the European Union like many parts of the world, has been on the increase since then. As this has changed frequently but has not significantly alter the overall results, we have decided to stay with the computed figure.

The cost for reparation was modelled based on the probability of failure. The Weibull distribution used for failure analysis in reliability engineering was applied. This is based on its reasonable accuracy in failure forecast given small samples [35].

In forecasting the 5G NPN adoption the Bass diffusion model was employed. Fitted with parameter values, the model generates a life-cycle S curve. Values of the parameters are approximated from histories of previous generations of wireless network penetration from the selected countries as in [45]. The justification for this approximation is based on the point that the adoption of the fifth generation Non-Public Networks as a product or service, can be considered analogous to those of previous generations of wireless networks. Similarities in both products are visible in their growth patterns, which follows the same market capacity (m) and behaviour.

The traditional *factor* method for Capex and Opex, TCO calculations is unsuitable for a sliced network. The *factor* technique simply approximates cost by applying unit cost against total size. This is a limitation because there can be variations in the Key Performance Indicators (KPIs) as these depend on different network resources which may be shared in the form of slices. Such variations result in fluctuations in expenditure calculations and thus render the conventional Capex and Opex approaches of cost estimation inappropriate for sliced networks. To overcome this, the study applied the same predefined KPIs for the slices across the different network resources in the selected NPN scenarios for the cost calculations. The KPIs include availability, throughput, reliability, capacity, efficiency, and latency, which are defined in the SLA.

Many research publications including some cited earlier, have explored the overall Capex and Opex gains from the use of NFV or Neutral Host. This study extends previous findings by examining the impacts of a combination of NFV and NH on individual elements of Capex and Opex. This breakdown deepens the understanding of NFV and NH and their implications on Capex and Opex components.

B. COST MODEL FOR SLICED BASED NETWORK

The sliced based Network calculations considered an end-to-end network slicing, from RAN to the Transport, and Core networks, which follows those of [36] and [37]. At the different segments of the network, a slice may denote various interpretations. At the RAN section, sub-channel frequencies can be categorised as slices, while Virtual Network Functions (VNFs) and network functions are mapped as slices in the Core network, and bandwidth specifications defined as slices at the Transport portion of the network [31]. Based on a given SLA, a VNF can be created to meet the requirements of a set of performance indicators expressed as:

$$\mathrm{K} = [K_1, K_2, K_3, K_4 \ldots K_m]$$

Following this, the capacity of the network resources such as spectrum, bandwidth, power, time, or other compute resources can be projected from the VNF V and slice size S, which is the size of client applications that runs within each slice. Where n is the quantity of resource types, the required volume in a vector is expressed as:

$$\mathbf{r} = [r_1, r_2, r_3, r_4 \ldots r_n]$$

The cost for every resource can be expressed as:

$$\mathrm{Cost} = \mathrm{Cost}(r), \quad \text{for } \mathrm{r} = r(k, S, V)$$

The cost of each type of resource is then assigned to the required slice. The cost of the RAN and Transport segments are evaluated against the cost of the throughput projected on the two portions of the network. The slice cost is obtained as follows:

$$C_{slice} = C_{Thp} + \sum_{i=1}^{k} C_{VNF(i)} + \sum_{j=1}^{l} C_{phNF(j)} \tag{1}$$

where C_{slice} denotes cost of the slice, C_{Thp} represents cost of the throughput of the slice, $C_{VNF(i)}$ is cost of the VNF, $C_{phNF(j)}$ is cost of physical network functions, k is number of VNFs in the slice and l is number of physical network functions in the slice.

C. COST MODEL FOR CAPEX, OPEX AND TCO

Following the integrated 5G NPN cost model building blocks, the next step provides the calculations for Capex, Opex and TCO.

$$TCO_{5G_{NPN}} = \sum_{i=1}^{N_c} Capex_{5G_{NPN(i)}} + \left(\sum_{i=1}^{N_o} Opex_{5G_{NPN(i)}} \right) N_{yrs} \tag{2}$$

where: $TCO_{5G_{NPN}}$ denotes total cost of 5G NPN deployment, $Capex_{5G_{NPN(i)}}$ represents sum of capital expenditures, $Opex_{5G_{NPN(i)}}$ is sum of operational expenditures plus inflation, N_c is number of cabinet(s), N_o represents number of office(s) and N_{yrs} denotes number of years used for Opex calculation.

Capex represents capital expenditure. This is a one-off cost to acquire or upgrade fixed assets. The computations are derived from the summation of all the Capex cost elements –equipment, infrastructure, installation cost and licence fee.

$$Capex = \sum_{i=1}^{N_{Eq}} Cost_{Eq(i)} + \sum_{i=1}^{N_{Infra}} Cost_{Infra(i)} + \sum_{i=1}^{N_{Insta}} Cost_{Insta(i)} + \sum_{i=1}^{N_L} Cost_{Lfee(i)} \tag{3}$$

where $Cost_{Eq}$, $Cost_{Infra}$, $Cost_{Insta}$ and $Cost_{Lfee}$ denotes cost of equipment, infrastructure, installation, and Spectrum licence fee respectively. The summation goes from $i = 1$ to the number (N) of the respective Capex components.

Opex characterizes Operational expenditure. This refers to all ongoing cost elements required to keep the service in operation. The key Opex components are energy consumption, maintenance, and fault management or reparation cost as discussed in [20].

$$Opex = 365 \left[\sum_{i=1}^{N} (24P_h \cdot C_E) \cdot N_{C(i)} \right] + \sum_{i=1}^{N_m} C_M \cdot C_{F(i)} + \sum_{i=1}^{S_n} C_{slice(i)} \tag{4}$$

where P_h, C_E, N_C, C_M, S_n and C_F stand for electric power needed per hour, energy cost per kWh, number of cabinets in Central Office, cell sites or street, costs of maintenance, number of slices and fault management respectively. The cost of energy consumption for one year has been calculated using the formulation.

$$Cost_{En} = 365\left(\sum_{i=1}^{N} 24P_h \cdot C_E \cdot N_{C(i)}\right) \tag{5}$$

Detail formulations for other cost elements such as equipment, infrastructure, maintenance, and fault reparation follow those presented in [21], as well as Table 2, which offers estimated costs used for the calculations.

TABLE 2. Values used for cost calculations.

Components / Parameters	Price (Euros)	Source
OLT core shell	5000	[50]
OLT cross connect	8000	[50]
OLT service shell	5000	[50]
ONT	150	[50]
Technician salary (hour)	52	[16]
Small / large microwave antenna	200 / 2000	[16]
Power splitter (1:16 / 1:32)	170 / 340	[16]
Fiber (km)	80	[16]
Trenching (km)	45000	[16]
Microwave link	400	[51]
Yearly cell site rent	8000	[51]
Microwave hub	800	[51]
Electricity cost	0.2 per kWh	[52]
Energy consumption per hour	1.4 kW	[52]

TABLE 3. Application of cost saving strategies on 5G NPN deployments.

Deployment Type	Neutral Host	Network Function Virtualization
Legacy 5G Network	No	No
SNPN	No	Yes
PNI-NPN	Yes	Yes

This study considered Neutral Host concept and NFV technology to determine the Capex, Opex and TCO. The results from these calculations were compared to that of the 5G Legacy network with similar dimensions. The TCO calculations for the 5G Legacy network is performed for a deployment without Neutral Host and NFV. In contracts, NFV technology was deployed in all the 5G NPN scenarios, but Neutral Host was only considered in the PNI-NPN cases and not in SNPN calculations. This is illustrated in Table 3, which shows the application of the cost saving strategies used in the selected deployments. It forms the basis for the constraint's formulation used in the multi-objective sensitivity analysis presented later.

Figure 4 expands the conventional concepts of TCO calculation found in previous works [16]–[19], upon which the building block for the cost model was formulated. It integrates the dynamic cost model for sliced networks in a Neutral Host based use case, on top of the traditional TCO calculation.

D. MULTI-OBJECTIVE SENSITIVITY ANALYSIS MODEL

Sensitivity analysis is presented to provide understanding of how variations in key parameters of the model can impact the network deployment outcome. It shows the models reaction to fluctuations in the weights of the input parameters. Following the analysis, the most significant parameters for 5G NPN deployment model are identified and ranked. Since there are different competing business interests and goals, single objective is unrealistic in this case. Multi-Objective analysis helps to determine priority levels for business interests such as the enterprise themselves, mobile operators and even a third-party stakeholder. The evaluation considered three objectives, which are derived from input parameters that can be optimised for cost effective 5G NPN deployment. The calculations for the formulation were solved using IBM ILOG CPLEX v.11.0 software [41].

1) 5G NPN DEPLOYMENT: PROBLEM DEFINITION

The aim is to find the optimal solution that implements the most secured 5G NPN, at the least deployment cost, with the most energy savings. These parameters form key deployment requirements for 5G NPN adopters [38]–[40].

The following parameters are defined as objectives:

- Deployment type
- Funding model and
- Cost saving strategy

Within the multi-objective framework, they assume the corresponding objective values $d(x)$, $f(x)$ and $e(x)$. The objectives are implemented subject to assigned performance metrics which forms a set of predefined constraints. The three deployment options - SNPN, NPN Shared RAN, and NPN Shared RAN + Control Plane, make up the variables of the first objective. Priority levels are set to high, medium, and low.

We analysed the trade-off between objectives $d(x)$, $f(x)$ and $e(x)$ by extending the multi-objective optimization models proposed in [42] and [43] and solved as Mixed-Integer Linear Programming (MILP) using IBM ILOG.

2) MATHEMATICAL FORMULATION FOR 5G NPN DEPLOYMENT OBJECTIVES

Using the weighted sum approach, we assigned weight to each objective as introduced in [43] and generalized in the equation:

$$f_{sum}(\cdot) = \sum_{n=1}^{N} a_n g_n(x) \tag{6}$$

where $a_1, \ldots, a_N$, are weights in positive values that indicates priorities assigned to each objective. The summation of all weights equal one. The objective value is represented in the equation as $g(x)$.

The first objective $k_1(x)$ seeks to maximize network security within the various deployment options. The second objective $k_2(x)$ attempts to minimize financial outlay based on the funding model and the third objective $k_3(x)$ maximizes energy savings based on the applied cost saving strategies. These objectives are formulated as:

$$k_1(x) = \sum_{n=1}^{N} a_n d_n(x) \tag{7}$$

$$k_2(x) = \sum_{n=1}^{N} a_n f_n(x) \tag{8}$$

and

$$k_3(x) = \sum_{n=1}^{N} a_n e_n(x) \tag{9}$$

Based on the model in [42] the 1st, 2nd and 3rd objective functions are denoted by k_1, k_2, and k_3. They are renormal-ized after assigning weights due to the resulting variations in their scale. The scaling factors Δ_1, Δ_2 and Δ_3 for the respective objective functions can be expressed as follows:

$$\Delta_i = \frac{max_{j=1,2,3} Range_j}{Range_i} \tag{10}$$

To establish the optimal range of the respective objective function, each of the objective formulations in equations (8) to (10) are computed and the solutions represented as s_1, s_2, and s_3. Their optimal range can then be calculated as:

$$Range = \max_{j=1,2,3} k_i(s_j) - \min_{j=1,2,3} k_i(s_j) \tag{11}$$

where $i = 1, 2, 3$

The respective k_1, k_2, and k_3 are multiplied by their assigned weights.

Where

$$\delta_1, \delta_2, \delta_3 \geq 0$$

and

$$\delta_1 + \delta_2 + \delta_3 = 1.0$$

$$max \begin{cases} +\delta_1 \Delta_1 k_1(x) \\ -\delta_2 \Delta_2 k_2(x) \\ +\delta_3 \Delta_3 k_3(x) \end{cases} \tag{12}$$

The constraints is the model are defined by (7) - (12).

The constraints are determined by the limits imposed by the cost saving strategies. This approach did not follow the conventional optimization which consider one of the objectives as the exclusive objective and the others become constraints. Instead, the concept which acknowledges the reality of multiple and competing objectives used in [43] was adopted.

Deployment type, funding model and cost savings constitute the key parameters of the model and together form the model's building blocks. The Deployment type is determined by any one of the considered deployment options - SNPN, NPN shared RAN and NPN shared RAN + Control Plane. The funding model defines the percentage of infrastructure sharing when applied, while the cost savings parameter is derived from the 40% energy reduction attributable to NFV implementation [33].

E. 5G NPN ADOPTION FORECAST MODEL

While the analysis on 5G NPN architecture and its deployment supports enterprises to make better choice of deployment, the assessment is further strengthened by the provi sion of a global penetration forecast. The adoption timeline provides the basis and validation for enterprises to make informed business decisions regarding 5G NPN adopt.

To achieve this, the study used Bass Diffusion Model to forecast the 5G NPN penetration for a period of ten years in seven countries. The countries are loosely representative of the diverse wireless markets around the world.

The concept of diffusion tries to describe how, why, and at what rate new technologies spread. Current NPN literature lack discussions of global 5G NPN diffusion trends. This study addresses that gap by modelling the 5G NPN diffusion prospects in different parts of the world. It will help to trigger research conversations around this subject. It will also widen perspectives on how global penetration tendencies relate to economic considerations and deployment strategies for industry verticals.

1) BASS DIFFUSION MODEL EXPLAINED

This models the adoption of new products or technologies in a given population m. It follows a binary diffusion pattern that has been classified into two types of adopters [44]:

- Innovators p – those with earliest adopter tendencies; and
- Imitators q – those with tendencies to observe a new product before adopting.

The Bass model equation can be expressed as:

$$y(t) = m(1 - e^{-(p+q)t})/(1 + (q/p)e^{-(p+q)t}) \tag{13}$$

with

$y(t)$: penetration (adoption) rate at time t,

m: cumulative market potential on the whole product's life cycle,

p: coefficient of innovation, characterised by external influence, and

q: coefficient of imitation, characterised by internal influence.

Successful products follow a trend regarding the values of p and q parameters, which are mutually dependent. The internal influence exceeds the external as represented below:

$$q > p; \quad -- > t > 0$$

The Bass model is designed to provide forecast explanations to the questions of how and at what rate new technologies are adopted.

The Bass model was applied to predict the rate of 5G NPN adoption in seven selected countries. The level of economic, demographic, and technological development of the countries are representative of the different regions of the world. The coefficients of innovation p relate to the probability of an early adoption, which is based on parameters from the adopters such as wealth, culture, and time effect [45]. This element substantially impacts the rest of the diffusion process including the imitators. Hence the behaviour leading to the trend for imitation is described in the coefficient of imitation.

2) ADOPTION RATE CALCULATION FOR 5G NPN

5G NPN is considered here as a new technology product. The market segment of the various countries that are likely to adopt NPN earliest are the innovator p while the imitators q would be late implementers.

The rate of wireless technology adoption has been used in the Bass model calculation to determine coefficients of p and q for the selected countries. This aligns with that of [45], which suggest that wealth and cultural similarity are factors that determines a country's tendency to be an early adopter. The value of m was assumed to be the size of the wireless market in the respective countries. The selected countries represent significant wireless markets, whose individual p and q parameters are considered reflective of countries with similar economic classification within the same region. This selection cuts across national economies at different stages of development according to the United Nations World Economic Situation and Prospects (WESP) report 2020. How the economic classification and market size impact on the adoption rate makes for a useful comparative analysis in forecasting global 5G NPN penetration rate.

TABLE 4. Coefficients of innovation and imitation for selected countries.

Country	*Classification	p	q
Australia	Developed	0.00072	0.64
Brazil	Developing	0.00097	0.77
China	Developing	0.00060	0.53
South Africa	Developing	0.00097	0.77
Sweden	Developed	0.00018	0.45
United Kingdom	Developed	0.00072	0.64
United States	Developed	0.00072	0.64

*United Nations World Economic Situation and Prospects 2020

Table 4 shows the values for p and q parameters for the chosen countries. Brazil and South Africa share identical values. The values of their parameter indicate high uncertainty avoidance and late adoption of wireless communication.

Australia, United Kingdom, and the United States all share parameter values that show early adoption. Sweden's values reflect the earliest adopters, while China shows adoption ahead of those in similar economic classification.

V. RESULTS AND SIMULATION ANALYSES

This section presents the results from the various models discussed in section IV. The outcomes are considered in the order in which they have been evaluated.

A. COST MODEL OUTCOMES

Results of four deployment scenarios have been analysed, to identify their viability against enterprise requirements. Consequently, better understanding of the different deployment parameters have emerged. The results put in comparison the different cost elements within the Capex and Opex components. A breakdown of the two components identifies

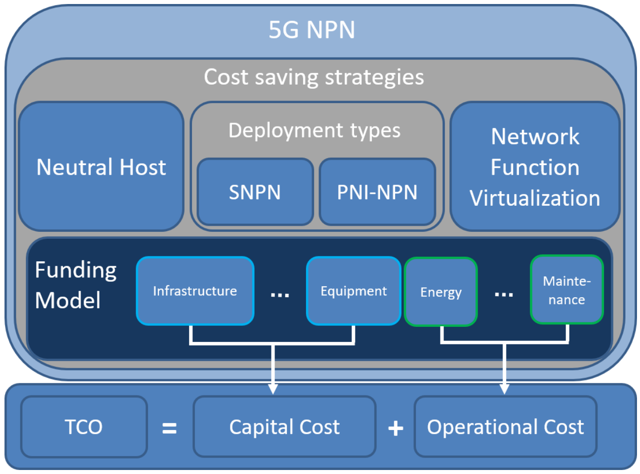


FIGURE 4. Integrated building block of the 5G NPN Cost model.

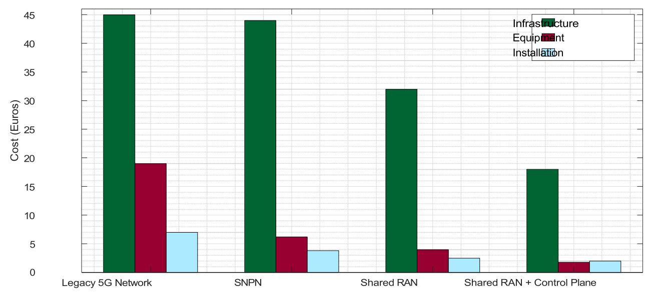


FIGURE 5. Capex breakdown calculations.

cost elements with the greatest cost reduction effects from the model's cost savings strategies. The various costs are presented in three forms. These are the raw cost in monetary unit - Euro, scaling factor and percentage.

1) CAPEX CALCULATION OUTCOMES

Infrastructure remains the dominant Capex cost element across all the deployment scenarios as Figure 5 illustrates. The result shows evidence of greater cost savings in the other Capex elements (Equipment and Installation) when Neutral Host and NFV are implemented. A breakdown of the result shows that Equipment holds the most cost savings - up to 68% for NPN shared RAN + Control plane and 33% for NPN shared RAN. Installation and Infrastructure cost elements follow next in that order. However, the cost reduction scaling factor (the extent of reduction) varies for the deployment types and Capex elements as shown in Figure 6 (a). The most reduced scaling factor for Infrastructure is in NPN Shared RAN + Control Plane. This means the highest reduction in Infrastructure cost will occur at NPN Shared RAN + Control Plane while the least will be at SNPN. Conversely, the least reduction in Installation cost occurs at NPN Shared RAN + Control Plane while the highest Installation reduction cost is at the SNPN. Across all scenarios, Equipment has the best reduction scaling factor at 0.32, against 0.56 for Infrastructure and Installation respectively. This demonstrates the cost reduction potentials of different Capex elements against the

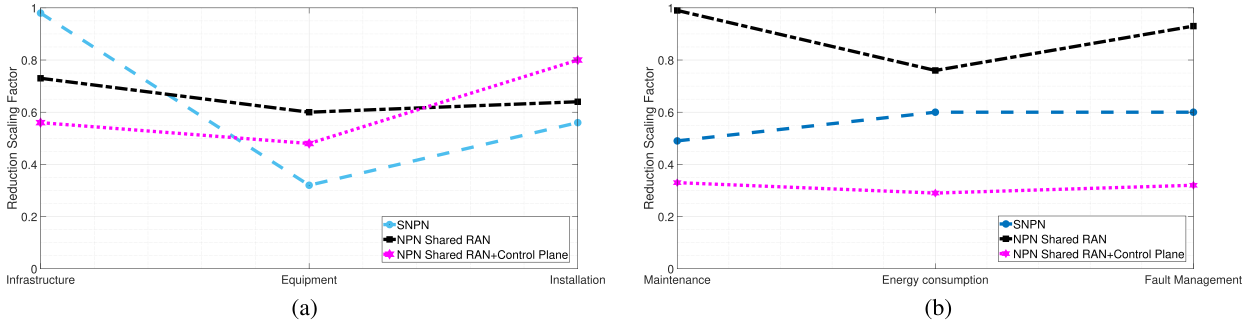


FIGURE 6. **(a) Capex reduction scaling factor. (b) Opex reduction scaling factor.**

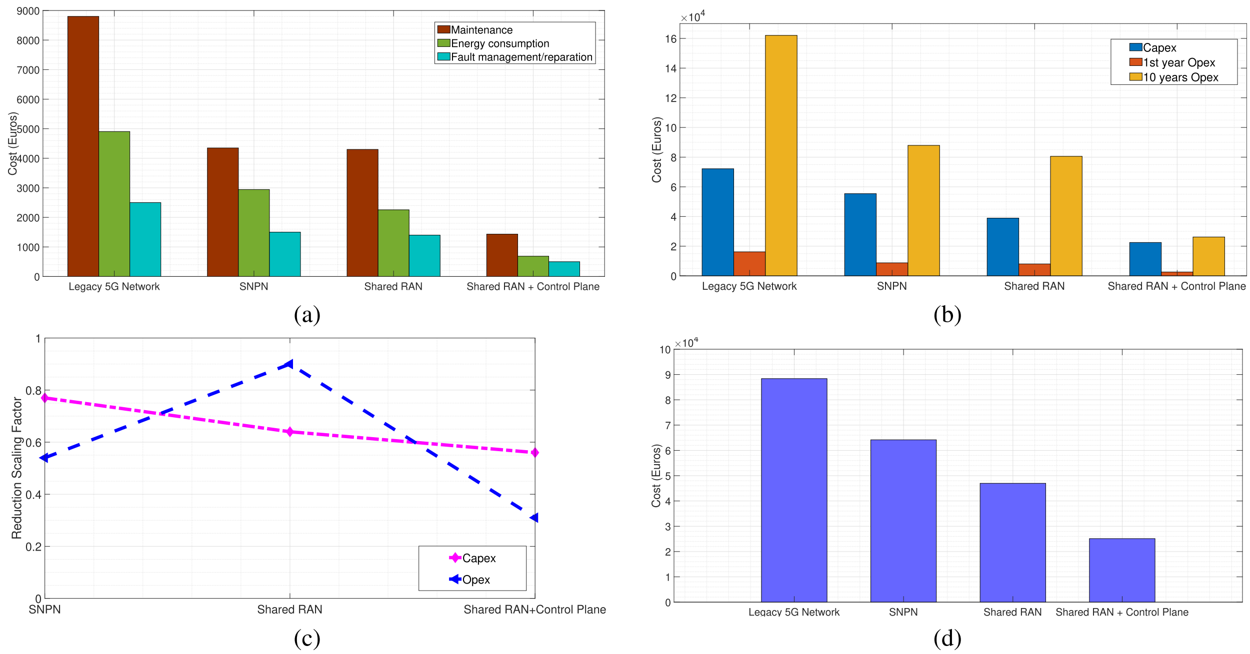


FIGURE 7. **(a) Opex breakdown calculations. (b) Capex and Opex comparison. (c) TCO reduction scaling factors for Capex and Opex and across NPN deployment types. (d) 5G NPN Total Cost of Ownership.**

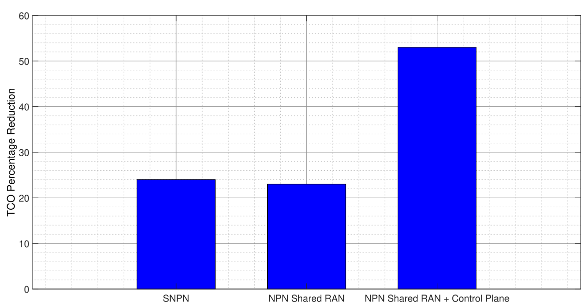


FIGURE 8. **Percentage reduction in total cost of ownership across NPN deployment types.**

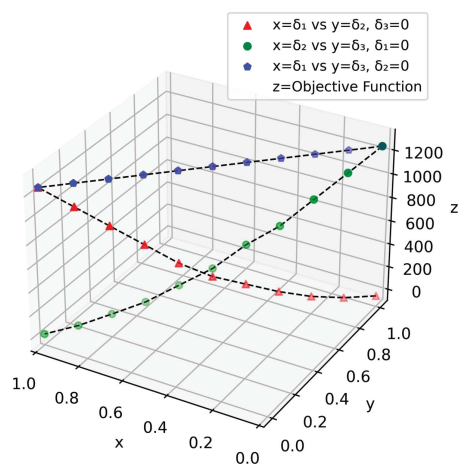


FIGURE 9. **Weights of δ_1, δ_2 and δ_3 corresponds to deployment type, funding model, and cost saving strategies parameters respectively.**

deployment types. It is instructive that SNPN has the best reduction scaling factor for Equipment and Installation. This is because SNPN was compared with the Legacy 5G network, which is the baseline for comparison. This understanding is important for Enterprise Network Operators who need to identify the cost elements with the potential for the most cost savings and understand how cost reduction progresses with deeper network integration.

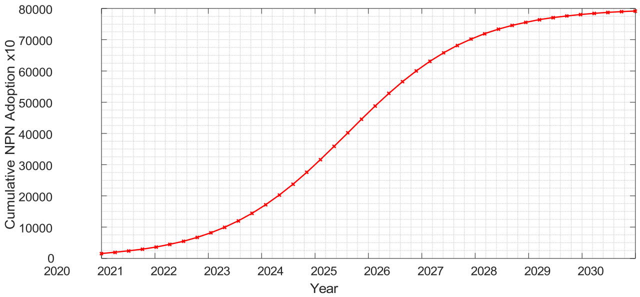


FIGURE 10. **NPN adoption forecast for 10 years.**

2) OPEX CALCULATION OUTCOMES

Using the reduction scaling factor, Figure 6 (b) shows that the best options for cost reduction are in energy consumption and NPN Shared RAN + Control Plane deployment. The Opex calculation show that energy consumption has the most cost savings across Opex cost elements as captured in Figure 7 (a). The results reveal up to 22% cost reduction for NPN shared RAN and 77% for NPN shared RAN + Control plane. The energy saving findings align largely with previous works on 5G Networks Opex calculations, in cases where NFV was considered. The use of NFV therefore, provides the reason for this corroboration in energy consumption savings. One striking feature of the result is the significant cost reduction across all Opex elements in NPN Shared RAN + Control Plane deployment.

3) CAPEX AND OPEX COMPARISON

Figure 7 (b) presents Capex and Opex comparison. It offers a breakdown of how infrastructure sharing or renting, through Neutral Host, impacts on the individual Capex and Opex cost elements across deployments. Neutral Host start out by inducing more savings on Capex than Opex. These savings arising from Capex and Opex, offers significant incentives to potential new customers to adopt 5G NPN in preference to the Legacy 5G network.

Generally, the cost reduction scaling factors tend to decrease as network integration increases. This is captured in Figure 7 (c). However, in the long term Opex savings assume prominence when private network allows deeper integration with public network. The exception is in the Opex of NPN Shared RAN. The spike in reduction scaling factor for NPN Shared RAN is due to the marginal cost difference between SNPN and NPN Shared RAN deployment.

4) TCO CALCULATION OUTCOMES

The TCO results are consistent in demonstrating greater cost savings with NFV and NH implementation. Figure 7(d) validates the cost advantages of NFV and NH cost saving strategies for 5G NPN deployments. TCO for the individual scenarios decreases with increase in network integration.

Figure 8 shows the percentage reduction in TCO across the three NPN deployment scenarios under investigation. It shows that NPN Shared RAN + Control Plane holds the most cost reduction at 53% when deployed.

B. OBJECTIVE FUNCTION ANALYSIS

Figures 9 and 11 illustrates the outcomes of the objective function performed on the different parameters. In Figures 9 and 11 (a), weights were assigned to the parameters in turns. While one of the three parameters was fixed at a time, the other two were allotted weights. As the weight of one parameter increases, there is a resultant decrease in the other.

Furthermore, Figure 9 presents the comparisons of optimization results obtained from different combinations of the three parameters. It reveals that the funding model makes less impact in 5G NPN implementation when compared with the choice of deployment type or cost saving strategies. This is evident in the consistently poor outcomes when δ_2 assumes greater weight against δ_1 and δ_3. However, the comparison of δ_1 and δ_3 presents the best combination of the three parameters and yields the best outcomes.

These optimization results show that funding model is the least significant of the three parameters. This is important in assigning priorities to parameters when considering techno-economic decisions towards the optimum deployment solution for 5G NPN.

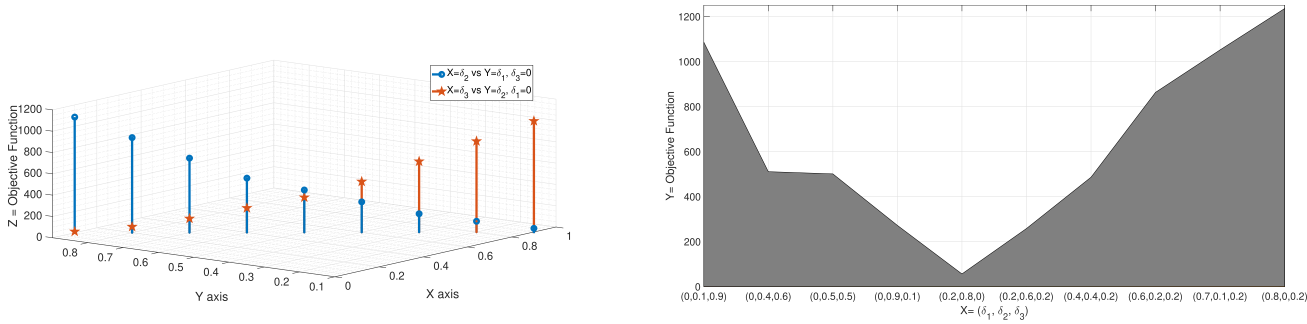
The dominance of δ_1 and δ_3 over δ_2 is made even clearer in Figure 11 (a). The Figure specifically compares the performance of the funding model parameter against the other two parameters. In both comparisons, the poor outcome in the objective function corresponds to increasing weight on δ_2. In this one-on-one parameter comparison, the objective function decline appears linear.

Figure 11 (b) considers the weights of δ_1, δ_2 and δ_3 and presents the boundary of the feasible optimal solution when all three parameters are combined. This result does not reveal the same linear deterioration of the objective function against comparable changes in the weights of δ_2, as recorded when a one-on-one parameter comparison was performed. It means that the introduction of a third parameter alters the outcome of the overall performance ratio, as the figure's objective function result illustrates. Despite δ_2 being the least significant parameter from the earlier results, the worst point, which translates to the narrowest point of the solution area is not when δ_2 has the highest weight. It is evident from the result of Figure 11 (b) that the worst solution point also depends on weights of δ_1 and δ_3. For instance, the interactions of the parameters show that the solution area's worst point, coincides with δ_3 weight $= 0$ and not when $\delta_2 = 0.9$. The solution area tends to be degraded under anyone of two scenarios.

- when δ_2 has highest weight, against low weights of δ_1 and δ_3
- when δ_2 has zero weight and δ_3 has minimum of 80% of the assigned weights

From the above discussions, the following can be adduced.

- The weights of δ_1 and δ_3 both have comparable significance depending on their weights and interactions with those of δ_2. This means deployment types and cost saving strategies are the more significant parameters.



(a) (b)

FIGURE 11. **(a) Outcome of objective comparison. (b) Solution set of the multi-objective optimization.**

- Assigning δ_3 weight $= 0$ is the strong determinant for the worst solution area. It means a techno-economic plan without cost saving strategies is a worst-off solution compared to over dependence on the funding model.
- The best solution area combines weight distribution between δ_1 and δ_3. Optimum solution requires that more weights be assigned to δ_1. Deployment types is the strong determinant for the optimum solution.

C. 5G NPN ADOPTION PREDICTION

The forecast follows the adoption of previous generations of wireless networks in the 1980s and 1990s. More developed economies are projected to adopt private 5G networks earlier than less developed regions of the world. Figure 10 shows a global forecast of the cumulative 5G NPN implementation over a period of 10 years. It reveals the overall private 5G network growth pattern. The deployment curve is consistent with the sigmoid function, which is the S-shaped adoption curve of new technologies [46], [47]. It predicts a rapid 82.2% annual average growth of 5G NPN deployment leading to 2026, when the adoption rate would reach its peak.

The forecast shows that crossing the chasm would occur between 2023 and 2024. This is the tipping point, from when adoption rate would accelerate away from the early adopters heading towards mainstream. Finally, adoption rate is expected to achieve global market stability by 2030, with an annual average adoption rate at 51.95%. With this, enterprises could make informed decisions on the timing and strategy of their 5G NPN adoption. As inherent in most forecasts, there exist the odds of variability in quantification, which also applies to this work, however probable. Variations in available data, impact of the global economic instability induced by unexpected situations such as Covid-19 and civil strife are factors worthy of consideration when checking the probability of the predicted outcomes.

VI. CONCLUSION AND FUTURE WORK

This paper has analysed the technical and economic implications of 5G NPN deployment. To the authors understanding, this is the first paper to specifically address the techno-economic assessment of the emerging 5G NPN. Our consideration has been mainly on the cost elements associated with network deployment. Recently, private 5G networks have started to gain considerable traction because of its potential to improve enterprise solutions and fast-track ROI.

The work articulates a cost model that enabled as much as 53% reduction in TCO, revealing substantial Capex and Opex savings of up to 68% and 77% respectively for NPN shared RAN + Control plane deployment. Using simulations analysis, we identified an order of ranking for 5G NPN deployment parameters in support of enterprise goals amongst trade-offs. Cost saving strategies and the deployment type emerged as the two most critical parameters for successful commercial deployment. Ongoing and future deployment prospects are captured in a 10-year worldwide 5G NPN adoption forecast, which predicts an initial annual average adoption rate of 82.2% with a peak rate towards 2026.

The various cost reductions arising from the use of our model offers real motivation to potential new customers to adopt 5G NPN in preference to the Legacy 5G network. In addition, 5G NPN's ability to customise enterprise solutions unlike the Legacy 5G network, makes NPN more attractive to deploy.

The predicted global penetration of 5G NPN, and the expected surge of big data occasioned by industry 4.0, calls for deeper network analysis. In this regard, future work would focus on innovative methods of monitoring the complex 5G wireless network parameters. The aim is to optimise network performance in order to raise production levels, facilitate operational cost savings, and potentially boost Return Of Investment.

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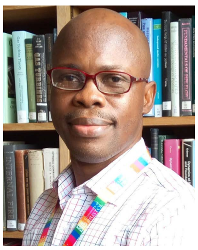

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